Chemical Treatment Methods Pilot (CTMP) System for Treatment of Urban Runoff –
Phase I. Feasibility and Design

Final Report for the City of South Lake Tahoe

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Table of Contents

List of Tables

List of Figures

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List of Abbreviations and Acronyms

Analytes

Al	Aluminum
As	Arsenic
C	Carbon
Cd	Cadmium
Cr	Chromium
DOC	Dissolved Organic Carbon
Fe	Iron
Ni	Nickel
P	Phosphorus
Pb	Lead
Mn	Manganese
N	Nitrogen
SRP	Soluble Reactive Phosphorus (orthophosphate-P)
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen (ammonia plus organic nitrogen)
TSS	Total Suspended Solids
Zn	Zinc

Location Acronyms

CI	Coon, North Shore
GE	Glorene and Eighth, South Shore
S	Stag, North Shore
SG	Shivagiri, North Shore (aka SHV)
SR	Ski Run, South Shore
TC	Tahoe City, North Shore (aka TCW)

Other Technical Terms

ACH	Aliminum Chlorohydrate
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BMP	Best Management Practice
CTMP	Chemical Treatment Methods Pilot Study
Epi/DMA	Epichlorohydrin dimethylamine polymers
ICP	Inductively Coupled Plasma Spectrometry
LICD	Low Intensity Chemical Dosing
mg/L	milligrams per liter (ppm)
NTU	Nephlometric Turbidity Units
O&M	Operation & Maintenance
PAC	Polyaluminum chloride (broad class of aluminum based coagulants)
PAM	Polyacrylamide (anionic coagulant)
PFS	Polyferric Sulfate

Poly-DADMAC	Polydiallydimethyl ammonium chloride
ppm	parts per million (mg/L)
ppb	parts per billion (μg/L)
PAH	Polycyclic Aromatic Hydrocarbons
PCA	Principal Components Analyses
PSD	Particle Size Distribution
QAPP	Quality Assurance Project Plan
QA/QC	Quality Assurance/ Quality Control
SCD	Streaming Current Detector
SCV	Streaming Current Voltage
TMDL	Total Maximum Daily Load
μg/L	micrograms per liter (ppb)

Organizations

Caltrans	California Department of Transportation
DANR	U.C. Davis Division of Agricultural and Natural Resources
EPA	United States Environmental Protection Agency
TERC	U.C. Davis Tahoe Environmental Research Center
TRG	U. C. Davis Tahoe Research Group
UCD	University of California Davis
USDA	United States Department of Agriculture

Registered Coagulants

PAX-XL9	Registered PAC of Kemiron, http://www.kemiron.com/subpage.asp?navid=&id=30
PASS-C	Registered PAC of Kemiron,http://www.kemiron.com/subpage.asp?navid=&id=30
JC 1720	Registered PAC of Jenchem, http://www.jenchem.com/
SumaChlor 50	Registered ACH of Summit Research Labs, http://www.summitresearchlabs.com/_water.htm

Executive Summary

The water quality constituents most likely affecting lake clarity are phosphorus (P) and fine particles (<20 microns). Phosphorus is considered the primary nutrient limiting algal growth in Lake Tahoe. An estimated 75% of the annual load of bioavailable P (as orthophosphate) is mobilized by rain events (Strecker and Howell, 2003). Fine suspended sediments less than 20 µm, commonly defined as clays and fine silt, degrade water clarity at Lake Tahoe by 50% or more.

Within the Tahoe Basin, structural best management practices (BMPs) are widespread (Bachand et al, 2005a). These systems have been deployed and constructed throughout the basin to reduce the amount of stormwater pollution that enters the lake. Several types of structural BMPs have been installed. Hydrodynamic devices designed to remove particulates are the most numerous BMPs. Dry detention basins, infiltration basins, bioretention basins, and water quality swales are also relatively numerous and widespread in the Tahoe Basin. Less common BMP types are the vegetated filter strips, wet ponds and stormwater wetlands.

Many of these BMPs are most effective at removing medium and coarse-grained particles greater then 63 µm (Caltrans, 2001; 2002). The national datasets suggest that these BMPs will not be effective at meeting surface water turbidity standards in the Tahoe basin of 20 nephlometric turbidity units (NTU) (Bachand et al., 2005). Furthermore, these devices are not likely to meet the surface water discharge standard for phosphorus, 100 µg/L, either. In fact, the national dataset suggests that a phosphorus concentration of 100 µg/L is at or below the typical minimum achievable (or irreducible) outflow concentration for many of these structural BMPs (Bachand et al., 2005).

Thus, efforts are currently underway in the Tahoe Basin to test alternative technologies that are more likely to be effective at phosphorus and fine particle removal. One such approach is the use of coagulant dosing of stormwater for treatment prior to discharge into settling basins and wetlands. Coagulation has been used widely for removal of phosphorus from lakes, drinking water and stormwaters (Harper 1994, Harper and Hall, 1999; Welch and Schreive, 1992; Smeltzer 1990; James et al. 1991). Coagulation has also been used to target the removal of fine particles (MacPherson, 2004; Clearwater Compliance Services, 2004). Opportunities exist for applying this technology in the Tahoe Basin as part of newly designed systems or for retrofitting existing basins.

However, several questions arise with the potential application of this technology in the Tahoe Basin. These questions center on issues of effectiveness, feasibility and toxicity effects. This report focuses on an examination of these issues with regard to implementing chemical dosing in the Tahoe Basin. Polyaluminum chlorides (PACs) were the coagulants used.

Performance

Settling columns were used to test the performance of several coagulants for removal of phosphorus and fine particles from stormwater in the Tahoe Basin. These column tests followed-up on earlier laboratory experiments that showed several coagulants provided robust performance with regard to removal of fine particles and phosphorus under varying water quality, temperature and dosing regimes (Bachand et al, 2006; Trejo-Gaytan et al, 2006). The settling columns tested physical and chemical characteristics of the flocculates removed from Tahoe stormwater. The stormwater tested was a composite sample collected from multiple locations in the Tahoe Basin. Several findings and conclusions were drawn from these studies.

Limitations on settling basins and wetlands

The settling columns demonstrated that turbidity, which is composed primarily of very fine particles, persisted for over 72 hours in raw, non-chemically treated stormwater. Settling velocities were calculated and, using Stokes Law, particle sizes were predicted. A settling velocity of about 0.001 cm/s is required for a particle to settle in 3 ft of water over a 24-hour period. These calculations suggested that particles of about 5 μm remained in solution after 40 hours of settling and that *clay and very fine silt could remain in solutions for days to weeks*.

Settling basins and some wetlands therefore have natural limits to the performance they can achieve. Their design is based primarily on physical settling processes and there is usually insufficient time for biotic processes, such as biological uptake and coagulation, to remove all constituents. In fact, settling times greater than 24 hours can be problematic because diel (24-hour period) changes in wind and temperature cause recurrent mixing and density gradients. These processes resuspend particles or prevent the settling of fine sediments (Horne and Goldman, 1994). Thus, particles exported from settling basins and wetlands are likely to be smaller then 10–20 microns, similar to the results observed in our column studies. These are the particles that require greater then 24 hours to settle or are exported because their settling is hindered by diel mixing or density gradients.

Coagulation Effectiveness

Coagulation improved settling times by an order of magnitude. In this study, chemical coagulation removed particles comprising up to 85–95% of the mean turbidity within 10 hours. This removal also included associated phosphorus. By comparison, with non-treated stormwater only 20% of the turbidity was removed after 10 hours of settling, 80% was removed after two days, but 90% removal was never attained during the 72 hours of this study. Stokes Law calculations show that particles remaining in solution were fines of 2.5 μm or less and would require a week or more of settling time to remove. ***Thus, coagulant dosing substantially improved settling velocities, primarily through aggregation of fine particles into larger and more settleable particles.*** Jenchem 1720 and PAX-XL9 were equally effective in removing turbidity and phosphorus for the stormwaters tested. For the stormwater tested, mean turbidity values below 20 NTU were achieved for both of these coagulants after about one hour of settling.

Results from the settling column studies were supported by preceding laboratory studies on a variety of real and synthetic stormwaters. Those studies established that coagulants effectively and robustly decreased dissolved P concentrations to very low levels. Dissolved P achieved median concentrations of around 6 μg/L for the four polyaluminum chlorides (PACs) tested under varying environmental and mixing conditions (Appendix H, Bachand et al, 2006). The settling column studies demonstrated these coagulants also enhanced removal of particulate phosphorus from stormwater, similar to results from the particle settling described above.

Laboratory and settling column studies showed that coagulation can reduce total phosphorus to less than 20–30 µg/L and turbidity below 10 NTU. The current Tahoe Basin turbidity standard of 20 NTU is likely to remain a difficult standard to achieve with most types of open treatment BMPs without coagulant technology or some alternative approach.

Given the order of magnitude increase in particulate settling velocities and improved removal rates for dissolved phosphorus achieved with coagulant treatment, it is likely that an efficiency equivalent to a standard BMP can be achieved with a much smaller footprint of about one tenth the area. Conversely, the same size basin could potentially treat larger hydrologic events of up to ten times greater runoff volume.

Coagulation Robustness

Many polyaluminum chlorides (PACs) had very robust performance (as measured by turbidity and P removal) under a variety of environmental and logistical conditions.[1] PACs are aluminum based polymer chains. Organic nitrogen-based coagulants[2] are often added to inorganic metal-based coagulants by the industry to provide better performance. In this study, these inorganic/organic blends (e.g. JenChem 1720[3]) were relatively less effective at removing phosphorus and reducing turbidity. However, lower dosing concentrations were required to achieve the optimal dosing level for these blends as compared to the optimal dosing level for the PACs. Sometimes dosing concentrations for the inorganic/organic blends were an order of magnitude lower[4] then for the PACs.

Mixing regimes, as defined by intensity and duration of mixing speeds, have been considered an important specification in the industry. Meeting these requirements is more difficult for stormwater systems, as compared to wastewater or water treatment systems, because volumes are highly variable and equipment deployment is not standardized. Fortunately, the performance of PACs was not greatly affected by mixing regimes, although it was found that slow mixing affected performance more then rapid mixing. This was most evident with the less robust coagulants.

Tools to determine appropriate dosing levels

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[1] PAX-XL9 and Pass-C were the most robust coagulants in the laboratory studies conducted for this project with the Caltrans funds (Bachand et al. 2006). These two coagulants performed equivalently.

[2] The primary cationic organic polymers being blended with inorganic polymers are polydiallydimethyl ammonium chloride (Poly-DADMAC) and epichlorohydrin dimethylamine polymers (Epi/DMA). These organic coagulants can have very high molecular weights that can lead to larger, stronger and faster settling flocculate.

[3] Registered polyaluminum chloride blended with an organic coagulant from JenChem.

[4] Dosing levels depend upon the stormwater characteristics and the coagulants. In the Caltrans laboratory studies, JenChem 1720 had a median dosing concentration of less then 1 mg metal/L (mg-Me/L) for all the tested stormwaters (Bachand et al, 2006; Appendix H, this report). Other PACs had median dosing concentrations ranging from around 1 mg-Me/L to about 6 mg-Me/L. The maximum dosing level in the laboratory studies were about 18 mg-Me/L. In the settling column and toxicity tests conducted for this study, PAC dosing levels ranged from 1.4 to over 20 mg-Me/L.

Both stormwater flow and chemistry vary considerably by event and location. Identifying appropriate dosing levels is likely to require more then just dosing to flow rate. In the laboratory studies and the toxicity studies for this project, streaming current detectors (SCDs) were useful for identifying an optimal dosing range for different coagulants and different stormwaters. The SCD measures surface charge to continuously determine the extent of particle destabilization[5] resulting from coagulant dosing. This tool facilitates adjustment of coagulant dosing levels to provide optimal destabilization, thereby minimizing over dosing or under dosing with coagulant chemicals. Streaming current meters have been widely and successfully utilized in water treatment plants (Dentel and Kingery, 1989; Dentel, 1991). In other applications, such as sludge dewatering (Dentel, 1993), their use is increasing. This may be important when low intensity chemical dosing (LICD) is implemented in the field, as stormwater have been shown to be highly variable in chemical characteristics (Caltrans, 2001a; Heyvaert, unpublished data). Based upon our findings and the review of recent practices in wastewater and stormwater treatment, we recommend that use of streaming current meters should be pursued for better identification of optimal dosing regimes and to prevent coagulant overdosing.

Water quality changes from chemical dosing

The PACs minimally affected alkalinity, pH and concentrations of nitrogen, iron and aluminum under optimal dosing levels. However, alkalinity and pH both decrease as dosing levels increase above optimal levels. Coagulant dosing precipitates both dissolved phosphorus species and dissolved organic carbon (DOC). Overdosing increases the soluble and total concentrations of the dose metal (Al) due to incomplete metal utilization and poorer particle settling. In this study, over-dosing did at times lead to total aluminum concentrations in solution that were greater then the EPA recommended water quality criteria of 0.75 mg/L.

Coagulation did not increase concentrations of priority metals such as cadmium (Cd), chromium (Cr), lead (Pb), manganese (Mn), arsenic (As) and nickel (Ni). Soluble zinc (Zn) did increase with coagulation, however.

Implications of coagulant-formed flocculates on long term phosphorus (P) removal

The particles removed from solution after coagulation are fundamentally changed. Particles formed from coagulation of the stormwater seem more thermally stable and more crystalline then the non-treated stormwater particles, suggesting that stable chemical bonds are formed during flocculatation.

Flocculated sediments also may continue to adsorb phosphorus, as aluminum concentrations are likely high in the formed flocs and should exhibit excess P adsorptive capacity.

Toxicity

A number of studies were conducted on stormwater toxicity as well as on the toxicity of coagulant-dosed stormwaters. Table ES-1 shows the results from each of these stormwater

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[5] When particles are destabilized, the surface charge has been neutralized and other phenomena such as interparticle bridging and aggregation of particles by van der Waals forces can then lead to particle aggregation (Stumm and Melia, 1968).

toxicity tests. There are no simple rules with regard to toxicity effects, but some generalizations can be made and these are discussed below.

Effects of stormwaters (without coagulants)

Tahoe Basin stormwaters can be toxic according to a number of metrics. Data from 2004 and 2005 show that non-dosed stormwater caused toxicity to zooplankton reproduction and to fish mortality. More pristine stormwaters from less developed areas tended to have lower toxicity. ***Stormwater effects do not appear consistently across all toxicity metrics. Zooplankton reproduction and fish mortality are the most sensitive metrics to stormwater related toxicity.***

Effects of coagulation

Coagulants under optimal dosing reduce the toxicity of stormwater. Optimal dosing ranges appear to be 0.5 to 1.0 times the dosing level determined as "optimal" by charge titration studies[6], in which a streaming current detector value of zero volts indicates charge neutralization. Half to one times that dosing level (to zero volts) seems to provide good performance and does not appear to introduce any toxicity risks.

Spatial and temporal variations in stormwater toxicity

Stormwater toxicity varies spatially and temporally throughout the Tahoe Basin. The variation in stormwater toxicity is driven by the variations in water chemistry that result spatially from varying land uses and temporally by different types of runoff events and their duration.

Toxicity metrics

Zooplankton reproduction appears to be the most sensitive toxicity metric. Zooplankton reproduction responded to toxicity differences between stormwaters and between dosing levels.

While a single toxicity metric can be used as a conservative indicator of toxicity, it cannot identify the underlying causes of toxicity nor predict the specific toxicity effects on different species.

Constituents relationships with toxicity measured in treated and non-treated stormwaters

Elevated total aluminum concentrations clearly cause toxicity. The observed effect from aluminum is to fish and zooplankton. Decreases in pH and alkalinity also seem to enhance toxicity, with those effects evident across all species tested, to some degree. High concentrations of total suspended solids (TSS) correlate to increased toxicity in zooplankton and fish.

TSS toxicity is likely related to total aluminum concentration. TSS tends to increase when stormwater is overdosed, due to floc formation (Snoeyink and Jenkins, 1980), and is related to increased total aluminum concentrations in the dosed stormwaters. Toxicity from total aluminum and total suspended solids is presumed to be from some combination of physical clogging and

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[6] SCDs estimate an optimal dosing level based upon a zero voltage reading from the unit. The dosing level related to that zero voltage reading corresponds is an estimated optimal dosing level. However, the true optimal dosing level is not exactly identified by the zero voltage level. Rather, the optimal dosing level may be that dosing level or as low as half of that dosing level (Bachand et al, 2006).

interference of biological respiratory or feeding functions, or from chemical adhesion or ingestion of soluble aluminum. ***The exact mechanisms for toxicity have not been identified, however.***

Total and soluble priority metals did not cause toxicity in the stormwaters tested in 2005. Data were not available to make a similar determination from the 2004 stormwaters.

Higher hardness values, particularly due to calcium ions, seem to slightly reduce toxicity to fish. Higher DOC concentrations also appear to reduce fish toxicity.

Table ES-2 identifies constituents most likely associated (either negatively or positively) with the different toxicity metrics.

Wildcards

First flush stormwaters greatly increased fish mortality to levels much higher then those observed for any of the other stormwaters, treated or non-treated. The stormwater constituents causing this toxicity were not determined. However, coagulation did not reduce the toxicity of first flush stormwater, indicating that constituents causing this toxicity were unaffected by coagulation. Possible causes of toxicity could be oil and grease, unusually high concentrations of priority metals, or the presence of Polycyclic Aromatic Hydrocarbons (PAHs), etc.

Means to minimize toxicity

Dosing coagulants at 0.5 to 1 times the optimal dosing level, as indicated by a streaming current detector, is expected to minimize or eliminate toxicity associated with coagulation.

Other measures are suggested to help minimize toxicity:

- ***Keep outflow total aluminum concentrations below the EPA recommended water quality criteria of 0.75 mg/L (through management of dosing levels);***
- ***Adjust pH in outflow towards 7;***
- ***Maintain alkalinity above 35 Ca-mg/L;***
- ***Maintain DOC concentrations above 2 mg/L; and***
- ***Keep TSS levels in outflow below 80 mg/L.***

Optimizing the dosing levels would be expected to help achieve the above criteria.

Conceptual Design and Logistics

Dosing control, hydrology and toxicity management are the key issues associated with implementing this LICD technology. Effective phosphorus, turbidity and particulate removal would be expected to occur in a properly implemented system.

Dosing control

Effectiveness and minimized toxicity both depend upon proper dosing levels. Stormwater flow and chemistry vary spatially and temporally, so dosing control implies at least a minimum level of control in order to dose according to flow and chemistry. Streaming current detectors (SCDs) appear to be effective at indicating a proper dosing level. ***So the use of a SCD and a flow meter should be sufficient to provide the data needed for developing a coagulant dosing regime.***

Additional safety features may be needed to manage dosing levels. High total aluminum concentrations and low pH both correlate with toxicity, so monitoring these variables post-treatment would provide a means to better manage downstream toxicity and would provide extra safety against over-dosing.

Hydrology

Coagulant dosing is likely to provide much improved performance over non-dosed basin and wetland treatments. This improved performance, estimated at an order of magnitude, suggests that basin sizes could be made smaller and still have the capacity to treat equivalent water volumes. This provides opportunities in design flexibility, including the implementation of equalization basins to store stormwater and then meter the flow to treatment systems. These designs would allow a basin area to increase the treatment volumes for storm events from three to ten times larger. Appendix F discusses the conceptual design to achieve these results.

Toxicity

Toxicity will be an issue if coagulant dosing is implemented. ***Dosing with aluminum based coagulants can greatly increase toxicity under over-dosed conditions.*** We discussed water quality objectives to minimize those risks and have discussed instrumentation needs to manage dosing levels. ***Essentially, minimizing toxicity will mean consistently managing dose and monitoring the constituents that indicate overdosing.***

Aside from these mechanical means to better control toxicity, the implementation of treatment wetlands downstream also may help to mitigate toxicity. Stormwater polishing with constructed stormwater wetlands could be one downstream method to help manage toxicity by removing additional coagulant pin-flocs and buffering coagulant reactions.

Experimental Studies Needed and their Costs

We propose an experimental approach to move forward with this LICD technology. This would consist of two complementary methods. The first recommended approach would be a small-scale mobile system to experiment with optimizing coagulant dosing methods at a scale that is more representative of full-scale applications. These tests would investigate processes that are energy or flow dependent, such as mixing regimes and methods to improve flocculate aggregation. The second recommended approach would be a replicated mesocosm system to test processes that are time dependent, such as the flocculate settling times, changes in water quality or sediment chemistry overtime, and time related effects on toxicity. These experiments are discussed in greater detail in Appendix G, and should be conducted before full-scale implementation of coagulant technology.

Appendix K presents a cost worksheet for implementing the experimental studies. The estimated costs to implement those studies as discussed above would be about $2 million dollars. This study would be planned for 3.5 years.

Estimated Costs for Full-Scale Implementation

Estimated costs for the full-scale implementation of this concept are presented in Chapter 4. Appendix F details the estimated costs for implementing a design option considered most promising at the Ski Run, Osgood and Wildwood basins complex. These basins cover approximately 8 acres and currently intercept urban runoff from the East Pioneer Trail Watershed (Lumos and Associates, 2006). The proposed design includes an equilibrium basin, a chemical dosing system and a treatment basin. Table F-6 in Appendix F shows the assumptions used for developing these cost estimates. Some important assumptions and constraints for the estimate are listed below:

- Capital costs included estimates for the chemical dosing system, for building of the ponds and demolition, and for O&M with chemical dosing are based on the actual costs of dosing systems constructed in Florida during the 1990s (Harper et al. 1999). Wetland and pond costs are based upon costs for the Bay Area. Pond costs include those costs anticipated for installation of raceway mixing zones and filtration zones to improve coagulant effectiveness and flocculate settling rates.
- Land costs and sediment disposal costs were not included in the estimated costs. Too many unknowns exist:
    - The rate of sediment accretion[7];
    - The chemistry of the sediments and the dilution with organic carbon; and
    - Resulting toxicity from the accreted sediments in the stormwater treatment basins and wetlands and the potential impact on the downstream waters.

These unknowns make it impossible to estimate the costs without further experimental studies. Formed flocculates were assumed to accrete in the stormwater basins at a rate of one foot over a 20 to 30 year period.

- A 20% contingency was applied to all estimates.
- Monitoring costs were estimated for bi-weekly sampling of key constituents (e.g. P, turbidity, and pH) and for flow monitoring.
- All costs have been converted to 2007 dollars using a 3% annual increase.
- Engineering costs were assumed to be 15% of the construction costs.

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[7] Bachand et al (2000) predicted accretion rates due to coagulation on the order of one foot every 20 to 30 years. This estimate is for stormwater treatment upstream of the Everglades under continual dosing. Accretion rates cannot be easily predicted from that study for several reasons. Prime among these are different coagulants are being considered, these systems will likely have intermittent dosing, and the water chemistry is much different.

Based upon the assumptions used, capital costs estimated for this project were about $406K for construction of the treatment ponds and wetlands, the stormwater dosing system and the electrical power modifications. Instrumentation installation was an addition $15K. Including contingencies and engineering and design costs, the total capital costs were estimated at about $600K.

Associated Operation and Maintenance (O&M) costs are estimated at about $50K. These costs are for all O&M costs associated with the treatment ponds and wetlands, and for the chemical dosing system. O&M costs are essentially split down the middle between the ponds and wetlands, and the dosing system.

Annual monitoring costs are estimated at about $40K. These costs include regular sampling of regulated discharge parameters (e.g. phosphorus, turbidity, and pH), flow monitoring, and an additional lump sum for other water quality parameters, not defined here.

Assuming a 3% interest rate, the 20-year Present Worth cost is about $2 Million.

The Bottom Line on Chemical Dosing

- Effective implementation of coagulant dosing using PACs should improve turbidity and phosphorus removal rates by an order of magnitude.
- Improved treatment could conceivably result in a much smaller required treatment footprint for an equivalent treatment performance.
- Tahoe Basin urban stormwaters produced positive response to the toxicity metrics used in these studies.
- Zooplankton reproduction was shown to be the most sensitive metric for assessing toxicity of non-dosed stormwaters and coagulant dosed stormwaters.
- Stormwater released under appropriate and controlled dosing regimes will have a lower toxicity than untreated stormwater.
- Improper dosing levels would likely worsen toxicity for some organisms.
- Hydrology is an important consideration in coagulant dosing, and incorporating a means to manage flows will be an important consideration in developing effective design facilities.

Table ES- 1. Responses of toxicity metrics to different tests conducted on 2004 and 2005 stormwaters.
The effects of stormwater, coagulant type, coagulant dose and floc management were studied under this project. Below we identify the results on ANOVA showing if there were statistically significant effects (Y = Yes, N = No effect, Y+ = Positive effect, Y- Negative effect).

Goal	ANOVA	Treatments			Stormwater Effects					Coagulant Effects					Floc	
	Test	Storm water[3]	Coag.[2]	Floc[4]	Algae	Zooplankton		Fish		Algae	Zooplankton		Fish		Zooplankton	
					Count	Repro.	Mort.	Bio.	Mort.	Count	Repro.	Mort.	Bio.	Mort.	Repro.	Mort.
May 2004																
1 Differences between non-dosed stormwaters and a control.	2-way, post hoc analyses	SR,S, TCW, C	none	De	Y - [10]	Y +/- [10]	N	N	Y - [10]							
2 Differences between non-dosed stormwaters	2-way, post hoc analyses	SR,S, TCW	none	De	Y	Y	N	N	Y							
3 Toxicity differences: different coagulants x different stormwaters	2-way	SR,S, TCW, C	none, PAX, SUM, JC[7,8]	De	Y	Y	Y	Y	Y	Y +/-[9]	Y -	Y +/-[9]	N	N		
Mar 2005																
1 Differences between non-dosed stormwaters and a control.	1-way	SR, S, TCW, SHV, C	0x	De	N	Y	N	N	Y							
2 Effects of optimal dosing on stormwaters with a polyaluminum chloride (PAX-XL9) and a chitin based coagulant (Chitison)	2-way factorial	SR, S, TCW	0x, 1x[6]	De	N	Y	Y	N	Y	Y +	Y +	N	N	N		
3 Effects of over-dosing on stormwaters	2-way factorial	SR, S, TCW	0x, 0.5x, 1x, 2x, 3x	De	N	Y	Y	N	Y	Y -[1]	Y -[1]	Y -[1]	Y -[1]	N		
October 2005																
1 Effects of over-dosing on stormwaters and testing if floc removal reduces toxicity.	3-way factorial	SR, S, TCW	1x, 2x, 3x	De, Fi		N	N				Y -[1]				Y+[5]	Y+[5]

1. At over-dosing of 2x and 3x optimal dose
2. Multiple of dose determined for SCD = 0 V.
3. SR = Ski Run, S= Stag, TCW = Tahoe City Wetland, SHV = Shivagiri, C= Control
4. Floc treatment: De = decanted after coagulation and settling. Fi = Filtered after coagulation and settling.
5. Zooplankton reproduction improved and mortality decreased when flocculate was removed through filtration.
6. Dosed at 1x with Chitosan and PAX-XL9
7. PAX = PAX-XL9, SUM = Sumachlor 50, JC = Jenchem 1720.
8. Coagulant dosing was not optimized using SCD. Dosing was estimated using jar tests.
9. Increased or decreased toxicity effect depending upon coagulant and dosing level.
10. Toxicity metric measured in stormwater when compared to control (- means worsened, + means improved).

Table ES- 2. Summary of variables implicated in toxicity

	Correlation, number and probability[2]					Source[1]	
	Algal Cell Count	Cerio Reproduction	Cerio Mortality	Fish Biomass	Fish Mortality	Coag.	StormW.
Dose mg-Me/L		🟨	🟨			🟩	
pH	🟨	🟨	🟨		🟨	🟩	
Alkalinity		🟨	🟨		🟨	🟩	
Soluble Ca				🟨			🟩
Total Fe		🟨		🟨			🟩
Total Al		🟨	🟨	🟨	🟨	🟩	🟩
TSS		🟨		🟨		🟩	🟩
Turbidity		🟨				🟩	🟩
DOC					🟨	🟩	🟩

1. Shaded area indicates possible source of analyte affecting toxicity.
2. Highlighted items are those expected to be most likely affecting the toxicity metric based upon a review of the data.

1. Introduction

This report presents results from a feasibility study on implementing a Chemical Treatment Methods Pilot (CTMP) system in the Tahoe Basin to treat stormwater. The specific approach studied in this report is an application of Low Intensity Chemical Dosing (LICD) of coagulants to treat stormwater entering treatment basins or wetlands. Three USDA Forest Service grants provided the initial seed funding for this study and were matched by funds from the California Department of Transportation (Caltrans). Results from the Caltrans study can be found in our final report (Bachand et al. 2006), as summarized in Chapter 2 here. USFS Grants 02-029 and 03-040 supported the work conducted to test this LICD technology in settling columns, as well as the initial toxicity assessments, site identification for implementing replicated mesocosm-scale field studies, and preliminary experimental and conceptual designs for implementing the technology. USFS Grant 05-038 supported additional toxicity investigations.

The hypothesis behind this technology is that coagulant dosing will precipitate dissolved phosphorus and aggregate those particulates and other fine particulates, and that these processes will improve the removal of total phosphorus and fine particles beyond levels achievable with current structural Best Management Practices (BMPs) being installed throughout the Tahoe Basin.

Current stormwater BMPs such as stormwater wetlands and basins are unlikely to remove sufficient quantities of fine particles and dissolved phosphorus to consistently meet current and future regulatory objectives. Centralized stormwater treatment facilities, on the other hand, could be designed to effectively remove phosphorus and fine particles, but are likely to be an expensive approach. The LICD technology studied in this report is considered an intermediate approach, which is expected to be more expensive and more effective then most standard structural BMPs, but less expensive then a treatment plant.

This report consists of four chapters. Chapter 1 is this introduction to the overall study design. Chapters 2 through 4 will focus on key issues regarding the feasibility of using coagulants in the Tahoe Basin to remove fine particles and phosphorus from urbanized stormwaters, including –

- An evaluation of the effectiveness of coagulants for fine particle and phosphorus removal (Chapter 2);
- The potential ecotoxicity or ecotoxicity concerns associated with raw and coagulant dosed stormwaters (Chapter 3); and
- A conceptual approach for furthering LICD technology, including a discussion of the supporting experimental investigations that are recommended (Chapter 4).

Each of the above chapters summarizes key information from the detailed studies and investigations conducted as part of this study. Manuscripts written to describe individual experiments and the Caltrans reports are all included in the appendices of this report. These appendices provide the details of analyses associated with this LICD project's studies and investigations.

Thus, Chapter 2 summarizes our findings regarding coagulant effectiveness and draws on data from the following appendices:

- Appendix A - summary of the laboratory studies on coagulant effectiveness and robustness, conducted under the Caltrans grant.
- Appendix B - detailed analyses of the settling column studies. These studies provided a larger-scale environment for assessing physical flocculate characteristics.
- Appendix H - final report from the Caltrans study.

Chapter 3 summarizes our findings regarding ecotoxicity from the following appendices:

- Appendix C - initial investigation of raw and dosed stormwater ecotoxicity testing for three coagulants that were among the most effective and robust, as tested by Trejo-Gaytan (2006) and Bachand et al. (2006). These tests were conducted on stormwater collected in 2004.
- Appendix D – a follow-up investigation using stormwaters collected in 2005 to test the effects of different LICD levels; this includes comparing an optimally dosed PAC to a chitin-based coagulant with regard to toxicity effects.

Chapter 4 discusses conceptual design issues as they relate to implementing the LICD technology. This chapter draws from a number of appendixes:

- Appendix F – presents a vision for implementing this technology full-scale at the Osgood (aka Ski Run) Basins in South Lake Tahoe.
- Appendix G - discusses smaller scale studies needed to move forward.
- Appendix K - provides cost estimates for moving forward with the technology.

Finally, Appendix J assembles most of the data associated with this project.

The Executive Summary at the beginning of this document summarizes and integrates the key findings from this report. It also provides recommendations on the next steps needed if the regulatory and planning community in the Tahoe Basin decides that LICD technology is a treatment alternative worth pursuing.

2. Coagulant Effectiveness

2.1. Introduction

In the Tahoe Basin, surface water discharge limits of 20 NTU for turbidity and 0.1 mg/L for total phosphorus are currently in effect (LRWQCB, 2003) and are likely to be strictly enforced by 2008 (Regenmorter et al., 2002). Dissolved phosphorus standards of 0.1 mg/L are currently regulated under Chapter 81 of the TRPA Code of Ordinances for surface water discharge (TRPA, 2001). And the 1981 208 Plan/SWRCB Water Quality Control Plan has turbidity discharge threshold for stormwater of 20 NTU (TIRRS, 2001). These metrics are indicators of fine particle and bio-available phosphorus loading, two constituents considered to be the main causes of decreasing clarity in Lake Tahoe (Reuter and Miller 2000, Swift et al. 2006).

Stormwater in the Tahoe Basin is being managed through better source control and by treating stormwater with a variety of structural Best Management Practices, such as stormwater basins and constructed wetlands. However, these standard treatment BMPs are designed primarily for hydraulic control and for removing solids and associated pollutants. While such practices generally can improve the quality of stormwater, they are not necessarily optimal for removal of soluble phosphorus or fine particles, especially under the environmental constraints typical of the Tahoe Basin. These constraints include a variety of subalpine runoff conditions (e.g. rain on snow, high intensity rain storms, and snowmelt), a wide range of water quality characteristics, flow rates and temperatures over the year, and relatively limited areas appropriate for the installation of basins and similar treatment BMPs.

This project has investigated the feasibility of an alternative approach, which involves the use of coagulant dosing upstream of a treatment BMP to improve the removal of fine particles and dissolved phosphorus. This approach is similar to technology currently in use to treat wastewater for removal of solids and phosphorus (Metcalf & Eddy, 1979; Snoeying and Jenkins, 1980; Gothenburg Symposium 2007). There are also examples where chemical dosing has been used in natural systems to remove phosphorus and control eutrophication. Alum addition, for example, has been used on a number of lakes and reservoirs in Florida, Washington, Vermont, Wisconsin and New Jersey to control eutrophication (Harper 1994; Welch and Schreive, 1992, Jacoby et al. 1994; Smeltzer 1990; James et al. 1991).

These dosing technologies have relied on two basic processes to specifically target removal of solids and phosphorus. Coagulation precipitates the dissolved phosphorus into a particulate form, through chemical reactions between phosphorus and the metal in the coagulant. For instance, with aluminum based coagulants, aluminum oxides and aluminum phosphates are the predominant flocculent solids formed. During this process, charge neutralization also occurs. Dissolved phosphorus, dissolved organic carbon and particulate organic matter are anionic (negatively charged). The addition of cationic (positively charged) coagulants neutralizes this charge and allows small particles to flocculate and aggregate, leading to larger and more settleable particles. These two fundamental processes allow chemical coagulation techniques to target dissolved phosphorus and fine particle removal. Dissolved constituents are usually defined operationally as what passes through a 0.45 micron filter, generally used to separate the dissolved from particulate constituents in water quality samples.

The application of coagulant technologies is relatively novel for treating stormwater. Bachand et al. (2000) implemented mesocosm studies in the Florida to for *in situ* removal of phosphorus in stormwater wetlands. Harper et al. (1999) reported on the use of alum to treat stormwater in Florida in the late 1980s through late 1990s for removal of total phosphorus, heavy metals and particulate associated pollutants such as fecal coliform. More recently, chitosan has been used at construction sites to remove sediments (MacPherson, 2004; Clearwater Compliance Services, 2004).

For this study in the Tahoe Basin, specific constraints were considered. In particular, this approach sought to dose chemicals at the lowest feasible concentration for effective removal of dissolved phosphorus and fine particles. While coagulation is effective over a range of dosing levels, this project sought to dose at the lowest range in order to minimize coagulant usage and maintenance costs associated with accumulation of flocculent, as well as to minimize the potential environmental issues associated with coagulant use and concentration.

Second, this proposed technology was planned for use in combination with treatment wetlands. Treatment wetlands at Tahoe have been shown effective for reducing dissolved phosphorus to low concentrations and for improving the removal of particulates by creating more quiescent conditions (Heyvaert et al. 2006). Wetlands can also act as water polishers, by removing other pollutants, like trace metals, and neutralizing some toxicants (Kadlec and Knight, 1996).

Third, stormwater chemistry varies spatially and temporally throughout the Tahoe Basin because of relatively steep landscapes, different kinds of runoff events, wide variation in temperature, differences in land use, and a number of other factors. Stormwater chemistry at any site in the Tahoe Basin can vary dramatically depending upon the type of runoff event and when the last runoff event occurred. Thus, environmental conditions in the Tahoe basin require that a treatment system be sufficiently flexible and robust so as to treat a variety of stormwaters, each with potentially unique chemistry.

This study investigated the feasibility of a low intensity chemical treatment process to target dissolved phosphorus and fine particle removal from stormwater in the Tahoe Basin. A variety of coagulants representing a broad spectrum of available products was investigated, using a series of laboratory and mesocosm studies. All four coagulants selected for final testing in the laboratory studies were found effective at meeting surface water discharge limits for total phosphorus and turbidity: JenChem 1720[8], Pass-C[9], PAX-XL9[10] and SumaChlor 50[11].

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[8] Registered coagulant of JenChem.
[9] Registered PAC of Kemiron. Used in early Caltrans studies.
[10] Registered PAC of Kemiron.
[11] Registered coagulant of Summit Research Labs Wastewater Treatment Division

2.2. Approach

Laboratory and mesocosm studies were conducted to investigate the feasibility of chemical coagulants. The laboratory experiments consisted of a combination of jar studies and charge titration studies, which had several goals:

- To identify effective coagulants for chemical dosing;
- To determine if streaming current detectors provided a reasonable indicator for optimal coagulant dosing; and
- To determine coagulant performance robustness with regard to various operational and environmental factors (e.g. water chemistry, temperature, and mixing regimes).

Mesocosm studies were conducted using settling columns, and were designed to transfer the results of the laboratory studies to a larger scale with more realistic operational and settling conditions.

2.3. Key findings

Specific results from the laboratory and mesocosm studies are provided in the Appendices:

- Appendix A gives a summary of the laboratory studies;
- Appendix B gives the results from settling column studies; and
- Appendix H provides the full Caltrans report that provided a preliminary examination of coagulant characteristics.

The following section does not intend to discuss the details or results of these specific studies. Rather it focuses on identifying the key findings, and refers to appendices and specific studies where needed.

2.3.1. Limitations on the effectiveness of basins and treatment wetlands for removing fine particles

Settling column experiments used in this study demonstrated the limitations of fine particle removal in standard detention basins. Based upon Stokes law, settling times are inversely and exponentially related to particle diameter, so the smaller particles require increasingly longer times to settle from a water column. Deposition of larger particles accounts for the initial rapid removal of high turbidity, but smaller particles remain in suspension much longer so the turbidity improvement slows dramatically.

Regenmorter et al. (2002) found that in runoff from highways, the stormwater particles generally ranged from 100 to 2000 μm. After treatment by sediment traps, the particle size distribution changed, with twenty percent of the mass represented by 10 μm particles or smaller. Further, turbidity-causing particles were generally in the range of 0.001 (colloidal) to 10 μm (see also Caltrans, 2006a).

For stormwater collected from several sites around the Lake Tahoe Basin turbidity values decreased by about 80% after 24 hours of settling in a 3 foot water column. Based on Stokes Law, we estimated that the particles remaining in solution after 24 hours of settling were less then 6 microns in size. After 72 hours, the turbidity values had only decreased to 40 NTU, still about twice the surface discharge standard.

Settling velocities of just over 0.001 cm/s correspond to a 24-hour settling period in three feet of water. Particles with these velocity characteristics are likely to be exported from settling basins because settling times in excess of 24 hours are problematic in most open surface basins. That is due to the temperature gradients and wind mixing events that tend to occur on a diel (24 hour) basis. For the stormwaters we tested, approximately 40% of turbidity resulted from particles with settling velocities less than then 0.001 cm/s (Figure 4-8).

2.3.2. Chemical coagulant effectiveness for removing phosphorus and fine particles

Settling processes are not the only mechanism in natural systems that remove particles and associated pollutants. Other processes such as natural coagulation, zooplankton grazing and bacterial mineralization also enhance fine particle removal (Weilenmann et al., 1989). Reuter et al. (2000) attributed the removal of finer particles in Lake Tahoe to some of these same biotic processes. Unfortunately, stormwater BMPs are not usually designed to fully exploit these natural processes. They are not typically complex biologically, and may have insufficient hydraulic residence time for the processes to contribute significantly toward fine particle and pollutant removal.

Chemical coagulation could potentially provide some of these benefits, similar to natural processes. Chemical coagulation would target phosphorus and fine particle removal through precipitation and subsequent flocculation and aggregation. The benefits of these processes are demonstrated in the settling column studies (Table 2-1). Chemically-treated stormwaters had resulting phosphorus levels under 15 µg/L after 72 hours of settling, which was well below the initial concentration of 339 µg/L. Turbidity levels averaged less than 2 NTU from an initial value of 225 NTU. These results stand in sharp contrast to the non-chemically treated stormwaters. After 72 hours of settling, non-treated stormwaters still had phosphorus levels of about 30 µg/L and turbidity levels of about 34 NTU. These results are likely not atypical for Tahoe stormwaters. Laboratory studies with the jar tests gave similar results (Caltrans, 2006b in Appendix H this report).

Table 2- 1. Resulting water quality after chemical dosing for stormwater from the Tahoe Basin.

Data is from 72 hours after dosing and sampled from three points vertically distributed in the settling columns. Three replicates were used per treatment. Stormwater had initial (t = 0) mean turbidity of 225 NTU, mean UTP of 339 µg/L and mean FTP of 8 µg/L.

Analytes[2]	No Treatment				Stormwater Treated with Coagulants at Jar Test Determined Dose											
					J1720				PXXL9				SUM50			
	Means[1]	N	SD	p<0.05	Means[1]	N	SD	p<0.05	Means[1]	N	SD	p<0.05	Means[1]	N	SD	p<0.05
Turbidity NTU	33.8	6	4.2	b	1.2	9	0.4	a	1.2	9	0.2	a	1.8	9	0.2	a
UTP ppb	30.0	6	2.9	b	5.8	9	1.2	a	13.2	9	12.3	a	9.1	9	6.1	a
FTP ppb	7.0	6	2.5	a	2.7	9	2.0	a	7.6	9	12.8	a	4.8	9	4.1	a
TKN ppm	0.7	4	0.2	b	0.5	6	0.1	ab	<RL	6	NA	a	0.5	6	0.1	ab
FTKN ppm	0.7	4	0.3	NA	<RL	6	NA	NA	<RL	6	NA	NA	<RL	6	NA	NA
Alkalinity mg/L	35.5	4	1.2	c	33.9	6	0.3	b	28.0	6	0.6	a	33.5	6	0.2	b
UAL ppm	1.2	4	0.4	b	<RL	6	NA	a	<RL	6	NA	a	<RL	6	NA	a
UFE ppm	1.0	4	0.4	b	<RL	6	NA	a	<RL	6	NA	a	<RL	6	NA	a
FAL ppm	<RL	4	NA	a	<RL	6	NA	a	<RL	6	NA	a	<RL	6	NA	a
FFE ppm	<RL	4	NA	a	<RL	6	NA	a	<RL	6	NA	a	<RL	6	NA	a

[1] RL=Reporting Limit. Metals = 0.1 mg/L. TKN =0.5 mg/L

[2] UTP = Unfiltered total P. FTP = Filtered Total P. UAL = Unfiltered Total Al. FAL = Filtere Total Al. UFE = Unfiltered Total Fe. FFE = Filtered Total Fe.

Chemical coagulation should greatly increase both particle (floc) size and settling velocities, and should improve stormwater basin performance by an order of magnitude for many stormwaters. This study showed that with coagulation 85 to 95% of mean turbidity was removed within 10 hours. This removal included the associated phosphorus. Settling velocities for particles removed within that time period were greater then 0.002 to 0.02 cm/s, depending upon the coagulant used. By comparison, for the non-treated stormwater, only 20% of the turbidity was removed after 10 hours of settling, 80% was removed after about 2 days, and 90% removal was never attained during the 72 hours of the study. Settling velocities for the non-treated stormwater were estimated at only 0.0002 to 0.00035 cm/s after 10 hours.

Thus, coagulation increased settling velocities and decreased settling times by over an order of magnitude. Using the calculated settling velocities, we predicted that 90% turbidity removal from the non-treated stormwater would occur by settling on the order of hundreds of hours, and the particles remaining in solution would be submicron to a few microns in size. Natural coagulation and biotic process are likely to hasten settling at some point, although removal by those processes is expected to be on the order of days to weeks.

The increase in settling velocities with coagulation is attributed mainly to increased particle size. Particle sizes calculated from Stokes Law showed an increase in size by orders of magnitude with coagulation, and these greater particle sizes promoted lower NTU values.

Jar tests were used to model coagulant performance with regards to phosphorus and fine particle removal for full-scale systems. This approach is common to the water and wastewater treatment industries with regard to predicting appropriate dosing levels and resulting performance. In these studies, both natural and synthetic stormwaters were tested with a variety of coagulants. The synthetic stormwaters were blended to have turbidity and phosphorus levels typical of the range found in natural stormwaters around the Tahoe Basin. The coagulants effectively removed both fine particles and phosphorus in these experiments.

In reviewing all the laboratory data from these studies, one conclusion is that turbidity standards will be more difficult to achieve then phosphorus standards using coagulant technology.

2.3.3. Robustness of coagulants to environmental and operational conditions

Coagulant robustness and performance were assessed in additional laboratory studies. These tests were conducted on four coagulants: SumaChlor 50, JenChem 1720, Pass-C and PAX-XL9. Based upon an assessment of their performance in treating the synthetic Tahoe stormwater, these four coagulants were selected from a broader list of 25 coagulants, representing –

- Proprietary and non-proprietary products;
- Aluminum and iron based coagulants;
- Chemically simple coagulants such as alum and ferric chloride and polymeric blends (PACs, ACHs);
- Organic polymers;
- Inorganic and organic polymer blends; and
- Chitin based coagulants.

The four selected coagulants represented distinct coagulant chemistries and different use histories:

- SumaChlor 50 is an ACH, the simplest and essentially non-proprietary PAC;
- JenChem 1720 is an organic (nitrogen-based) and inorganic (aluminum-based) polymer blend;
- Pass-C is a sulfinated PAC and has been extensively used in Caltrans studies; and
- PAX-XL9 was a more locally available PAC with slightly different chemistry then Pass-C[12].

More information on these coagulants can be found in the complete Caltrans report in Appendix H.

Two polyaluminum chlorides (PACs), PAX-XL9 and Pass-C, were determined to be the most effective and most robust coagulants in our studies. These coagulants are sulfinated, medium to medium-high basicity coagulants. The performance of these coagulants with regard to

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[12] PAX-XL9 is a Kemiron product. Kemiron produces this product on the West Coast. Pass-C was a product from a Canadian Company. Since this work was completed, Kemiron has bought the manufacturer of Pass-C.

phosphorus and turbidity removal was minimally affected by changes in temperature, mixing regimes, storm water quality and dose.

The robustness of coagulation is dependent upon the type of coagulant and other variables. Several variables were tested to determine their effect on coagulant performance:

- Stormwater source, by selecting stormwaters from the northern and southern areas of the Lake Tahoe Basin at different times of the year, as well as by using synthetic stormwaters created with road sweepings;
- Water temperature;
- Mixing regime, with different rapid mix rates and different slow mixing times; and
- Dosing levels, by testing levels near optimal (determined using a streaming current detector) as compared to over-dosing levels.

For the better coagulants, these factors minimally affected performance in the laboratory studies of phosphorus and turbidity removal. Less effective coagulants were more affected by these variables.

Many PACs had very good performance over a broad dosing range, though at more optimal dosing ranges (as determined by the streaming current detector – See Section 2.3.4) they generally gave better performance. Organic nitrogen-based coagulants are often added to inorganic metal-based coagulants in the industry to provide better performance. These inorganic/organic blends (e.g. JC 1720) were relatively less effective in removing phosphorus and at reducing turbidity in the Tahoe test applications. However, lower dosing levels were required for optimal dosing as compared to the PACs. Sometimes dosing levels were an order of magnitude lower.

Mixing regimes, as defined by intensity and duration of rapid and slow mixing speeds, have been considered an important specification in the industry. Meeting these requirements is more difficult for stormwater systems as compared to wastewater or water treatment systems because volumes are highly variable and equipment deployment is more challenging. The performance of PACs was not greatly affected by mixing regimes. Slow mixing affected performance more then rapid mixing, and this was more evident with the less robust coagulants

2.3.4. Tools to determine appropriate dosing levels

Both stormwater flow and chemistry can vary greatly by site and event. Identifying appropriate dosing levels is likely to require more then just dosing according to flow rate. Streaming current detectors were found to be useful for predicting an optimal dosing range for different coagulants and different storm waters.

Streaming current meters have been widely and successfully utilized in water treatment plants (Dentel and Kingery, 1989; Dentel, 1991) and in other fields, such as sludge dewatering (Dentel, 1993). Their use is increasing. The current meter measures surface charges of suspended particles based on the streaming current principle. Data from the current meter can be used to continuously monitor the extent of particle destabilization and then adjust coagulant dosing to provide optimal destabilization, thereby minimizing overdosing or under-dosing of chemicals. When particles are destabilized, the surface charge is neutralized and other phenomena such as interparticle bridging and aggregation of particles by van der Waals forces can then lead to particle aggregation (Stumm and Melia, 1968). This characteristic may be important if LICD is implemented in the field. Stormwater has been shown to be highly variable in chemical characteristics (Caltrans, 2001a; Heyvaert, unpublished data), so a streaming current meter may be useful for identifying optimal dose and thereby helping to prevent coagulant overdosing. Similar instrumentation will likely be needed for larger scale stormwater treatment applications.

2.3.5. Water quality changes from chemical dosing

The PACs minimally affected alkalinity, pH and concentrations of nitrogen, iron and aluminum under optimal dosing levels, although alkalinity and pH decreased proportionally with dosing level.

Overdosing was investigating using the coagulant PAX-XL9. Overdosing increased soluble concentrations of dosed metal due to the usage in excess of metal required for efficient coagulation. This was more important for coagulants that require higher dosing levels of aluminum to achieve charge neutralization. For instance, with the inorganic/organic blends the increased concentrations of soluble aluminum were small because such low doses of aluminum were used. But for coagulants such as PAX-XL9 and Pass C, which required higher aluminum dosing levels to neutralize charge, the soluble aluminum concentrations increased from around 0.25 mg/L to over 1 mg/L with a dosing increase of about 2–3 mg-Aluminum/L above the zero charge (optimal) dosing level.

Effects on ecotoxicity are discussed in the next section.

2.3.6. Implications of formed flocculates on long-term P removal

The particles removed from solution after coagulation are fundamentally changed. In our analyses of a subset of particles formed from coagulation of stormwater, the particles formed from coagulation were more thermally stable then the particles in non-treated stormwater, suggesting that stable chemical bonds form during flocculation. Whereas particulates from freeze dried natural stormwater samples had amorphous structure, the flocculates from chemical treatment showed increased crystallinity (Figure 4-11), i.e., more structure and presumably more stability.

The sediments formed by coagulation and flocculation may have additional P adsorptive capacity. Bachand et al. (2000) conducted coagulant dosing with *in situ* mesocosm studies in the Everglades Nutrient Removal Project, a large constructed wetland built for stormwater treatment. In these studies, stormwaters with P concentrations near or below 100 µg/L were dosed with coagulants to remove P through precipitation. They found that the percent of aluminum and humic bound phosphorus in the very top layer of soils increased above background levels in these mesocosm studies after an experiment in which stormwater was dosed with alum for 8 months. These formed flocs had P:Al ratios below equilibrium ratios, suggesting that the floc formed sediments would also have excess P adsorptive capacity. Ullman (1999) showed that much of the flocculate formed initially from coagulation was amorphous (oxalate extractable fraction) and therefore had high P uptake capabilities (Baskaran et al., 1994; Sakadevan and Bavor, 1998, Reddy et al., 1995). Thus, sediments formed from flocculation would be expected to have high uptake P uptake capacity and to continue to adsorb phosphorus from surface waters and to suppress an upward flux of phosphorus from the soils or a downward flux to groundwater.

The adsorptive capacity of these floc-formed sediments is not known at present. However, because these sediments would have excess aluminum, and some of that aluminum would be amorphous, these sediments would likely have retardation factors[13] higher then background sediment levels but at or below the value of more engineered media, such as activated alumina and lanthanum coated diatomaceous earth (Table 2.2).

Table 2- 2. Preliminary Retardation Factors for Selected Soils and Adsorptive Media (Bachand and Heyvaert, 2005).

Soil/Media	**Retardation Factor R_d[c]**
Activated Alumina	1117
Lanthanum Coated DE	888
Coon St. Basin	81
Round Hill Basin	25
Eloise Basin	125
Fine Truckee Sand[b]	23
Course Truckee Sand[b]	6

Notes

a. Based upon equilibrium phosphorus concentrations in the water of < 10 ppm.

b. From Martis Valley, Truckee, CA.

c. Assumed porosity of 30% and a dry bulk density of 1.86 g/cm^3 based upon dense mixed-grain sand (Terzaghi and Peck, 1967) or fine gravel and sand (Garde and Rau, 1987)

2.3.7. Implications for system design

Incorporating coagulation into the design of a stormwater treatment system should greatly improve the performance of that system. A 10-fold improvement in the removal of fine particles and phosphorus is possible. Total phosphorus would be removed through more effective settling of fine particles as well as through the precipitation of dissolved phosphorus with particulate species (and then subsequent removal by settling) (Trejo-Gaytan et al, 2006). For removal of particles through settling, the fraction of particles removed are those with settling velocities less then the (basin) design velocity V_c (Metcalf and Eddy, 1979), where

$$V_c = {}^{Water\ Depth}\!\big/_{Detention\,Time} \, .$$

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[13] Retardation factor is the ratio of the velocity of water to the velocity of the pollutant. Higher retardation factors mean slower movement of the targeted pollutant.

In addition to reducing average turbidity, coagulants should also result in less stratification of turbidity in the water column (Figure 4-6). These turbidity stratifications (gradients) result when particles settle slowly and segregate in the water column. Coagulation reduces this effect because it eliminates most smaller particles from solution and the remaining particles settle more rapidly. This rapid settling eliminates the turbidity stratification effect after a few hours. More rapid settling and the accompanying reduction in stratification should reduce the negative effects of wind- or temperature induced mixing.

Formed flocculates once settled to the bottom of a basin should continue to adsorb phosphorus from the water column through diffusion processes. Furthermore, these flocculates should suppress phosphorus migration towards groundwater.

3. Coagulant Toxicity

An important question associated with the possible application of chemical coagulants in the Tahoe Basin is what are the toxicity effects from coagulants? This question is more complex then it would seem at first glance. There are several relevant issues to consider:

- Does stormwater toxicity in the Tahoe Basin vary spatially and temporally?
- Do coagulants decrease or increase the toxicity of stormwater?
- Which toxicity metric is most appropriate or sensitive for testing as it relates to stormwater treatment in the Tahoe Basin?
- What are the water quality constituents that cause toxicity in coagulant-treated and non-treated stormwaters?
- What are the ideal coagulant dosing levels to minimize toxicity?
- What steps can be taken to mitigate toxicity from treated and non-treated stormwaters?

A series of investigations were conducted with stormwater collected during 2004 and 2005 to provide preliminary answers to some of these questions. The main goal of these studies was to decide whether to proceed with investigating Low Intensity Chemical Dosing (LICD) in the Tahoe Basin, based on whether toxicity issues were determined too great to be overcome. These analyses were conducted with PAC coagulants that were investigated by Trejo-Gaytan et al. (2006) and Bachand et al. (2006, Appendices A[14] & H) for stormwater treatment in the Tahoe basin: JenChem 1720, PAX-XL9 and SumaChlor 50. Chitosan, a chitin-based coagulant was also investigated because of growing interest in this coagulant in the Tahoe basin.

Preliminary data from LICD tests (presented earlier in this report) suggest that chemical dosing may offer an effective alternative treatment for phosphorus and fine particle removal in the Tahoe Basin. However, LICD is an active technology, requiring routine operational maintenance, skilled personnel and more complicated control technologies then the standard structural BMPs most often used (passive systems such as detention basins, treatment wetlands, sand traps and filters). Thus, the investment in LICD is greater then standard BMPs, and further investigations and technology development can only be justified if it meets the following objectives:

- Treatment advantages are so great that the investment in technology and resources can be justified; and
- Toxicity issues, if they exist, can be overcome or mitigated.

Under the Total Maximum Daily Load (TMDL) regulatory environment, desired load reductions may be achieved through a number of strategies. One such strategy would be to focus funding and personnel resources on locations with the highest stormwater pollutant loading. These locations would likely be the more urbanized areas. Targeting high pollutant load areas with more complex but better performing technologies may help agencies and jurisdictions meet the

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[14] Appendix A is a summary of the Caltrans report by Bachand et al (2006) which is included in Appendix H.

TMDL requirements, while investing less in BMPs at other locations where the pollutant loading rates are much lower. LICD technology may also provide treatment for runoff volumes associated with much larger storm events, which will be discussed in the next chapter of this report.

This chapter addresses the questions listed above based upon results from several toxicity investigations conducted in 2004 and 2005 on dosed and non-dosed stormwaters. These investigations were conducted as a series of experiments with individual goals, objectives and hypotheses for each investigation. The specifics of each study are presented in detail in Appendices C and D. This chapter provides a summary of those investigations, which consolidates our findings and presents an overview of what we do and do not know as a result. More detailed analyses and discussions of the underlying experimental designs, hypotheses, results and conclusion can be found in Appendices C and D.

3.1. Does stormwater toxicity in the Tahoe Basin vary spatially and temporally?

Stormwater was collected during three events for this project:

1. May 2004 rain event representing first flush conditions after a period of minimal precipitation or runoff;
2. March 2005 snowmelt runoff; and
3. October 2005 late autumn rain runoff event.

Each of these three stormwater events represented different runoff conditions.

Stormwater was collected from three locations for all of these events: Stag in north Tahoe, Ski Run in south Tahoe, and Tahoe City in north Tahoe. Additionally, we collected runoff in March 2005 from the Shivagiri site, to represent runoff from a non-developed drainage. Thus, stormwaters tested in this study were collected under spatially and temporally diverse conditions.

For these different stormwaters, the EPA standard 3-species tests were followed, using five toxicity metrics:

1. Algae cell counts;
2. Zooplankon reproduction;
3. Zooplankton mortality;
4. Fish (fat-head minnow) mortality; and
5. Surviving fish biomass.

Additionally, tests on the survival and fecundity of medaka fish were conducted with the March 2005 stormwater. These tests were conducted to provide additional insight into toxicity issues beyond those which could be discerned from the standard EPA tests.

Table 3-1 summarizes data from 2004 tests and Table 3-2 summarizes data from March 2005 tests. Non-dosed stormwaters were generally toxic. The results of toxicity testing differed between locations during both 2004 and 2005. Though these differences were not always statistically significant, they oftentimes were. Algae cell count, zooplankton mortality and fish mortality were significantly different for stormwaters from each location in 2004, and zooplankton reproduction and fish mortality were significantly different in March 2005. With larger datasets and more samples (n), statistical differences will become more apparent (increased numbers of samples result in tighter 0.95% confidence intervals).

These toxicity metrics differed between the storm events as well. Appendices C and D discuss this in greater detail. The conclusion from the analyses in those appendices is that toxicity varies temporally. This result is not surprising, as stormwater chemistry has been shown to vary spatially and temporally in response to different levels of development and from different types and durations of runoff events. The effects of these different chemistries are then reflected in the spatial and temporal differences of toxicity from those stormwaters.

A final note, on close examination of these tables it is evident that temporal differences can be considerable. For instance, the fish mortality exceeds 70% at Ski Run and Stag for the 2004 event, but is 5% and less for those same sites with stormwater from the 2005 event. These differences likely result from the very different nature of those runoff events.

From a review of the 2004 and 2005 data taken together, some conclusions can be drawn with regard to the variations in stormwater toxicity in the Tahoe Basin:

1. Stormwater chemistry and its effect on toxicity vary spatially and temporally throughout the Tahoe Basin. These differences are likely to remain statistically significant as the data set increases.
2. Temporal variations can be considerable at a given site, reflecting the very different nature of runoff event types. For instance, stormwater collected in May 2004 from a first flush event was generally more toxic then stormwater collected subsequently (Tables 3-1 and 3-2).
3. Stormwaters from urban areas generally required higher dosing levels to achieve optimal dosing levels (as determined with a streaming current detector).

A more thorough discussion reviewing all the 2004 and 2005 data is in Appendix D.

Table 3- 1. Summary of toxicity metrics for dosed and non-dosed stormwaters for 2004 first flush collection event.

Toxicity metrics included algae cell counts, zooplankton percent mortality and number reproduced, and fish mortality and biomass per surviving fish. Toxicity metrics were statistically different by stormwater. For some metrics such as algae cell count, all stormwaters had statistically significant effects. For others, such as fish mortality, only one of the three (in this case Tahoe City) differed significantly.

			N	No Dosing	JenChem 1720	Pxxl9	Sum50	All Coagulants	All Treatments	*Sig. (p<0.05) (see note below for letter key)*
Algae Toxicity (Cell count)										
	Control		12	2.24E+06						
		Ski Run	4	5.82E+05	9.87E+04	3.64E+05	8.85E+05	4.50E+05	4.83E+05	*a*
		Stag	4	1.54E+06	1.25E+06	9.34E+04	1.86E+06	1.07E+06	1.19E+06	*b*
		TCW	4	1.14E+06	1.21E+06	1.72E+06	1.94E+06	1.62E+06	1.50E+06	*c*
		All Stormwaters		*1.09E+06*	*8.52E+05*	*7.27E+05*	*1.56E+06*	1.05E+06	*1.06E+06*	
		Sig. (p<0.05)		*c*	*b*	*a*	*d*			
Zooplankton										
	Mortality (%)									
		Control	10	5%						
		Ski Run	10	0%	90%	0%	0%	30%	23%	*b*
		Stag	10	20%	10%	0%	0%	3%	8%	*a*
		TCW	10	10%	10%	20%	0%	10%	10%	*ab*
		All Stormwaters		*10%*	*37%*	*7%*	*0%*	14%	*13%*	
		Sig. (p<0.05)		*a*	*b*	*a*	*a*			
	Reproduction (#)									
		Control	20	28.4						
		Ski Run	10[1]	39.0	0.0	10.4	8.4	6.3	14.5	*b*
		Stag	10	23.4	2.3	6.4	9.9	6.2	10.5	*a*
		TCW	10	16.5	16.2	24.9	29.4	23.5	21.8	*c*
		All Stormwaters		*26.3*	*6.2*	*13.9*	*15.9*	12.0	*15.6*	
		Sig. (p<0.05)		*c*	*a*	*b*	*b*			
Fish										
	Mortality (%)									
		Control	8	5%						
		Ski Run	4	73%	100%	98%	83%	93%	88%	*b*
		Stag	4	100%	100%	88%	95%	94%	96%	*b*
		TCW	4	15%	10%	18%	10%	13%	13%	*a*
		All Stormwaters		*63%*	*70%*	*68%*	*63%*	67%	*66%*	
		Sig. (p<0.05)		a	a	a	a			
	Survivor Biomass (mg/survivor)									
		Control	8	0.22						
		Ski Run	4	0.16		0.33	0.29	0.31	0.26	*b*
		Stag	4			0.16	0.14	0.15	0.15	*a*
		TCW	4	0.26	0.29	0.27	0.31	0.29	0.28	*b*
		All Stormwaters		*0.21*	*0.29*	*0.26*	*0.25*	0.26	*0.25*	
		Sig. (p<0.05)		*a*	*a*	*a*	*a*			

Notes:

- Stormwater collected at Ski Run Basin, Stag, and Tahoe City Wetland (TCW).
- Coagulants tested are JenChem 1720, PAX-XL9 and SumaChlor 50.
- N = Number of analyses
- "sig" column and rows identify if values are statistically significant from each other. Different letters (a, b, c) signify statistical differences (p<0.05).

Table 3- 2. Zooplankton reproduction and fish biomass varied significantly for the March 2005 collection.
Table shows toxicity for non-treated (raw) stormwater collected during March 2005. These samples represented runoff from an undeveloped drainage (Shivagiri) and from more developed sites. Tahoe City, Stag and Ski Run samples represented stormwater from more urban areas. Algae cell counts, zooplankton mortality and fish mortality did not differ significantly between the different stormwaters or with a laboratory control from the U.C. Davis Aquatic Toxicology Lab. Zooplankton reproduction and fish survivor biomass did differ significantly ($p<0.05$). Zooplankton reproduction and fish biomass were most suppressed in stormwater from Stag.

	Algae			Zooplankton						Fish					
	Cell Count			Reproduction			Mortality			Mortality			Survivor Biomass		
Stormwater Treatment	Mean #	SD #	Stat Sig[1]	Mean #	#	Stat Sig[1]	Mean %	%	Stat Sig[1]	Mean %	%	Stat Sig[1]	Mean mg	mg	Stat Sig[1]
Control	1.42E+06	2.66E+05	a	22.0	3.8	cd	2.5%	15.8%	a	1.7%	3.9%	a	0.273	0.032	b
Shivagiri	1.62E+06	8.16E+04	a	15.6	5.8	bc	0.0%	0.0%	a	2.5%	5.0%	a	0.263	0.022	ab
Ski Run	1.34E+06	8.36E+04	a	18.4	6.1	bcd	0.0%	0.0%	a	2.5%	5.0%	a	0.265	0.006	ab
Stag	1.49E+06	1.28E+05	a	5.0	1.7	a	0.0%	0.0%	a	5.0%	5.8%	a	0.213	0.025	a
Tahoe City Wetland	1.52E+06	1.75E+04	a	27.5	2.6	e	0.0%	0.0%	a	2.5%	5.0%	a	0.260	0.029	ab
p-value			0.300			0.000			0.915			0.814			0.197

1. Different letters represent statistical differences by post-hoc tukey analyses, $p<0.05$

3.2. Do coagulants decrease or increase the toxicity of stormwater?

Coagulant dosing can cover a gradient of dosing levels, from not dosing to overdosing. To simply ask if coagulants decrease or increase stormwater toxicity ignores the fact that dosing levels can be adjusted to stormwater chemistry and dosed accordingly. In wastewater systems, streaming current detectors are commonly used for that purpose. Advanced methods in stormwater treatment at construction sites are beginning to use similar technologies. Thus, in considering toxicity effects, we must consider the full range of stormwater dosing levels.

Table 3-3 provides a summary of the responses of the different ecotoxicity metrics to different dosing levels. A general trend observed was that toxicity decreases at lower dosing levels and increases at over-dosing levels. In this project we have termed “optimal dosing” as the dosing level identified by charge titration measurements to yield a streaming current detector (SCD) value of zero volts (0 V). SCDs are commonly used in to indicate the point at which particle charges in solution are neutralized. Neutralization of the charges allow for flocculation and aggregation of particles, and the creation of larger and more settleable particles. However, SCDs are not exact instruments. From our work and that of others it was determined that SCD values from slightly negative to about 0 V represent a more optimal dosing range. Thus, in this study, dosing at one half (0.5 x) and one times (1 x) the “optimal dosing level” produce very similar results with regard to phosphorus and turbidity removal. Those dosing levels therefore represent an optimal dosing range.

Higher dosing levels lead to less efficient utilization of dissolved aluminum, as dissolved aluminum is not consumed efficiently and concentrations in solution increase. Moreover, at higher dosing levels, the charge on particles reverse from a negative charge (common to natural waters and representative of organics) to a positive charge[15].

These water chemistry responses to dosing levels are reflected in the toxicity results. As discussed earlier, coagulant over-dosing can increase ecotoxicity. In this stormwater dosing study, over-dosing led to increased toxicity in the zooplankton mortality and reproduction, and fish mortality metrics (Table 3-3). In some cases, the toxicity response is more of a trough shape, with optimal dosing reducing toxicity and over-dosing increasing it. Such was the case with algae cell count and to some extent with zooplankton reproduction metrics. Overall, the toxicity at optimal dosing levels either decreased or stayed the same for each stormwater. No toxicity metric worsened at the optimal dosing range.

In summary, stormwater toxicity is reduced with optimal dosing (0.5–1 x optimal dosing level). When over-dosing occurs, toxicity worsens. Depending upon the metric, these effects can be very great. Zooplankton reproduction was the most sensitive metric to over-dosing. Algae cell count and fish biomass were the least sensitive, showing no effects from over-dosing. Appendix D provides a full discussion of this issue.

Table 3- 3. Mean ecotoxicity metric values for different dosing levels.
Overdosing of coagulants at 2 and 3 times optimal levels decreased the zooplankton reproduction, increased zooplankton mortality and increased fish mortality. Dosing levels near optimal levels (e.g. 0.5 and 1 times optimal dose) reduced the toxicity to algae, increased zooplankton reproduction and did not affect fish when compared to non-dosed stormwaters. Treatments highlighted in yellow show a reduction in toxicity when compared to the non-dose treatment (0 times optimal dose). Treatments highlighted in orange show an increase in toxicity when compared to the non-dose treatment.

	Algae			Zooplankton						Fish					
	Cell Count			Reproduction			Mortality			Mortality			Survivor Biomass		
Dosing (Multiple of Optimal)	Mean #	SE #	Stat Sig[1]	Mean #	SE #	Stat Sig[1]	Mean %	SE %	Stat Sig[1]	Mean %	SE %	Stat Sig[1]	Mean mg	SE mg	Stat Sig[1]
0	1.45E+06	4.05E+04	a	17.0	0.9	b	0%	3%	a	3.3	2.0	a	0.25	0.01	a
0.5	1.49E+06	4.05E+04	ab	21.3	0.9	c	0%	3%	a	5.0	2.0	a	0.26	0.01	a
1	1.63E+06	2.87E+04	b	19.0	0.6	bc	2%	2%	a	4.6	1.4	a	0.26	0.01	a
2	1.59E+06	4.05E+04	ab	3.7	0.9	a	13%	3%	b	14.2	2.0	b	0.25	0.01	a
3	1.48E+06	4.05E+04	ab	3.2	0.9	a	67%	3%	c	13.4	2.0	b	0.24	0.01	a
p-value			0.002			0.000			0.000						

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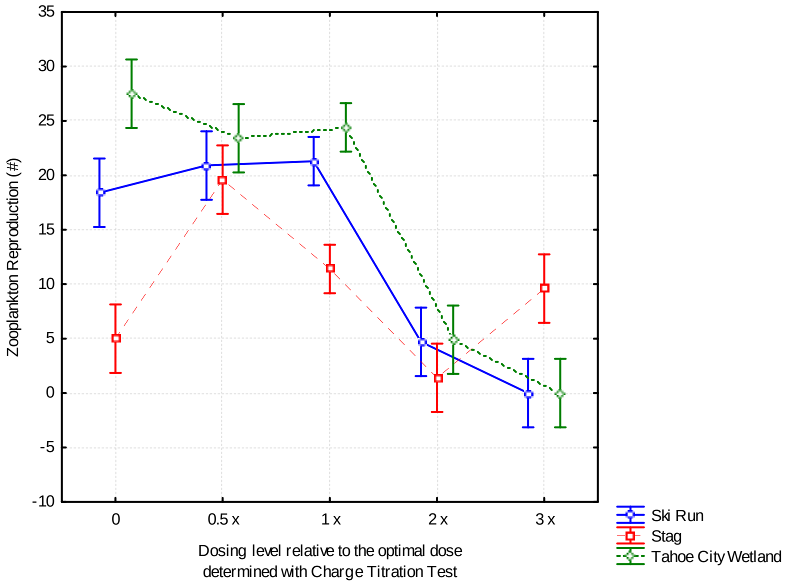
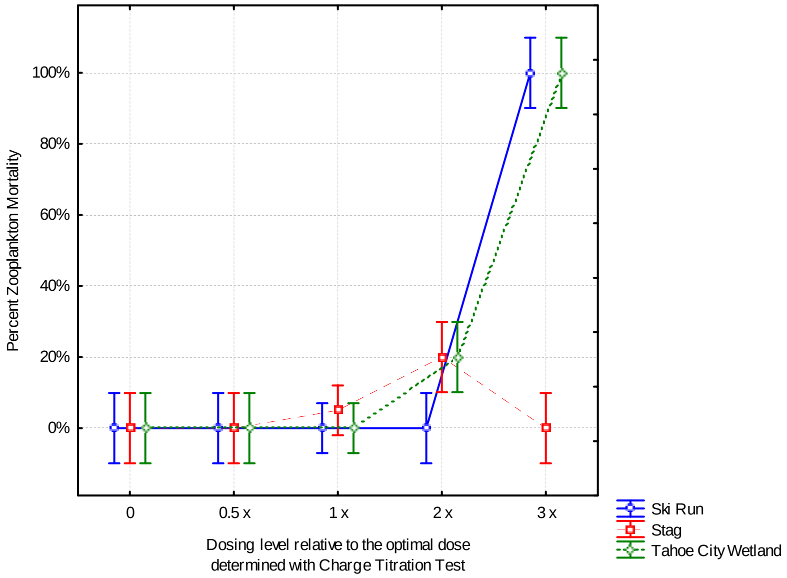
[15] The positive charge re-stabilizes the particles and hinders particle aggregation into larger and more settleable flocculates.

Figure 3- 1. A reduction in toxicity occurs around optimal dosing levels and then toxicity increases at higher dosing levels.
Figure shows toxicity metric responses for the different stormwaters. Error bars represent 95% confidence interval. Zooplankton toxicity metrics are very sensitive to coagulant effects. These metrics are conservative indicators of toxicity. Optimal dosing ranges sometimes improved but never worsened the toxicity of a given stormwater to these metrics. Over-dosing oftentimes worsened toxicity.

a) Reproduction



b) Mortality



3.3. Which toxicity metric is most appropriate or sensitive for testing ecotoxicity as it relates to the Tahoe Basin?

Table 3-4 summarizes the results of the different experiments conducted on toxicity for this project. The effects of stormwaters, coagulant types, coagulant dosing levels and floc management were tested during this period. For these studies, floc management refers to the presence of floc or its removal by either decanting or filtering.

Zooplankton reproduction and fish mortality were very sensitive to the toxicity associated with non-dosed stormwaters. Zooplankton reproduction was the most sensitive toxicity metric to coagulant effects. This metric therefore was used to assess whether toxicity could be reduced by removing the floc with filtration (Table 3-4; October 2005 investigation).

As shown in Table 3-4, zooplankton reproduction was a conservative (sensitive) indicator for toxicity effects: a yes/no flag in Table 3-4 indicates potential toxicity. However, zooplankton reproduction does not necessarily identify the more subtle toxicity issues:

- What are the specific analytes causing toxicity?
- What are their possible mechanisms?
- What are the effects throughout the food chain?
- And other questions.

Although zooplankton reproduction provides a very sensitive indicator of toxicity it may not be sufficient for understanding the deeper causes and possible solutions to coagulant and stormwater toxicity.

Table 3- 4. Responses of toxicity metrics to different tests conducted on 2004 and 2005 stormwaters.
The effects of stormwater, coagulant type, coagulant dose and floc management were studied under this project. Below we identify the results on ANOVA showing if there were statistically significant effects (Y = Yes, N = No).

Goal	ANOVA	Treatments			Stormwater Effects					Coagulant Effects					Floc	
	Test	Storm water^{3}	Coag.^{2}	Floc^{4}	Algae	Zooplankton		Fish		Algae	Zooplankton		Fish		Zooplankton	
					Count	Repro.	Mort.	Bio.	Mort.	Count	Repro.	Mort.	Bio.	Mort.	Repro.	Mort.
May 2004																
1 Differences between non-dosed stormwaters and a control.	2-way, post hoc analyses	SR,S, TCW, C	none	De	Y - ^{10}	Y +/- ^{10}	N	N	Y - ^{10}							
2 Differences between non-dosed stormwaters	2-way, post hoc analyses	SR,S, TCW	none	De	Y	Y	N	N	Y							
3 Test the effects of different coagulants on dosing	2-way	SR,S, TCW, C	none, PAX, SUM, JC^{7,8}	De	Y	Y	Y	Y	Y	Y +/-^{9}	Y -	Y +/-^{9}	N	N		
Mar 2005																
1 Differences between non-dosed stormwaters	1-way	SR, S, TCW	0x	De	N	Y	N	N	Y							
2 Effects of optimal dosing on stormwaters with a polyaluminum chloride (PAX-XL9) and a chitin based coagulant (Chitison)	2-way factorial	SR, S, TCW	0x, 1x^{6}	De	N	Y	Y	N	Y	Y +	Y +	N	N	N		
3 Effects of over-dosing on stormwaters	2-way factorial	SR, S, TCW	0x, 0.5x, 1x, 2x, 3x	De	N	Y	Y	N	Y	Y -^{1}	Y -^{1}	Y -^{1}	Y -^{1}	N		
October 2005																
1 Effects of over-dosing on stormwaters and testing if floc removal reduces toxicity.	3-way factorial	SR, S, TCW	1x, 2x, 3x	De, Fi		N	N				Y -^{1}				Y+^{5}	Y+^{5}

1. At over-dosing of 2x and 3x optimal dose
2. Multiple of dose determined for SCD = 0 V.
3. SR = Ski Run, S= Stag, TCW = Tahoe City Wetland, SHV = Shivagiri, C= Control
4. Floc treatment: De = decanted after coagulation and settling. Fi = Filtered after coagulation and settling.
5. Zooplankton reproduction improved and mortality decreased when flocculate was removed through filtration.
6. Dosed at 1x with Chitosan and PAX-XL9
7. PAX = PAX-XL9, SUM = Sumachlor 50, JC = Jenchem 1720.
8. Coagulant dosing was not optimized using SCD. Dosing was estimated using jar tests.
9. Increased or decreased toxicity effect depending upon coagulant and dosing level.
10. Toxicity metric measured in stormwater when compared to control (- means worsened, + means improved).

3.4. What are the water quality constituents causing ecotoxicity in coagulant treated and non-treated stormwaters?

In Appendix D, we provide in depth discussion of the possible mechanisms for toxicity with regard to each specie and each metric. Table 4-5 provides a brief summary of those analyses.

The discussion in Appendix D reviews the results from several different statistical and analytical tools: Principal Component Analyses (PCA), ANOVA, regressions, correlation matrices and data trends. One issue regarding this data analysis is a difficulty in differentiating between direct effects from dosing with aluminum (or other coagulants) versus the indirect effects from changes in water quality resulting from dosing, such as changes in pH and alkalinity. Using these different statistical approaches, however, we are able to make some conclusions with regard to the variables that may be causing or not causing toxicity. These are discussed below.

Table 3- 5. Summary of variables implicated in toxicity

Highlighted toxicity metrics are those most likely are affected by a given variable. Shaded areas (in green) show possible source of the factor causing toxicity. Coagulants affect pH, alkalinity, total aluminum, TSS, turbidity and DOC of a stormwater. Stormwaters themselves are characterized by water quality differences as well. Water quality differences of stormwaters were characterized by soluble calcium, total aluminum and iron, TSS, turbidity and DOC. Stormwater chemistry varied spatially and temporally.

	Correlation, number and probability[2]					Source[1]	
	Algal Cell Count	Cerio Reproduction	Cerio Mortality	Fish Biomass	Fish Mortality	Coag.	StormW.
Dose mg-Me/L		🟨	🟨			🟩	
pH	🟨	🟨	🟨		🟨	🟩	
Alkalinity		🟨	🟨		🟨	🟩	
Soluble Ca				🟨			🟩
Total Fe		🟨		🟨			🟩
Total Al		🟨	🟨	🟨	🟨	🟩	🟩
TSS		🟨		🟨		🟩	🟩
Turbidity		🟨				🟩	🟩
DOC					🟨	🟩	🟩

1. Shaded area indicates possible source of analyte affecting toxicity.
2. Highlighted items are those expected to be most likely affecting the toxicity metric based upon a review of the data.

3.4.1. Analytes causing or affecting Toxicity

Total Aluminum

Total aluminum is clearly a culprit with regard to stormwater toxicity. This toxicity was evident in both dosed and non-dosed stormwaters. Aluminum toxicity is well documented (Gensemer and Playle, 1999; Soucek et al., 2001). Gensemer and Playle (1999) present a comprehensive and excellent review of aluminum toxicity. In general, aluminum is most toxic to algae under slightly acidic conditions; invertebrates are not very sensitive to aluminum as compared to fish

— largely because aluminum is a gill toxicant to fish, with the degree of toxicity dependent upon water pH and aluminum concentration. For waters with pH exceeding 7, there is little data.

In this study, total aluminum toxicity is particularly evident for zooplankton and fish. Zooplankton toxicity occurs under different water chemistries for non-dosed and over-dosed conditions when total aluminum concentrations are high. Zooplankton reproduction was always suppressed at total aluminum concentrations greater then 5 mg/L and was always zero at concentrations above 10 mg/L. Fish mortality increased with total aluminum concentrations in stormwater; but fish mortality was always low, less then 10%, for total aluminum concentrations below 3 to 4 mg/l. Removing floc by filtering after coagulant dosing eliminated or greatly reduced toxicity (Table D-19).

Several possible mechanisms could be causing toxicity to the aquatic organisms, some physical and some chemical. Particulate aluminum from stormwater suspended solids or from aluminum precipitated with coagulation can cause stress on organisms by inhibiting respiration (Gensemer and Playle, 1999). In Cladoceran (such as *ceriodaphnia*), cationic polymers are thought to bind to the surface of the integument and/or to appendages, inhibiting movement and uptake of nutrients (Rosemond and Liber 2004). Cationic particles would be expected to behave similarly. More cationic particles will be present in higher dosed water because coagulants change the net ionic and colloidal surface charge in stormwaters from negative to positive.

Relating aluminum toxicity to alum and aluminum coagulant toxicity is not simple. Obviously, proper coagulant dosing should be conducted to keep the dissolved aluminum concentrations low. Kennedy and Cooke (1982) state that proper dosing should keep dissolved aluminum concentrations below 50 μg/L, while Livingston et al. (1994) state concentrations should be below the 4-day EPA Ambient Water Quality Criteria of 87 μg/L. These concentrations are often below levels found to be toxic though pH, aluminum specie and concentrations of other constituents, such as dissolved organic carbon, complicate the toxicity issue (Gensemer and Playle, 1999). Laboratory data from this study suggested optimal dosing does not significantly ($p<0.05$) increase aluminum concentrations over background levels (Bachand et al. 2006). And results in this study showed total aluminum concentrations in the water decreased with optimal dosing levels (Appendix D, Figure D-14).

This disconnect between aluminum concentrations and dosing levels may explain why the data on toxicity of waters dosed with coagulants is fairly sparse. Changes in aquatic species in alum treated lakes have been attributed to changes in trophic structure and status, and many of these changes have been considered positive (Doke et al., 1995; James et al. 1991; Welch and Schreive 1992; Souza et al. 1994).

In our 2005 stormwater tests, the toxicity threshold for total aluminum was at concentrations of 3–4 mg/L. At aluminum concentrations greater then 3 mg/L, zooplankton reproduction decreased for all stormwaters (Figure 3-2; Appendix D, Figure D-18)[16]. This dataset includes

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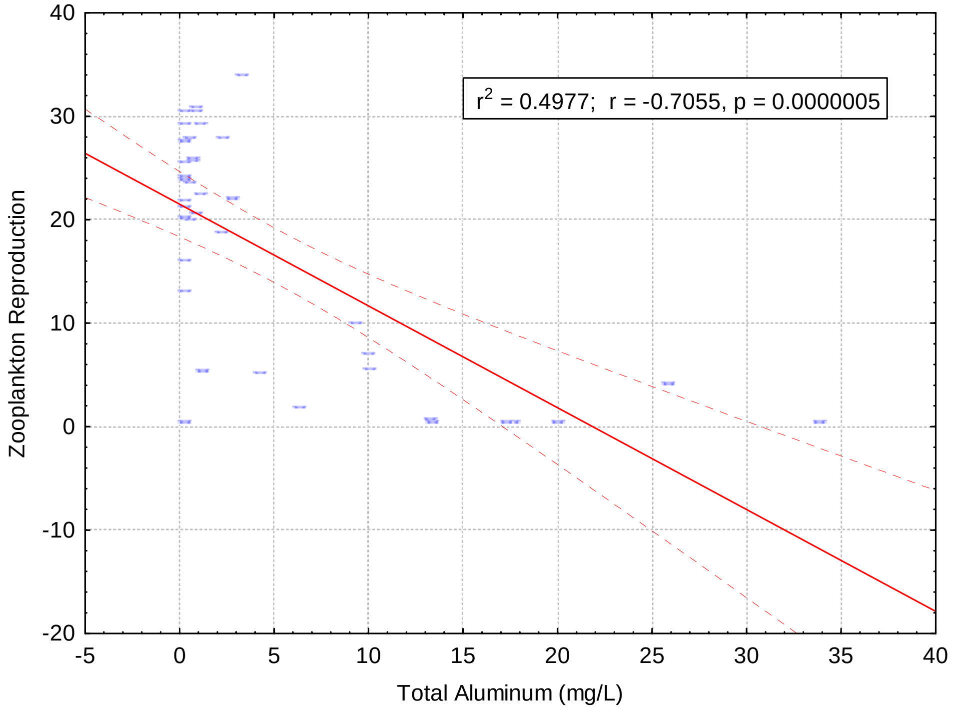
[16] Zooplankton reproduction for March 2005 stormwater samples were generally around 20 for all raw (non-dosed stormwaters, Table 3-2), similar to the value found for the Control. Stag stormwater had unusually low zooplankton reproduction. At total aluminum concentrations greater then 3 mg/L, reproduction is often below 10 and generally below 5.

dosed and non-dosed stormwaters. Generally, zooplankton mortality increased at total aluminum concentrations above 10 mg/L (Appendix D, Figure D-26). Fish mortality appeared to have an aluminum threshold of around 3 mg/L, at which mortality increased (Appendix D, Figure D-28). Below an aluminum concentration of around 3 mg/L, toxicity did not appear to affect any of the metrics, regardless of whether the stormwater was dosed or non-dosed (raw). The EPA recommended water quality criteria for total aluminum is 0.75 mg/L (Table D-10). Staying below that level in the outflow to natural waters should minimize and may eliminate downstream toxicity from aluminum.

Soluble aluminum was not found to be a direct cause of toxicity in this study.

Figure 3- 2. Zooplankton reproduction is always very low at total aluminum concentrations greater then 3 to 4 mg/L

For all the stormwaters tested in 2005, zooplankton reproduction generally was not suppressed at total aluminum concentrations less then 3 mg/L. Zooplankton reproduction for the laboratory control was about 20. At total Al concentrations greater then 3 mg/L, zooplankton reproduction was always 10 or less, and usually less then 5. Zooplankton reproduction was the most sensitive toxicity metric to aluminum in this study.



pH and alkalinity

Much evidence implicates alkalinity and pH as contributing to toxicity across all species tested:

- pH showed clear effects on algae cell counts, with cell counts dramatically dropping at pH levels below 6.8 (Figure D-20).
- Zooplankton reproduction decreases with decreasing alkalinity and pH (Figure D-22). pH level of around 6.0 appeared to be the threshold for these effects.
- Alkalinity significantly affects fish mortality in a correlation analyses (Table D-19). The threshold appeared to be concentrations between 20 and 35 Ca-mg/L.

This analysis is discussed in greater detail in Appendix D on a species by species basis, and provides a broader discussion of the evidence, which supports the hypothesis that pH and alkalinity changes cause toxicity. Both these constituents can be affected by coagulant dosing, as coagulants consume alkalinity (Snoeyink and Jenkins, 1980). In this study, alkalinity decreased linearly with increasing dosing levels for each of the different stormwaters (Appendix D, Figure D-35). This decrease in alkalinity correlated with a decrease in pH (Appendix D, Figure D-37). The pH decrease was relatively modest, being about 0.3 to 0.4 for the full dosing range tested, from no dosing at all to over-dosing each of the stormwaters at three times the optimal dosing level.

Suspended solids

Suspended solids can be high naturally in stormwater or result from over-dosing through particle restabilization[17] (Snoeyink and Jenkins 1980). Elevated total suspended solids (TSS) above 80 mg/L appear to be a main factor for toxicity with regard to zooplankton reproduction. TSS corresponds to some degree with total aluminum concentrations, and thus some of the same mechanisms may apply: chemical interference with biological processes, particle adhesion clogging or inhibiting of respiratory and feeding functions. The effect from TSS was greatly reduced at TSS concentrations below 30 mg/L.

DOC

DOC significantly correlated with fish mortality. Decreasing DOC corresponded to higher fish mortality (Table D-19). DOC concentrations at around 2 mg/L seem to represent a threshold. Below that threshold mortality is nearly always greater then 10% and above that threshold it is nearly always below 10%. Coagulants decreased DOC concentrations. In this study, optimal dosing levels resulted in optimal phosphorus removal. But higher coagulant dosing levels, greater then optimal, continued to remove DOC from the water column (Appendix D, Figure D-17). Bachand et al (2000) found similar results in the Everglades Nutrient Removal Project. While coagulants can remove both phosphorus and DOC, if dosing levels are targeted to achieve optimal phosphorus removal there should still be sufficient DOC remaining in solution to reduce toxicity effects.

3.4.2. Less likely causes of toxicity

Some constituents appear to not be causing toxicity in this study.

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[17] Particle charges going from neutrally to positively charged through too high of dosing of cationic coagulants. See Appendix D results for discussion of restabilization.

Soluble aluminum

Soluble aluminum does not seem to be a concern. During coagulation, soluble aluminum concentrations remain relatively constant. The PCA and correlation analyses of the 2005 datasets provided little evidence that soluble aluminum had much of an effect on toxicity.

Priority metals

Total and soluble priority metals at the levels reported in this study do not pose a toxicity concern. These metals were near or below EPA recommended water quality criteria, which are very similar to California Toxic Rule requirements. These priority metals are Ag, As, Zn, Pb, Cu, Cr, Mn, and Ni. These metals were generally not affected by coagulant dosing. Only zinc showed a weak relationship (Appendix D).

3.4.3. Wildcards

The data from this study indicates we do not have all the answers with regard to identifying the chemical constituents that cause toxicity in the Tahoe stormwaters.

First flush events – what caused toxicity?

First flush had a great effect on fish biomass. Stag and Ski Run stormwaters from the May 2004 first flush event had fish mortalities much higher then any other recorded in this study. We do not know what caused the toxicity in those stormwaters. Neither do we know the concentrations of priority metals in those waters, nor the concentrations of other potential toxicants that include oil and grease, or organics such as PAHs.

We do know that coagulant dosing did not reduce the toxicity of these first flush stormwaters. Coagulant dosing under optimal conditions appears to greatly reduce total aluminum toxicity. So the evidence suggests that toxicity from the first flush stormwaters was not caused by total aluminum, and it suggests that constituents causing toxicity could not be removed through coagulation.

Stormwater with similar hardness and turbidity levels oftentimes had similar toxicity responses to dosing – what don't we know?

In this study, stormwater toxicity responses often clustered in PCA analyses according to water quality chemistry. Most notably, the initial chemistries of Tahoe City and Ski Run stormwaters collected during March 2005 were more similar then that of Stag stormwater. Hardness, its related constituents[18] and particles defined the similarities in stormwater chemistry (Table D-11). Tahoe City and Ski Run stormwaters responded more similarly to the different dosing levels with regard to toxicity then did Stag stormwater.

These results suggest hardness and related factors affect the response of stormwater to dosing. Table D-12 results support this hypothesis, showing a weak but statistically significant relationship between hardness and fish toxicity as measured with fish biomass. In water that is non-dosed or dosed at 0.5 or 1 times optimal, lower alkalinity and hardness are both associated with higher toxicity.

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[18] Hardness relates to calcium and magnesium concentrations.

There are possible mechanisms for the effects of hardness on toxicity. Hardness can ameliorate metal toxicity in aquatic organisms and is thought to result from the competitive binding of Ca at the Ca channels of the cell membrane (Markich et al, 1994). However, our data suggests this analysis is too simple. In this study, hardness and associated variables do not strongly correlate with the different toxicity metrics used in this study.

Thus, the picture does not seem complete with regard to the causes of toxicity.

3.5. What are the ideal dosing levels to minimize toxicity?

Dosing levels within an optimal range were based upon measurements taken with a Streaming Current Detector[19]. "Optimal dose" is considered a SCD value equal to 0 V. As discussed earlier, that is not the true optimal dose but an indicator and likely represents an upper dosing level. The laboratory studies conducted for this project and results from this component suggest lower dosing levels provide equally good treatment. The dosing level of 0.5 times optimal dose effectively removed TSS and turbidity in these tests. Most of the toxicity tests showed a trough response curve with lowest toxicity centered near the 0.5–1 dosing levels. Thus an optimal dosing range of 0.5 to 1 times the dose determined by the SCD would seem a good initial target.

3.6. What steps can be taken to mitigate toxicity from treated and non-treated stormwaters?

Several steps can be taken to reduce toxicity associated with treated and non-treated stormwaters.

Clearly, chemical dosing can decrease stormwater toxicity when properly dosed. For all the stormwaters tested in 2005, optimal coagulant dosing decreased toxicity. For stormwaters from 2004, dosing frequently decreased stormwater toxicity.

However, coagulant dosing carries the risk of worsening toxicity as well. This result typically occurs under over-dosing conditions. Several variables are clearly identified as likely affecting toxicity:

- Increases in total aluminum increase toxicity;
- Decreases in pH and alkalinity likely contribute to increasing toxicity;
- Hardness may help reduce toxicity;
- Increases in total suspended solids seem to correspond to increasing toxicity;
- Decreasing DOC is correlated to increasing toxicity.

We identify a number of outflow water quality targets that we believe should help control toxicity resulting from coagulant dosing:

- Keep outflow total aluminum concentrations below the EPA recommended water quality criteria of 0.75 mg/L;

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[19] See Section 2.3.4 for discussion of streaming current detectors.

- Adjust pH in outflow towards 7;
- Maintain alkalinity above 35 Ca-mg/L; and
- Maintain DOC concentrations above 2 mg/L;
- Keep TSS levels in outflow below 80 mg/L[20].

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[20] Note that over-dosing can increase toxicity. See Section 3.4.1 for brief discussion.

4. A Conceptual Design for Implementing Coagulation

Appendices E through G discuss logistical issues associated with the application of this LICD technology. Appendix E discusses the type of sites that would benefit from LICD installations. Appendix F discusses a vision for implementing this technology full-scale at the Osgood Basins in South Lake Tahoe, and Appendix G discusses smaller scale studies needed to move forward.

Performance and toxicity issues were summarized in the earlier chapters. This chapter discusses a conceptual design for implementing chemical dosing, with discussion pulled from Appendices F and G.

4.1. Conceptual Design for Full-Scale Implementation of LICD – A Target for Experimental Investigations

Figure 4-1 presents a conceptual design for implementing coagulant dosing at a large-scale. This design serves as one option towards which smaller-scale studies can be focused. Under this conceptual design, an equalization basin receives stormwater from the watershed and provides storage for metered delivery to a second stormwater basin or wetland that subsequently treats the dosed stormwater. A static mixer between these two basins or wetlands provides rapid mixing to blend coagulants with the stormwater, and a subsequent raceway to create a slow mixing environment for improved aggregation. These raceways are fairly simple to construct and potentially can be constructed from wood (Figure 4-2). At the outflow of the treatment system is a simple filtration system. The exact design of this filtration area is not defined, but could be constructed of geotextile fabrics. Another alternative would be to use more natural materials such as woven jute (Figure 4-3). Jute has been used in conjunction with polyacrylamide dosing to remove turbidity in stormwater systems in the southern U.S. (Iwinski, 2004). Additionally, the first equalization basin could be lined with an adsorptive media for phosphorus removal to minimize any export of phosphorus to groundwater (Bachand and Heyvaert, 2006).

Table 4-1 presents different possible configurations. These configurations are grouped into five different scenarios: A, B1, B2, B3 and C. Scenario A represents a treatment wetland without an upstream equalization basin, and this represents a typical dry or wet basin, or wetland design. Scenarios B1 through B3 represent separate equalization and treatment wetlands, all located at a 4-acre site, which for the purposes of the report could be assumed as the Osgood Basins. Scenario C represents equalization and treatment basins occupying a larger area, which could be assumed as the Wildwood Basin for equalization storage and the Osgood Basins for treatment.

Table 4 - 1. Design options for stormwater treatment basins at the Osgood and Wildwood Basin Complex.

Different design options for implementing stormwater basins at Osgood and Wildwood. Specifications are shown in the table. Shaded blue means that storage volume for given scenario exceeds treatable storm event. Current and rerouted conditions are described in Lumos and Associates (2006) East Pioneer Trail Report.

Scenario		**A**	**B1**	**B2**	**B3**	**C**
Parameter	**Unit**	**Value**				
Eq:Tr Area[1]	Ratio	0:1	1:1	2:1	3:1	1.7:1
Locations used[3]						
Osgood Basins		T	T & E	T & E	T & E	T
Wildwood Basins						E
Total Wetland Area[2]	Acres	2.9	2.9	2.9	2.9	8.1
Assumed wetland area to parcel area		85%	75%	75%	75%	75%
Total Wetland Area for Stormwater Processing[4]	Acres	2.5	2.2	2.2	2.2	6.1
Equalization Wetland Specifications						
Max Depth	Ft	6	6	6	6	6
Area	Acres	0.0	1.1	1.5	1.6	3.8
Capacity	Ac-ft	0.0	6.5	8.7	9.8	23.0
Treatment Wetland Specifications						
Operating Depth	Ft	1.5	1.5	1.5	1.5	1.5
Area	Acres	2.5	1.1	0.7	0.5	2.3
Capacity	Ac-ft	3.7	1.6	1.1	0.8	3.4
HRT	days	1	1	1	1	1
Flow	ac-ft/d	3.7	1.6	1.1	0.8	3.4
	cfs	1.9	0.8	0.5	0.4	1.7
Combined System Specifications						
Total Capacity	Ac-ft	3.7	8.2	9.8	10.6	26.3
Time to treat all stored water		1.0	5.0	9.0	13.0	7.8
Treatable Storm Event by Volume (ac-ft)						
Current Conditions[5]						
Q_2 14	%	26%	58%	70%	76%	188%
Q_{10} 44	%	8%	19%	22%	24%	60%
Q_{100} 88	%	4%	9%	11%	12%	30%
Rerouted Conditions[5]						
Q_2 4	%	92%	204%	245%	265%	658%
Q_{10} 11	%	34%	74%	89%	96%	239%
Q_{100} 24	%	15%	34%	41%	44%	110%
Estimated maximum depth of Equalization Basin						
Current Conditions[5]						
Q_2 14	ft	NA	6.0	6.0	6.0	3.2
Q_{10} 44	ft	NA	6.0	6.0	6.0	6.0
Q_{100} 88	ft	NA	6.0	6.0	6.0	6.0
Rerouted Conditions[5]						
Q_2 4	ft	NA	2.9	2.5	2.3	0.9
Q_{10} 11	ft	NA	6.0	6.0	6.2	2.5
Q_{100} 24	ft	NA	6.0	6.0	6.0	5.5

[1] Equalization to Treatment Area

[2] Based upon basins identified for use

[3] T = Treatment Wetland; E = Equalization Wetland

[4] Processing defined as storage and treatment

[5] Lumos and Associates hydrologic scenarios

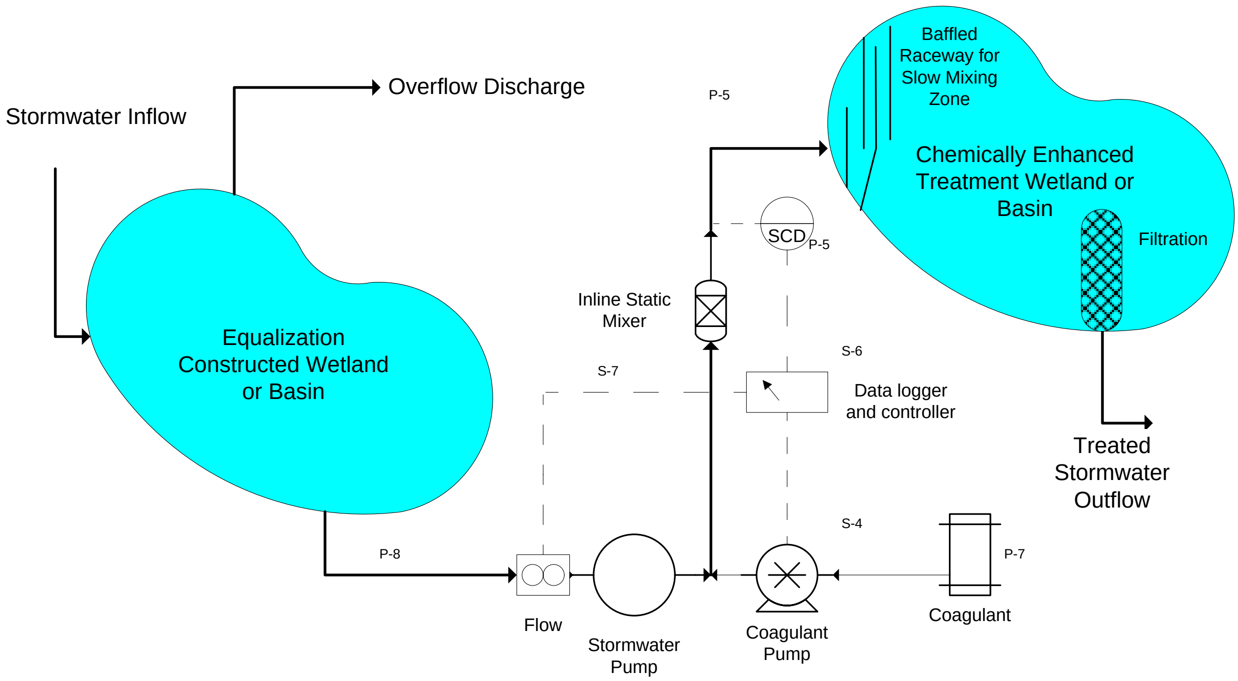

Figure 4 - 1. Conceptual Process Flow Diagram for Stormwater LICD System. Figure shows the conceptual design for a stormwater treatment system using coagulant dosing. An equalization basin is a key element in controlling flow to the treatment wetland. Storage of stormwater is a major factor limiting the capacity of treatment BMPs.

For all the configurations in which an equalization basin is included, the maximum depth for the equalization basin is 6 feet. Also, for all these configurations the maximum and operational depths for the treatment wetland is 1.5 feet, with an assumed residence time of 24 hours for the treatment basin or wetland.

Scenarios B1 through B3 differ only in the ratio of equalization basin to treatment wetland. For B1, each basin occupies the same area. For scenario B2, the equalization basin occupies twice the area, and for scenario B3 it occupies three times the area.

The comparison shows that using an equalization basin or wetland greatly increases capacity without increasing the area used. Equalization basins result in an increased capacity of 220 to 290%. Because the equalization basin provides storage, all the water does not need to be treated in the amount of treatment time typically planned for the treatment basin. Thus, without an equalization basin all the stormwater would need to be treated in one day, as designed, whereas with an equalization basin the amount of time available to treat this stormwater can be spread to five to thirteen days, depending upon the area ratio design.

Figure 4 - 2. Baffle grids used for filtering treated stormwaters (Iwinski, 2004).

Figure 4 - 3. Particle curtains of woven jute on wood frames (Iwinski, 2004).

With an equalization basin, the 2.9 acres of total basin area can treat up to 11 ac-ft of stormwater volume. This is equivalent to a 10-year storm event under the rerouting conditions described in the East Pioneer Trail Hydrologic Study (Lumos and Associates 2005). If the basin configurations were enlarged to include both the Wildwood and Ski Run basins, with the Wildwood Basins used for equalization storage, this system could treat up to a 100-yr storm event under rerouting conditions and a 2-year storm event under current conditions[21].

In the design shown in Figure 4-1, we identify some components considered necessary for implementing LICD under this configuration:

- A pump to move water from the equalization basin to the treatment wetland;
- A pump to dose coagulants;
- A controller and data logger to control the operation of the systems; and
- Necessary sensors to help control the dosing system and properly dose.

The design configuration shown in Figure 4-1 addresses many of the design issues raised earlier.

4.1.1. Water Quality

Coagulation can precipitate dissolved phosphorus and can aggregate fine particles to increase settling velocities by an order of magnitude. This conceptual design also provides some wetland treatment to enhance fine particle and dissolved phosphorus removal. Coagulation is a proven technology, but cost, robustness and the logistics of implementation are likely challenges for implementing coagulant dosing.

4.1.2. Flow

The equalization basins will dampen flow peaks and will extend the period of time available for treatment. When operated at full capacity, the hydraulic retention time in the equalization basin will be in the general range of 4 to 10 days, depending upon the exact configuration (Table 4-1), allowing time for removal of particles with settling velocities in the range of 0.002 to 0.005 cm/s. Stormwater delivered to the treatment wetlands would be treated with coagulants to precipitate dissolved phosphorus, and to aggregate and removal fine particles.

4.1.3. Groundwater Issues

Both basins shown in Figure 4-1 are designed to minimize the infiltration of phosphorus to groundwater. The equalization wetland could be lined with an adsorptive media to take up phosphorus and minimize its movement through soils. The treatment wetland will contain coagulated sediments which would likely have excess capacity for additional phosphorus uptake (Bachand et al, 2000). This effect would begin with the deposition of aluminum-rich sediments.

4.1.4. Space

The combination of an equalization basin and treatment wetland greatly increases system capacity within limited space. Much larger storm events can be accommodated (Table 4-5).

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[21] These are conditions described in Lumos and Associates 2005 report as the current conditions.

4.1.5. Toxicity Issues

Wetlands have been shown to mitigate toxicity and this concept could be tested further. Coagulants change stormwater toxicity, but as discussed in the preceding chapters, those changes can be positive or negative (Chapter 3, Appendices C & D).

4.1.6. Other Issues: Safety and Aesthetics

Two other issues that would need to be addressed in the conceptual design are safety and aesthetics. The equalization basins can be operated as shown in the design at 6 feet. But these depths would create a safety issue at high flows.

The equalization basin could be constructed in many ways. One would be to have it set deeper into the soils. This may produce wetter conditions within the equalization basin as compared to the treatment wetland. Thus, the equalization wetland and treatment wetland would be expected to have different vegetation conditions, although both could be wetlands. Even with potential operating depths of six feet, wetland vegetation could be expected to persist because of the relatively short duration of deep water conditions.

4.2. Pilot Study Conceptual and Experimental Design

We propose an experimental approach to move forward with LICD implementation, if there is support to do so within the Tahoe community. The approach planned for testing this technology would be to use two complementary experimental systems. The first recommended system is a small-scale mobile facility designed to optimize coagulant dosing methods at scales representative of full-basin treatment. The tests conducted with this mobile system would look at processes that are energy or flow dependent, such as mixing regimes and methods to improve flocculate aggregation. The second recommended system is a replicated mesocosm to test processes that are time dependent, such as the time to settle flocculates, changes in water quality or sediment chemistry and time effects on toxicity. These experiments are discussed in greater detail in Appendix G.

4.2.1. Small-scale mobile pilot study

The small-scale mobile pilot study would be conducted to test processes that are scalable, based upon dynamic processes such as velocity and energy. These would include selecting and understanding static mixers in order to provide sufficient energy to initially mix coagulants with stormwater at larger-scales; and tests for modeling velocities and times to provide sufficient slow mixing regimes for optimal flocculate aggregation, and in order to better design the slow mixing region in a full-scale system. Additionally, this study would be used to assess the initial toxicity of non-dosed and dosed stormwaters under *in situ* conditions.

The process flow diagram for this mobile pilot is shown in Figure 4-4. Stormwater is pumped from a stormwater source through a static mixer where it is dosed with coagulant. Some of the dosed coagulants are slip-streamed to a slow mixing tank, where flocculate aggregation is monitored. Water samples would be collected to measure performance indicators, such as ortho-phosphate and turbidity, but also to measure additional metrics such as particle size distribution

(PSD), streaming current value (SCV) and toxicity metrics. Table 4-2 shows the hypotheses and goals for this study.

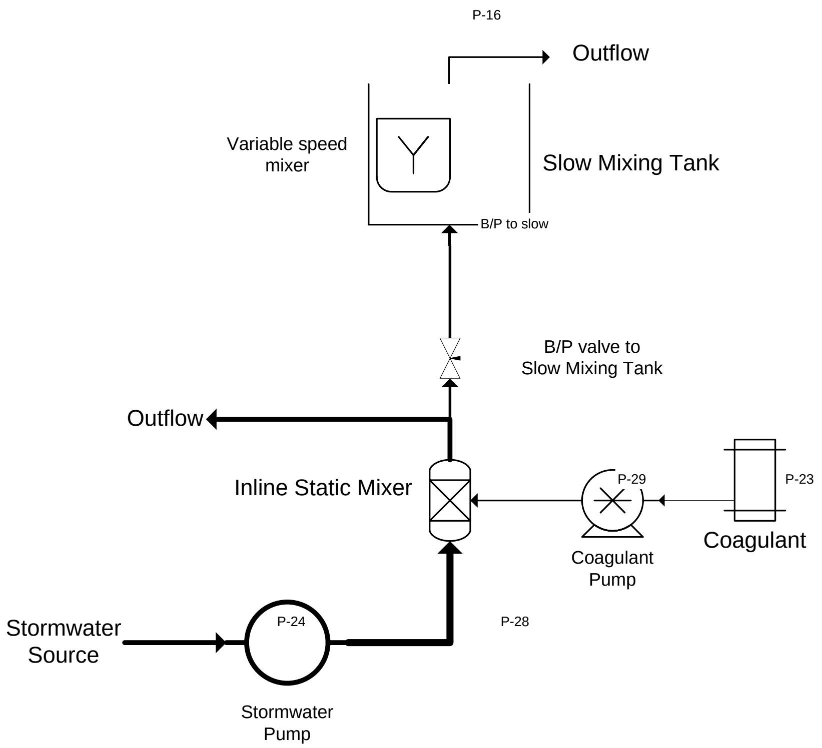

Figure 4 - 4. Mobile Pilot Testing System

4.2.2. Mesocosm Study

The mesocosm system would enable study of time-dependent processes such as phosphorus and fine particle removal in the water column, changes in sediment over time, changes in toxicity over time, and soil accretion (Table 4-2). Figure 4-5 presents the process flow diagram for the mesocosm study. Stormwater is stored on site to provide a volume for experimentation. Treatment stormwater would either be chemically dosed stormwater or non-dosed stormwater, depending upon the treatment test. Treatment stormwater enters the mesocosm and flows at low velocities through a raceway to allow for flocculate aggregation. Stormwater then passes through the mesocosm for a defined hydraulic residence time, eventually flowing through a particle curtain to help capture any remaining flocculate before discharge.

At the Osgood Basin, there is infiltration to groundwater. To assess groundwater effects, the mesocosm cells would be lined (Figure 4-6) and groundwater captured from the underlying soils above the liner. Analysis of this “groundwater” would show how the different treatments affect groundwater transport of phosphorus and other constituents.

Table 4 - 1. Experimental Design

Variable	Hypothesis/Goal	Scale Issues		Proposed metrics
		Variable	Comment	
1. Portable Batch Studies to Test Coagulation and Chemical Dosing[1]				
Operational				
Slow Mixing	G: Determine slow mixing and water velocities for near optimal flocculate formation	Velocity	Simulate velocities for full-scale implementation	PSD, Bulk Density, total and dis P, SCV, total and dis Al
Rapid Mixing	H: Static mixers will provide sufficient energy for precipitation.	Energy	Simulate turbulence for full-scale implementation	
Initial Surface Water Quality Effects				
Dissolved P removal	H: Dissolved P is reduced to < 10 ppb	Energy	In situ conversion from dissolved to particulate P	Dissolved P
Dissolved Aluminum	H: Proper dosing levels result in dissolved Aluminum levels below water quality standards	Energy	Efficiency of Al utilization	Dissolved Al
Toxicity	G: Spot checking of toxicity	Energy	Initial toxicity of treated and non-treated stormwaters	Toxicity metric
2. Replicated Mesocosm Sites to Test				
Longer-term Surface Water Quality Effects				
P and fine particle removal	H1: TP values below 30 ppb can regularly be achieved. H2: Turbidity can be reduced regularly below discharge standards. G: Determine optimal HRT for operation.	Time	Use replicated results across mesocosms compared to control (no chemical dosing)	P, turbidity, PSD
Toxicity Changes	G: Assess toxicity changes through mesocosms. H: Toxicity is mitigated by the biotic conditions in the wetland.	Time	Subset of samples from replicated mesocosms	Toxicity metric
Groundwater and Soil Effects				
Phosphorus and aluminum transport through sediments	G: Assess movement of water quality constituents through groundwater. H: P transport is greatly retarded because of the formed flocculates combining with sediments and through use of adsorptive media.	Time	Groundwater extracted from replicated mesocosms	dissolved P, dissolved Al
Soil accretion and changes in sediment	G: Estimates of soil accretion rates and resulting soil quality from floc and biomass accumulation.	Time	In situ measurements of accretion	Bulk density, wet and dry weight, total P, total Al, organic carbon
Other effects				
Effects on vegetation biomass and chemistry	G: Changes in vegetation C/N/P/Al ratios.	Time	annual sampling in mesocosms	total Al, C, N and P
Temperature mixing effects	H: Temperature gradients do not resuspend P or fine particles after removal by flocculation	Time	diel studies	Total P and turbidity

[1] Temporal replication using different stormwaters from different locations and times

[2] Spatial replication using multiple mesocosms

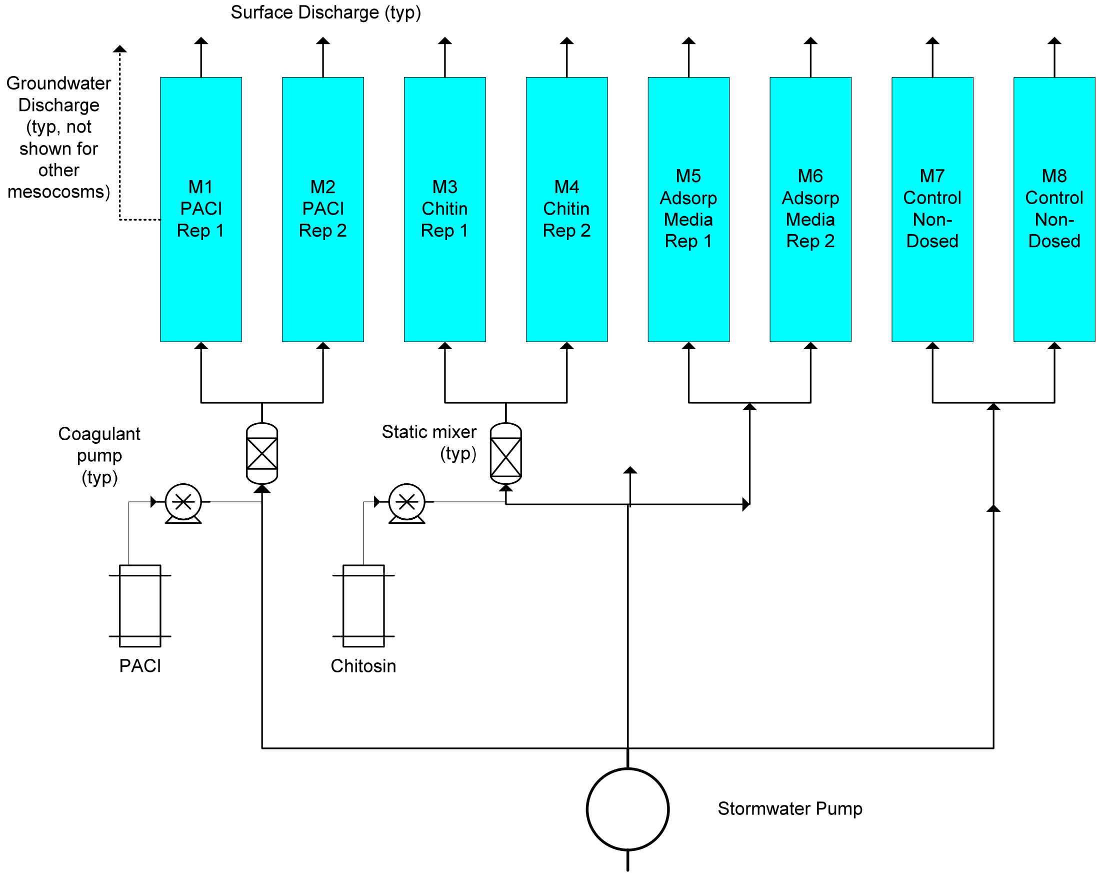

Figure 4 - 5. Mesocosm Process Flow Diagram

Table 4 - 2. Planned Treatments for Mesocosm Studies

Treatment	Justification
PACl	Polyaluminum chlorides have been found to be the most robust and effective coagulants for removing phosphorus
Chitin	There is much interest in the Tahoe Basin with regard to chitin, based upon concerns about using chemicals and their potential toxicity. Chitosan is considered a safer alternative.
Control	Provides baseline comparison
Adsorptive media blended with soils	Adsorptive media used in equilization basins (See Chap 8) should help retard P movement to groundwater

The treatments planned would include two chemical dosing treatments, along with one control and one adsorptive media treatment[22] (Table 4-3). These would test chemical dosing of both a polyaluminum chloride and of chitosan. Polyaluminum chlorides have been determined to be the most effective coagulants for removing P from Tahoe stormwaters (Bachand et al. 2006, Trejo-

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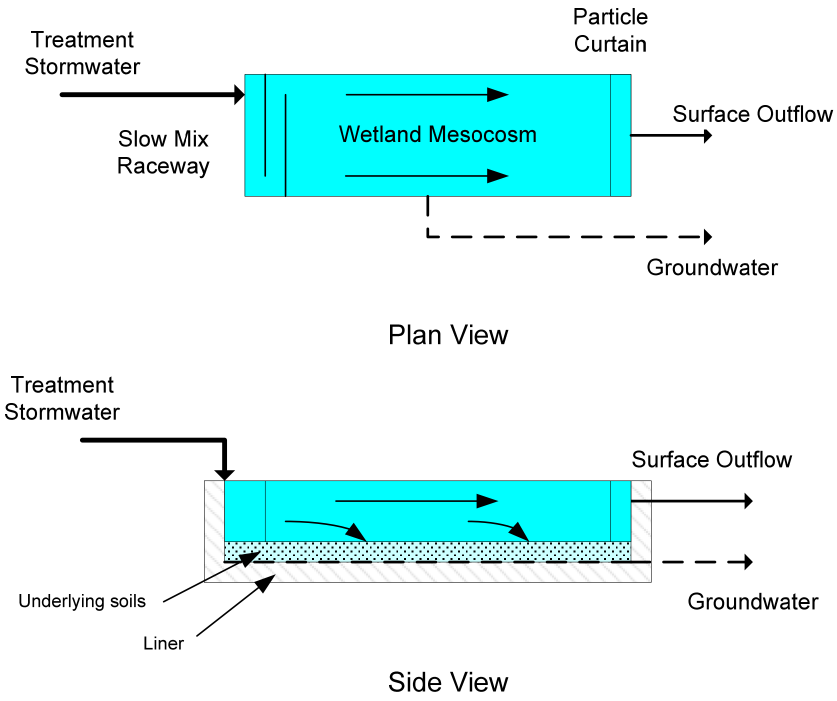
[22] Adsorptive media would be blended with the soil to test P removal through adsorption. No chemical dosing would be done in that treatment.

Gaytan et al. 2006). The resource management community at Tahoe remains interested in chitosan because of concerns about using chemicals in the Tahoe Basin, due to potential toxicity and environmental issues associated with the chemicals[23]. The adsorptive media treatment would blend soils with adsorptive media to simulate the equalization basin concept discussed previously. Adsorptive media blended with basin soils would theoretically help retard the movement of surface water phosphorus to groundwater (Bachand and Heyvaert, 2006).



Notes
1. Each basin is lined to allow groundwater collection.
2. Not to scale.
3. Preliminary conceptual design.

Figure 4 - 6. Plan and Side Views for Mesocosms

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[23] Toxicity is the focus of Chapter 3 and Appendices C & D in this report. Chitosan is envisioned as a more natural alternative by many in the Tahoe community. Work by Bachand et al. (2006) and Gaytan et al (2006) show that chitosan is less effective then the PACs for removing P and turbidity. However, it has been used in the Tahoe Basin and so we propose further investigation in this plan.

This design would provide opportunities to investigate both surface and groundwater effects associated with a number of issues (Table 9-1):

- Fate and transport of phosphorus and aluminum
- Temporal wetland effects on toxicity
- Changes in soil and groundwater chemistry
- Effects on vegetation
- Diel (24 hour) effects on surface water and flocculate sequestration

5. References

Bachand, P.A.M., C.J. Richardson and P. Vaithiyanathan. 2000. Everglades Phase II report Phase II Low Intensity Chemical Dosing (LICD): Development of Management Practices. Final Report submitted to Florida Department of Environmental Protection in fulfillment of Contract No. WM720. December 2000.

Bachand, P.A.M., S.M. Bachand and A. Heyvaert. 2005a. Draft Technical Memorandum, Task 2. BMP treatment technologies, monitoring needs, and knowledge gaps: Status of the knowledge and relevance within the Tahoe Basin. Submitted to El Dorado County, April 2005.

Bachand, P.A.M. and A. Heyvaert. 2006. Adsorptive Media Investigations and Testing for Improved Performance of Stormwater Treatment Systems in the Tahoe Basin. Submitted to Placer County and Tahoe Conservancy. May 1, 2006.

Bachand, P, J. Trejo-Gaytan, J. Darby, and J. Reuter. 2006. Final Report: Small-Scale Studies on Low Intensity Chemical Dosing (LICD) for Treatment of Highway Runoff. April 2006. CTSW-RT-06-073.13.1

Baskaran, S., N.S. Bolan, A. Rahman, R.W. Tillman and A.N. Macgregor. 1994. Effect of drying of soils on the adsopriotn and leaching of phosphate and 2,4-Dichlorophenoxacetic acid. Australian Journal Soil Res. 32:491-502.

Caltrans, 2006a. Caltrans Highway 267 Filter Fabric Sand Trap Pilot Study, 2004-2005 Interim Report **CTSW-RT-05-157.01.2**

Caltrans 2006b. Caltrans Lake Tahoe Storm Water Small-Scale Pilot Treatment Project Phase IV Final Report, April 2006 **CTSW-RT-05-157.04.02**

Doke, J.L., W.H. Funk, S.T.J. Juul and B.C. Moore. 1995. Title Habitat availability and benthic invertebrate population changes following alum treatment and hypolimnetic oxygenation in Newman Lake, Washington. Journal of Freshwater Ecology 10(2): 87-102

Gensemer, R.W. and R.C. Playle. 1999. The bioavailability and toxicity of aluminum in aquatic environments. Critical Revies in Environmental Science and Technology, 29(4):315-450.

Gothenburg Symposium. 2007. The Bi-annual International Gothenburg Symposium on Chemical Treatment. http://www.gothenburgsymposium.com/insite/programme.htm

Harper, H.H. 1994. Alum treatment of stormwater runoff - Orlando's Lake Dot and Lake Lucerne systems. Lake Reservoir Manage. 9(2):81.

Harper, H.H.; Herr, J.L.; and L Livingston, E.H. (1999) Chapter 9: Alum Treatment of Stormwater: the First Ten Y ears. In: *New Applications in Modeling Urban Water Systems.* Monograph 7 in the series. W. James, Ed. Pub. by CHI, Guelph, Canada

Heyvaert, A.C., J.E. Reuter, and C.R. Goldman. 2006. Subalpine, cold climate, stormwater treatment with a constructed surface flow wetland. Journal of the American Water Resources Association (JAWRA) 42(1):45-54.

Iwinski, S.R. 2004. Soil Specific Polymer Blend, Applications and Corresponding BMPs. Presentation at the CONFERENCE ON ADVANCED TREATMENT FOR CONSTRUCTION SITES, October 21, 2004, California State Water Resources Control Board Water Quality Storm Water Program. http://www.swrcb.ca.gov/stormwtr/advtreatment.html, http://www.swrcb.ca.gov/stormwtr/docs/advtreat/appliedpolymer.pdf.

Jacoby, J.M., H.L. Gibbons, K.B. Stoops and D.D. Bouchard. 1994. Response of a shallow, polymictic lake to buffered alum treatment. Lake Reserv. Manage. 10(2):103-112.

James, W.F., J.W. Barko and W.D. Taylor. 1991. Effects of alum treatment on phosphorus dynamic in a north-temperate reservoir. Hydrolobiologia 215(3):231-241.

Kadlec, R.H. and R.L. Knight. 1996. Treatment Wetlands. Lewis Publishers, CRC Press, Boca Raton, FL.

Kennedy, R.H. and G.D. Cooke. 1982. Control of lake phosphorus with aluminum sulfate: dose determination and application techniques. Water. Res. Bull 18:389-395.

Lahontan Regional Water Quality Control Board (LRWQCB). 2003. Water Quality Control Plan for the Lahontan Region (Basin Plan). California Regional Water Quality Control Board, Lahontan Region. South Lake Tahoe, CA.

Livingston, E.H., H. Harper and J.L. Herr. 1994. The use of alum injection to treat stormwater. In: Proceedings of the 2nd Annual Conference on Soil and Water Management for Urban Development. pp. 31-53. (Livingston, E.H. and Harper, H.H., Eds.) Sydney, N.S.W.

Lumos and Associates, Inc. 2006. East Pioneer Trail Watershed Hydrology Study Final Report. Submitted to City of South Lake Tahoe and California Tahoe Conservancy. October 2005. Prepared by Lumos and Associates, Inc., Carson City, NV 89706. cc@lumosengineering.com

Markich, SJ and RA Jeffree. 1994. Absorption of divalent trace metals as analogues of calcium by Australian freshwater bivalves: An explanation of how water hardness reduces metal toxicity. Aquatic Toxicology 29(304): 257-290.

Metcalf and Eddy. 1979. Wastewater Engineering, Treatment, Disposal and Reuse, Second Edition. Revised by G. Tchobanoglous. McGraw-Hill. N.Y.

Reddy, K.R., O.A. Diaz, L.J. Scinto and M. Agami. 1995. Phosphorus dynamics in selected wetlands and streams of the lake Okeechobee Basin. Ecological Engineering 5:184-207.

Regenmorter, L.C., M. Kayhanian and K. Tsay. 2002. Stormwater Runoff Water Quality Characteristics From Highways in Lake Tahoe, California. Presented at: StormCon 2002, San Marco Island, Florida, August 12-15, 2002. Storm Water Program. CSUS Office of Water Programs. http://www.owp.csus.edu/research/papers/papers/PP038.pdf. Accessed February 11, 2007.

Regenmorter, L.C., M. Kayhanian, R.W. Chappell, T. Burgessor and K. Tsay. 2002. Particles and the Associated Pollutant Concentrations in Highway Runoff in Lake Tahoe, California

Reuter, J.E. and W.W. Miller. 2000. Aquatic Resources, Water Quality, and Limnology of Lake Tahoe and Its Upland Watershed. In: D.D. Murphy and C.M. Knopp (Eds.) Lake Tahoe Watershed Assessment: Volume 1. Gen. Tech. Rep. PSW-GTR-175. Albany, CA: Pacific Southwest Research Station, Forest Service, US Department of Agriculture.

Presented at: StormCon 2002, San Marco Island, Florida, August 12-15, 2002 (included in conference proceedings).

Rosemond, S.J.C. and K. Liber. 2004. Wastewater treatment polymers identified as the toxic component of a diamond mine effluent. Environmental Toxicology and Chemistry, Vol. 23(9): 2234–2242.

Sakadevan, K and H.J. Bavor. 1998. Phosphate adsorption characteristics of soils, slags and zeolite to be used as substrates in constructed wetland systems. Wat. Res 32(4)394-399.

Smeltzer, E. 1990. A successful alum/aluminate treatment of Lake Morey, Vermont. Lake Reserv. Mange. 6(1):9-19.

Snoeyink, V.L. and D. Jenkins. 1980. Water Chemistry. John Wiley & Sons. New York.

Soucek, D.J., D.S. Cherry, and C.E. Zipper. 2001. Aluminum-dominated acute toxicity to the cladoceran Ceriodaphnia dubia in neutral waters downstream of an acid mine drainage. Can. J. Fish. Aquat. Sci. 58:2396-2404.

Swift, T.J., J. Perez-Losada, S.G. Schladow, J.E. Reuter, A.D. Jassby, and C.R. Goldman. 2006. Water clarity modeling in Lake Tahoe: Linking suspended matter characteristics to Secchi depth. Aquat. Sci. 68: 1-15.

Trejo-Gaytan, J; P. Bachand, and J. Darby. 2006. Treatment of Urban Runoff at Lake Tahoe: Low-Intensity Chemical Dosing. Water Environment Research 78(14): 2487-2500

TIRRS. 2001. Planning Guidance for Implementing Permanent Storm Water Best Management Practices in the Lake Tahoe Basin. Tahoe Interagency Roadway Runoff Subcommittee. November 2001. http://www.waterboards.ca.gov/lahontan/BMP/Index.htm. Accessed February 11, 2007.

TRPA. 2001. 2001 Threshold Evaluation Report. Tahoe Regional Planning Agency. July 2002. http://www.trpa.org/default.aspx?tabindex=1&tabid=174. Accessed February 11, 2007

Ullman, J.L. 1999. Characterization of Iron in a constructed wetland following metal dosing for phosphorus removal from agricultural runoff. Masters of Science Thesis. Duke University Department of the Environment.

Weilenmann, U., C.R. O'Melia and W. Stumm. 1989. Particle Transport in Lakes: Models and Measurements. Limnology and Oceanography 34(1): 1 – 18.

Welch, E.B. and G.D. Schrieve. 1994. Alum treatment effectiveness and longevity in shallow lakes. Hydrobiologia 275-276(0):423-431.

A. Investigating Coagulants and their Robustness

In the Tahoe Basin, strict surface water discharge limits of 20 NTU for turbidity and 0.1 mg/L for total phosphorus are currently in effect for discharge to surface waters[24]. The main concern in terms of water quality is the discharge of fine particles and nutrients into Lake Tahoe. The overall goal for these laboratory studies was to determine the feasibility of low intensity chemical dosing (LICD) as a new technology for improving stormwater runoff quality in the Lake Tahoe Basin.

One of the primary objectives was to identify promising coagulants for turbidity and phosphorus reduction that could be tested further in small-scale and full-scale pilots. This project combined a series of literature reviews, laboratory studies (charge titration and jar test experiments using synthetic and actual stormwater runoff) and settling column studies to assess treatment performance and feasibility.

An initial list of 25 potential coagulants was assembled, based upon a literature review and the information obtained from manufacturers. These coagulants represented a wide-range of available coagulant types:

- Proprietary and non-proprietary products
- Alum, aluminum chlorohydrates and polyaluminum chlorides (PACs; inorganic aluminum-based polymers)
- Ferric sulfate, ferric chloride and polyferric sulfate (inorganic iron-based polymers)
- Organic polymers
- Inorganic/organic polymer blends
- Chitosan-based coagulants

These 25 coagulants were then narrowed to nine through charge titration studies. These studies identified the relative dosing levels required by the different coagulants to remove turbidity from synthetic stormwater produced from Tahoe Basin road sweepings. These nine coagulants were subsequently narrowed to four, based upon a selection model that considered performance, cost and environmental characteristics. This model used (and weighted) several different measures of performance, including: turbidity and phosphorus removal performance and robustness to varying dosing levels; the dosing levels required for good removal; settling characteristics of flocculates; and effects on the pH of treated water. The coagulants selected for further investigation were –

- JenChem 1720,
- Pass-C,
- PAX-XL9, and
- SumaChlor 50

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[24] Lahontan Regional Water Quality Control Board (LRWQCB). 2003. Water Quality Control Plan for the Lahontan Region (Basin Plan). California Regional Water Quality Control Board, Lahontan Region. South Lake Tahoe, CA.

JenChem 1720 is a complex product in which organic polymers are blended with inorganic polymers. Pass-C and PAX-XL9 are PACs. Pass-C, which is a sulfinated PAC, has been tested extensively by the California Department of Transportation (Caltrans), so was used for a comparison between studies. SumaChlor 50 is essentially a straight aluminum chlorohydrate (ACH) and equivalent products can be found amongst most manufacturers. These four selected coagulants did not necessarily represent the most effective coagulants in the screening tests, but they did represent coagulants that provided relatively robust performance for different dosing levels with regard to turbidity and phosphorus removal, and were diverse with regard to chemistry.

Laboratory studies were then conducted on these four coagulants to test their robustness with regards to performance against variations in real-world environmental and operational variables. Typically, when using coagulants, a dosing regime is developed to optimize coagulant usage. This dosing regime includes a period of rapid mixing to increase the energy input and improve reaction kinetics between the added coagulant and targeted constituents in the waters. This step is usually followed by a slow mixing period to aid with flocculation. This mixing strategy was developed early in the wastewater treatment industry, with use of coagulants such as ferric chloride, ferric sulfate and alum, and it has persisted with coagulants that have more advanced engineered chemistries. However, in stormwater applications, these mixing regimes are less likely to be as tightly controlled as with wastewater and water treatment systems, for which the coagulation methods were originally developed. Thus, one goal of the laboratory studies was to test the robustness of coagulant performance to variations in specified mixing regimes. Additionally stormwater chemistry varies spatially and temporally in the Tahoe Basin, and seasonal changes in temperature are great. Thus, the laboratory studies also tested robustness of this technology to changes in environmental conditions.

Therefore, these laboratory studies tested robustness of the four coagulants against –

- Different dosing levels;
- Different dosing regimes, as defined by different rapid mixing conditions and the presence or absence of a subsequent slow mixing regime;
- Differences in water temperature; and
- Differences in stormwaters.

One synthetic and two real stormwaters were used for these tests.

The main findings of this study were:

1. Chemical dosing shows promise in helping to meet current Tahoe Basin stormwater discharge limits of turbidity less than 20 NTU and phosphorus less than 0.1 mg/L. All four coagulants in the final selection were effective at meeting surface water discharge limits for total phosphorus and turbidity in the laboratory studies.
2. Selection of an effective coagulant can help to overcome the variable effects of temperature, mixing, water quality and dosing on coagulant performance. Indeed, coagulant selection was found to be the most important variable for determining

phosphorus and turbidity removal efficiency. Although performance of the less effective coagulants was affected by changes in temperature, mixing regime, water quality and dosing.

3. PAX-XL9 and Pass-C were the most effective and most robust coagulants tested of the final four that were selected. These coagulants are sulfinated, medium to medium-high basicity coagulants. The performance of these coagulants with regard to phosphorus and turbidity removal was minimally affected by changes in temperature, mixing regimes, stormwater quality and dose. These two coagulants were considered equivalent in performance.
4. Though the inorganic/organic blends (e.g., JC 1720) were relatively less effective in removing phosphorus and reducing turbidity, they required lower dosing levels (sometimes by an order of magnitude) compared to the PACs and they had minimal effect on water pH.
5. Many PACs had very good performance over a broad dosing range, while the inorganic/organic polymer blends appeared to be more difficult to overdose. Approaching optimal dosing levels was found to improve coagulant performance. Mean turbidity and total phosphorus removal showed an average improvement of 25% during the intermediate tests (used to narrow coagulants tested in this study from nine to four), where the performance of coagulants was tested across the full-dosing range (instead of limited to the optimal dosing range).
6. Overdosing was found to increase soluble concentrations of the dosing metal, which does not occur under more optimal dosing conditions. Overdosing is defined in this report as dosing above the point of zero charge on a streaming current detector, which for practical purposes represents the point of complete charge neutralization. Inefficient metal utilization due to overdosing will most likely increase coagulant and maintenance costs, and may also lead to greater environmental issues. This is more important for coagulants that require higher dosing levels of aluminum to achieve charge neutralization. For instance, with the inorganic/organic blends the increased concentrations of soluble aluminum were small because such low doses of aluminum were required, compared to PACs without organic polymers added. But for coagulants such as PAX-XL9 and Pass C, which required higher aluminum dosing levels to neutralize charge, the soluble aluminum concentrations increased from around 0.25 mg/L to more than 1 mg/L with a dosing increase of 2–3 mg-Aluminum/L above the zero charge dosing level.
7. The effects with different rapid mixing regimes and the effect from presence or absence of a subsequent slow mixing period were tested with each of the four different coagulants. The most robust coagulants (PAX-XL9 and Pass-C) were least affected by differences in rapid mixing regimes or by the presence or absence of subsequent slow mixing, as compared to the less robust coagulants (JenChem-1720, Sumachlor-50). For the less robust coagulants, slow mixing appears to affect coagulant performance in terms of turbidity and phosphorus removal more than does rapid mixing. These coagulants generally showed better performance with the addition of a slow mixing step after the period of rapid mixing.

8. Turbidity discharge limits (20 NTU) were generally more difficult to meet than the total phosphorus discharge limits (0.1 mg/L).
9. Streaming current meters were proven useful for predicting optimal dosing range for the different coagulants and with different stormwaters.
10. The PAC coagulants have minimal effect on alkalinity, pH or the concentrations of nitrogen, iron and aluminum. Alkalinity generally decreased in these tests, and that decrease was dependent upon dosing level. Nitrogen concentrations, as well as concentrations of total iron and aluminum, also decreased. These reductions appear to be due to increased precipitation and improved particulate settling.
11. Settling column experiments showed that treated stormwaters would more rapidly remove turbidity than the non-dosed stormwaters. Thus, chemical dosing should either reduce the aerial footprint required for treatment or increase the capacity of an existing footprint. Moreover, because chemical dosing causes aggregation and settling of fine particles, the outflow from a chemically treated system should have relatively fewer fine particles then outflow from a non-treated system.

This study has shown that chemical dosing may be an effective stormwater treatment approach for the Tahoe Basin. The results suggest that chemical treatment of highway and urban stormwater runoff, when properly implemented, may markedly improve stormwater quality in terms of reduced turbidity and lower phosphorus concentrations. Based upon these results, further testing of this technology should be continued. Although PAX-XL9 and Pass-C (both polyaluminum chlorides) demonstrated the best treatment performance, SumaChlor 50 (an aluminum chlorohydrate) and JC 1720 (an inorganic/organic blend) should also be considered for further testing, since both SumaChlor 50 and JC 1720 required lower dosing levels than PAX-XL9 and Pass-C, and are therefore likely to have lower potential environmental effects and maintenance costs. Dose optimization should also be considered in future studies because inefficient metal utilization when dosing is not optimized can lead to increased coagulant costs, increased basin maintenance costs for flocculate management, and increased soluble concentrations of the dosed metal.

The full report on these tests is attached in Appendix H. Additional findings were summarized by Trejo-Gayton et al. (2006).

B. Settling Studies – Using coagulants to increase settling rates of fine particles in Tahoe stormwaters, with implications for water quality treatment

Bachand, P.A.M, A. Heyvaert, J. Darby

B.1. Abstract

Small sediment particles in stormwater are likely to pass through stormwater treatment basins, and are not easily settled in lakes because of slow settling velocities and normal lake mixing or currents. Several processes help aggregate these small particles in natural lakes, including biotic processes such as zooplankton grazing, as well as natural coagulation processes driven by both biotic and abiotic processes. However, these natural coagulation processes are relatively slow, on the order of days to weeks, and are unlikely to be important processes in removing fine particles from stormwater basins, which are typically operating under short detention times (a few days) because of either high flows or frequent events.

Coagulation should greatly increase both particle size and settling velocities, and should improve stormwater basin performance by an order of magnitude for many stormwaters. In this study, coagulation removed 85–95% of mean turbidity and associated phosphorus within 10 hours of settling. By comparison, for the non-dosed and non-treated stormwater, 20% of turbidity was removed after 10 hours of settling, 80% was removed after about 2 days and 90% removal was never attained during the 72 hours of the study. Using calculated settling velocities, it was predicted that 90% turbidity removal for non-treated stormwater would occur on the order of hundreds of hours by settling, and that particles remaining in solution would range from submicron to a few microns in size. Natural coagulation and biotic process are likely to hasten settling at some point, although removal by those processes is expected to be on the order of days to weeks.

Chemical coagulation could also affect the nature of the formed sediments. These sediments are likely to include organic, amorphous and crystalline forms of aluminum. The coagulant formed sediments should be more structured and stable then the solids typically formed in settling basins.

B.2. Introduction

Reduced water clarity in Lake Tahoe has been attributed to increased loading of fine sediment particles and nutrients (phosphorus and nitrogen). Stormwater technologies currently in use have limited effectiveness for removing these constituents. Treatment Best Management Practices (BMPs) typically remove from 47–86% of total suspended solids and from 34–59% of total phosphorus (Winer, 2000; not including infiltration). However, these practices are of limited use for addressing fine particle and phosphorus removal needs at Lake Tahoe, where stormwaters discharged from BMPs, such as sediment traps and detention basins, often show high particle concentrations in the size range of 0.5 to 20 microns and phosphorus concentrations that exceed local regulatory limits for discharge to surface water (0.1 mg/L). Moreover, there is limited acreage available in the Tahoe Basin for implementing treatment BMPs, which constrains the suitable locations and size of structural BMP installations.

To help alleviate this limitation, there is interest in the Tahoe Basin in developing other treatment technologies that remove phosphorus and fine particles more efficiently. One such technology, chemical coagulation, has been used in the wastewater treatment industry for years to remove phosphorus and fine particles from wastewater discharge. The coagulants increasingly used by this industry are polyaluminum chlorides, since these coagulants are less affected by mixing regimes and are engineered to provide more controlled particle aggregation characteristics.

Coagulation is beginning to be used to treat stormwaters. *In situ* investigations in Florida Everglades have shown that phosphorus can be removed effectively by using aluminum and iron-based coagulants (Bachand et al, 2000), and some coagulation methods with aluminum-based chemicals have been implemented to treat stormwater entering Florida lakes (Harvey, 2003). For decades, alum has been used to remove phosphorus from lakes in the battle against eutrophication (Welch and Cooke, 1999). More recently, chitosan, a chitin-based coagulant derived from crab shells or equivalent sources, is being used to treat stormwater runoff from construction sites (e.g. Benedict et al., 2004).

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Recent laboratory studies have shown that polyaluminum chlorides have great promise for removing phosphorus and turbidity from Tahoe stormwaters (Trejo et el. 2006, Bachand et al., 2006). Furthermore, with the more effective coagulants, treatment effectiveness was robust to changes in temperature, mixing regimes and water quality.

This study follows up on that earlier work by using settling columns for determining settling velocities, by examining settling trends for coagulated sediments, and by characterizing the flocculates formed in non-treated and chemically-treated stormwaters. This study was conducted on a composited stormwater collected from three locations in the Tahoe Basin (Figure B-1). The settling column tests were conducted at a water depth considered characteristic of treatment basins (3–4 feet). Based upon these analyses, the implications on design and logistical issues of treatment basins in the Tahoe Basin will be discussed.

B.3. Methods

Stormwater runoff was collected from four sites around the Tahoe Basin (Figure 1). These samples were taken directly from points of discharge by filling clean 5 gallon HDPE buckets and transporting to the laboratory. Equal volumes of stormwater from all four sites were combined into clean 35 gallon HDPE tanks to produce a total volume of about 400 liters for subsequent chemical treatment experiments. At the initiation of settling column studies, this stormwater had a mean turbidity 221 NTU, a mean total P concentration of 339 ppb and an alkalinity of 35.5 mg-CaCO3 L-1 (Table B-1).

For the column studies each 35 gallon stormwater tank was individually dosed with a different coagulant and then thoroughly mixed using a Lightning Mixer™, according to a uniform protocol that we had determined to be effective. Dosing levels were determined over a range developed from charge titration tests previously conducted on representative Tahoe stormwaters (Trejo-Gaytan et al. 2006) and then further narrowed with jar studies.

B.3.1. Experimental design

Each stormwater tank was dosed with one of three polyaluminum chloride coagulants (PACs), PAX-XL9, JenChem 1720 and SumaChlor 50, based upon work by Trejo-Gaytan et al. (2006) in which these coagulants were found to be both robust and effective in removing turbidity and phosphorus from synthetic and real Tahoe stormwaters under various dosing, mixing, temperature and water quality conditions (Table B-2). These three coagulants also were selected for this study to represent slightly different coagulant chemistries. SumaChlor 50 is an aluminum chlorohydrate (aluminum chlorohydrate was the first PAC developed and represents a non-proprietary product). PAX-XL9 is a more engineered polyaluminum chloride and is a proprietary product based upon its manufacturing method. PAX-XL9, along with another PAC (Pass-C) was the most robust and effective coagulant in the study by Trejo-Gaytan et al. (2006). Because PAX-XL9 represented a locally available product and had similar performance as Pass-C, it was selected for further study in this project. JenChem 1720 is a polyaluminum chloride in which organic N-based coagulants are blended with the inorganic polyaluminum chlorides.

After blending with coagulant, the treated stormwater was distributed rapidly to replicate (N=3) settling columns. Then samples were extracted during a 72 hour period at 3 locations in the column: 0.5, 1.5 and 2.5 feet from the bottom (Figure B-2). Water samples were collected initially (at time=0), then at 30 minutes, and thereafter at progressively longer time periods (Table B-3).

B.3.2. Water Analyses

Turbidity was measured with a HACH 2100N Laboratory Turbidimeter (SM 2130B) on each of the water samples, as it had been found previously to be a reasonable indicator for total P removal (Trejo-Gaytan et al., 2006). Samples for total and dissolved P were collected at every other sampling interval (time) and were analyzed colorimetrically (SM 4500-PE). Iron, aluminum and nitrogen analyses were run on water samples collected at 72 hours (Table B-3).

B.3.3. Flocculent Analyses

The flocculent at the base of each column was collected at the end of the settling study. These samples were collected by flushing water through the bottom of the column. The samples were then allowed to settle and decanted to extract the flocculent.

Flocculents were kept cold in HDPE 1-liter bottles ($\approx 4^{o}C$) prior to freeze drying. The samples were designated from a generic numbering system in order to remove association with a specific coagulate blend. After the flocs were allowed to settle to the bottom of the bottle, the excess water was siphoned off using 1/16 diameter tygon tubing. The removed water was centrifuged 5 minutes at 1000 rpm in order to ascertain if any flocculent or particulate material was left suspended in the water samples. Very little extra material was obtained by centrifugation and was determined to be an unnecessary step for the remaining samples. Additionally, two 1-liter raw (untreated) storm water samples were freeze dried for analytic comparison.

Thermal gravimetric analyses, x-ray powder diffraction, and Aluminum-27 magic angle spinning Nuclear Magnetic Resonance Spectroscopy were run on these samples to assess their structure and stability. Thermal gravimetric analyses that measure sample loss as a function of temperature were performed using a DuPont thermal gravimetric analyzer. X-ray diffraction using a Siemens D-500 X-ray Diffractometer was conducted on the freeze dried raw stormwater samples, coagulant blends, and flocculates. NRM analyses were performed on a Bruker MSL 300 spectrometer, with samples packed in 7 mm zirconium rotors and spun at approximately 5000 rotations per second. A 90 degree pulse width of 5.0 μsec was employed with a delay of 0.5 seconds. The samples were scanned at 2θ angles from 5 degrees to 50 degrees at 0.1 degree steps with a 2 second dwell per step.

B.3.4. Statistics and numerical analyses

ANOVA and Principal Component Analyses were used to describe statistical differences in the analytes measured for each treatment (StatSoft, 2003). Using the column data collected, settling curves were generated relating particle settling velocity to turbidity and total P removal (Pisano, 1996).

Stokes' Law (Equation B-1) was used to estimate particle sphere diameters from the settling velocities (Metcalf and Eddy, 1979; EPA, 1999):

$$v_s = {g(\rho_s - \rho)d^2} \big/ {18\upsilon}$$

Equation B-1

where
v_s = velocity of sphere, m/s
g = acceleration due to gravity, 981 m/s^2
ρ_s = density of the particle, kg/m^3
ρ = density of the fluid
d = diameter of sphere, m
υ = dynamic viscosity, N-s/m^2.

B.4. Results

B.4.1. Changing Water Quality Relationships

Table B-4 shows the constituent concentrations for non-treated and three chemically treated stormwaters after 72 hours of settling. Total concentrations for most of the measured constituents decreased dramatically in the treated stormwaters as compared to non-treated stormwater. Chemical dosing significantly ($p<0.05$) and greatly decreased the turbidity, total P, total iron and total aluminum concentrations for all coagulants, and decreased the TKN for one coagulant, PAX-XL9 (Table B-4). Mean turbidity, total iron and total aluminum values recorded after 72 hours of settling were an order of magnitude less for the treated stormwaters compared to non-treated stormwaters. Mean turbidity values for treated stormwaters were less then 2 NTU (compared to 34 NTU in untreated replicates and 222 NTU at the start). Mean values for total iron and total aluminum in the treated stormwaters were below the 0.1 mg/L analytic reporting limit.

Mean concentrations of total phosphorus in treated stormwaters after 72 hours of settling were in the range of 6 to 13 ppb, which was about 65–80% less than in the non-treated stormwater. Dissolved phosphorus concentrations were slightly less for two of the treated stormwaters, with means in the range of 3 to 5 ppb, but were equivalent to non-treated stormwater for PXXL9 (7 to 8 ppb). TKN values were only slightly lower for the treated versus non-treated stormwaters, being at or below the reporting limit.

For treated stormwaters, the water quality values recorded at 72 hours are likely good indicators of earlier conditions achieved at about 8 hours, because immediately after coagulation the turbidity values in treated stormwaters greatly decreased asymptotically until reaching an apparent steady-state condition after 4 to 6 hours (Figure B-3), when turbidity concentrations were below 5 NTU and continued to decrease only slightly from that point onward.

For non-treated stormwater, the 72 hour interval is not likely to represent a final steady state condition, as turbidity was continuing to decrease (Figure B-3), and since smaller particles present in the non-treated stormwater would require more time to settle than flocs in the treated stormwater.

These results from coagulant treatment are likely to be similar for all other constituents in which particulates are the dominant fraction. For the treated stormwater, total P concentrations asymptotically achieved steady state conditions within a few hours (Figure B-4). Total P concentrations did not differ significantly ($p<0.05$, ANOVA repeated measures) for measurements taken after 4 hours, indicating that optimal treatment was achieved within that time period. Conversely, total P concentrations were still decreasing significantly in the non-treated stormwater at 72 hours.

B.4.2. Changing settling rates

Stratification (gradients) occurred in the non-treated stormwater tests, but were not observed in the treated stormwater (Figure B-5). Turbidity levels under 5 NTU were achieved within a few hours throughout the water column when coagulants were used. However, non-treated stormwater, turbidity values persisted above 40 NTU throughout the water column, and increased with depth in the water column (2.5 ft depth) during the first 72 hours as particles moved downward. These differences were statistically significant throughout the water column during the first 24 hours (Figure B-6). After 24 hours, the differences were not statistically different and turbidity averaged 40–50 NTU at all water depths. Slow removal of the fine particles continued over the next 48 hours in non-treated stormwater, with a final turbidity of 30–NTU observed at all depths.

Settling velocities were calculated from these data. The particles which accounted for 95% of turbidity removed when stormwater was treated with JenChem 1720 or PAX-XL9 had settling velocities greater then 0.01 cm s^{-1} (Figure B-7). For stormwater treated with SumaChlor 50, the particles that accounted for about 80% of turbidity removed had settling velocities greater then 0.01 cm s^{-1}, and particles that accounted for 95% of turbidity removed had settling velocities over 0.001 cm s^{-1}. In contrast, particles that accounted for only about 10% of the turbidity in the non-treated stormwater had settling velocities as high as 0.01 cm s^{-1} or greater. Particles that accounted for 20% of the turbidity had settling velocities less then 0.0001 cm s^{-1}. Thus, coagulant dosing increased settling velocities by one or two orders of magnitude.

Similar results were found with total P removal. Most of the total P removed with chemically dosed stormwaters had settling velocities greater then 0.01 cm s^{-1}. In contrast, 10% of the total P found in non-treated stormwater had settling velocities below 0.0001 cm s^{-1} and only about 40% had settling velocities greater then 0.01 cm s^{-1} (Figure B-8). In general, for this study, total P removal correlated well with turbidity removal ($r=0.96$).

To estimate particle sizes we used Stokes' Law, which relates particle size to settling velocity. Thus, based upon the settling velocities recorded, the sizes of particles initially in solution were estimated. For the non-treated stormwaters, 80% of the turbidity was due to calculated particles sizes of around 4–15 microns and about 20% was due to particles in the range of 1–3 microns or smaller (Figure B-9). The chemically treated stormwater had much larger calculated particle sizes. Assuming a specific gravity of 1.2, slightly above the density of water, up to ninety percent of the turbidity was due to calculated particle sizes from 15–60 microns or greater. Depending upon the coagulant used, the percent of turbidity due to particle sizes below 15 microns varied. About 10% of the turbidity in Sumachlor 50 treated stormwaters was caused by particles of 15 microns or smaller. For JenChem 1720 and PAX-XL treated stormwaters, that percentage decreased to about 4%. For all treated stormwaters the decrease in particles 15 microns or smaller was dramatic, at nearly an order of magnitude change.

B.4.3. Flocculent Stability Analyses

The structure and the stability of formed flocculants were analyzed using thermal analysis, x-ray diffraction and NMR as discussed in the methods.

Thermal Analysis Experiments and Results:

Freeze dried raw storm water sediments generally lost 25% of mass during the temperature cycling, as compared to mean values of around 12–15% for the flocculate collected from treated stormwaters. For both the treated and non-treated stormwater, about 5% of mass loss occurred below 200°C. These results did not differ significantly between the different treatments or between dosed and non-dosed treatments (Figure B-10; $p<0.05$). However, at thermal temperatures greater then 200°C, statistically different percent mass amounts were lost in the flocculates collected from treated stormwaters as compared to the non-treated stormwaters. For treated stormwaters, around 10 to 13% mass loss occurred whereas for the sediments from the non-treated stormwaters, about 20% mass loss occurred. These results suggest that freeze dried flocculates are significantly more stable (thermally) than the residues in raw settled stormwater, which implies that stable chemical bonds form in the flocculates resulting from chemical treatment.

B.5. Discussion

Stormwater basins, sediment traps, wetlands, and other BMPs are all being used in the Tahoe Basin to improve stormwater quality before it runs off into the Lake. Lake Tahoe has been losing clarity over the last 30 years at an approximate rate of one foot per year (Jassby et al., 2003). This reduction has been primarily attributed to excess loading of fine particles and nutrients, such as phosphorus and nitrogen (Reuter and Miller 2000, Swift et al. 2006).

Stormwater best management practices such as dry basins, wet basins and treatment wetlands are part of a large effort in the Tahoe Basin to address point sources of runoff from mostly urbanized areas in order to help address the clarity issue. The typical design criteria for these various stormwater basins is to collect all runoff water from the 20-year, 1-hour design storm, which corresponds to approximately one inch of precipitation (LRWQCB, 2003). After such an event, these basins are designed to reach capacity and any subsequent inflow will result in basin outflow and relatively short treatment times.

There are a number of shortcomings with this design approach. First, basin design cannot always meet this criterion. For example, insufficient area along the shoreline for implementing basins or other treatment systems in this zone of rising property values makes it difficult to accomplish. Lumos and Associates (2005) found that basins along the south shore of Lake Tahoe generally were of insufficient capacity to meet design requirements.

A second problem with this approach is that high frequency storms can overwhelm a treatment basin, even if it does meet the design requirements. It is not unusual in the Tahoe Basin to have a series of relatively frequent storm events during fall and winter months. For instance, the sequence of storm events that occurred from December 2005 to January 2006 resulted in runoff volumes that exceeded the capacity of most stormwater basins. Furthermore, this event was rain-on-snow with very high runoff rates, a not uncommon storm type for the Tahoe Basin.

Finally, data from basins and other treatment systems such as sediment traps around the Tahoe Basin show that while these systems can remove high volumes of coarse solids, they are not very effective at the removal of fine particles or dissolved phosphorus. Regenmorter et al. (2002) found that in stormwater from highways, the bulk (mass) of stormwater particles generally ranged from 100 to 2000 µm. After treatment by traps, the particle size distribution changed with twenty percent of the mass 10 µm or smaller. Most of the lake turbidity causing particles are in the range of 0.5 to 10 µm (Swift et al. 2006).

B.5.1. Factors affecting and limitation on removing fine particles in Tahoe stormwaters with detention basins

These situations where several runoff events follow in short succession can be problematic for basins designed to hold the design storm. For the stormwater we tested, after a 24 hour hydraulic retention time (HRT), turbidity values remained about 50 NTU (Figure B-3), representing nearly 20% of the initial turbidity. This turbidity stratified in the water column after 24 hours, with deeper waters having a turbidity level of about 75 NTU and shallow waters having a turbidity level of about 40 NTU (Figure B-6). Increasing the holding time to 72 hours improved turbidity removal, decreasing the average turbidity levels to 40 NTU (Figure B-5). However, small diameter particles will continue to be exported. Only with holding times calculated in excess of 100 hours would we expect to get 80% removal of turbidity (Figure B-11). These relationships would hold true for total phosphorus as well, if the majority of phosphorus is in a particulate form, as was the condition with this tested stormwater. For this study, turbidity removal was a good indicator of total P removal.

Regardless of stormwater source in the Tahoe Basin, holding times will likely be a problem. The stormwater we tested, which represented stormwater entering basins, had particle sizes estimated to range from under 1 micron to over 20 microns (Figure B-9). Eighty percent of the turbidity was composed of particles estimated at under 8 microns (Figure B-9). For stormwaters with a greater percent of larger particles, a greater percent of turbidity will be removed over equivalent time periods because of greater settling velocities. For stormwaters composed of finer particles, the percent removal will be worse. But for all stormwaters, the size of the exported particles will be similar for given holding times because particle size effectively controls settling rates. Finer particles will have slower settling rates. If the holding time is shorter then needed to settle that particle size, the particle will be exported.

Our settling column studies predict particles of a few microns take about a day to settle in 3 feet of water whereas particles less then 2 microns take on the order of 100 hours to settle (Figure B-11).

These predictions assume quiescent conditions. Unfortunately, wind or temperature driven mixing will compromise performance. A settling velocity of just over 0.001 cm s^{-1} corresponds to 24 hour settling in three feet of water. For the stormwater we tested, approximately 40% of the turbidity had settling velocities lower then 0.001 cm s^{-1} (Figure B-8). However, wind, temperature and vegetation can affect settling performance. Stephan et al. (2005) found for kaolin particles (with mean diameters of 7.4 µm and specific gravity of 2.6) wind mixing reduced settling by about 20% due to deformation in the velocity profile. They also found vegetation did not necessarily improve settling rates. Flow patterns can be related to a stem Reynolds number Re*:

$$\mathrm{Re}^* = {velocity \times d_P}/{\nu} \qquad \textbf{Equation B-2}$$

With
d_P = stem diameter and
ν = kinematic viscosity.

They found for higher stem Re*, vortexes developing behind the plant stems can reduce flocculation and settling velocities. At lower stem Re*, these effects can be somewhat mitigated through the development of velocity shadows behind the vegetation where decreased velocities improved settling. Others have found different results. Braskerud (2001) determined that vegetation improved particle removal by reducing resuspension and improving hydraulic efficiencies during higher flow events by reducing short-circuiting or preferential flow paths. Jams et al (2004) showed in a model that submerged vegetation could substantially reduce sediment resuspension through reducing wind induced shear stresses. Harter and Mitsch (2003) measured sedimentation that accrued in a created marsh and found highly variable rates. They attributed the variability in measured rates to high variability in spatial loading, bioturbation, turbulence and preferential flow paths.

Other factors also aid or hinder particle removal: natural coagulation, bacterial mineralization and grazing by zooplankton (Weilenmann et al 1989). All the processes together essentially ultimately contribute to removal of particle sizes in which removal probabilities are otherwise very low.

B.5.2. Importance of coagulation for removing fine particles

Natural coagulation is an important process for removing fine particles (Weilenmann et al. 1989). However, natural coagulation processes are relatively slow. Weilenmann et al (1989) reported natural coagulation in natural lakes in Switzerland to take from days to weeks, depending upon the water chemistry. Divalent metals such as Ca2+, Mg2+ destabilize particles and enhance coagulation whereas dissolved organic carbon (DOC) acts as a dispersing agent and hinders coagulation in natural waters. Thus, low DOC concentrations and high calcium or magnesium concentrations favor natural coagulation processes.

In stormwater detention basins, a residence time of less than a few days is likely too short for natural coagulation processes to be effective. Using chemical treatment is one way to introduce coagulation into these systems within an appropriate time scale. Chemical coagulation increased the settling velocities in our experiments by orders of magnitude. For the treated stormwaters, particles accounting for 90% of the turbidity had calculated settling velocities greater then 0.004 to 0.02 cm s^{-1}, depending upon the coagulant used (Figure B-7). Whereas in the non-treated stormwaters, particles accounting for 40% of the turbidity had settling velocities less then 0.001 cm s^{-1}, and particles accounting for about 2 to 4 percent of the turbidity in treated-stormwaters had settling velocities below 0.001 cm s^{-1}.

Chemical coagulation increases effective particle size, so settling rates improved dramatically in our tests as the particle sizes increased by an order of magnitude. Eighty percent of the turbidity removed by SumaChlor 50 and about 95% of the turbidity removed by Jen Chem 1720 and PAX-XL9 had calculated particle sizes greater then 30 microns. This compares to about 80% of the turbidity non-treated stormwater having calculated particle sizes less then about 8microns. Furthermore, increasing the particle sizes will fundamentally decrease the importance of other factors that affect settling, such as wind shear and temperature gradients, or basin hydrologic short-circuiting. These higher settling velocities result in turbidity removal occurring within a few hours as compared to several days.

B.5.3. Implications of formed flocculates on long-term P removal

The particles removed from solution after coagulation are fundamentally changed. Particles formed from coagulation of the stormwater are more thermally stable then those removed from non-treated stormwater (Figure B-10). This result suggests that stable chemical bonds are created during flocculate formation. X-ray diffraction analyses of the flocculates showed that untreated freeze-dried storm water samples had amorphous physical structures, whereas the flocculates resulting from treated stormwater had increased crystalline structure (Figure B-12) and thus more stability. Aluminum-27 magic angle spinning Nuclear Magnetic Resonance Spectroscopy analyses of these same flocculates suggested that coagulation and flocculation formed stable aluminum complexes in tetrahedral environments.

Ullman (1999) conducted a series of *in situ* microcosm settling column studies, where ferric chloride was added to surface waters of constructed wetlands in the Everglades Nutrient Removal Project (ENRP) to determine the fate of added iron in formed flocculates and sediments. After iron additions, iron accumulated in sediments in organic, amorphous and crystalline-bound forms. All forms of iron increased after iron addition with the greatest increases occurring in the top 1 cm of the sediments. For successively greater iron applications, increases in crystalline iron were significantly greater and different. Organic and amorphous iron increased greatly but equally under all iron applications. Thus, the sediments formed from iron additions had similar percentage compositions between organic and non-organic bound iron, although with increasing iron application the non-organic bound iron was more crystalline in structure. Bachand et al. (2000) had similar findings with *in situ* mesocosm studies in the ENRP. They found the percent of aluminum and humic bound phosphorus in the very top layer of soils increased above background levels in these mesocosm studies after an experiment in which stormwater was dosed with alum for 8 months.

These flocculate formed sediments are expected to retain phosphorus, and perhaps to continue adsorbing phosphorus. Ullman (1999) showed that much of the flocculate formed was amorphous (oxalate extractable fraction) and therefore had high P uptake capabilities (Baskaran et al., 1994; Sakadevan and Bavor, 1998, Reddy et al., 1995). Bachand et al (2000) showed that flocculates formed from coagulant dosing of stormwater with P levels near or below 100 ppb had low phosphorus:aluminum ratios as compared to stoichiometric ratios. These flocculates would be expected to have high uptake P uptake capacity and would continue to adsorb phosphorus from surface waters and suppress an upward flux of phosphorus from the soils or a downward flux to groundwater.

B.5.4. Incorporating coagulation into basin design and characteristics

The most immediate effect from incorporating coagulation into the design of stormwater detention basins around the Tahoe Basin is a likely 10-fold improvement in performance with regard to the removal of fine particles and total phosphorus. Total phosphorus would be removed through more effective settling of fine particles, as well as through the sorption of dissolved species on particulate phases with subsequent removal by settling (Trejo-Gaytan et al, 2006). For removal of particles through settling, the fraction of particles removed are those with settling velocities less then the design velocity V_c (Metcalf and Eddy, 1979), where

$$V_c = {}^{Water\ Depth}\!\big/_{Detention Time}. \qquad \textbf{Equation B-3}$$

With settling velocities increased an order of magnitude by treatment, the design detention times can be an order of magnitude less. After 10 hours, the basin receiving treated stormwater would be predicted to have about 85% of the turbidity removed whereas for the non-treated basin approximately 80% is expected to still remain in the water column (Figure B-11). The particle sizes remaining in solution for the treated stormwaters would be expected to be about twice as large as for the non-treated stormwaters, which would have particle sizes in the range of 4 to 5 microns.

Douglas et al (2003) measured particle settling rates in lakes with an *in-situ* method, and also surveyed the settling rates measured by others. They found that measured particle settling rates in lakes varied over two orders of magnitude, between 0.0006 to 0.09 cm s^{-1}. Under Stokes' Law, the lower end of this range corresponds to a particle size of about 7 microns assuming a specific gravity of 2.8. This particle size may be near the lower limit of what naturally settles in lakes, as it would become increasingly difficult to remove smaller particles due to lake mixing effects and currents. This would be particularly apparent in a system like Lake Tahoe, which does not freeze and has a depth (500 m), which is greater than the annual settling distance for very fine particles.

In addition to reducing average turbidity, the chemical coagulants also result in less stratification of turbidity in the water column of settling basins (Figure B-5). Rapid settling eliminates the stratification effect (turbidity gradient) after a few hours. Then mixing would not be as likely to move suspended particles upward through the water column.

Finally, the formed flocculates should continue to adsorb phosphorus from the water column through diffusion, and flocculates would likely suppress the export of dissolved phosphorus from the surface water through groundwater. These flocculates would likely be of amorphous form, although our analyses suggest they would be more structured then the settleable solids typical of stormwater.

B.5.5. Predicting performance of basins at different Hydraulic Residence Times

The increased particle sizes resulting from coagulation would affect basin designs needed for removal of turbidity and fine particles. Assuming a water depth of three feet, we calculate that a hydraulic residence time of 40 hours would be needed to remove 60% of turbidity from the non-treated stormwater tested (Figure B-11). The remaining particles are estimated to have a diameter of less then 3 microns, assuming spherical shape and a specific gravity of 2.8. We predict that more than 100 hours would be needed for 80% removal of turbidity, and the particle sizes remaining in solution would be less then 2 microns. These estimated times assume quiescent conditions, with no wind or temperature driven mixing, and no physical disturbances to the flow regime. For treated stormwaters, an equivalent of 60% turbidity removal is estimated to occur within less then 4 hours, and particles remaining in solution are estimated to be greater then 20 microns, assuming a specific gravity of 1.2. Over 90% of the turbidity would be removed within about 24 hours, and the remaining turbidity would be due to particle sizes of less then 10 microns.

B.6. Conclusion

Sediments in stormwater passing through stormwater basins are of a size not easily settled in lakes. Thermal and diel mixing processes hinder the settling of these particles that have very low settling velocities. Several processes help aggregate these particles in natural lakes, including biotic processes such as zooplankton grazing and natural coagulation processes (biotic and abiotic). These natural coagulation processes are relatively slow, however, on the order of days to weeks, and are unlikely to be important processes in removing fine particles in stormwater basins because most treatment basins operate under short detention times, on the order of a few days.

Chemical treatment coagulation would greatly increase particulate settling velocities and could improve stormwater basin performance by as much as an order of magnitude. This study showed that with chemical coagulation up to 85–95 % of mean turbidity was removed within 10 hours. This removal also included associated phosphorus. By comparison, for the non-treated stormwater, only 20% of the turbidity was removed after 10 hours of settling, 80% was removed at about 2 days, and 90% removal was never attained during the 72 hours of the study. Using the calculated settling velocities, we have predicted 90% turbidity removal from the non-treated stormwater by settling would not occur until after a week or more, with micron sized particles remaining in solution. Natural coagulation and biotic process would tend to augment these physical processes to some extent, but the effects are likely to be minor as compared to chemical coagulation because of the faster kinetics involved with chemical treatment.

Chemical coagulation also is likely to improve the condition of the formed sediments for particle and nutrient retention. These sediments would likely include organic, amorphous and crystalline forms of aluminum, which our data suggests should be more structurally stable and may have additional P uptake capacity.

B.7. References

Ann, Y-K. 1996. Phosphorus immobilization by chemical amendments in a constructed wetland. Ph.D. Dissertation. University of Florida. UMI Number 9703504.

Bachand, P.A.M., C.J. Richardson and P. Vaithiyanathan. 2000. Everglades Phase II report

Bachand, P.A.M, P. Vaithiyanathan and C.J. Richardson. 2000. Development of Management Practices, Final Report submitted to Florida Department of Environmental Protection in fulfillment of Contract No. WM720. December, 2000

Bachand, P, J. Trejo-Gaytan, J. Darby, and J. Reuter. 2005b. Final Report: Small-Scale Studies on Low Intensity Chemical Dosing (LICD) for Treatment of Highway Runoff. April 2006. CTSW-RT-06-073.13.1

Baskaran, S., N.S. Bolan, A. Rahman, R.W. Tillman and A.N. Macgregor. 1994. Effect of drying of soils on the adsorption and leaching of phosphate and 2,4-Dichlorophenoxacetic acid. Australian Journal Soil Res. 32:491-502.

Benedict, A., Oliver, G., Franklin, R., and Devitt, R. 2004. Raising the Bar on Construction Stormwater Treatment. Stormwater Journal, May/June 2004: 5(3).

Braskerud, B.C. 2001. The Influence of Vegetation on Sedimentation and Resuspension of Soil Particles in Small Constructed Wetlands. J. Environ. Qual. 30:1447 – 1457.

Cristina, C.M., Tramonte, J.C., and Sansalone, J.J. 2002. A Granulometry-Based Selection Methodology for Separation of Traffic-Generated Particles in Urban Highway Snowmelt Runoff. Journal of Water, Air and Soil Pollution 136: 34-53.

Dean, C.M, Howerter, K.M. and J.J. Sansalone. 2002. The Potential for In-situ Treatment By Primary Clarification Through Detention of Transportation Land Use Snowmelt Runoff. Submitted to Transportation Research Board 2003 Annual Meeting (04-3239). Accessed at **http://www.ltrc.lsu.edu/TRB_82/TRB2004-001239.pdf** on March 23, 2006.

Douglas, R.W., B. Rippey and C.E. Gibson. 2003. Estimation of the in-situ settling velocity of particles in lakes using a time series sediment trap. Freshwater Biology 48:512-518.

EPA. 1999. Development of Bench-Scale Settling Apparatus: Settling Velocity Data for Design and Operation of Wet Weather Flow Solids-Liquid Separation Processes, Interim Report. United States Environmental Protection Agency, Office of Research Development. EPA/600/X-99/031. September 1999. Washington, DC 20460

Harper, H.H. 2003. Chemical and Ecological Impacts of Alum Coagulation. Proceedings of the 12th Annual North American Lake Management Society, Southeast Lakes Conference. June 2-5, 2003. Orlando, Florida.

Harter, S.K and W.J. Mitsch. 2003. Wetlands and Aquatic Processes: Patterns of Short-Term Sedimentation in a Freshwater Created Marsh. J. Environ. Qual 32:325-334.

James, W.F., E.P. Best and J. W. Barko. 2004. Sediment resuspension and light attenuation in Peoria Lake: can macrophytes improve water quality in this shallow system? Hydrobiologia 515:194-201.

Jassby, A.D., J.E. Reuter and C.R. Goldman. 2003. Determining long-term water quality change in the presence of climatic variability: Lake Tahoe (USA). Can. J. Fish. Aquat. Sci. 60:1452-1461.

Lahontan Regional Water Quality Control Board (LRWQCB). 2003. Water Quality Control Plan for the Lahontan Region (Basin Plan). California Regional Water Quality Control Board, Lahontan Region. South Lake Tahoe, CA.

Metcalf and Eddy. 1979. Wastewater Engineering, Treatment, Disposal and Reuse, Second Edition. Revised by G. Tchobanoglous. McGraw-Hill. N.Y.

O'Melia, C.R. 1980. Aquasols: the behavior of small particles in aquatic systems – an introduction to the processes involved in the transport and removal of particles that have major effects on water quality. ES&T Feature. Environmental Science and Technology14(9):1052 - 1060.

Pisano, W.C. 1996. Summary: United States "Sewer Solids" Settling Characterization Methods, Results, Uses and Perspectives. Wat. Sci. Tech. 33(9):109-115.

Reddy, K.R., O.A. Diaz, L.J. Scinto and M. Agami. 1995. Phosphorus dynamics in selected wetlands and streams of the lake Okeechobee Basin. Ecological Engineering 5:184-207.

Regenmorter, L.C., M. Kayhanian, R.W. Chappell, T. Burgessor, K. Tsay. 2002. Particles and the Associated Pollutant Concentrations in Highway Runoff in Lake Tahoe, California. Proceedings of StormCon 2002, August 12–15, San Marco Island, Florida.

Reuter, J.E. and W.W. Miller. 2000. Aquatic Resources, Water Quality, and Limnology of Lake Tahoe and Its Upland Watershed. In: D.D. Murphy and C.M. Knopp (Eds.) Lake Tahoe Watershed Assessment: Volume 1.

Gen. Tech. Rep. PSW-GTR-175. Albany, CA: Pacific Southwest Research Station, Forest Service, US Department of Agriculture.

Regenmorter, L.C., M. Kayhanian, R. Chappell, T. Burgessor and K. Tsay. Particles and the Associated Pollutant Concentrations in Highway Runoff in Lake Tahoe, California. University of California Davis under contract 43A0036 and Task Order 14 with Caltrans.

Sakadevan, K and H.J. Bavor. 1998. Phosphate adsorption characteristics of soils, slags and zeolite to be used as substrates in constructed wetland systems. Wat. Res 32(4)394-399.

Standard Methods *for the Examination of Water and Wastewater 20th Edition.* Edited by Lenore S. Clesceri, Arnold E. Greenberg, and Andrew D. Eaton.

StatSoft, Inc. (2003). STATISTICA (data analysis software system), version 6. www.statsoft.com.

Stephan, U., M. Hengl, and B.H. Schmid. 2005. Sediment Retention in Constructed Wetland Ponds – A Laboratory Study. Journal of Environmental Science and Health 40:1415-1430.

Trejo-Gaytan, J; P. Bachand, and J. Darby. 2006. Treatment of Urban Runoff at Lake Tahoe: Low-Intensity Chemical Dosing. Water Environment Research 78(14): 2487-2500

Stumm, W. and J.J. Morgan. 1962. Chemical aspects of coagulation. Journal of AWWA 60:515-539.

Swift, T.J., J. Perez-Losada, S.G. Schladow, J.E. Reuter, A.D. Jassby, and C.R. Goldman. 2006. Water clarity modeling in Lake Tahoe: Linking suspended matter characteristics to Secchi depth. Aquat. Sci. 68: 1-15.

Ullman, J.L. 1999. Characterization of Iron in a constructed wetland following metal dosing for phosphorus removal from agricultural runoff. Masters of Science Thesis. Duke University Department of the Environment.

Weilenmann, U., C.R. O'Melia and W. Stumm. 1989. Particle Transport in Lakes: Models and Measurements. Limnology and Oceanography 34(1): 1 – 18.

Welch, E.B. and G.D. Cooke. 1999. Effectiveness and Longevity of Alum Treatments in Lakes. Lake and Reservoir Management. 15: 5-27.

Winer, R. 2000. National Pollutant Removal Performance Database for Stormwater Treatment Practices. Second Edition. Final Report to US EPA, Office of Science and Technology. Center for Watershed Protection. Ellicott City, Maryland.

Table B-1. Initial conditions

	Valid N	Mean	Std.Dev.
Turbidity (NTU)	4	221.5	10.3
Unfiltered Total P (ppb)	3	338.7	8.1
Filtered Total P (ppb)	3	7.7	2.5
Alkalinity (mg-$CaCO_3$/L)	4	35.5	1.2

Table B-2. Company published coagulant specifications and dosing level

Coagulant Code	**Vendor**	**Coagulants**	**NSF Designation**	**Dose mg-Al/L**	**% basicity**	**pH**	**SG[2]**	**% Al**
J1720[1]	JenChem	JC 1720 ®	Polyaluminum chloride	1.4	70	4.3	1.29	5.95
PXXL9	Kemiron	PAX-XL9 ®	Polyaluminum chloride	4.3	67	2.8	1.26	5.6
SUM50	Summit	Sumachlor 50 ®	Aluminum chlorohydrate	2.2	83.5	4.2	1.34	12.4

[1] Blended with an organic polymer

[2] Specific gravity

Table B-3. Experimental Design

Coagulant[1,2]	**Sampling locations (ft from bottom)**	Elapsed Time after dosing	**Water Sampling** [3,4]			
			Turbidity	**temperature**	**UTP, FTP**	**UFE, FFE, UAL, FAL, pH, Alk, FTKN, UTKN, TSS**
		Pre-dose	X	X	X	
		Post-dose	X	X	X	
SumaChlor 50	2.5	**0.25**	X			
PAX-XL9	1.5	0.5	X			
No Dosing	0.5	1	X		X	
JenChem 1720		2	X			
		4	X		X	
		6	X			
		24	X		X	
		48	X			
		72	X		X	X

Notes

1. Coagulants dosing levels were determined using jar tests.
2. Includes controls (no coagulant, no dose)
3. First sample event begins approximately 10-15 minutes after adding dosed water to columns.
4. U = Unfiltered, F = Filtered, TP = Total Phosphorus, FE = Iron, AL = aluminum

Table B-4. Chemical treatment resulted in statistically significant reduction of phosphorus, nitrogen, iron and aluminum.

Data is from samples after 72 hours of settling. Samples were taken at 0.5 and 1.5 feet above the column bottoms for nitrogen, metals and alkalinity, as there was insufficient volume at the highest sampling port (2.5 feet). Phosphorus samples were taken at all three ports.

Analytes[2]	No Treatment				Stormwater Treated with Coagulants at Jar Test Determined Dose											
					J1720				PXXL9				SUM50			
	Means[1]	N	SD	$p<0.05$	Means[1]	N	SD	$p<0.05$	Means[1]	N	SD	$p<0.05$	Means[1]	N	SD	$p<0.05$
Turbidity NTU	33.8	6	4.2	b	1.2	9	0.4	a	1.2	9	0.2	a	1.8	9	0.2	a
UTP ppb	30.0	6	2.9	b	5.8	9	1.2	a	13.2	9	12.3	a	9.1	9	6.1	a
FTP ppb	7.0	6	2.5	a	2.7	9	2.0	a	7.6	9	12.8	a	4.8	9	4.1	a
TKN ppm	0.7	4	0.2	b	0.5	6	0.1	ab	<RL	6	NA	a	0.5	6	0.1	ab
FTKN ppm	0.7	4	0.3	NA	<RL	6	NA	NA	<RL	6	NA	NA	<RL	6	NA	NA
Alkalinity mg/L	35.5	4	1.2	c	33.9	6	0.3	b	28.0	6	0.6	a	33.5	6	0.2	b
UAL ppm	1.2	4	0.4	b	<RL	6	NA	a	<RL	6	NA	a	<RL	6	NA	a
UFE ppm	1.0	4	0.4	b	<RL	6	NA	a	<RL	6	NA	a	<RL	6	NA	a
FAL ppm	<RL	4	NA	a	<RL	6	NA	a	<RL	6	NA	a	<RL	6	NA	a
FFE ppm	<RL	4	NA	a	<RL	6	NA	a	<RL	6	NA	a	<RL	6	NA	a

[1] RL=Reporting Limit. Metals = 0.1 mg/L. TKN =0.5 mg/L

[2] UTP = Unfiltered total P. FTP = Filtered Total P. UAL = Unfiltered Total Al. FAL = Filtere Total Al. UFE = Unfiltered Total Fe. FFE = Filtered Total Fe.

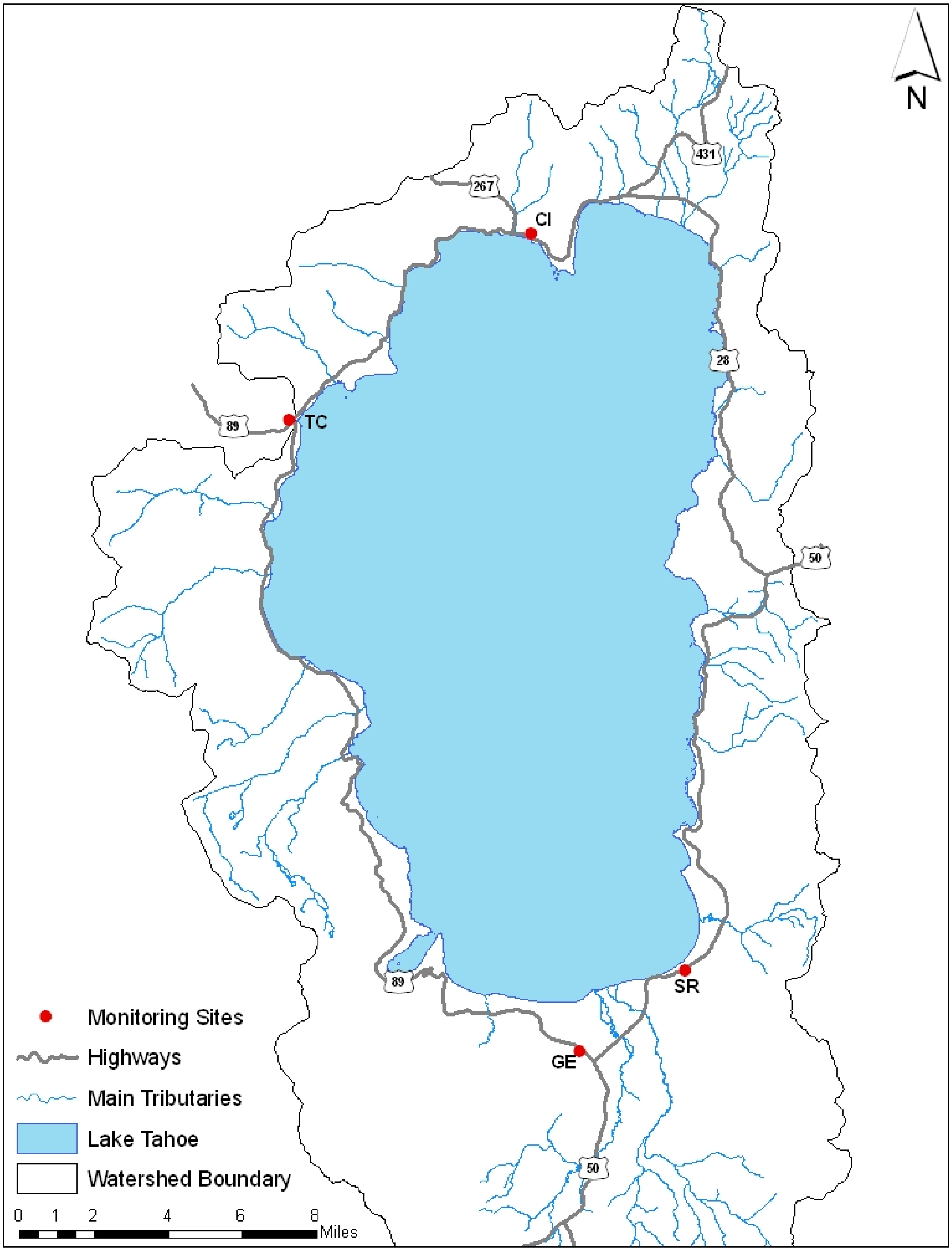


Figure B-1. Locations in the Tahoe Basin from which stormwater was collected for the column studies. TC=Tahoe City, CI=Coon, GE=Glorene and Eighth, SR=Ski Run.

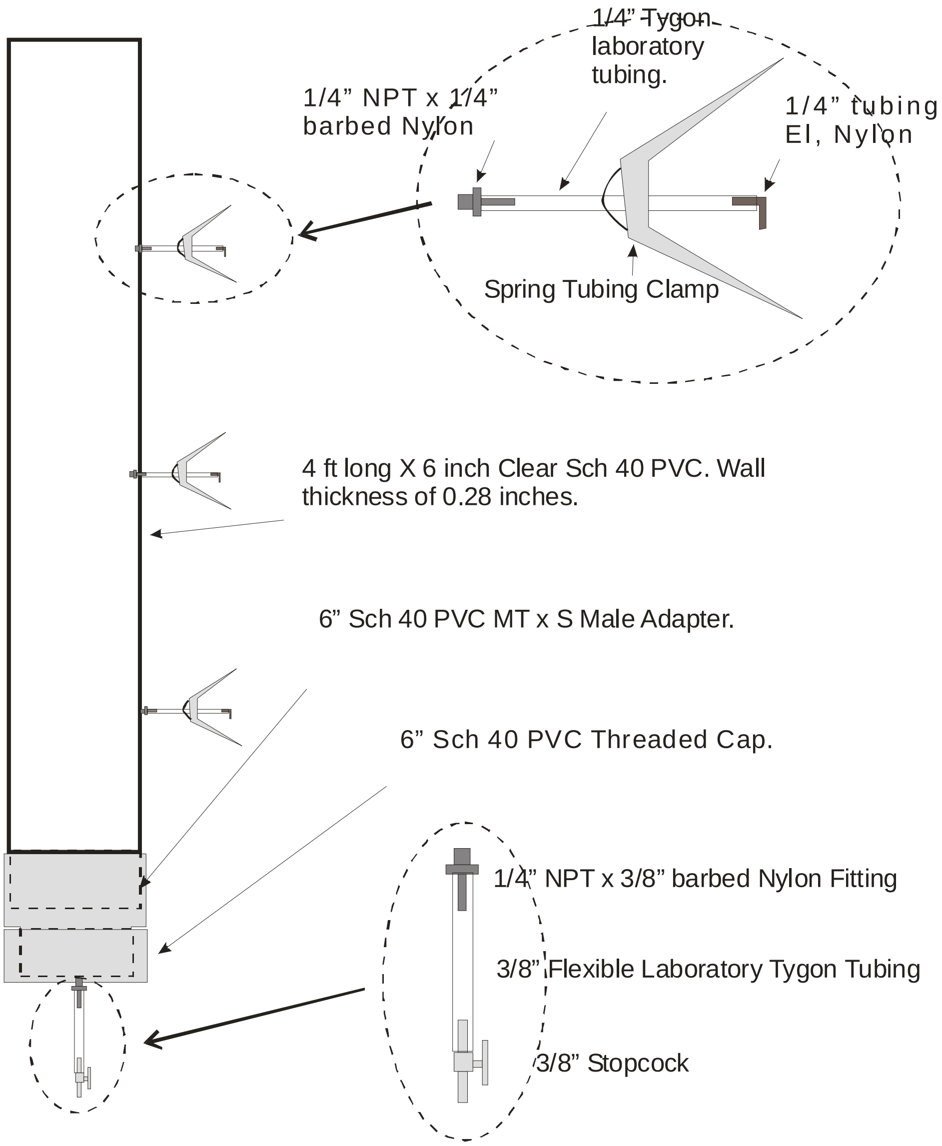


Figure B-2. Settling Column Design

Column was filled to three feet high with three sample locations along the side for collecting water samples. Flocculent samples were collected from the bottom at the end of the settling study. The flocculant structure was analyzed to assess its stability and to help in assessing the fate of the removed constituents.

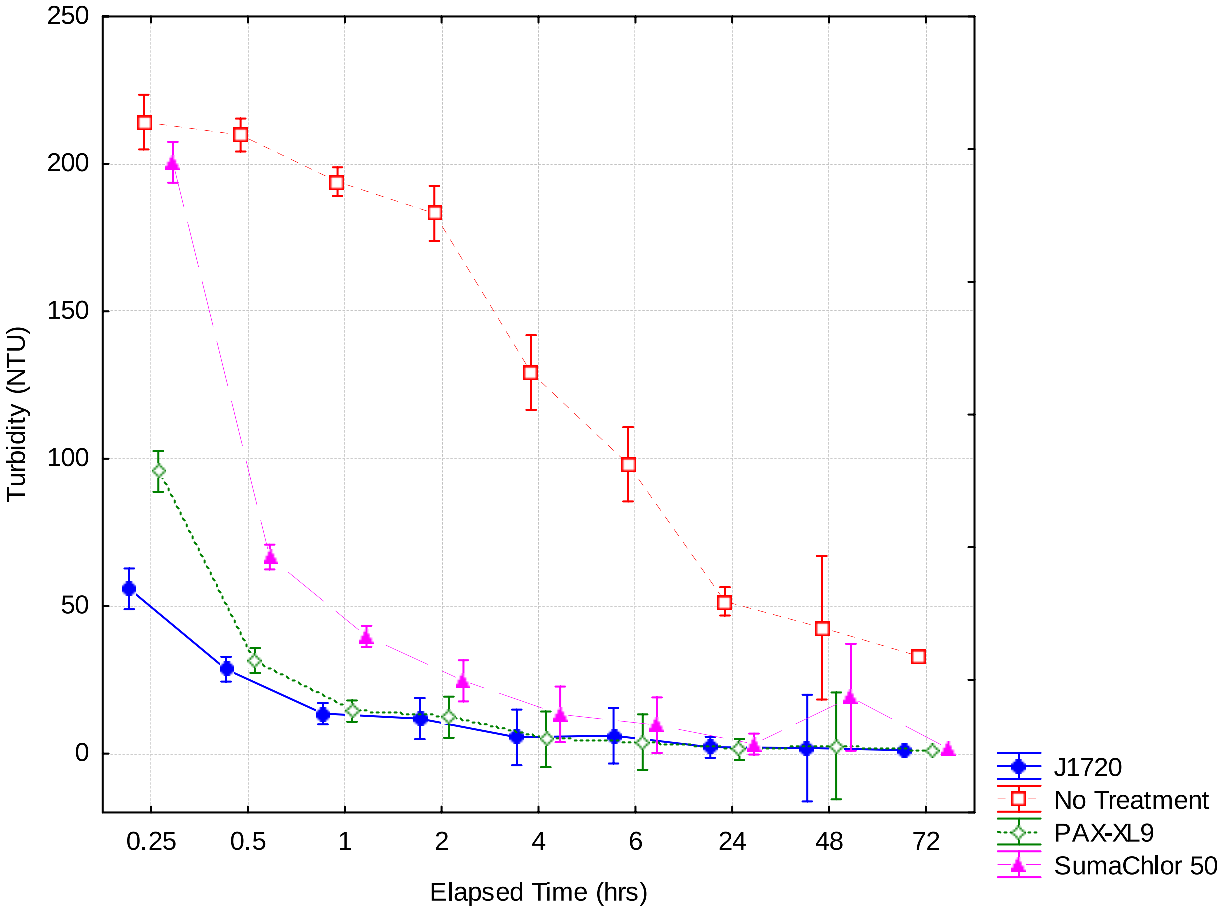


Figure B-3. Turbidity decreases rapidly for chemically dosed columns. Turbidity drops rapidly during the first four hours and asymptotically reaches a steady state condition at the end of that time. For non-treated stormwaters, the stead state condition is not reached after 72 hours of settling. Vertical bars represent 95% confidence interval.

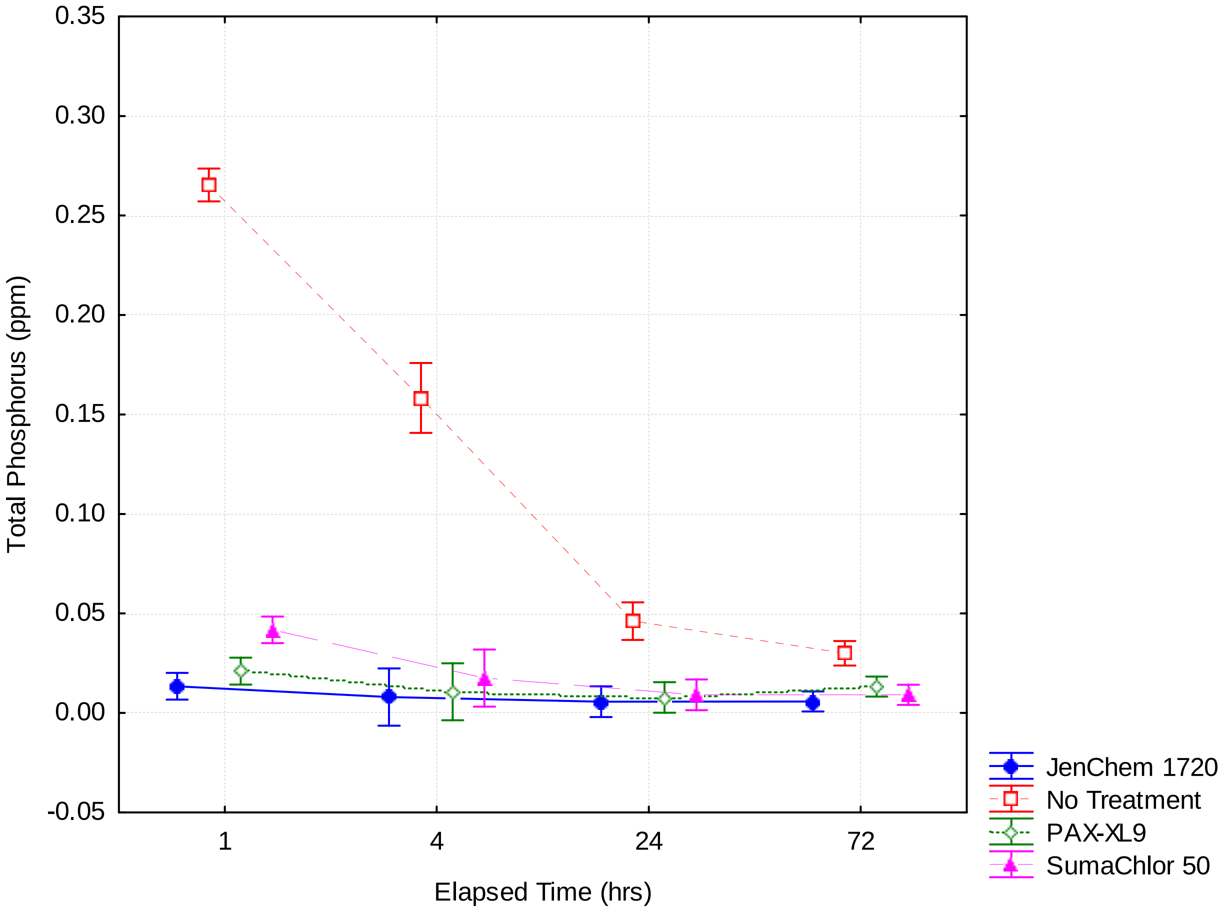


Figure B-4. Total P concentrations are at steady state within a few hours after dosing. Total P concentrations achieved a steady state condition at 4 hours for the chemically treated stormwaters. P concentrations for each stormwater did not differ significantly at 4 hours and after ($p<0.05$, ANOVA repeated measures). Total P concentrations in non-treated stormwater continued to decrease up to 72 hours.

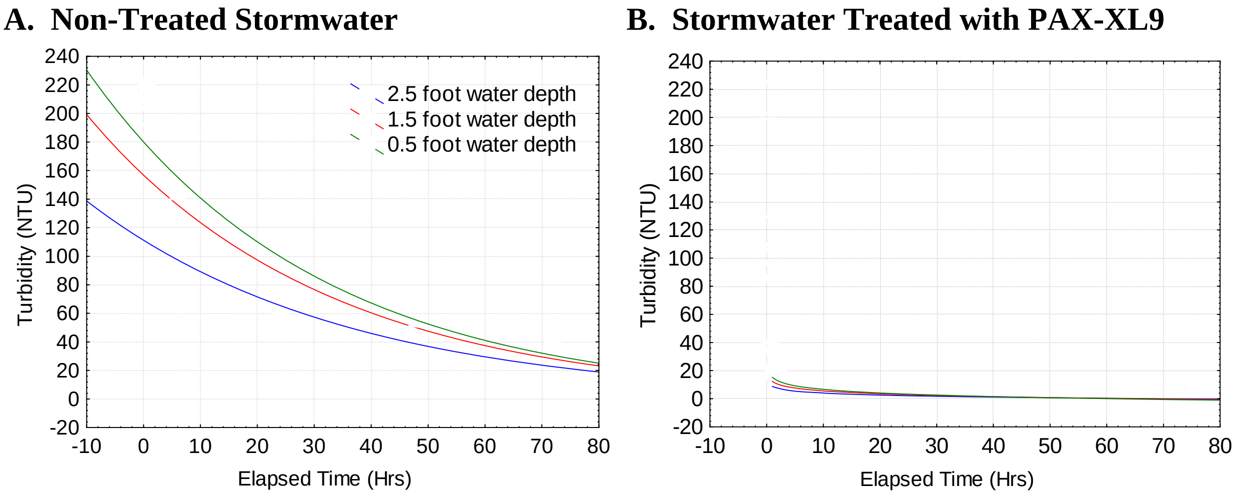


Figure B-5. Effective Removal of Turbidity Throughout the Water Column Using a PAC. Turbidity levels under 5 NTU were achieved throughout the water column when coagulants were used and these levels were achieved within a few hours. For non-treated stormwater the turbidity values persisted above 40 NTU throughout the water column up to 72 hours or more.

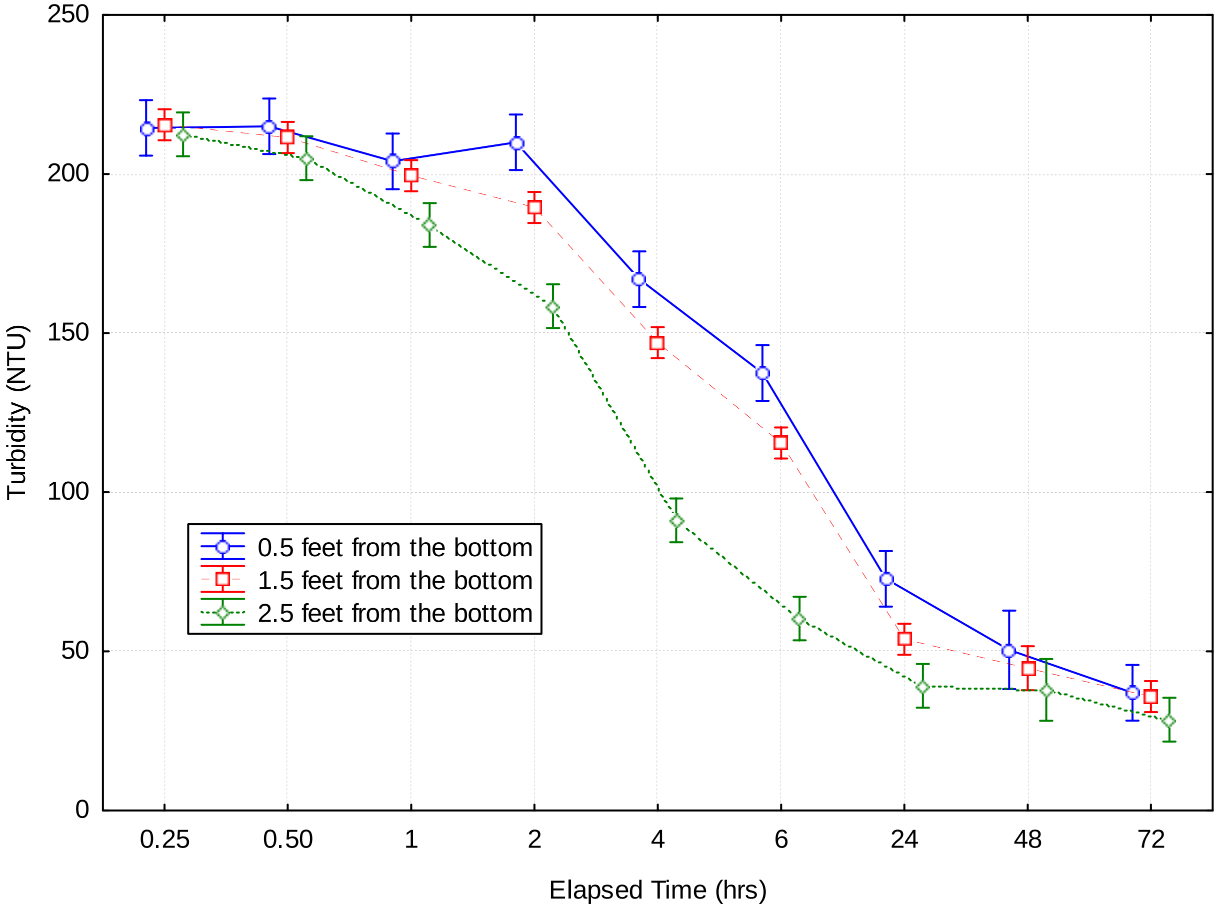


Figure B-6. Turbidity (NTU) stratification in the water column differed significantly with depth for non-treated stormwaters.
Bars represent a 0.95 confidence interval

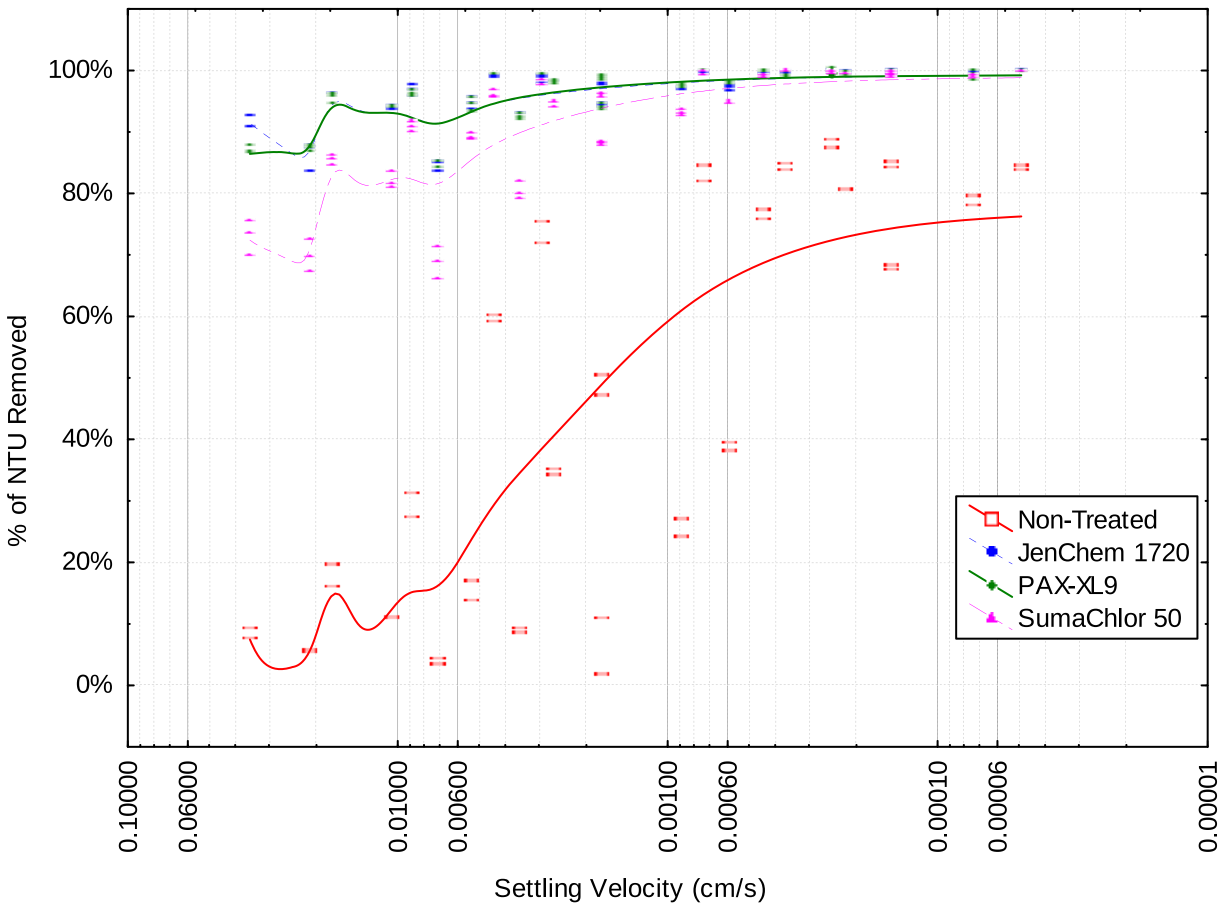


Figure B-7. Statistical difference in coagulant settling results with settling velocities (estimated from the time it has effectively completed most of its settling)

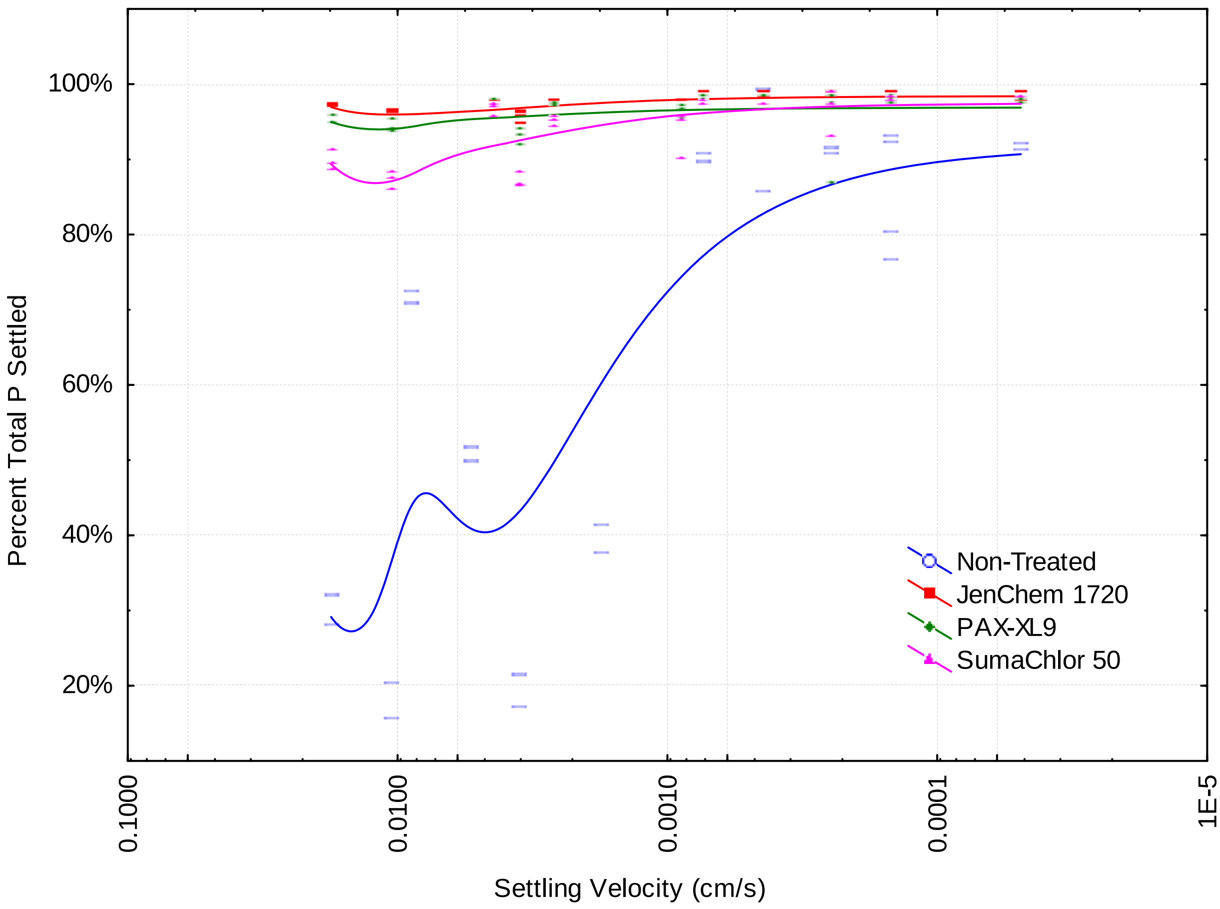


Figure B-8. Removal of UTP over time for treated and non-treated stormwaters

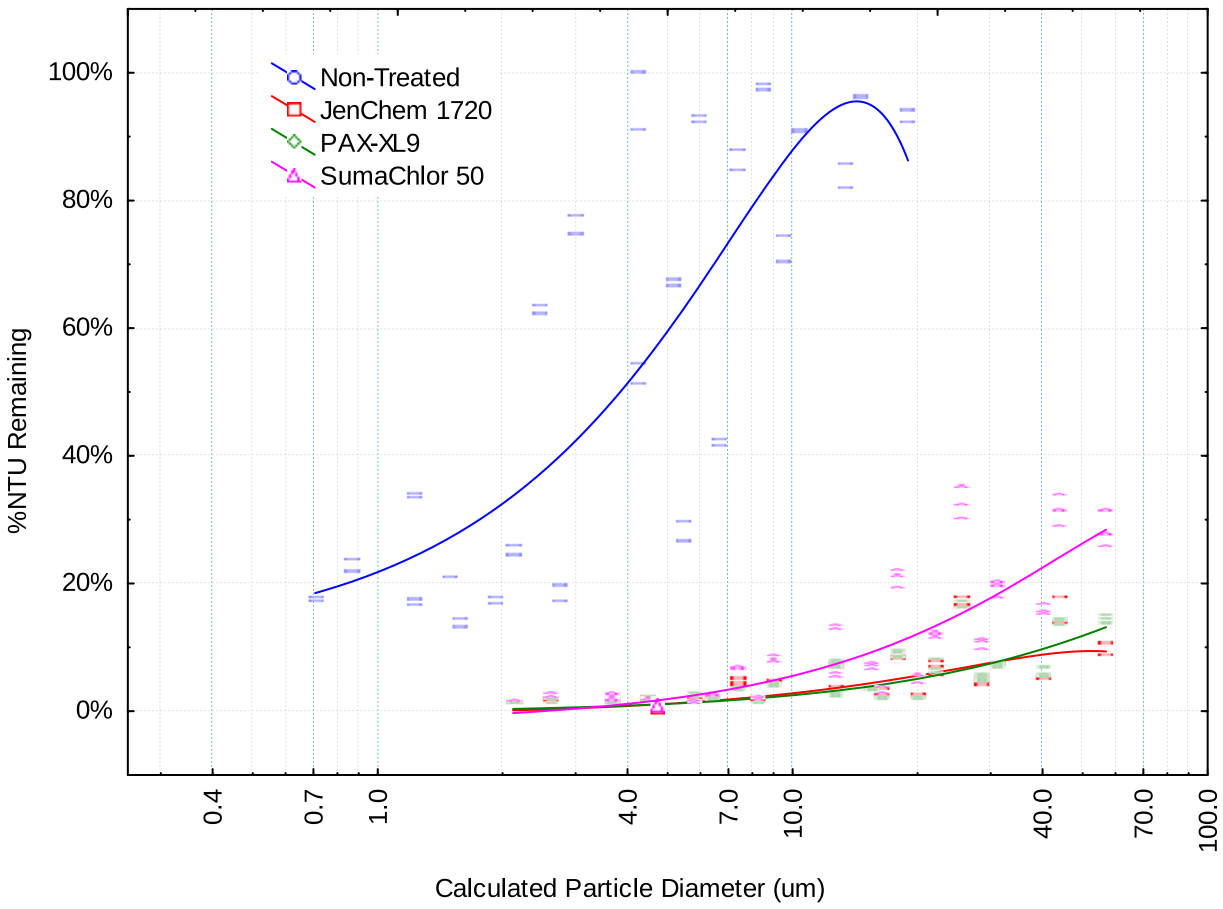
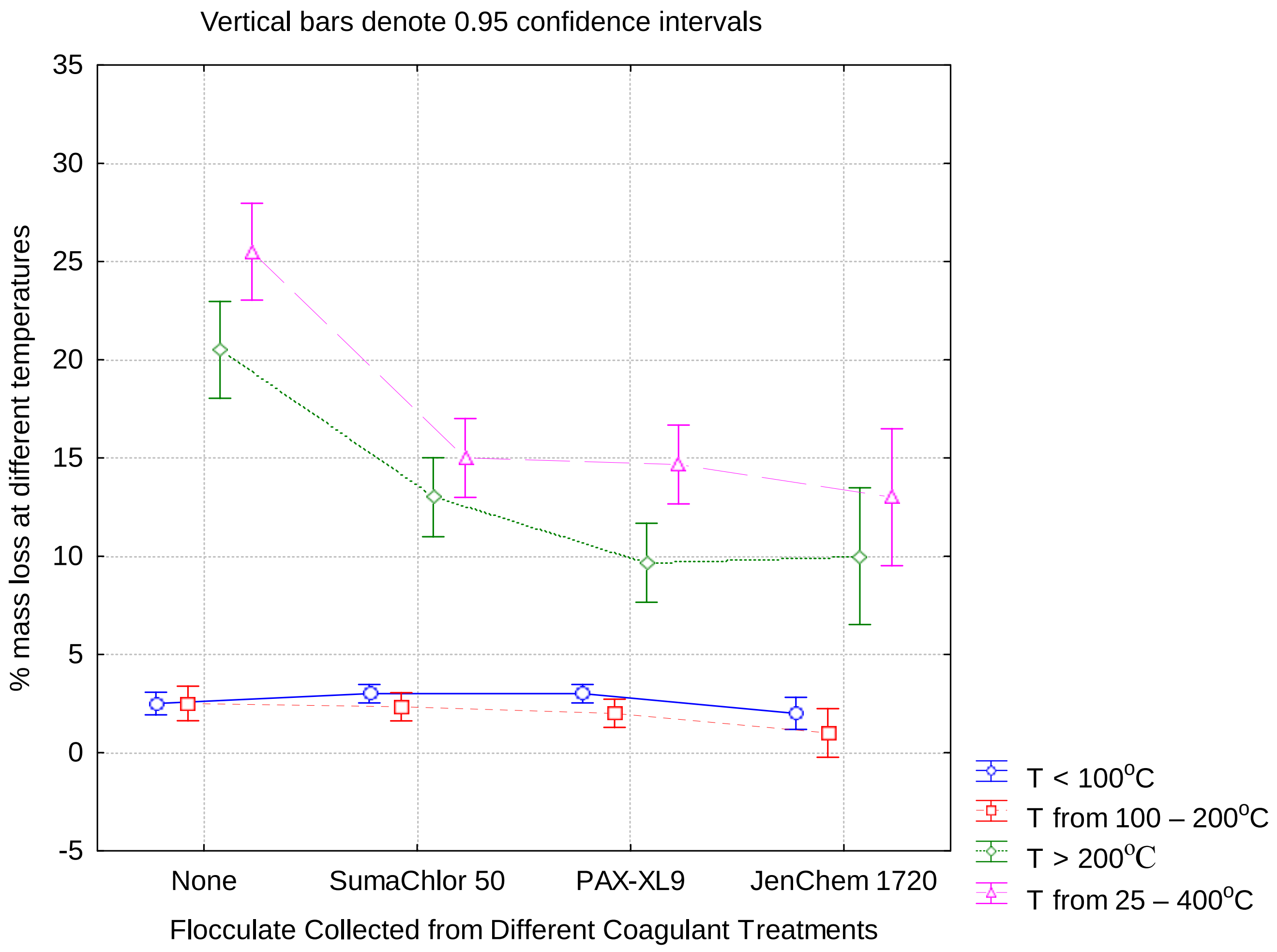
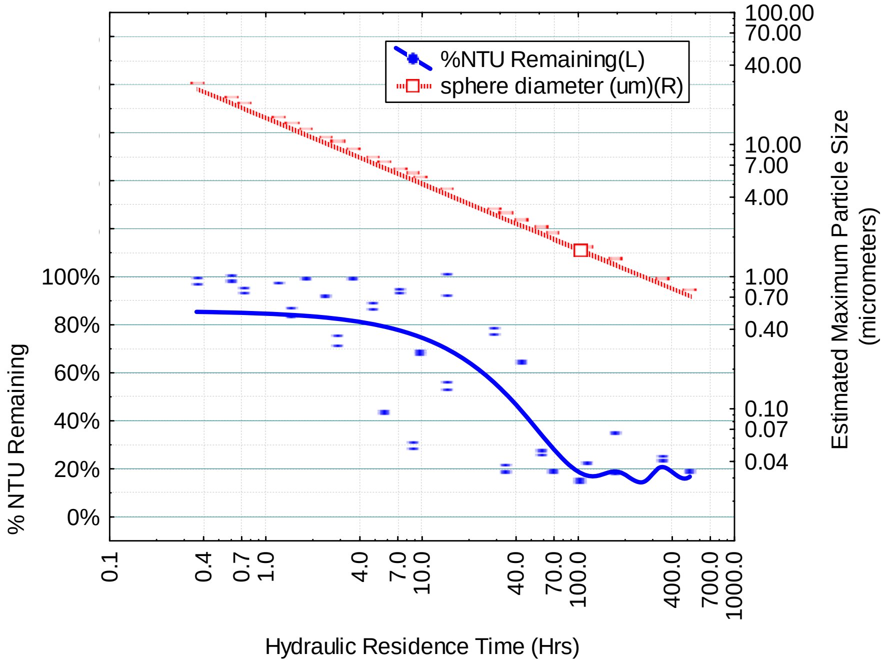


Figure B-9. Estimating Particle Diameters Remaining in Solution

Figure B-10. Mass Losses for different temperature treatments
Thermal losses from sediments collected from settling alone were statistically different for mass loss at temperatures between 100 and 200 degrees Celsius, suggesting differences in flocculent stability.



a. Non-Treated Stormwater



b. Treated Stormwater

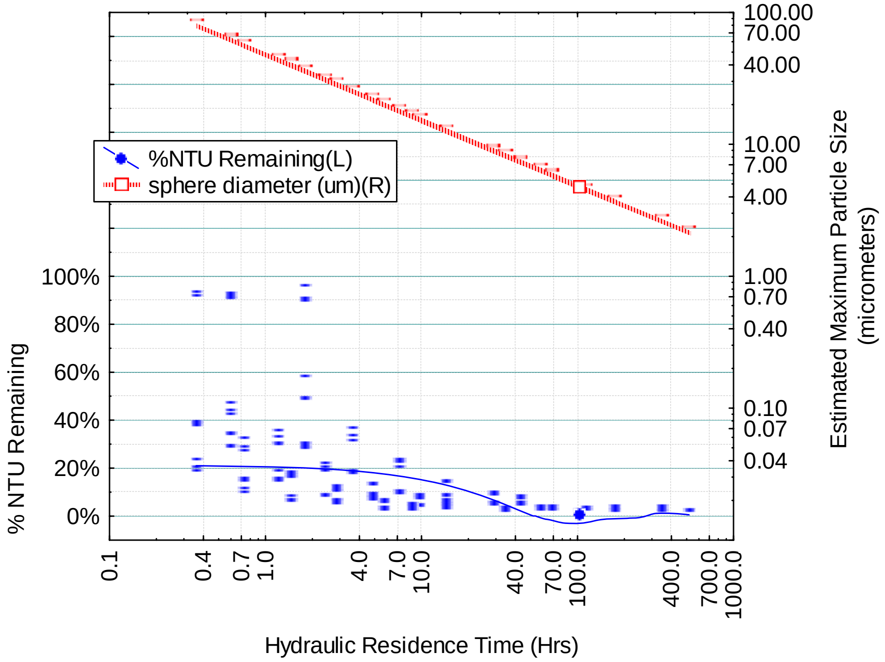


Figure B-11. Estimating Particle Size and Turbidity Removal for Different HRTs
Non-treated stormwater model assumes a specific gravity of 2.8 and a 3 foot water column under quiescent conditions. Fitted line is estimated using least squares.

C. Potential Toxicity Concerns from Chemical Coagulation Treatment of Stormwater in the Tahoe Basin.

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C.1. Abstract

Polyaluminum chlorides (PACs) are being investigated as a means to remove fine particles and phosphorus from Tahoe stormwaters. These coagulants have shown great promise in laboratory and small-scale mesocosm studies for removing the constituents that decrease water clarity in Lake Tahoe. However, implementing this type of technology in the Tahoe Basin requires an understanding of the potential risks to aquatic toxicity. As an initial assessment of this risk, the EPA 3-species toxicity test and a Medaka fish test were used to determine the aquatic toxicity of PAC treated and non-treated stormwaters. The EPA 3-species toxicity test evaluates aquatic toxicity through algae cell counts, zooplankton mortality and reproduction, and fish mortality and biomass. The Medaka test includes various indices of toxicity: fecundity, hatching success and days to hatch. The stormwaters used in these tests were collected from three sites in the Tahoe Basin that represented runoff from different urbanized areas. Stormwater was collected in May 2004, representing an early summer or late spring first flush runoff event. These stormwater samples received coagulant dosing at levels optimized with jar tests to remove turbidity. Various statistical tools were used to assess toxicity: principal component analyses (PCA), factorial ANOVA and nonparametric statistical analyses. The effects on different toxicity metrics varied between non-treated stormwaters as well as between stormwaters treated with different coagulants. Stormwaters that were not treated with coagulants decreased algae cell counts and increased days to hatch for Medaka fish larvae. Stormwaters treated with coagulants generally affected fathead mortality, zooplankton brood size and zooplankton hatching success, though sometimes these effects were positive and sometimes negative. Coagulants altered stormwater toxicity. In general, stormwaters most affected algae cell counts and fish mortality whereas coagulants most affected zooplankton, especially zooplankton reproduction.

C.2. Introduction

Phosphorus and fine particles in the range of 0.5 to 20 microns have been identified as the major constituents leading to reduced clarity in Lake Tahoe. Several general sources have been identified for these constituents, including runoff from undeveloped or undisturbed areas, runoff from developed or urbanized areas, and air pollution (Reuter and Miller, 2000).

Of these general pollutant sources, the runoff from developed areas has been the focus of most recent efforts as these sources are more confined and accessible to treatment than the other sources. Urbanized areas around Lake Tahoe include land developed for residential, commercial or industrial use, and highway areas, which together comprise about 10% of the total watershed area contributing to Lake Tahoe. Efforts have been made to reduce runoff from these developed areas by increasing stormwater infiltration. Additionally, various stormwater treatment best management practices (BMPs) have been implemented to capture and treat stormwater runoff from these areas. Currently, a large number of stormwater treatment BMPs are being utilized in the Tahoe Basin to treat stormwater runoff, including hydrodynamic devices such as oil-water separators, centrifugal concentrators, sedimentation traps and drain inlets; various basin types such as wet ponds, dry detention basins, infiltration basins, bioretention basins; media filters; and porous pavements (Table C-1). Of these, hydrodynamic devices are the most numerous and widespread BMPs throughout the Basin, while ponds and basins are also widely used.

However, the effectiveness of many of these BMPs in treating phosphorus and fine particles is not very promising. The national performance databases report high variability in treatment by all these BMPs. For instance, the minimum mean total phosphorus (TP) outflow concentrations achieved are in the range of 0.1 to 0.2 mg/L for a wide variety of BMPs, including dry detention basins, media filters, wetland channels and stormwater wetlands (ASCE/USEPA, 2005; Winer, 2000). Expected load removal rates are on the order of 22 to 50% for these BMPs (Bachand et al., 2005). Other BMPs generally report less effective performance.

Although these datasets provide some information on suspended solids removal, they do not contain information about the removal of fine particles. Particle size distribution in stormwater throughout the Tahoe Basin generally ranges from fine clays to coarse sands. Caltrans (2005) has shown that stormwater from highway runoff is characterized by particle sizes from less than 0.5 μm to greater than 9.5 mm, with grain sizes from 5 to 12 microns representing the highest number and the greatest mass of particles in runoff samples. Bachand et al. (Appendix B, this report) showed that fine particles in stormwater runoff to Lake Tahoe would take days to weeks for removal by settling. Given that most hydrodynamic devices have detention times on the order of hours, and that ponds and basins are designed to treat the 20-year, 1-hour design storm and can be overloaded with either frequent storms or high flows, the required settling times may not be achieved with these BMPs.

Efforts are currently underway in the Tahoe Basin to test alternative technologies, including the use of chemical dosing to improve phosphorus and fine particle removal (Trejo-Gaytan et al., 2006, Bachand et al., 2006; Bachand et al., 2005b; Heyvaert et al. 2005; Caltrans, 2006b). These approaches include coagulant dosing of stormwater in combination with constructed basins and stormwater wetlands (Bachand et al., 2006; Trejo-Gaytan et al., 2006; Appendix B, this report). Bachand et al. (Appendix B, this report) showed that settling velocities increased by orders of magnitude after treating stormwater with different polyaluminum chlorides (PACs). The authors estimated that particle size increased by an order of magnitude when stormwater was treated with chemical coagulants to induce flocculate formation.

While application of this technology to the treatment of stormwater would be innovative for runoff to a subalpine lake, there are examples where chemical dosing has been used in other natural systems to remove phosphorus and control eutrophication. Alum addition has been used on a number of lakes and reservoirs in Florida, Washington, Vermont, Wisconsin and New Jersey to control eutrophication. The city of Orlando injects alum into stormwater entering two natural lakes (Lake Dot and Lake Lucerne) on a flow proportional basis (Harper 1994). Early results showed that in-lake total P and chlorophyll concentrations were reduced by 90% in Lake Dot and by 25% in Lake Lucerne, with lower water quality improvements in Lake Lucerne due primarily to internal nutrient cycling. Welch and Schreive (1992) evaluated the success of alum additions to six natural lakes in Washington during the 1980s. These single alum treatments were generally effective in reducing eutrophic conditions and the effects lasted at least for five years (as of 1992). It was noted also that aluminum was effective in blocking P release from the sediments in stratified lakes with anoxic bottoms. In 1991, another shallow lake in Seattle, (Green L.) was treated with a mixture of alum and sodium aluminate to a dose of 8.6 mg Al/liter (Jacoby et al. 1994). Total P concentrations decreased from 40 to 14 μg/L after treatment, and remained below the goal of 30 μg/L for two years. Likewise, Lake Morey in Vermont, was treated with a mixture of alum and sodium aluminate in 1986 (44 g Al/m^2) with a reduction in eutrophic conditions for at least 4 years (Smeltzer 1990). The shallow Mohawk Lake in New Jersey was treated with alum to form a sediment "blanket" of alum, intended to block internally recycled sediment P. In 1986, alum was added to Eau Galle Lake in Wisconsin, resulting in a temporary reduction in P regeneration and chlorophyll, until heavy external P loading later negated these improvements (James et al. 1991). Recently, coagulation has begun to be used for reducing sediment loads from construction sites (MacPherson, 2004; Clearwater Compliance Services, 2004).

Bachand et al. (2000) have demonstrated that *in situ* application of iron and aluminum coagulates in the Florida Everglades could reduce phosphorus levels to the range of 10 to 30 μg/L. In general, the phosphorus retention capacity of wetland soils was strongly related to the extractable iron and aluminum content (Richardson 1985, Walbridge and Struthers 1993) as well as calcium content (Richardson and Vaithiyanathan 1995).

A central question regarding the application of chemical dosing in the Tahoe Basin regards aquatic toxicity. Aluminum toxicity is well documented (Gensemer and Playle, 1999; Soucek et al., 2001). Gensemer and Playle (1999) present a comprehensive and excellent review of aluminum toxicity. In general, aluminum is a considered a gill toxicant to fish, with the degree of toxicity dependent upon water pH and aluminum concentration. Invertebrates are not as sensitive to aluminum as fish, and aluminum is most toxic to algae under slightly acidic conditions. For waters with pH exceeding 7, there is little data on aluminum toxicity.

Relating aluminum toxicity to alum and aluminum coagulant use is not simple. Proper coagulant dosing must be conducted to keep the dissolved aluminum concentrations low. Kennedy and Cooke (1982) state that proper dosing should keep dissolved aluminum concentrations below 50 μg/L, and Livingston et al. (1994) state that concentrations should be kept below the 4-day EPA Ambient Water Quality Criteria of 87 μg/L. These concentrations are generally below levels found to be toxic. However, factors that include pH, the type of aluminum species present, and concentrations of other constituents, such as dissolved organic carbon, complicate this toxicity issue (Gensemer and Playle, 1999).

The data on toxicity of waters dosed with coagulants is fairly sparse. After a massive dose of 44 g Al/m^2 during alum treatment of Morey Lake in Vermont, a temporary elevation in aluminum in white perch tissue was observed. The pH levels in the lake were not discussed. In Newman Lake in Washington, *Chaoborus sp*. densities doubled while chironomid and oligochaete densities remained the same following alum treatment (Doke et al. 1995). The effect on *Chaoborus sp*. was attributed to a change in trophic structure. Narf (1990) assessed changes in the profundal benthic and merobenthic fauna of five selected lakes treated with alum. Faunal density and diversity increased in nearly all lakes after treatment. In other studies of alum treated lakes the changes in biodiversity and specific changes in algal, invertebrate and fish populations, were generally regarded as beneficial and were considered the result of changes in trophic status (Welch and Schreive 1992, Souza et al. 1994, James et al. 1991, Doke et al. 1995, Jacoby et al. 1994).

It has been shown that even without chemical coagulation treatment stormwater can be toxic. Skinner and Schiff (1999), for example, found that urban runoff produced significant toxicity to early life stages of fish. Caltrans (2003) also found stormwater to be toxic, with much of that toxicity associated with the sediments. One important question, therefore, is whether coagulant treatment would tend to exacerbate or reduce stormwater toxicity.

This paper begins to address that question by evaluating the toxicity of raw and coagulant treated stormwaters. Stormwaters were collected from three locations selected to represent different areas of urbanization. This study was designed to provide a foundation for more extensive toxicity studies by first identifying the key issues and addressing two basic hypotheses:

1. Stormwater entering the Tahoe Basin introduces toxicity to the Lake.
2. Coagulants will reduce the toxicity of stormwater being treated.

C.3. Methods

Stormwaters were collected from three locations in the Tahoe Basin during a late May 2004 stormwater runoff event. This event was characterized as a first flush event, being the first late spring rain event runoff to occur in the Tahoe Basin that year. The previous storm event was snow that had occurred in early May. The three locations chosen are identified in Figure C-1: Tahoe City, Ski Run and Stag. These sites represented stormwater from the northern urbanized (Tahoe City) and southern urbanized (Ski Run) regions of Lake Tahoe and also from highway (Stag) runoff.

Stormwater from these sites were dosed with three different polyaluminum chlorides (PAC): PAX-XL9, SumaChlor 50 and JenChem 1720 (Table C- 2). The three coagulants represent slightly different coagulant generations and recipes. SumaChlor 50 is a typical aluminum chlorohydrate, a first generation PAC. This PAC is available from different manufacturers and does not represent a proprietary recipe. PAX-XL9 was a coagulant found to be very effective for removing fine particles and stormwater from stormwater typical of the Tahoe Basin (Trejo et al. 2006, Bachand et al. 2006). JenChem 1720 is a PAC blended with nitrogen-based organic coagulant to improve aggregation. Table C- 3 provides specifications for these coagulants.

Stormwater dosing levels were determined using standard jar testing methods. Determining the dosing levels and then treating the stormwaters required several weeks. Treated stormwaters were tested for toxicity to zooplankton, fish and algae following USEPA protocols at the UC Davis Aquatic Toxicity Laboratory against a control supplied by the toxicity laboratory. Rudimentary water quality parameters were measured by the toxicity lab: temperature, DO, pH, EC, initial hardness and alkalinity. The toxicity tests assessed toxicity to zooplankton (reproduction and mortality), algae (production) and fish (biomass and mortality). Toxicity to the teleost fish species medaka (*Oryzias latipes*) was also tested. This method quantified the fecundity of exposed adult fish, and the days to hatch and hatching success of their offspring.

Statistical Analysis

ANOVA and Principal Component Analysis (PCA) techniques were the statistical tools used for data analysis. PCA analysis is a statistical tool using a series of factors to describe decreasingly significant combinations of features that explain the distribution of results.

For each stormwater and coagulant tested, a different optimal dosing level was determined (Table C- 3). Thus, these variables are interdependent and are considered a single factor, called the stormwater dosing regime (SDR) in this assessment.

Based upon the correlation analyses, a Principal Component Analysis (PCA) was conducted with the four toxicity metrics shown in Table C-4 against initial temperature, final pH, initial EC and coagulant dosing level. The PCA used mean results from treatment with each toxicity metric.

C.4. Results

Zooplankton and fish were both significantly ($p<0.05$) affected by the SDR (Table C-4). SDR reduced zooplankton reproduction ($R = -0.75$) but did not affect zooplankton mortality. The coagulant dose also increased fish mortality ($R=0.64$), though this effect was much lower. Fish biomass was not included in the correlation matrix because under conditions of fish mortality, fish biomass was a null value.

These four toxicity metrics were not related to each other and showed correlations with the water quality parameters, some statistically significant. Algae cell counts and fish mortality were significantly correlated with initial temperatures. Algae cell count were significantly and highly correlated with the final pH, and correlated with initial pH, although this correlation was not statistically significant. Fish mortality was significantly correlated with initial EC ($R = 0.72$). Zooplankton metrics showed no correlations with water quality constituents.

C.4.1. EPA 3-species test

Figure C-2 shows the results of the PCA. Factor 1 explains about 50% of the variance in the data and Factor 2 explains about 20%. Factor 1 shows the relationship between dosing level, conductivity and pH, where pH is related to dosing levels. As dosing level increases, pH decreases. More highly contaminated stormwaters require higher dosing levels. These higher dosing levels result in decreased zooplankton reproduction and algae cell counts, and they increased fish mortality.

Factor 2 is shown to correlate primarily with zooplankton mortality and is unaffected by dosing level. Factor 2 also weakly correlates with conductivity and pH. This factor shows zooplankton mortality is unaffected by the dosing levels used in these stormwaters. Zooplankton mortality is thus dependent upon another unidentified variable.

Following the above PCA analyses, more in depth analyses were conducted to assess the effects of dosing levels on algae cell counts, zooplankton reproduction and fish mortality and the effects of stormwater on zooplankton mortality. For these analyses, the raw data files from each toxicity test were used. With algae cell counts and fish mortality four replicates were used for each treatment (i.e. stormwater x coagulant), whereas with zooplankton toxicity ten replicates were used for each treatment.

Dosing effects on algal cell counts

In Figure C-3, data labels identify the stormwater being treated. Higher cell counts indicate lower toxicity and vice versa. Higher coagulant dosing levels generally correlated with lower cell counts (R = -0.604; Figure C-3), explaining just over one third of the variability in these data. Cell counts were generally lowest for treated stormwater from Ski Run and were highest for treated stormwater from Tahoe City.

Two-way factorial ANOVA were run to assess the effects of SDR from the different stormwater-coagulant combination on algae cell counts (Table C-5). Algae cell counts statistically differed for the different stormwaters, for the different coagulants and for stormwater-coagulant interactions (Figure C-4). Dosing with SumaChlor 50 increased algae cell counts above those for non-dosed stormwaters. On average, when stormwaters were dosed with SumaChlor 50, cell counts increased from an average of 1.0 million to an average of 1.6 million. Inversely, dosing with either JenChem 1720 or PAX-XL9 negatively affected cell counts, resulting in a 15 and 30 percent decrease, respectively. All cell counts, even the non-dosed stormwaters were below those of the control. Cell counts for the control at 2.2 million were about twice those of the non-dosed stormwaters. Thus, the stormwaters alone accounted for approximately 50 % reduction in cell counts below the control, and then each coagulant additionally affected the stormwater toxicity, with Sumachlor 50 reducing toxicity, and JenChem 1720 and PAX-XL9 increasing toxicity.

Individual stormwaters were toxic to different degrees. Both treated and non-treated stormwaters from Tahoe City had an average cell count of about 1.5 million, over three times higher then the waters from Ski Run. Figure C-4 graphically shows algae cell counts for the different stormwaters and dosing regimes. Numeric labels show the dosing levels used as mg-Al L^{-1}. Stormwater from Tahoe City had relatively high algae cell counts, required relatively light dosing to remove turbidity, and generally had improved algae cell counts when treated with the different coagulants. Stormwater from Stag initially supported high cell counts. For the Stag stormwater, the coagulants did not generally affect cell counts negatively, except for dosing with PAX-XL9. Algae cell counts for Ski Run water were the lowest of all the stormwaters. Dosing with JenChem 1720 or Sumachlor 50 only slightly reduced or increased the algae cell counts.

Table C-6 summarizes whether coagulants negatively or positively affected algae cell counts. A negative one (-1) or positive one (+1) were assigned if the coagulant had a statistically significant negative or positive effect, respectively. A zero was assigned if the effect was not statistically significant ($p<0.05$). When stormwaters were dosed with Sumachlor 50, which had dosing ranges between 2.6 and 20.6 mg-Al L^{-1}, algae cell counts increased. When stormwaters were dosed with PAX-XL9, the cell counts decreased in two cases and increased in one case. When stormwaters were dosed with JenChem 1720, cell counts decreased in two cases and there was no statistical effect in the third case. Both Stag and Ski Run stormwaters on average saw a slight decrease in cell counts, while the Tahoe City stormwater saw an improvement in cell counts. Overall, the coagulants as a whole did not greatly affect cell counts in stormwater according to the ranking criteria used in Table C-6.

Dosing and stormwater effects on Zooplankton reproduction and mortality

The PCA analyses suggested coagulants reduced zooplankton reproduction and that stormwater increased zooplankton mortality. Coagulant dosing levels did not correlate strongly with zooplankton mortality ($R = 0.1352$, $p = 0.1113$). In a 2-way factorial ANOVA, however, stormwater, coagulant and stormwater-coagulant interactions all resulted in significant differences in mortality. All these differences resulted from one combination, JenChem 1720 dosing of Ski Run stormwater (Figure C-6). Under all other SDR, zooplankton mortality did not differ significantly ($p < 0.05$) as can be seen with the confidence intervals shown in Figure C-6. JenChem 1720 was dosed at a much higher level for the Ski Run stormwater as compared to the other two coagulants, and for that SDR there were also very low algae cell counts (Figure C-4) as compared to the other coagulant treatments for that stormwater.

In general, however, zooplankton mortality averaged less than 20%, and in many cases there was no mortality for the treated stormwaters. Average mortality for the control was 5% and for the non-treated stormwaters was 10% (Table C-5). For the treated stormwaters, average mortality was 13%. When the one SDR of JenChem 1720-Ski Run stormwater is excluded, average mortality relating to all coagulants was equal to or less then 10% and the average overall mortality was 6%.

Coagulants, stormwaters and coagulant-stormwater interactions all significantly decreased zooplankton brood size ($p<0.05$) in a 2-way factorial ANOVA analysis (Statistica). For the control, the brood size averaged around 28. For the non-treated stormwaters, the brood sizes averaged between 16 (Tahoe City stormwater) to near 40 (Ski Run stormwater).

Coagulant dosing greatly affected brood size. As indicated by Figure C-5, zooplankton brood size negatively correlated with dosing ($r = -0.67$). Brood sizes for both Stag and Ski Run stormwaters greatly and significantly decreased with coagulant dosing. For Ski Run stormwaters, brood sizes dropped to between 0 and 10.4 for the treated coagulants, as compared to 39 for the non-treated stormwaters (Table C-5, Figure C-7). For Stag stormwaters, average brood sized dropped to between 2.3 and 9.9, as compared to 23.4 for the non-treated Stag stormwater. Only the Tahoe City stormwater was not negatively affected. Treating Tahoe City water with coagulants showed effects ranging from no significant change to significantly improved brood size. SumaChlor 50 treated Tahoe City stormwater had the second highest mean brood size at 29.

Table C-5 summarizes the effects of both coagulant and stormwater on zooplankton mortality and brood size. Neither stormwater nor coagulant significantly affected zooplankton mortality, except under one dosing condition. Zooplankton reproduction was the more sensitive toxicity metric. For the most part, coagulants negatively affected zooplankton reproduction. Brood sizes for chemically dosed stormwaters from both Stag and Ski Run were greatly below those for non-treated stormwaters. However, brood sizes for Tahoe City stormwater were not affected. Coagulant dosing levels were generally higher for Stag and Ski Run stormwaters as compared to Tahoe City stormwater. Dosing levels for Stag stormwaters averaged about 14 mg-Al L^{-1} and for Ski Run stormwater averaged about 18.3 mg-Al L^{-1}. Dosing levels for Tahoe City stormwater were much lower at about 3.6 mg-Al L^{-1}.

Dosing and stormwater effects on fish mortality and biomass

Fish mortality significantly correlated to dosing levels (Figure C-8, r = 0.6551). However, unlike relationships for zooplankton reproduction (Figure C-7), fish mortality was strongly influenced by stormwater source (Figure C-9). Tahoe City stormwater had lower fish mortality then the other stormwaters, regardless of dosing levels. Figure C-10 shows that fathead minnow mortality was greatly dependent upon the stormwater source and relatively independent of coagulant treatment. Stormwater from Tahoe City had mean mortality in the range of 10 to 20% and this did not differ significantly from the control, which recorded a mean mortality of about 5%. Both Stag and Ski Run stormwaters had very high fish mortality. Stag stormwater had 100% fish mortality when no coagulant was used. Coagulant dosing appeared to reduce the toxicity of the Stag stormwater somewhat, though that difference was not statistically significant. Non-treated Ski Run stormwater was slightly less toxic, with fish mortality at about 70%. The toxicity of the Ski Run stormwater generally increased with chemical dosing; however, only when treated with JenChem 1720 was percent mortality significantly different.

Figure C-10 shows that fish biomass was not related to dosing levels (r = 0.0300, p = 0.8602), and not affected by coagulants (p=0.80) or by coagulant-stormwater interactions ($p<0.39$). Fish biomass differed significantly with stormwaters ($p<0.05$), with biomass associated with the Stag stormwater significantly below those for Tahoe City or Ski Run (2-way factorial ANOVA, post-hoc analyses).

Table C-5 summarizes the mean values for each fish treatment. Table C-6 summarizes the overall effects of the coagulants using the ranking method described earlier. Fish mortality increased with the use of coagulants for the Ski Run stormwater though it remained unaffected for the other two stormwaters. Coagulants did not affect biomass of the surviving fish.

C.4.2. Medaka Tests

A toxicity test using medaka measured toxic effects on mortality and fecundity of exposed adult fish, as well as hatching success and days to hatch of their offspring. This test uses a repeated measures approach where a single male and two females are put in 500 ml of water for nine days prior to exposure, and then the fish are exposed to stormwater samples or control water for four days and the effects of that exposure are tracked for each set of fish.

Fecundity, hatching success or days to hatch measured for successive days of exposure generally did not correlate greatly, though some correlations were significant. The correlations (R) between fecundity measured on different days of exposure ranged from a low R of 0.29 to a high of 0.65. The correlations for hatching success measured for the different days of exposure ranged from a low R of -0.17 to a high of 0.58. The correlation for days to hatch measured for different days of exposure ranged from a low of 00.12 to a high of 0.39. Thus, measurements on any one day were a poor predictor of measurements on another day for each of these metrics.

Fecundity, hatching success and days to hatch were not well correlated either. This lack of relationship had much to do with very different distributions. Both fecundity and days to hatch were relatively normally distributed, whereas hatching success was not (Figure C-11).
Based upon the distributions, ANOVA analyses were used to statistically analyze fecundity and days-to-hatch relationships but a non-parametric analysis was used to assess hatching success (Table C-7). Both stormwater and coagulant effects were tested, as well as the effect from extended exposures on reproduction and fish larvae survival.

Fecundity (the eggs produced per day) was not affected by coagulants used but was affected by both stormwater and the number of days of exposure. Fecundity measured for fish exposed to Stag stormwaters were significantly different and about half of the fecundity measured for fish exposed to Tahoe City stormwaters (repeated measures 2-way ANOVA: $p = 0.005148$; Figure C-12a.). Fecundity also generally declined with increasing length of exposure. Initially, fecundity averaged just over 12 eggs per day per treatment but by the end of the test, after 4 days of exposure, fecundity had declined one third to about 8 eggs per day and this decline was statistically significant in all treatments (repeated measures 2-way ANOVA: $p = 0.001605$; Figure C-12b).

Days to hatching was similarly affected. Coagulants did not affect hatching success but stormwater did (Repeated measures 1-way ANOVA: $p = 0.007326$; Figure C-13a). The number of days to hatch was one day longer for fish exposed to Ski Run stormwaters as compared to fish exposed to Tahoe City and Stag stormwaters. Moreover, with increasing days of exposure, the days to hatching increased so that by the end of the test, nearly two more days were needed on average for hatching (Repeated measures 1-way ANOVA: $p = 0.0000$; Figure C-13b).

Hatching success quantifies the effects of parent exposure on developing fish embryos and larvae. Nonparametric analyses were used due to the non-normal distribution. Using Kruskal-Wallis ANOVA, hatching success did not differ statistically with exposure to different coagulants but it did differ with exposure to different stormwaters ($p = 0.0012$; Figure C-14a). Hatching success was smallest for fish exposed to Ski Run stormwaters and statistically below that for fish exposed to both Tahoe City and Stag stormwaters. Hatching success decreased significantly (Friedman ANOVA and Kendall Coeff of Concordance) with increasing days of parent exposure ($p = 0.0042$; Figure C-14b). At the initiation of the test, median hatching success was over 90%, though by the last day it had decreased to 80%.

C.5. Discussions

This study is the first to assess the aquatic toxicity of coagulants used to remove phosphorus and fine particles from stormwater. These ecotoxicity effects cannot be considered for the coagulants alone. Rather, there is an interaction of the coagulants with the treated stormwaters. The ecotoxicity that results from this interaction needs to be studied. Towards that goal, this study addressed a number of questions:

2. Did ecotoxicity of the different stormwaters vary by location?
3. Did coagulants affect stormwater ecotoxicity?
4. Which toxicity metric(s) was most sensitive to stormwater and coagulant effects?
5. What is the usefulness and application of toxicity tests for assessing stormwaters and coagulants in the Tahoe Basin?

C.5.1. Did ecotoxicity of non-treated stormwaters vary by source?

Stormwater toxicity varied with the stormwater source and with the toxicity metric used. Zooplankton mortality did not differ significantly between the non-treated stormwaters and the control (Figure C-6, Table C-5). While zooplankton mortality was not affected by stormwaters, the coagulants generally decreased zooplankton brood size (C-7). Fish fecundity was not affected by coagulants but was affected by stormwaters (Figure C-12). Survivor biomass did not differ significantly between the control and the non-treated stormwaters ($p<0.05$).

All non-treated stormwaters decreased the algae cell counts, though to varying degrees and Stag stormwater had the least affect (Figure C-4). Non-treated stormwaters showed varying effects on zooplankton brood size, with the brood size higher than the control ($p < 0.05$) for Ski Run stormwater and lower then the control ($p< 0.05$) for Tahoe City stormwater. Both Stag and Ski Run stormwaters greatly increased fathead minnow mortality, whereas Tahoe City stormwater did not cause a statistical increase in fathead mortality ($p < 0.05$). Days to hatch for the Medaka fish increased slightly with the only statistical difference being with Ski Run stormwaters. Hatching success was slightly better with Tahoe City stormwater and about 20% lower for Ski Run stormwater.

So in general, stormwaters affected the different toxicity metrics, though the effect was not consistent or predictable. Stormwater did not affect zooplankton mortality or fish survivor biomass. Fish fecundity increased with non-treated stormwaters. Algae cell counts decreased markedly for all non-treated stormwaters and Medaka fish larvae required more days to hatch. Stormwaters generally affect fathead minnow mortality, zooplankton brood size and hatching success, though sometimes these metrics improved and sometimes they worsened.

No stormwater was consistently more toxic then the others (Table C-8). Tahoe City stormwater least affected fish (fathead minnow, medaka), but most affected zooplankton reproduction. Ski Run stormwater least affected zooplankton reproduction but most affected days for fish embryos to hatch and their hatching success. Stag had the greatest effect on fish mortality and a relatively large effect on the number of medaka embryos that hatched successfully.

This variance in aquatic toxicity for stormwater is expected to vary spatially and temporally. Different land uses contribute different toxicants, which would be expected to have different effects on the toxicity metrics. For example, insecticides are generally more toxic to zooplankton than fish or algae, whereas PAHs and heavy metals tend to be more toxic to fish and algae than zooplankton. Stormwater toxicity also is expected to vary temporally as well seasonally, and may depend upon the type of runoff: rain, snowmelt, rain on snow, etc.

Thus, aquatic toxicity differed at the three Tahoe Basin locations where these stormwaters were collected. All three stormwaters were collected at the same time, and generally represent a first rainfall flush from a late spring event after snowmelt. Clearly these stormwaters are delivering toxicity to downstream waters, although the degree and type of toxicity cannot be easily predicted.

C.5.2. Did coagulants affect stormwater ecotoxicity?

Coagulant dosing altered stormwater ecotoxicity. The PCA analyses of summary data from the EPA 4-species test suggested that zooplankton reproduction, algae cell counts and fathead minnow mortality were closely related to coagulant dosing level, but that zooplankton mortality was not (Figure C-2). However, coagulant dosing is not simply a function of dosing. Rather it results from an interaction between the coagulant and the stormwater being dosed. All dosing levels were determined using standard jar tests, and dosing levels selected represent the threshold at which optimal flocculates formed. Jar tests are commonly used to develop coagulant dosing levels. Higher dosing levels are needed for those stormwaters requiring greater treatment. This result is reflected in the PCA analyses. In Figure C-2, Factor 1 is most related to toxicity. It is negatively related to fish mortality and positively related to algae cell count and zooplankton reproduction. Tahoe City water and non-dosed stormwaters were the least toxic, while dosed Ski Run and Stag stormwaters were more toxic. This represents not only the nature of the stormwaters but also the dosing levels required to remove fine particles and turbidity.

Table C-6 summarizes the effects of the different coagulants. In general, Sumachlor 50 least affected the inherent toxicity of stormwaters, as compared to non-treated stormwater (Table C-6). Sumachlor 50 negatively affected zooplankton reproduction and either positively or neutrally affected other toxicity metrics. Both JenChem 1720 and PAX-XL9 occasionally increased toxicity. JenChem 1720 increased toxicity for half the toxicity metrics, with the greatest affect on zooplankton reproduction and algae, and decreased toxicity for one metric, the Medaka larvae hatching success. PAX-XL9 increased toxicity for half the metrics, with the greatest affect on zooplankton reproduction.

C.5.3. Which toxicity metric(s) was most sensitive to stormwater and coagulant effects?

Algae cell count and fish mortality were the most sensitive toxicity metrics for stormwater. Non-treated stormwaters reduced algae cell counts by about 50% and increased fish mortality by an order of magnitude (Table C-5). Stormwaters alone showed only small effects on zooplankton mortality and reproduction, fathead minnow biomass and the different Medaka fish toxicity metrics. When stormwaters were dosed with coagulants, the different coagulants had diverse effects on the different toxicity metrics. All coagulants greatly decreased zooplankton reproduction and algae cell counts. Minimal effects were observed on zooplankton mortality, except for a single SDR of JenChem1720 treating Ski Run stormwater.

C.6. Conclusions

The standard EPA 3-species toxicity test and a medaka test (in which fecundity of parents and hatching success of offspring were measured) were used to assess the toxicity of coagulant applications to decrease fine particle and dissolved phosphorus concentrations in stormwaters. It was shown that untreated stormwater contained contaminants toxic to the aquatic test species. For the EPA 3-species test, PCA analyses identified zooplankton reproduction, fathead minnow mortality and algae cell counts as affected by coagulant dosing level. Other water quality characteristics such as temperature, pH and alkalinity contributed toward development of settleable flocculants. The dosing levels represent a dosing regime that will effectively remove fine particles and dissolved phosphorus. Higher dosing levels may be needed for stormwaters in which those constituents are more difficult to remove. The toxic effects from stormwaters and coagulants were statistically separated using factorial ANOVA and nonparametric analyses. The effects on different toxicity metrics varied between non-treated stormwaters as well as between stormwaters treated with different coagulants. In general, stormwaters most affected algae cell counts and fish mortality, whereas coagulants most affected zooplankton, especially zooplankton reproduction.

C.7. References

ASCE and USEPA. 2005. International Stormwater BMP Database. Under cooperative agreement of the American Society of Civil Engineers (ASCE) and the U.S. Environmental Protections Agency (USEPA) with support and funding from Water Environment Research Foundation (WERF), ASCE Environmental and Water Resources Institute (EWRI), USEPA, Federal Highway Administration (FHWA) and the American Public Works Association (APWA). Database maintained and operated by Wright Water Engineers, Inc. and GeoSyntec Consultants. Available at http://www.bmpdatabase.org/index.htm. Accessed January 2005.

Bachand, P.A.M., C.J. Richardson and P. Vaithiyanathan. 2000. Everglades Phase II report

Bachand, P.A.M., S.M. Bachand and A. Heyvaert. 2005a. Draft Technical Memorandum, Task 2. BMP treatment technologies, monitoring needs, and knowledge gaps: Status of the knowledge and relevance within the Tahoe Basin. Submitted to El Dorado County, April 2005.

Bachand, P, J. Trejo-Gaytan, J. Darby, and J. Reuter. 2005b. Final Report: Small-Scale Studies on Low Intensity Chemical Dosing (LICD) for Treatment of Highway Runoff. April 2006. CTSW-RT-06-073.13.1

Caltrans 2006b. Caltrans Lake Tahoe Storm Water Small-Scale Pilot Treatment Project Phase IV Final Report, April 2006 **CTSW-RT-05-157.04.02**

Caltrans, 2006a. Caltrans Highway 267 Filter Fabric Sand Trap Pilot Study, 2004-2005 Interim Report **CTSW-RT-05-157.01.2**

Caltrans 2005. Caltrans Tahoe Highway Runoff Characterization and Sand Trap Effectiveness Studies, 2000-2003 Monitoring Report. Revised March 2005. **CTSW-RT-03-054.36.02**

Caltrans 2003. **A Review of the Contaminants and Toxicity Associated with Particles in a Storm Water Runoff. CTSW-RT-03-059.73.15**

Clear Water Compliance Services. 2004. Advance Treatment Systems Overview – Washington. Presentation by Thomas C. Leggiere, TLeggiere@clearwatercomplianceservices.com , at the Conference on Advanced Treatment for Construction Sites. CalEPA, October 21, 2004. Sacramento.

Doke, J.L., W.H. Funk, S.T.J. Juul and B.C. Moore. 1995. Title Habitat availability and benthic invertebrate population changes following alum treatment and hypolimnetic oxygenation in Newman Lake, Washington. Journal of Freshwater Ecology 10(2): 87-102

Gensemer, R.W. and R.C. Playle. 1999. The bioavailability and toxicity of aluminum in aquatic environments. Critical Revies in Environmental Science and Technology, 29(4):315-450.

Goodfellow, W.L., L.W. Ausley, D.T. Burton, D.L. Denton, P.B. Dorn, D.R. Grothe, M.A. Heber, T.J. Norberg-King and J.H. Rodgers, Jr. Annual Review — Major ion toxicity in effluents: A review with permitting recommendations. Environmental Toxicology and Chemistry, 19(1):175-182.

Harper, H.H. 1994. Alum treatment of stormwater runoff - Orlando's Lake Dot and Lake Lucerne systems. Lake Reservoir Manage. 9(2):81.

Heyvaert, A.C., P.A.M. Bachand and J.M. Thomas. 2005. Phosphorus Sorption Characteristics of Soils from Selected Stormwater Infiltration Sites in the Lake Tahoe Basin, Final Report. Prepared for Tahoe Regional Planning Agency, Stateline, NV by the Tahoe Regional Planning Agency, Stateline, NV; the Tahoe Environmental Research Center, University of California at Davis, Tahoe City; Bachand and Associates, Davis, CA; and the Desert Research Institute, Reno, NV.

Jacoby, J.M., H.L. Gibbons, K.B. Stoops and D.D. Bouchard. 1994. Response of a shallow, polymictic lake to buffered alum treatment. Lake Reserv. Manage. 10(2):103-112.

James, W.F., J.W. Barko and W.D. Taylor. 1991. Effects of alum treatment on phosphorus dynamic in a north-temperate reservoir. Hydrolobiologia 215(3):231-241.

Kennedy, R.H. and G.D. Cooke. 1982. Control of lake phosphorus with aluminum sulfate: dose determination and application techniques. Water. Res. Bull 18:389-395.

Livingston, E.H., H. Harper and J.L. Herr. 1994. The use of alum injection to treat stormwater. In : Proceedings of the 2nd Annual Conference on Soil and Water Management for Urban Development. pp. 31-53. (Livingston, E.H. and Harper, H.H., Eds.) Sydney, N.S.W.

Macpherson, J. 2004. Storm-Klear (Chitosan) Toxicity and Applications, Construction Stormwater Treatment. Presented for Natural Site Solutions at the Conference on Advanced Treatment for Construction Sites, CalEPA, October 21, 2004. Sacramento.

Metcalf and Eddy. 1979. Wastewater Engineering, Treatment, Disposal and Reuse, Second Edition. Revised by G. Tchobanoglous. McGraw-Hill. N.Y.

Narf, R.P. 1990. Interactions of Chironomidae and Chaoboridae (Diptera) with aluminum sulfate treated lake sediments. Lake Reserv. Manage. 6(1):33-42.

Reuter, J.E. and W.W. Miller. 2000. Aquatic Resources, Water Quality, and Limnology of Lake Tahoe and Its Upland Watershed. In: D.D. Murphy and C.M. Knopp (Eds.) Lake Tahoe Watershed Assessment: Volume 1. Gen. Tech. Rep. PSW-GTR-175. Albany, CA: Pacific Southwest Research Station, Forest Service, US Department of Agriculture.

Skinner, L., A. de Peyster and K. Schiff. 1999. Developmental Effects of Urban Storm Water in Medaka (Oryzias latipes) and Inland Silverside (Menidia beryllina). Arch. Environ. Contam. Toxicol 37:227-235.

Smeltzer, E. 1990. A successful alum/aluminate treatment of Lake Morey, Vermont. Lake Reserv. Mange. 6(1):9-19.

Soucek, D.J., D.S. Cherry, and C.E. Zipper. 2001. Aluminum-dominated acute toxicity to the cladoceran Ceriodaphnia dubia in neutral waters downstream of an acid mine drainage. Can. J. Fish. Aquat. Sci. 58:2396-2404.

Trejo-Gaytan, J., P.A.M. Bachand and J.L. Darby. 2004. Low Intensity Chemical Dosing Treatment of Urban Runoff at Lake

Welch, E.B. and G.D. Schrieve. 1994. Alum treatment effectiveness and longevity in shallow lakes. Hydrobiologia 275-276(0):423-431.

Winer, R. 2000. National Pollutant Removal Performance Database for Stormwater Treatment Practices, 2nd Edition. Prepared by the Center for Watershed Protection (www.cwp.org) for the EPA Office of Science and Technology in association with Tetratech. Available at www.stormwatercenter.net. Accessed January 2005.

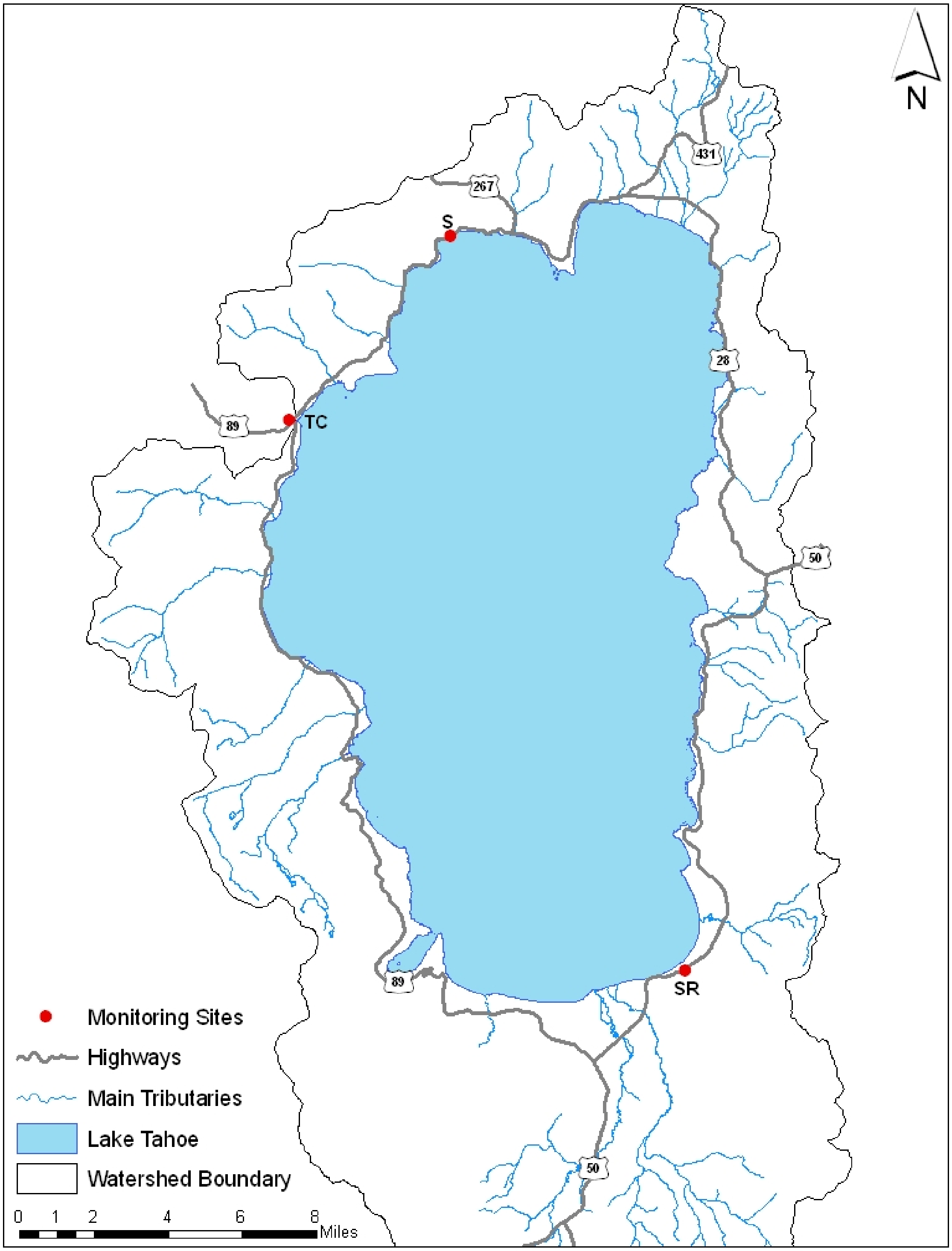


Figure C-1. Map of locations from which stormwater was sampled.
S=Stag, TC=Tahoe City, SR=Ski Run.

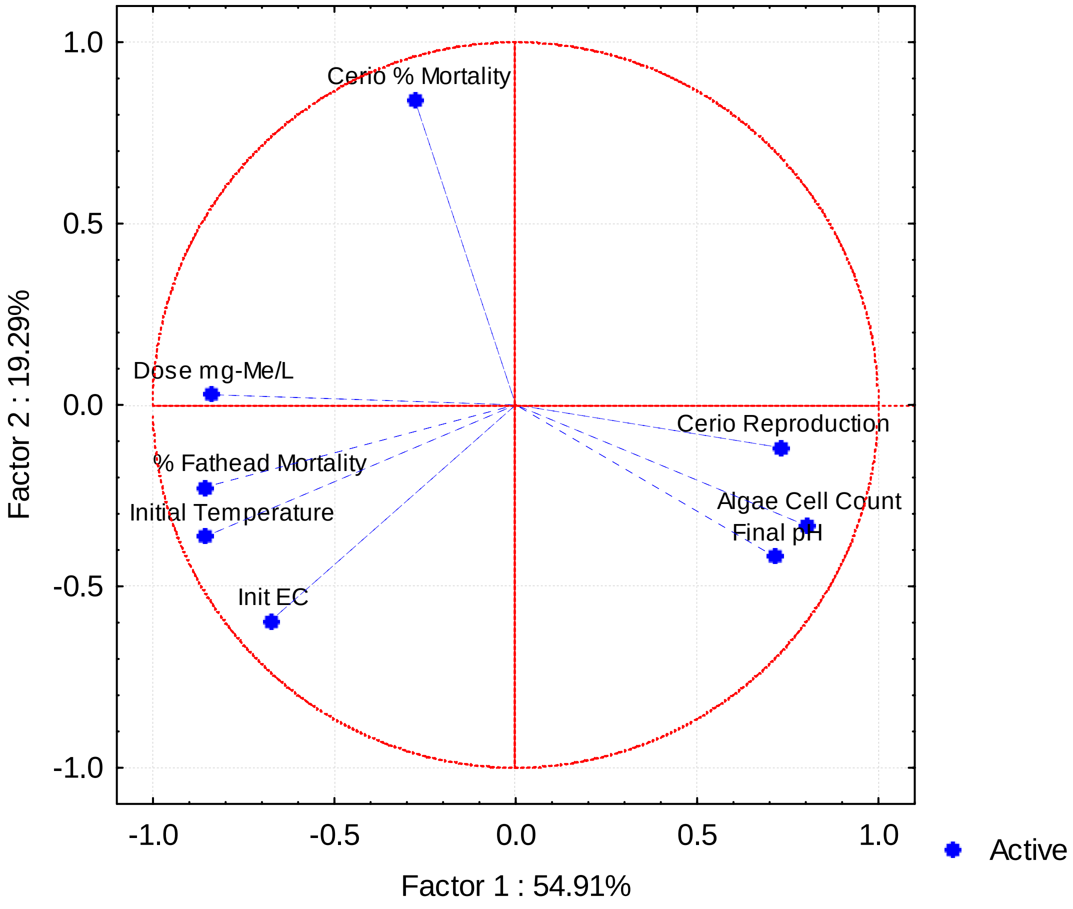


Figure C-2. PCA analyses showing the relationships between dosing levels and different toxicity metrics.

Factor 1 shows relationship between dosing level, conductivity and pH and explains over half the variance in the data. As dosing level increases, pH decreases. Higher dosing levels are used on more polluted stormwaters and higher dosing levels result in decreased zooplankton reproduction and algae cell counts and increased fish mortality. Factor 2 explains about 20% of the variance in the data and shows zooplankton mortality is unaffected by dosing level.

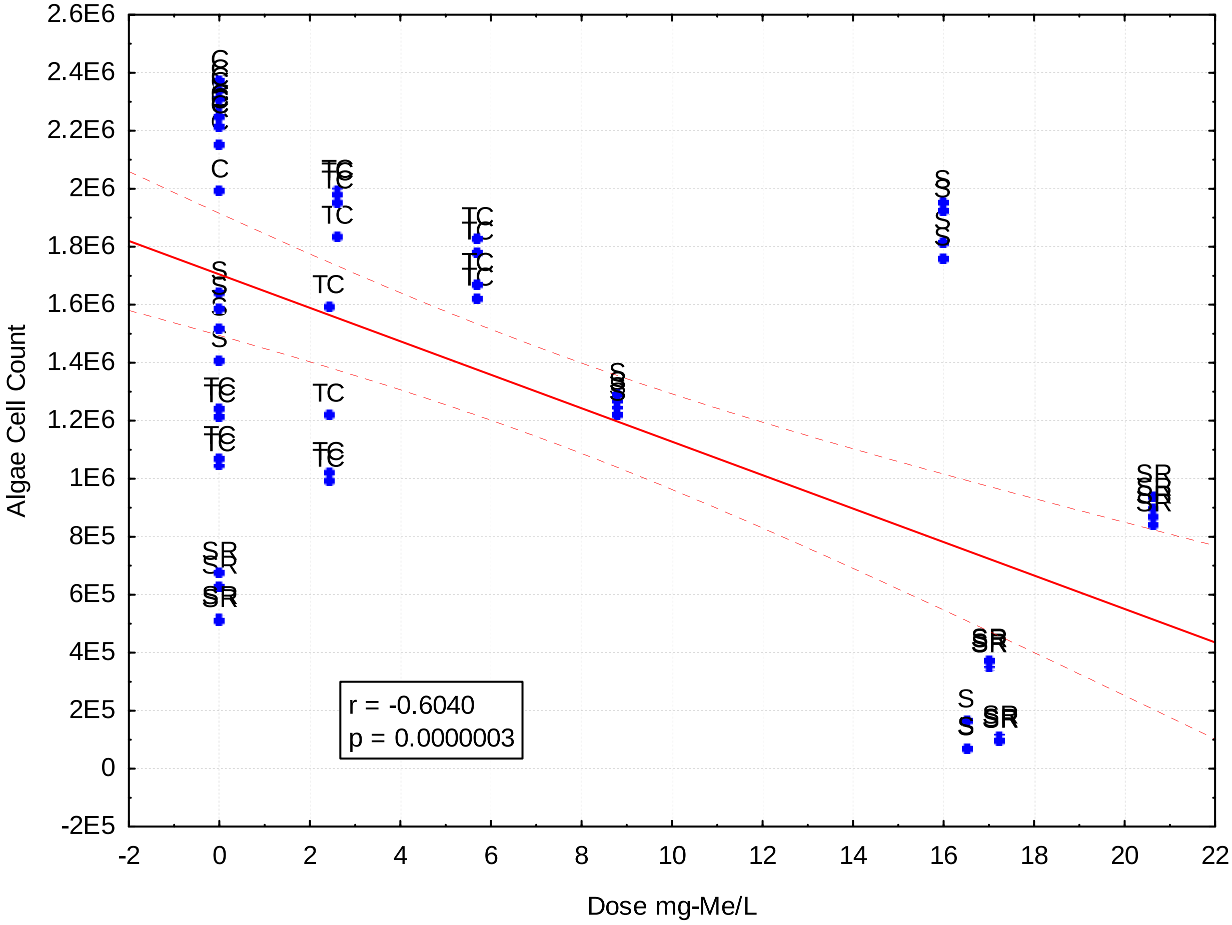


Figure C-3. Dosing level explains one third of the variance in algae cell counts. Labels identify stormwater being treated. Higher coagulant dosing levels correlated with lower cell counts. Cell counts were generally lowest for stormwaters from Ski Run and highest for stormwater from Tahoe City.

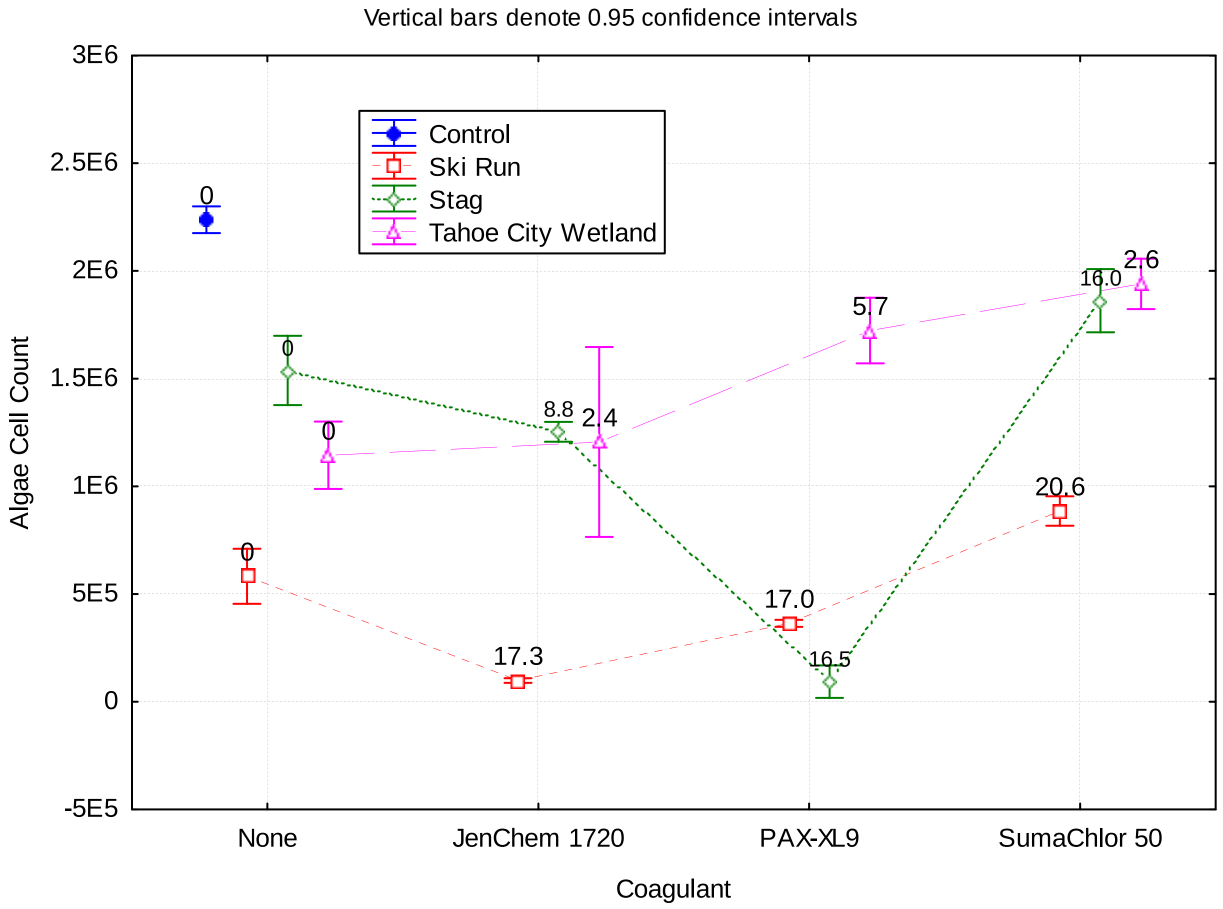


Figure C-4. Coagulants Both Positively and Negatively Affected Cell Counts
Numbers represent the dosing level used for each coagulant and stormwater combination. Tahoe City stormwater was lightly dosed by all coagulants and algae cell counts improved over a non-treated stormwater, reducing toxicity. Stag and Ski Run stormwaters were more heavily dosed by all coagulants. For both stormwaters, two coagulants negatively affected cell counts whereas one coagulant improved cell counts.

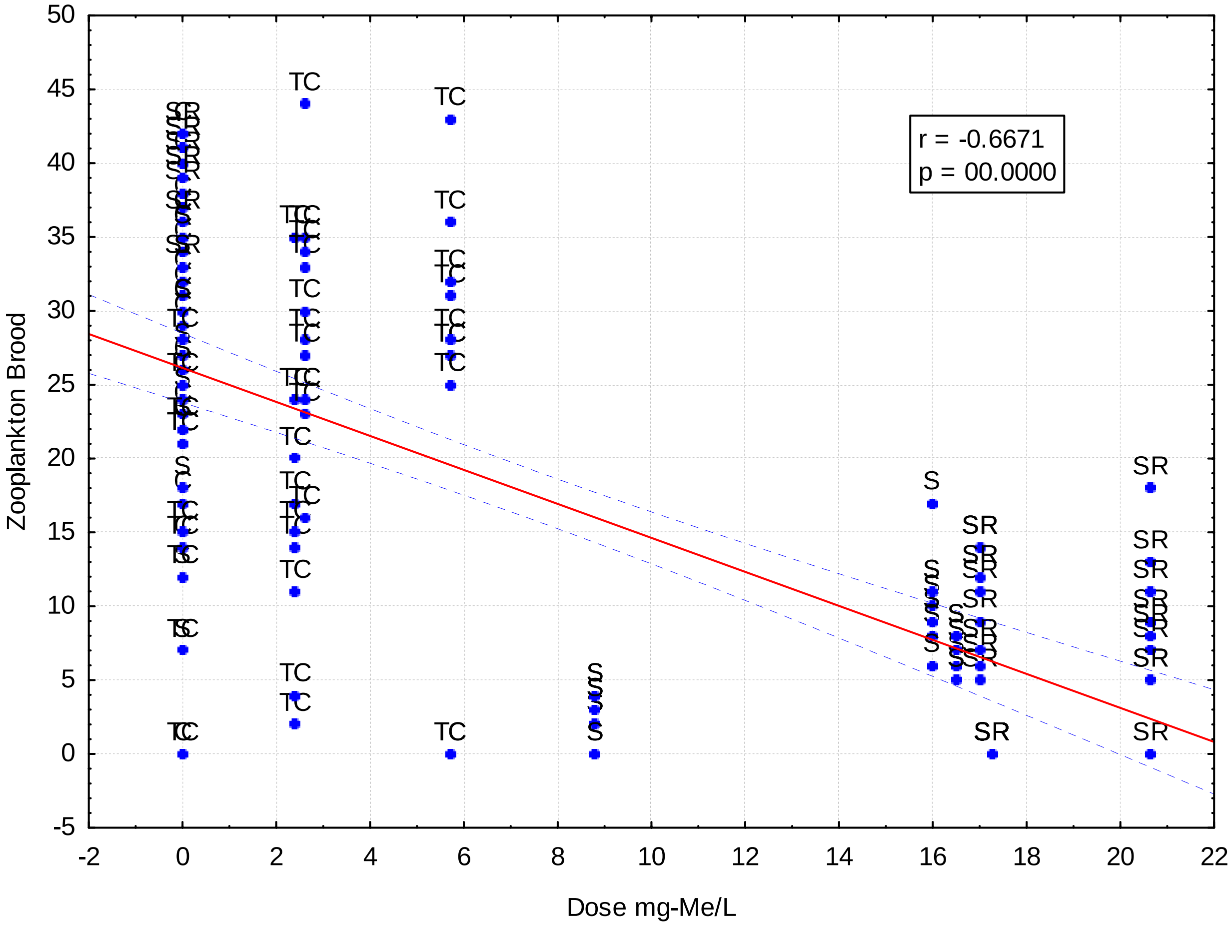


Figure C-5. Dosing level explains 43 % of the variance in zooplankton reproduction
Labels identify stormwater being treated. Higher dosing levels correlate with lower reproduction.

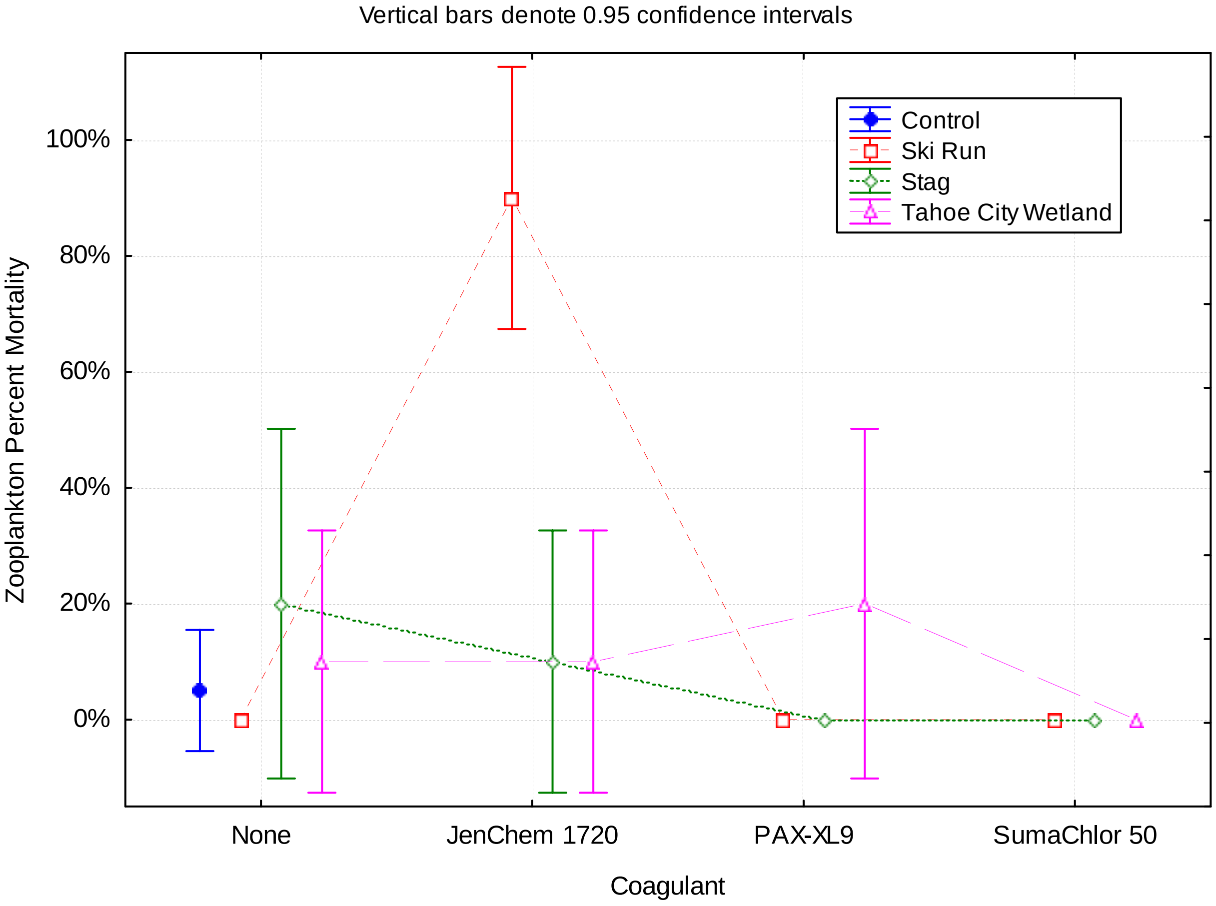


Figure C-6. Coagulant and Stormwater Effects on Zooplankton Mortality
In general, SDR for different coagulants did not affect zooplankton mortality. One SDR, JenChem 1720 dosing of Ski Run stormwater, experienced a high mortality count. All other differences were not statistically significant ($p < 0.05$).

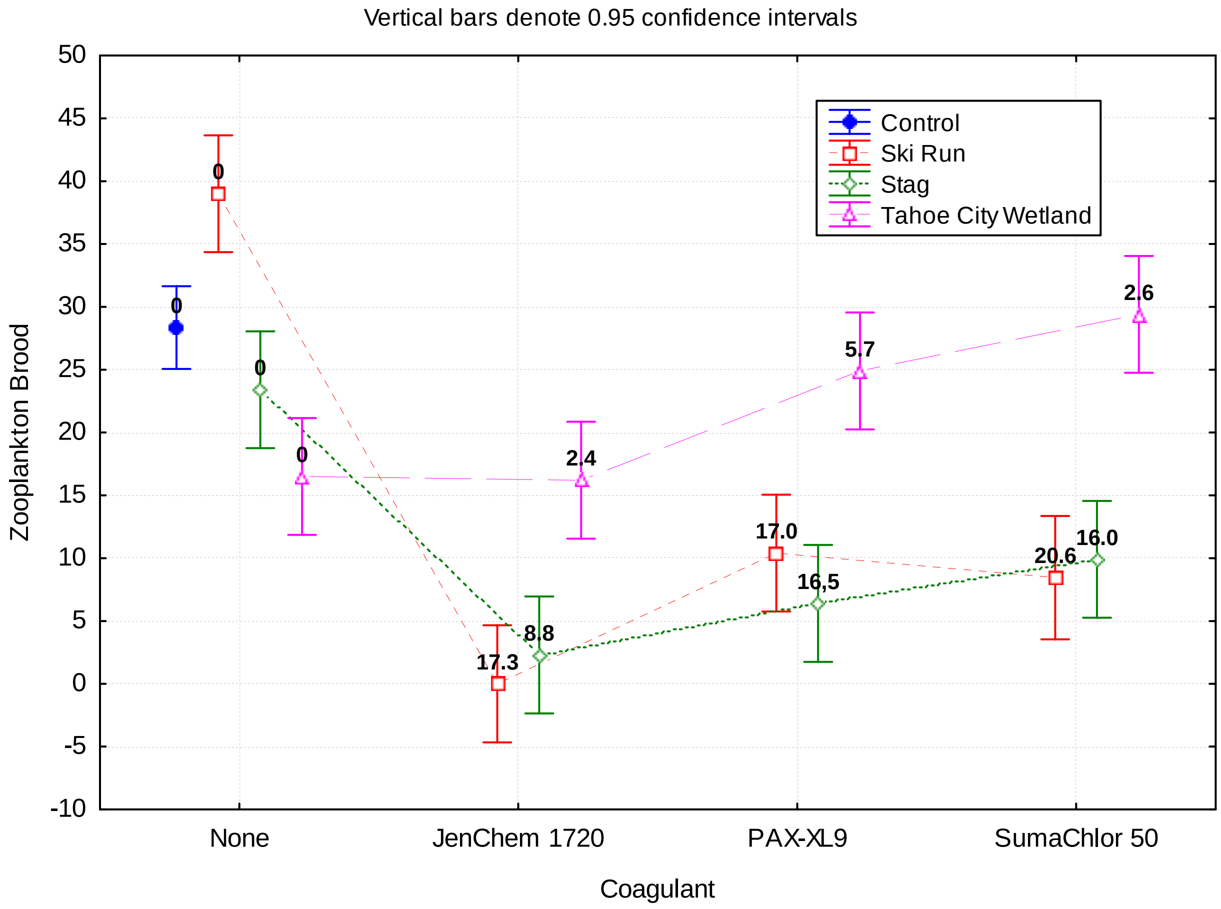


Figure C-7. Coagulation significantly decreased brood sizes for Stag and Ski Run stormwaters.
Brood sizes at no dosing significantly differed between stormwaters, with Ski Run stormwater having the highest brood size. Coagulant dosing of both Ski Run and Stag stormwaters greatly and significantly decreased zooplankton brood sizes. For Ski Run and Stag stormwaters, brood sizes did not differ for the different coagulant treatments.

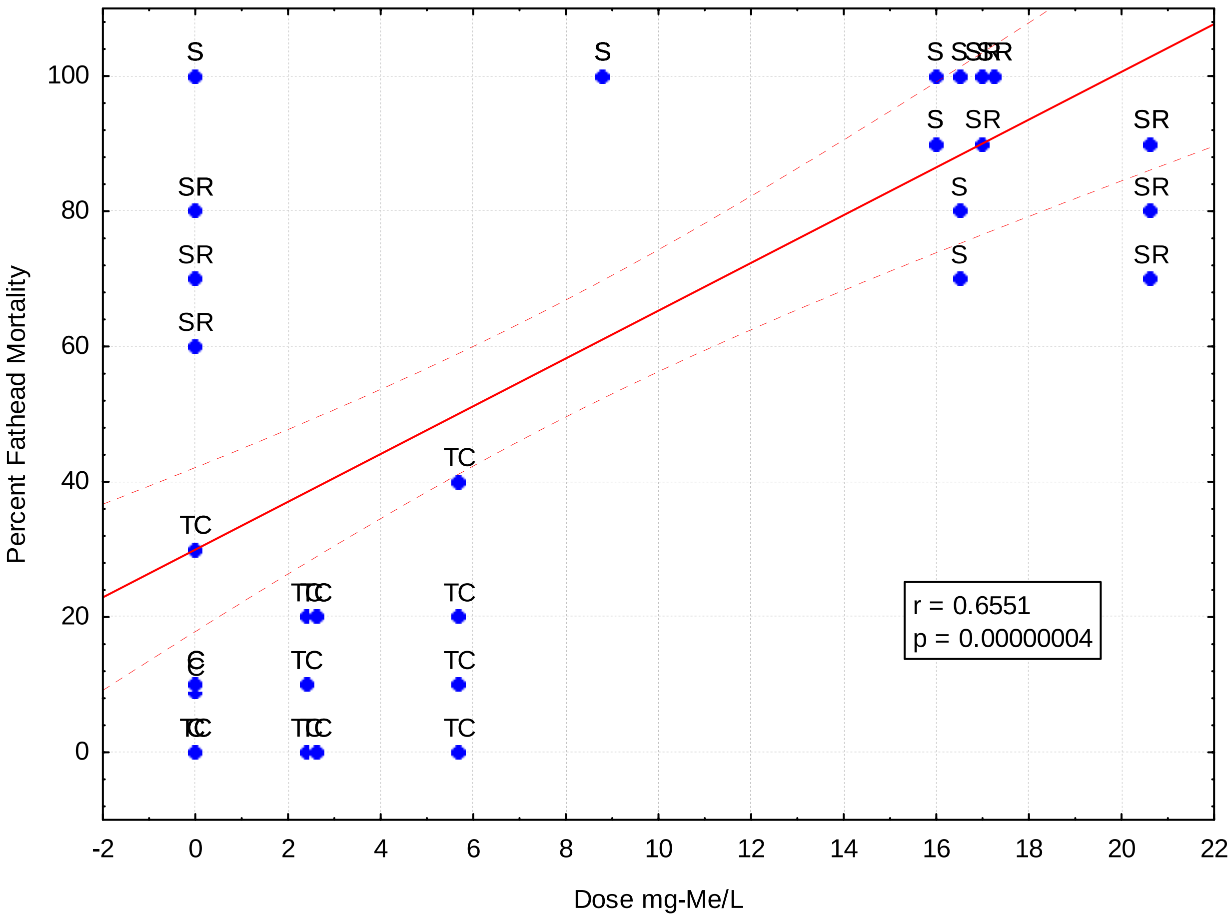


Figure C-8. Fathead Mortality corresponded with dosing level, though mortality is generally lowest for Tahoe City stormwater.

Dosing level explains about 40% of the fathead mortality. However, mortality corresponds with stormwaters as well. Tahoe City stormwater has the lowest mortality and Ski Run and Stag stormwaters have higher mortality, regardless of the dosing levels.

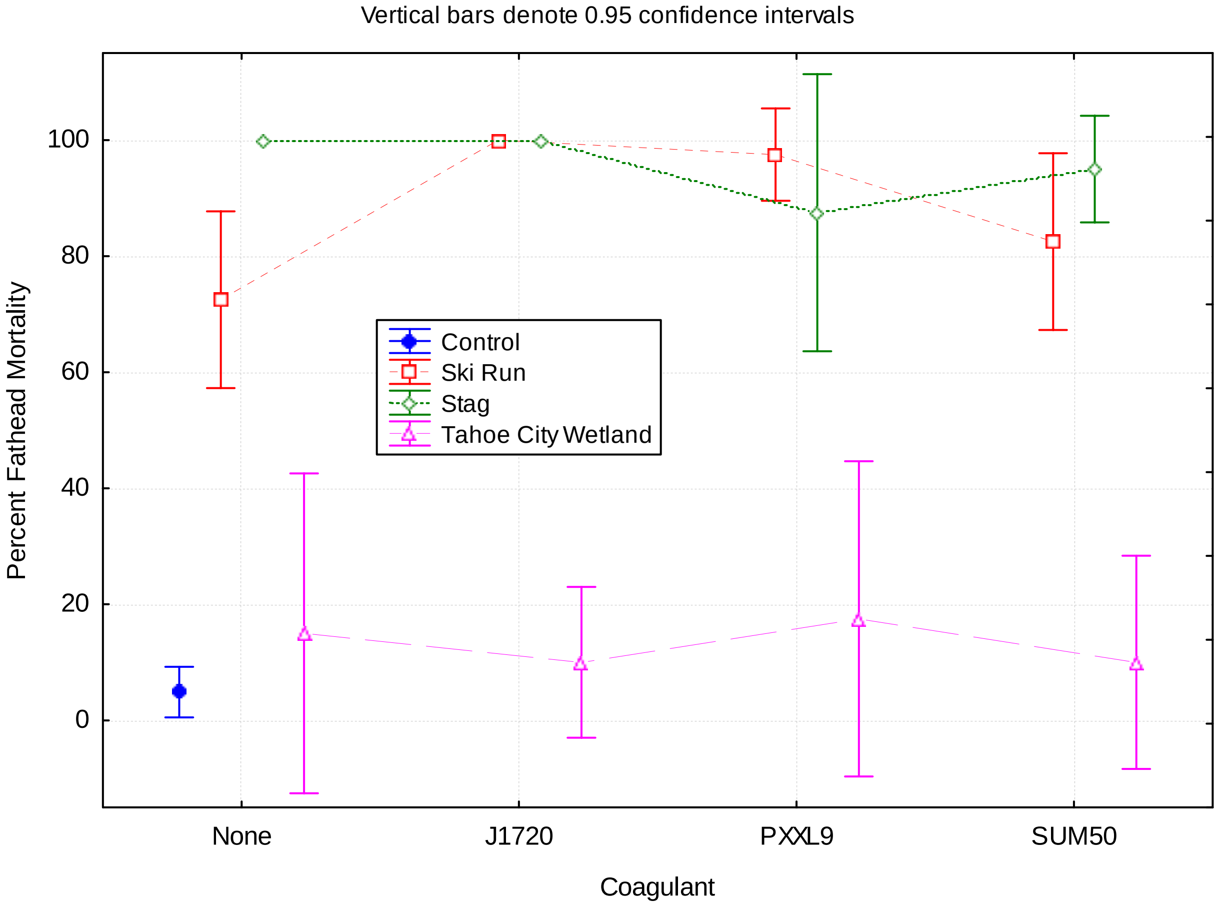


Figure C-9. Stormwater Effects on Fish Mortality
Coagulants generally did not affect fish mortality ($p<0.05$). JenChem 1720 resulted in complete mortality for Ski Run stormwaters which significantly differed from mortality for Ski Run stormwater under no chemical dosing and under dosing with Sumachlor 50. Mortality at Tahoe City was the least and was not significantly different from the control.

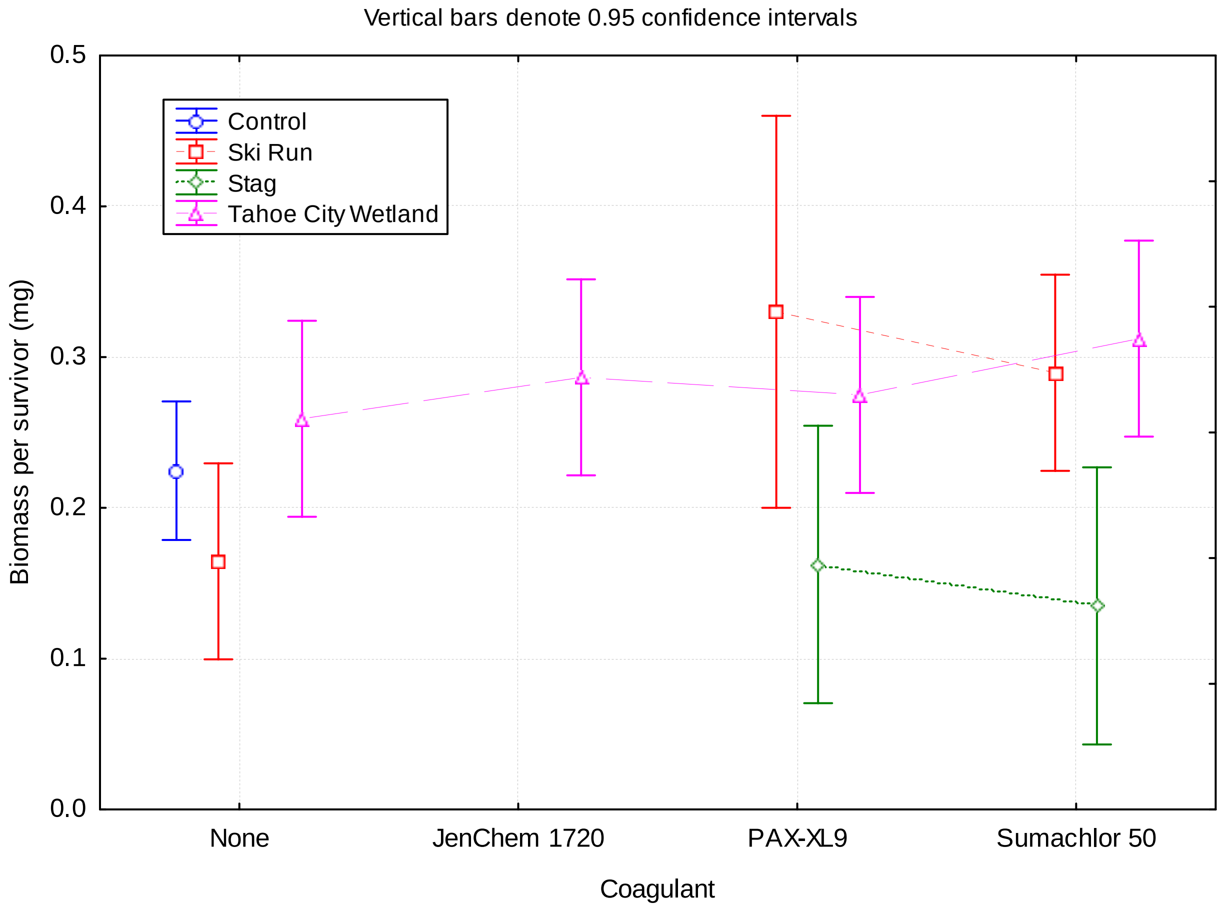
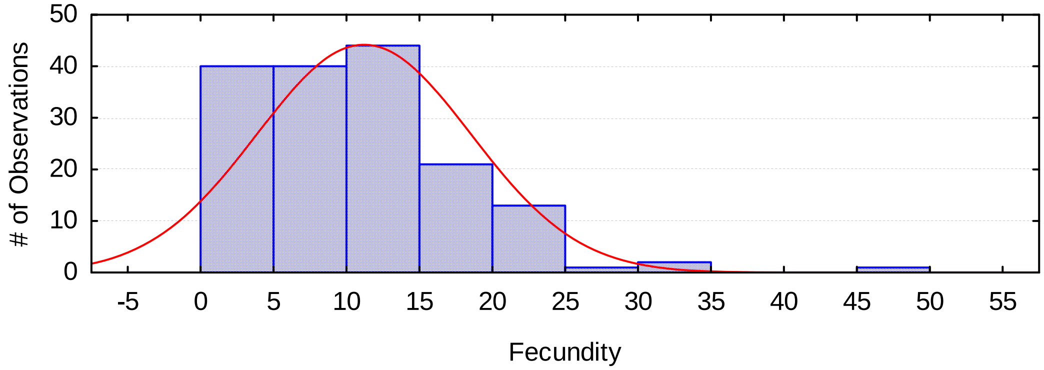
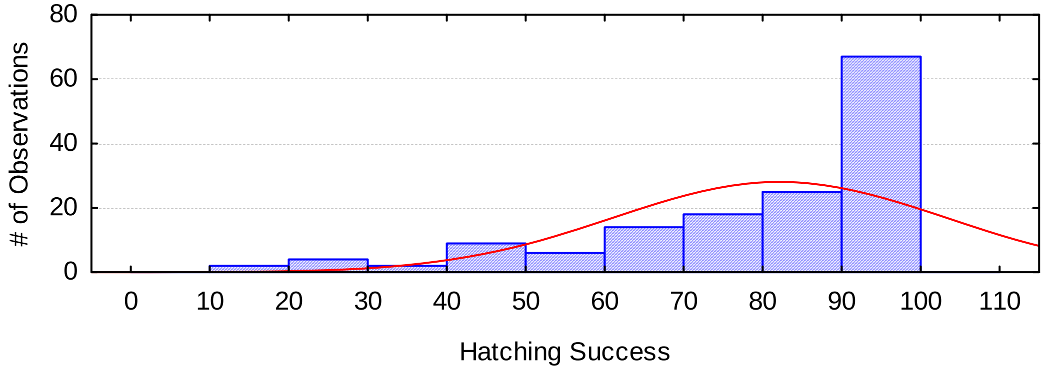


Figure C-10. Stormwater Effects on Biomass of Survivors.

a. Fecundity Distribution



b. Hatching Success Distribution



c. Days to Hatch Distribution

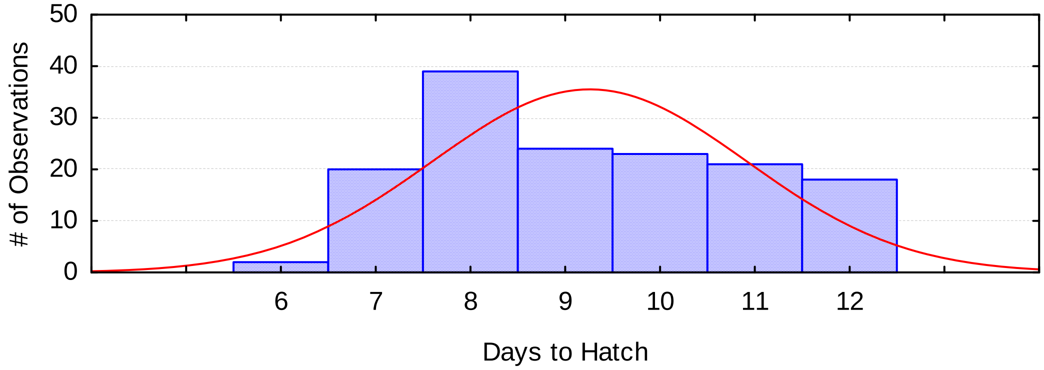
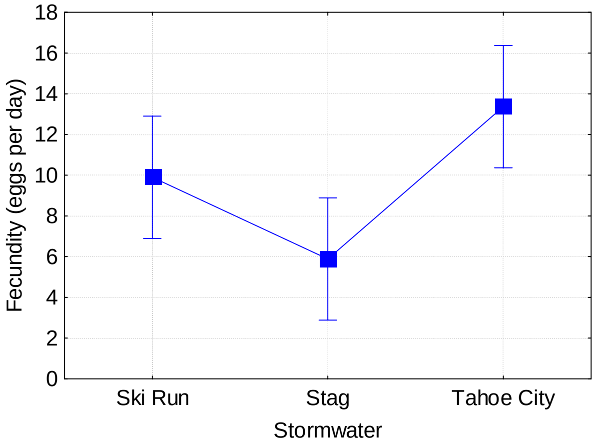


Figure C-11. Distribution of Toxicity Metrics for Medaka Test

A. By Stormwater



By Days of Exposure

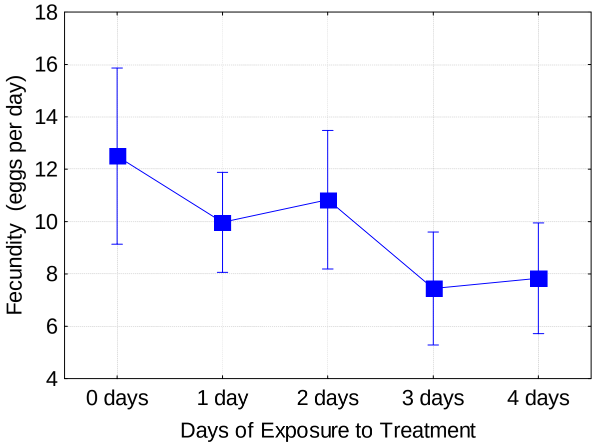
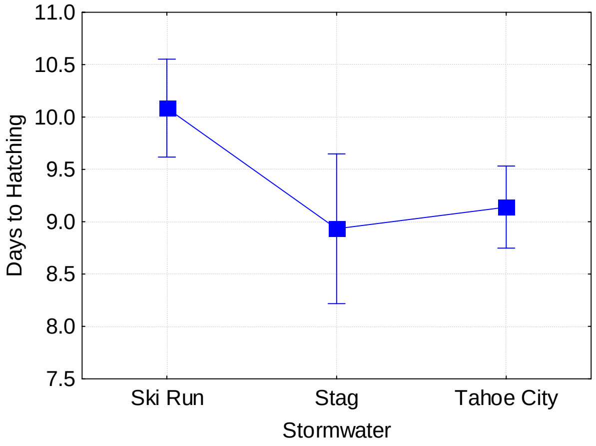


Figure C-12. Statistical Effects on Fecundity from Stormwater and Days of Exposure. Stormwater affected the fecundity of Medaka, with Tahoe City water having the most fecund Medaka fish and Stag stormwater having the least fecund. Fecundity had a decreasing trend with successive days of exposure and after 3 days the differences were statistically significant. Coagulant treatment did not statistically affect fecundity. Analyses were made using a 2-way repeated measures ANOVA design.

A. By Stormwater



B. By Days of Exposure

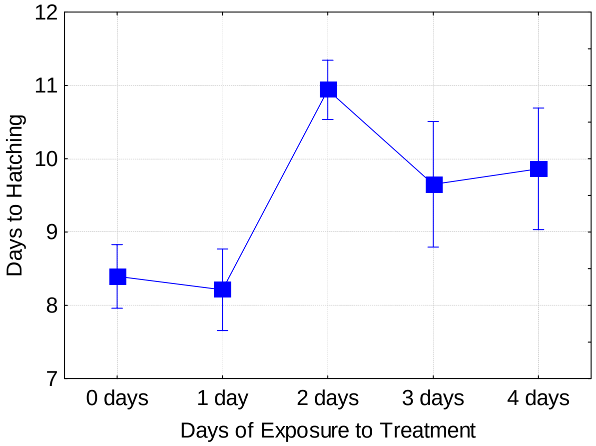
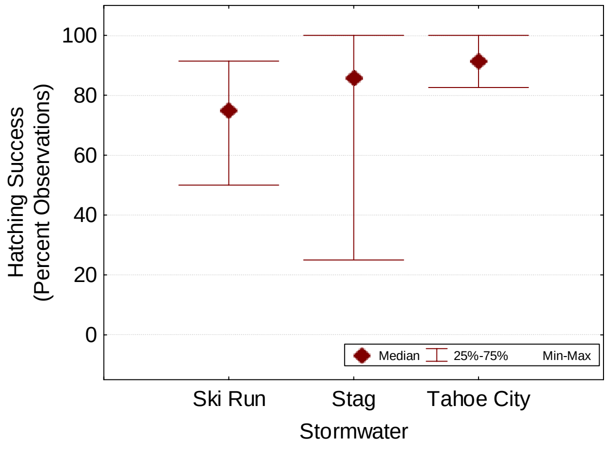


Figure C-13. Statistical Effects on Days to Hatch from Stormwater and Days of Exposure Two 1-way repeated measures ANOVA design was to test the effects of coagulants and stormwaters. Days to hatching did not differ with coagulants but did differ with the stormwaters used and the days of exposure. Days to hatching were statistically greater ($p<0.05$) for Ski Run stormwater as opposed to stormwater from Stag and Tahoe City (a.). Days to hatching generally and statistically ($p<0.05$) increased with consecutive days of exposure.


A. By Stormwater

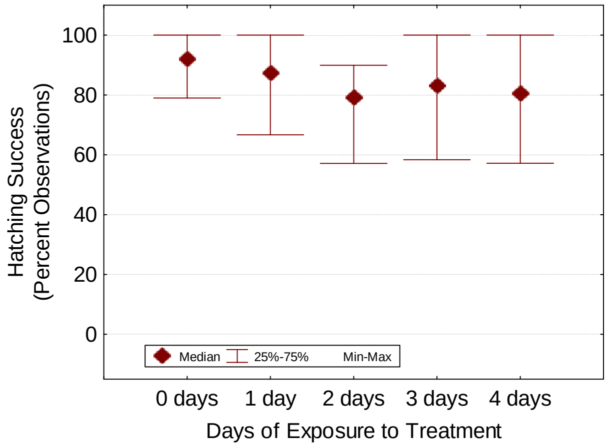

By Days of Exposure

Figure C-14. Statistical Effects on Hatching Success for Stormwater and Days of Exposure Kruskal-Wallis ANOVA showed no effects of coagulants on hatching success, but an effect of stormwater (p=0.0012). Hatching success was smallest for Ski Run stormwaters and statistically different and from and lower then Tahoe City and Stag stormwater (a). Friedman ANOVA and Kendall Coeff. of Concordance to test dependent samples showed for all the tested stormwaters, hatching success decreased over time (p-0.0042) though those differences were not apparent when single stormwaters were tested (b).

Table C-1. Treatment BMPs in the Tahoe Basin

The listed BMPs are those reported in use in the Tahoe Basin. Drain inserts with and without media are defined as hydrodynamic devices and these include traps, oil-water separators and centrifugal concentrators. Many proprietary BMPs are categorized as hydrodynamic devices.

Best Management Practice (BMP)	BMP Description	Used in or by:				Estimated Usage
		City of South Lake Tahoe	Placer County	El Dorado County	Caltrans	
Treatment BMPS:						
Bioretention basin	Landscaped area that accepts water through a buffer zone or filter strip. It is a depression comprised of several layers; plants, mulch, soil, and sand bed. A pipe at the bottom conveys stormwater away. It is assumed that these basins do not include th	X				RN
Media Filter	Granular or membrane filters that remove pollutants by passing runoff volumes through peat, compost, geotextiles, or other porous media. Water is collected by underdrain.	X				LU
Dry Detention Basin	Basin that captures stormwater but completely dries between runoff events.	X	X		X	RN
Wet Pond or retention pond	Basin that retains a permanent pool of water between storms. Pond is generally deeper than a stormwater wetland. Generally requires a consistent baseflow or high groundwater table.	X				LN
Water quality swale (dry swale, wetland channel, grass channel)	Channels designed for slow water flow during runoff events. Wetland channels or grass channels are covered with wetland vegetation or grass-lined . They are shallow with gently sloping sides. May have underdrains.	X	X			RN
Grass Filter strip (biofilter strip, buffer strips)	Vegetated areas designed to accept sheet flow .	X	X			LN
Infiltration Basin	Basins that capture a given stormwater runoff volume and infiltrate it into the ground, transferring surface flow to groundwater flow	X	X		X	RN
Infiltration Trench (percolation trench or dry well)	A ditch filled with gravel or other porous media to facilitate the rapid percolation of runoff to groundwater. It is assumed that they do not include the use of adsorptive media.		X			LU
Porous pavement	Modular block or porous concrete, generally used in in lower traffic areas.		X			LU
Stormwater wetland[3]	Basin that retains a permanent pool of water between storms. Basin has varying depths, with 50% of its surface is covered by emergent wetland vegetation. Generally requires a consistent baseflow or high groundwater table.	X	X			LN
Drain Inserts without filters	Hydrodynamic devices that collect and direct flow and capture sediment. Some systems have porous bottom to allow some infiltration. Some have sediment removal tank followed by filters. Filters can vary with contaminant. Proprietary products exist.	X	X		X	MN
Drain Inserts with filters	Wastewater flows through set of filters contained within drain. Filters can vary with contaminant. Many available proprietary products that may not have been tried: Drop-In-Drain-Interceptor, Multi-Cell Filter, Raynfiltr, SeaLife Saver, StormFilter.	X				LU

Table C-2. Coagulant Specifications

List of manufacturer provided characteristics for each of the coagulants tested.

Coagulant Code	Vendor	Coagulants	NSF Designation	Dose mg-Al/L	% basicity	pH	SG[2]	% Al
J1720[1]	JenChem	JC 1720 ®	Polyaluminum chloride	1.4	70	4.3	1.29	5.95
PXXL9	Kemiron	PAX-XL9 ®	Polyaluminum chloride	4.3	67	2.8	1.26	5.6
SUM50	Summit	Sumachlor 50 ®	Aluminum chlorohydrate	2.2	83.5	4.2	1.34	12.4

[1] Blended with an organic polymer

[2] Specific gravity

Table 3. Experimental Design

Dosing levels (mg-Al L-1) for different stormwater dosing regimes (SDRs) as defined by stormwater and coagulant.

Stormwater	Coagulant and code			
	No Treatment NOTRT	JenChem 1720 J1720	PAX-XL9 PXXL9	Sumachlor 50 SUM50
Control	0.0	NA	NA	NA
Stag	0.0	8.8	16.5	16.0
Ski Run	0.0	17.3	17.0	20.6
Tahoe City Wetland	0.0	2.4	5.7	2.6

Table C-3. Correlations between selected water quality measurements and toxicity

		SDR[3] (mg-Al/L) Treatment	Stormwater Toxicity			
			Algae	Zooplankton		Fish
			Cell Count	Reproduction	% Mortality	% Mortality
SDR	mg-Al/L	**1.00**	-0.53	-0.75	0.26	0.64
Algae	Cell Count	-0.53	**1.00**	0.42	-0.35	-0.55
Zooplankton	Reproduction	**-0.75**	0.42	**1.00**	-0.40	-0.51
	% Mortality	0.26	**-0.35**	-0.40	**1.00**	0.18
Fish	% Mortality	0.64	-0.55	-0.51	0.18	**1.00**
Water Quality	Initial Temp	**0.70**	-0.58	-0.52	-0.11	**0.82**
	Initial DO	-0.19	0.15	0.21	0.10	-0.12
	Initial pH	-0.56	**0.71**	0.22	-0.16	-0.23
	Initial EC	0.47	-0.38	-0.43	-0.24	**0.72**
	Final Temp	0.49	-0.29	-0.24	-0.08	0.43
	Final pH	-0.49	**0.91**	0.31	-0.35	-0.45

[1] Highlighted correlations are statistically significant

[2] Bolded blue font show correlations with R >= 0.70

[3] Stormwater dosing regime - For each stormwater-coagulant combination, a different optimal dosing level was determined.

Table C-4. Mean values for the different toxicity metrics

Mean values are shown for each toxicity metric. An average value is given for all the coagulants and stormwaters. Different letters indicate statistical differences ($p<0.05$) between stormwaters and coagulants.

	N	No Dosing	JenChem 1720	Pxxl9	Sum50	All Coagulants	All Treatments	*Sig. (p<0.05)*
Algae Toxicity (Cell count)								
Control	12	2.24E+06						
Ski Run	4	5.82E+05	9.87E+04	3.64E+05	8.85E+05	4.50E+05	4.83E+05	*a*
Stag	4	1.54E+06	1.25E+06	9.34E+04	1.86E+06	1.07E+06	1.19E+06	*b*
TCW	4	1.14E+06	1.21E+06	1.72E+06	1.94E+06	1.62E+06	1.50E+06	*c*
All Stormwaters		*1.09E+06*	*8.52E+05*	*7.27E+05*	*1.56E+06*	1.05E+06	*1.06E+06*	
Sig. (p<0.05)		*c*	*b*	*a*	*d*			
Zooplankton								
Mortality (%)								
Control	10	5%						
Ski Run	10	0%	90%	0%	0%	30%	23%	*b*
Stag	10	20%	10%	0%	0%	3%	8%	*a*
TCW	10	10%	10%	20%	0%	10%	10%	*ab*
All Stormwaters		*10%*	*37%*	*7%*	*0%*	14%	*13%*	
Sig. (p<0.05)		*a*	*b*	*a*	*a*			
Reproduction (#)								
Control	20	28.4						
Ski Run	10[1]	39.0	0.0	10.4	8.4	6.3	14.5	*b*
Stag	10	23.4	2.3	6.4	9.9	6.2	10.5	*a*
TCW	10	16.5	16.2	24.9	29.4	23.5	21.8	*c*
All Stormwaters		*26.3*	*6.2*	*13.9*	*15.9*	12.0	*15.6*	
Sig. (p<0.05)		*c*	*a*	*b*	*b*			
Fish								
Mortality (%)								
Control	8	5%						
Ski Run	4	73%	100%	98%	83%	93%	88%	*b*
Stag	4	100%	100%	88%	95%	94%	96%	*b*
TCW	4	15%	10%	18%	10%	13%	13%	*a*
All Stormwaters		*63%*	*70%*	*68%*	*63%*	67%	*66%*	
Sig. (p<0.05)		a	a	a	a			
Survivor Biomass (mg/survivor)								
Control	8	0.22						
Ski Run	4	0.16		0.33	0.29	0.31	0.26	*b*
Stag	4			0.16	0.14	0.15	0.15	*a*
TCW	4	0.26	0.29	0.27	0.31	0.29	0.28	*b*
All Stormwaters		*0.21*	*0.29*	*0.26*	*0.25*	0.26	*0.25*	
Sig. (p<0.05)		*a*	*a*	*a*	*a*			

Table C-5. Summarizing the effects of coagulant dosing on the different stormwaters.

			JenChem 1720	PAX-XL9	Sumachlor 50	*Summary for Coagulants*
Algae						
	Cell Count					
		Ski Run	*-1.0*	*-1.0*	1.0	*-0.3*
		Stag	*-1.0*	*-1.0*	1.0	*-0.3*
		Tahoe City	0.0	1.0	1.0	*0.7*
		Summary for Stormwater	*-0.7*	*-0.3*	*1.0*	***0.0***
Zooplankton						
	Mortality1					
		Ski Run	*-1.0*	*0.0*	0.0	*-0.3*
		Stag	*0.0*	*0.0*	0.0	*0.0*
		Tahoe City	*0.0*	*0.0*	*0.0*	*0.0*
		Summary for Stormwater	*-0.3*	*0.0*	*0.0*	***-0.1***
	Reproduction					
		Ski Run	-1.0	-1.0	-1.0	*-1.0*
		Stag	*-1.0*	*-1.0*	-1.0	*-1.0*
		Tahoe City	*0.0*	*0.0*	1.0	*0.3*
		Summary for Stormwater	*-0.7*	*-0.7*	*-0.3*	***-0.6***
Fish						
	Mortality					
		Ski Run	-1.0	-1.0	0.0	*-0.7*
		Stag	*0.0*	*0.0*	0.0	*0.0*
		Tahoe City	*0.0*	*0.0*	0.0	*0.0*
		Summary for Stormwater	*-0.3*	*-0.3*	*0.0*	***-0.2***
	Survivor Biomass					
		Ski Run	NA	0.0	0.0	*0.0*
		Stag	*NA*	*NA*	*NA*	*NA*
		Tahoe City	*0.0*	*0.0*	0.0	*0.0*
		Summary for Stormwater	*0.0*	*0.0*	*0.0*	***0.0***
Medaka Fish						
	Fecundity					
		Ski Run	0.0	-1.0	0.0	*-0.3*
		Stag	*0.0*	*0.0*	0.0	*0.0*
		Tahoe City	*0.0*	*0.0*	0.0	*0.0*
		Summary for Stormwater	*0.0*	*-0.3*	*0.0*	***-0.1***
	Days to Hatch					
		Ski Run	0.0	0.0	0.0	*0.0*
		Stag	*0.0*	*0.0*	0.0	*0.0*
		Tahoe City	*0.0*	*0.0*	0.0	*0.0*
		Summary for Stormwater	*0.0*	*0.0*	*0.0*	***0.0***
	Hatching Success[2]					
		Ski Run	1.0	0.0	0.0	*0.3*
		Stag	*1.0*	*1.0*	0.0	*0.7*
		Tahoe City	*-1.0*	*-1.0*	0.0	*-0.7*
		Summary for Stormwater	*0.3*	*0.0*	*0.0*	***0.1***

[1] All effects due to single SDR combination (Ski Run stormwater dosed with JenChem 1720).

[2] Based upon comparison of means. Unable to use ANOVA due to non-normal distribution

Table C-6. Summarizing coagulant-stormwater effects on Medaka fish

Means

	None	JenChem 1720	PAX-XL9	Sumachlor 50	*Average*	*$p < 0.05$*
Fecundity (eggs per day)						
C	8.2					
Ski Run	13.1	13.4	8.8	8.9	*11.1*	*b*
Stag	8.8	9.0	6.8	12.3	*9.2*	*a*
TC	10.0	13.3	18.6	16.2	*14.5*	*c*
Average	*10.7*	*11.9*	*11.4*	*12.5*	*11.6*	
$p < 0.05$	*a*	*a*	*a*	*a*		
Days to Hatch						
C	8.3					
Ski Run	10.7	9.5	9.4	9.2	*9.7*	*b*
Stag	9.2	8.6	8.1	9.9	*9.0*	*ab*
TC	8.7	8.7	9.2	9.3	*9.0*	*a*
Average	*9.5*	*8.9*	*8.9*	*9.5*	*9.2*	
$p < 0.05$	*a*	*a*	*a*	*a*		
Hatching Success (%)						
C	86					
Ski Run	63	86	68	66	*70.8*	*NA*
Stag	78	92	96	79	*86.3*	*NA*
TC	94	82	83	90	*87.3*	*NA*
Average	*78.6*	*86.8*	*82.4*	*78.2*	*81.5*	
$p < 0.05$	*NA*	*NA*	*NA*	*NA*		

Table C-7. Ranking the effects on non-dosed stormwaters on different toxicity metrics
Ranking is from 1 to 3 with 1 being the most favorable (least toxic). Half numbers identifies no statistical difference between higher and lower ranked stormwater.

			Tahoe City Wetland	Stag	Ski Run
EPA 3-species					
	Algae				
		Cell Count	2	1	3
	Zooplankton				
		Mortality	1	1	1
		Reproduction	2	2	1
	Fish				
		Mortality	1	3	2
		Survivor Biomass	1	NA	1
Medaka Test					
	Fish				
		Fecundity	1	1	1
		Days to Hatch	1	1.5	2
	Fish Larvae				
		Hatching Success[1]	1	2	3

[1] Based on mean ranking.

D. Changes to Stormwater Ecotoxicity when Treating with Chemical Coagulants under Different Dosing Levels

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D.1. Abstract

This study investigated stormwater and coagulant toxicity interactions under non-dosed, optimally dosed, and over-dosed conditions. Toxicity was assessed with a number of metrics: algae cell count, zooplankton reproductions, zooplankton mortality, fish mortality and surviving fish biomass. For this study, stormwater was collected during a 2005 spring snowmelt runoff event and during a 2005 autumn rain runoff event. Stormwaters were collected from various developed regions around Lake Tahoe and these stormwaters were dosed with a chitosan and a polyaluminum chloride for removal of small particles and phosphorus. Additional stormwater collected from a non-developed location in the Tahoe Basin served as an environmental control to assess the toxicity of more pristine Tahoe stormwater runoff. For non-dosed stormwater, zooplankton reproduction was the most sensitive toxicity metric. Nearly all stormwaters collected in the spring significantly affected ($p<0.05$) zooplankton brood size. Surviving fish biomass was also generally negatively affected by stormwaters, although this metric was less sensitive. Optimal dosing with both chitosan and polyaluminum chloride coagulant (as determined with a streaming current detector - SCD) decreased stormwater toxicity to algae and zooplankton, resulting in increased algae cell counts and generally improved zooplankton reproduction for the stormwaters tested. The effects of overdosing were studied by applying polyaluminum chloride at two and three times the optimal dose, as determined by the SCD. Overdosing of stormwater dramatically decreased zooplankton reproduction and greatly increased fish mortality. Algae were not affected as much, although at the higher overdosing conditions algae cell count declined for all stormwaters, suggesting that a dosing threshold had been reached above which algae toxicity would become more apparent. Using a variety of statistical tools, total aluminum was identified as a primary toxicant, although pH, alkalinity and DOC may also have influenced the toxicity. A number of measures were identified to minimize toxicity effects from coagulant dosing of stormwater in treatment systems:

- Keep total aluminum concentrations in treated outflow below the EPA recommended water quality criteria (0.75 mg/L);
- Adjust pH in outflow towards 7;
- Maintain alkalinity above 35 mg-Ca/L; and
- Maintain DOC concentrations above 2 mg/L.

D.2. Introduction

Coagulants combined with stormwater basins, ponds and constructed wetlands are being considered as a means to improve fine particle and phosphorus removal from stormwater runoff. Lake Tahoe and the surrounding area are sensitive ecosystems. Decreases in lake clarity have been attributed to accumulation of fine particles and phosphorus (Reuter and Miller, 2000; Swift et al., 2006), even though phosphorus levels in this oligotrophic lake are relatively low compared to other parts of the country, and many structural best management practices (BMPs) have been constructed recently to manage stormwater. The sensitivity of the Tahoe ecosystem raises concerns about other pollutant issues, such as the potential input of toxic chemicals associated with stormwater runoff. For coagulation treatment of stormwater to move forward in the Tahoe Basin as a viable means to decrease fine particle and phosphorus pollution to the lake, such concerns need to be addressed. The primary questions are: do coagulants decrease or increase the toxicity of stormwater, and are most sensitive to stormwater-related toxicity??

This study focused on assessing the effects of coagulation on stormwater toxicity over a range of dosing levels, from under-dosing to over-dosing with coagulants. It measured changes in toxicity to algae, zooplankton and fish, and also investigated the possible causes behind toxicity. Several hypotheses were tested in this study:

H1: Optimal dosing with coagulants reduces the toxicity of stormwater.
H2: Over-dosing with coagulants increases the toxicity of stormwater.
H3: Toxicity metrics do not respond uniformly to stormwater and coagulants.

Two coagulants were used in this study to address the above hypotheses: Chitosan, a product derived from chitin, and PAX-XL9®, a cationic polyaluminum chloride.

D.3. Methods

Sample Collection

Samples were collected during two storm events in 2005. Stormwater collected during the first event, in March 2005, was used to experimentally study the effects of different coagulant dosing levels on stormwater toxicity and to identify potential causative agents of toxicity. Stormwater collected during the second event, in October 2005, was used to further identify the chemical compounds causing observed toxicity.

Tahoe stormwaters were collected at four sites in the Lake Tahoe Basin (Figure D-1). The characteristics of each drainage area are summarized in Table D-1. Shivagiri stormwater drained from an unimpacted area and was used as a control for comparison with the other three stormwaters, which drained from residential, commercial, highway land use areas at Tahoe City, Ski Run and Stag. The stormwater from these three urban sites was considered representative of what would likely be targeted for treatment with coagulants in stormwater basins.

Optimum coagulant dosing levels were determined with a Streaming Current Meter, which measures net ionic and colloidal surface charge in the stormwater as Streaming Current Voltage (SCV). Theoretically, the optimal precipitation of suspended sediments occurs when particle charge is neutralized, and the SCV is near zero. Water quality parameters were measured and toxicity tests performed on both coagulant dosed and non-dosed stormwater samples.

The stormwaters collected in March 2005 were treated with optimum doses (1x) of Chitosan and 0.5x, 1x, 2x, and 3x[25] the optimum doses of PAX-XL9. Since Shivagiri stormwater represents runoff from an undeveloped area, it was used as a treatment control. Additionally, a laboratory control was used by the UC Davis Aquatic Toxicology Lab.

A follow-up study with stormwater samples collected in October 2005 was conducted to assess possible mechanisms of toxicity. This follow-up study tested whether removal of particulates through filtration would reduce toxicity. As zooplankton was the most sensitive metric to stormwater toxicity, only zooplankton toxicity was considered.

Toxicity Testing

All toxicity testing procedures followed those outlined by US EPA (2002). All samples were tested using *Ceriodaphnia dubia* (a cladoceran, zooplankton species), larval *Pimephales promelas* (a cyprinid minnow), and *Selenastrum capricornutum* (a freshwater algae). Prior to exposing test organisms, assay water was shaken in the original container to homogenize the sample. All waters for *C. dubia* and *P. promelas* assays were poured through a 53 µm screen, warmed to 25 ºC, and briefly aerated at a rate of 100 bubbles/minute until the dissolved oxygen fell below saturation. Before *S. capricornutum* cells were introduced to the sample, water was filtered through a type A/E glass fiber filter (nominal pore size 1.0 µm) and allowed to warm to 25 ºC.

C. dubia: This test consisted of ten replicate glass vials containing 15 mL of sample per vial. *C. dubia* were obtained from in-house cultures. At test initiation, a single less than 24-hour-old *C. dubia* was placed into each vial. Each animal was transferred into a vial containing 15 mL of fresh sample water and food (a mixture of *S. capricornutum*, yeast, CEROPHYLL® and trout chow) daily. The test was performed in a temperature-controlled room maintained at 25 ± 1°C with a 16:8 hour light:dark photoperiod. Mortality and number of neonates (reproductive success) were recorded daily and upon test termination after 6-8 days.

S. capricornutum: This test consisted of four replicate flasks, each containing 100 mL of sample. Samples were filtered using a type A/E glass fiber filter to remove any algae that may have already been present in the test sample. Each treatment was inoculated with the standard US EPA amounts of algal nutrients (without EDTA) and 10,000 cells/mL of *S. capricornutum*. The *S. capricornutum* were obtained from the University of Texas Starr collection (#1648). Cultures were grown in US EPA algae nutrient media (with EDTA) for four to seven days prior to test initiation to ensure the cells were in an exponential growth phase. Test flasks were then randomly placed on shaker tables and continuously shaken at 100 rpm. Tests were performed at 25 ± 1°C under a continuous light source (400 ± 40 ft-candles) for 96 hours. The flask positions

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[25] Dosing levels are represented in this manuscript as multiples of the optimal dose as determined with a streaming current detector. "1x" optimal dose is the optimal dose. "2x" and "3x" are dosing levels two and three times the optimal dosing level.

were randomized twice daily. Upon test termination, cell concentration was measured using a Coulter Counter® model Z1.

P. promelas: Fish larvae were obtained from Aquatox, Hot Springs, Arkansas. The test consisted of four replicate 600 mL beakers, each containing 250 mL of sample and 10 less than 48-hour-old *P. promelas* (at test initiation). *P. promelas* were fed three times daily with brine shrimp (*Artemia spec.)* nauplii. Approximately 80% of the test solution was renewed daily, and dead fish, *Artemia*, and debris were removed from the test beakers. Water temperature was maintained at 25 ± 1°C. The test was performed with a 16:8 hour light:dark photoperiod for seven days. Mortality was recorded daily and at test termination. The surviving minnows were euthanized with MS-222, dried to constant weight at 103-105 °C (approximately 16 hours), and weighed with a Mettler AE-163 balance to determine relative growth.

Quality Assurance

Each set of toxicity tests included a laboratory control. The laboratory control water varies for each species. For the *C. dubia* assay, the laboratory control is commercial bottled water amended to a hardness of 80 to 100 mg/L as $CaCO_3$. Glass distilled water is used as the control in the *S. capricornutum* assay, and de-ionized water amended to a hardness of 80 to 100 mg/L as $CaCO_3$ is used in the *P. promelas* assay.

Positive control reference-toxicant tests were conducted monthly for each species during the study period. These tests include a laboratory control and a dilution series of NaCl or $ZnCl_2$ in laboratory control water. Resulting data points are plotted in a control chart to assess changes in organism sensitivity to a known toxicant. Any points falling outside of two standard deviations from the total mean are discussed in the quality assurance section of reports.

Test Acceptability Criteria

Test acceptability for all *C. dubia* and larval *P. promelas* 7-day tests requires 80% or greater survival in the controls. In addition, 60% of the surviving *C. dubia* adult females in the control must have their third brood within 7 ± 1 days, and the average number of surviving young must be 15 or greater per surviving female. For *S. capricornutum* 96-hour tests, the cell number of the control must equal or exceed 200,000 cells/mL, and the replicates in the control must not vary by more than 20%. When the control performance does not meet test acceptability criteria, the test data is rejected.

Statistical Analysis

For each endpoint, toxicity is defined as a statistically significant difference ($p < 0.05$) to the laboratory control. All data is analyzed following the statistical guidelines outlined in US EPA (2002) using CETIS v1.1.2 software (TidePool Scientific Software).

Water Quality Parameters

Initial and final temperature, dissolved oxygen (DO), pH, electrical conductivity (EC), initial hardness and alkalinity were measured for each sample at UCD-ATL. The UC Davis Department of Agriculture and Natural Resources (DANR) laboratory determined the concentrations of metals; filtered and unfiltered pH and hardness; unfiltered alkalinity; TDS; TSS; and turbidity.

Additionally, the stormwater was tested for dissolved organic carbon (DOC), dissolved organic phosphorus (DOP), soluble reactive phosphorus (SRP), and total phosphorus by the UC Davis Soils Laboratory.

D.4. Results – March 2005 Event Experiment

This study began with a toxicity assessment of non-dosed stormwaters collected during the spring snowmelt runoff event. Several hypotheses were subsequently investigated in this project using the initial stormwater toxicity results as baseline data:

H1: Optimal dosing with coagulants reduces toxicity of stormwater.
H2: Over-dosing with coagulants can increase the toxicity of stormwater.
H3: Aquatic toxicity metrics do not respond uniformly to stormwater and coagulants.

D.4.1. Toxicity of Non-dosed Stormwaters

Stormwaters from developed urbanized areas were tested against the laboratory control, as well as against stormwater from the non-developed area (Shivagari). The toxicity metrics used included algae cell count, zooplankton mortality, zooplankton reproduction, fish mortality and fish biomass. Table D-2 shows the results of the analyses. Zooplankton reproduction was the most sensitive metric to stormwater toxicity. Nearly all stormwaters had statistically different effects on zooplankton brood size. Brood size in Stag stormwaters was about 20% of the control. All other treatments had brood sizes within 25% of that measured in the Control.

Stormwaters also affected fish, but to a lesser degree. Stormwater did not significantly affect fathead minnow mortality (p=0.8). The mean mortalities were between 1.7% and 2.5% for all stormwaters except Stag, which had a mean mortality of 5%. Stormwaters significantly affected the biomass per surviving fish (p=0.0197, Table D-2). Although the total survivor biomass is the usual EPA measure, we calculated the biomass per surviving fish because it effectively separates out mortality effects and indicates the health of surviving fish. A posthoc analyses (Tukey) of the data indicated that the only Stag stormwater significantly affected fish weight.

D.4.2. Toxicity Effects on Optimally Dosed Stormwaters

An earlier study by Bachand et al. (Appendix C, this report) showed that both non-dosed and coagulant-dosed stormwaters could be toxic. In the earlier study, jar tests were used to approximate the optimal dose. In the experiment reported here, a more precise estimate of dose was determined with streaming current detectors used to measure charge titration.

Three stormwaters were tested for three dosing regimes: no dosing, optimal dosing with PAX-XL9, and optimal dosing with Chitosan. Stormwater, coagulants, and their interactions significantly affected ($p<0.05$) two toxicity metrics: algae count and zooplankton reproduction. Coagulants and their interaction with stormwater did not affect zooplankton or fish mortality, or fish biomass (Table D-3).

Figure D-2 shows the effects of optimally dosed coagulants on algae cell counts. For both non-dosed and optimally dosed stormwaters, the algae cell counts were lower for Ski Run and Stag stormwaters then for Tahoe City stormwater. In general, coagulants significantly improved algae cell counts. The greatest cell increases were seen in treated stormwater from Stag, where non-treated stormwater had the lowest algae cell counts. On average, cell counts did not differ significantly between dosing with PAX-XL9 and dosing with Chitosan.

Similar results were observed with zooplankton brood size (Figure D-3). For both Ski Run and Stag runoff samples, the zooplankton brood size increased with optimal dosing, and those improvements were statistically significant for the Stag stormwater. Only Tahoe City stormwater experienced no improvement in zooplankton reproduction with optimal dosing.

Chitosan appeared the more effective coagulant at reducing toxicity, as measured by brood size, improving the Stag stormwater significantly over both non-dosed and PAX-XL9 dosed Stag stormwater. Overall, the Tahoe City stormwater had higher measured zooplankton brood sizes than runoff from the other urban sites, though these differences were not always statistically significant.

D.4.3. Toxicity Effects on Overdosed Stormwaters

Overdosing stormwater with coagulants negatively affected zooplankton and fish. When dosing at 2 times or 3 times the optimal dosing level (as determined using charge titration tests), the zooplankton reproduction dramatically decreased and mortality greatly increased (Table D-4). Mortality increased an average 67% at three times the optimal dosing levels. Zooplankton reproduction was generally highest for Tahoe City stormwater and worst for the Stag stormwater (Figure D-4). Greater effects resulted from increased coagulant dosing.

The effects on fish mirrored those with zooplankton. Fish mortality increased from about 5% to 15% mortality at dosing levels two and three times the optimal dosing (Figure D-5). These results were statistically significant (Table D-4). Biomass was not significantly affected at any of the tested dosing levels.

The increased toxicity on zooplankton and fish from higher dosing levels contrasts with the results for algae (Figure D-6). Results from toxicity tests with algae were more variable, but generally showed a decrease at all dosing levels when compared to non-dosed conditions. These differences were not always significant when compared to the control (Table D-4). For all stormwaters, algae toxicity effects increased when dosing was increased from two to three times the optimal dosing level. This was the only time an incremental increase in dosing from one dosing level to the next had the same effect on algae toxicity for all stormwaters. Thus, that trend suggests that higher dosing levels would be expected to further negatively affect algae. However, most changes in algae cell counts for a specific stormwater were not significantly different (Figure D-6).

Tables D-5 through D-7 summarize the toxicity data for algae, zooplankton and fish as it relates to stormwater, coagulants and different dosing levels.

D.4.4. Changes in Water Quality and Mechanisms for Toxicity

Water Quality in the Context of the National Recommended Water Quality Criteria

Table D-8 shows the analytes measured during these tests, with reporting limit for the methods used, whether analytes exceeded the reporting limit, and freshwater standards based upon the EPA-822-R-02-047 (National Recommended Water Quality Criteria, 2002). These analytes were measured to help identify changes in water quality resulting from coagulation and to help identify potential mechanisms for toxicity. Highlighted values in Table D-10 show analytes for which data were reported above the reporting limit.

Table D-8 also identifies the water quality criteria recommended by the EPA for heavy metals (e.g. Ag, As, Cd, Cu, Cr, Pb, Zn, Ni) in freshwater systems. These criteria are for dissolved species using an ICP-MS. Digestion is not required for water quality sample analyses. We used two methods to identify dissolved constituents. The first method filtered, digested and then analyzed the samples using atomic absorption spectrometry (AAS) and Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) (DANR Method 890). Those results we identify as filtered total analyses. These analyses represent the analyte that is dissolved or colloidal that passes through a 0.45 micron filter. The second method measures soluble constituents (DANR Method 835), does not include a digest, and corresponds to the water quality criteria recommended by the EPA for metals.

For this stormwater event (March 2005), all soluble metals analyses for Ag, As, Cd, Cu, Cr, Pb, Zn and Ni were below the reporting limits. These reporting limits were generally at or below the freshwater standards. Thus, none of these metals in either the dosed or non-dosed water appear to be at a level considered toxic for freshwater systems, but little is known of the combined effects of such complex mixtures of metals.

Aside from these metals, total aluminum and iron as well as pH have recommended water quality criteria. pH was always within the range recommended by EPA for freshwater systems. Total aluminum and iron concentrations varied with treatment. Unfiltered aluminum was detected above the criteria at a maximum concentration of 17.7 mg/L. The EPA acute toxicity concentration is 0.78 mg/L, based on a toxicity test in water with pH 6.5 to 6.6 and hardness less than 10 mg/L. The EPA guidance notes that aluminum is “substantially less toxic at higher pH and hardness” (Water Quality Criteria, www.epa.gov/waterscience/criteria/wqcriteria.html) which is the case for the studied stormwaters.

Principal Component Analyses

In order to determine how water quality of the dosed and non-dosed stormwaters were affected by coagulant dosing at different dosing levels, and to determine their relationships to changes in the various toxicity metrics, a Principal Component Analyses (PCA) was conducted. A PCA reduces the variables in a multivariate problem by combining related variables into factors that are distinct from each other. We included all water quality parameters that were detected above the reporting limits and the different toxicity metrics.

Identifying key relationships and factors

The PCA indicated that the stormwater can be characterized by three factors that account for 78% of variance in the data. Table D-9 shows the correlation-based factor coordinates of different variables with the PCA coordinate factors. We highlighted coordinates above 0.65 as relatively important variables.

Factor 1, which accounts for about 33% of the data variance, is essentially a measure of hardness, strongly corresponding to hardness and the cations from which it is primarily caused: calcium and magnesium. This factor weakly relates to zooplankton reproduction and fish biomass. Table D-10 shows the direct correlations between various hardness metrics and zooplankton reproduction and fish biomass. Correlations with fish biomass are much stronger, accounting for about 25% of the variance in the data. Some of these correlations are statistically significant ($p<0.05$).

Factor 2, which accounts for approximately 25% of data variance, is strongly related to dosing level. A number of toxicity metrics are strongly correlated as well: cerio reproduction is negatively correlated, and cerio and fish mortality are positively correlated. . A number of water quality variables also strongly relate to Factor 2: alkalinity, pH, soluble zinc, total aluminum and DOC. These relationships are not surprising, since coagulant dosing reduces pH, consumes alkalinity, removes DOC and phosphorus, and can result in an increase in total aluminum under over-dosing conditions (Figure D-7). Coagulant dosing also affected soluble zinc and this is likely a constituent from the coagulant. This is the only priority metal for which the relationship with coagulant dosing was statistically significant ($p<0.05$). Table D-11 shows the correlations between these various water quality variables and zooplankton reproduction, zooplankton mortality and fish mortality. These correlations generally explain on the order of 37 to 55% of the variance associated with the different toxicity metrics. Most these correlations are statistically significant ($p<0.05$).

Factor 3 negatively relates to soluble iron and aluminum; total iron, arsenic and chromium; and total suspended solids and turbidity. Factor 3 has no effect on any of the toxicity metrics and it shows no correlation with dosing levels. Factor 3 suggests 1) the presence of particulates relates to the presence of several priority metals, and 2) suspended particles and turbidity levels are not dosing dependent at the dosing levels for which this study was conducted. Suspended particles and total iron are the most consistently affected variables (Figure D-8). They are affected throughout the entire dosing range. Chromium and arsenic are more affected at over-dosing levels, in which poor settling and the creation of additional floc results in their suspension in the water column.

Based upon these analyses, dosing is identified as a key factor related to toxicity. No other factors are clearly identified, although earlier analyses (2004 tests) demonstrated that non-treated stormwater can produce toxicity as well, with both algae cell count and fish mortality strongly affected (Appendix C, this report). In the 2005 tests, reported here, zooplankton reproduction, zooplankton mortality and fish biomass were each affected by stormwater, and these metrics show up as weakly related to Factor 1, which suggests that hardness affects toxicity. These relationships seem too weak, however, to fully explain the toxicity relationships with stormwater.

Viewing stormwaters in PCA factor-plane space

By plotting the 2005 stormwater data in PCA factor-plane space and grouping by different characteristics, general relationships can be identified. The stormwater data is plotted relating Factor 1 to Factor 2 and grouped by stormwater (Figure D-9), which shows that both Ski Run and Tahoe City stormwaters correspond to a Factor 1 value in the range of -2 to -4. Stag stormwaters correspond to a Factor 1 value near 4. Factor 1 is primarily characterized by its hardness. Thus, this graph suggests that the stormwater from Ski Run and Tahoe City are more similar with regards to hardness and associated variables then stormwater from Stag.

The similarity in water quality as identified in Factor 1 appears to relate to the toxicity of the given stormwaters. Tables D-5 and D-6 show that for this tested stormwater, zooplankton reproduction and mortality, and algae cell count were affected significantly for stormwater and coagulant interactions. Figure D-4 shows that both zooplankton mortality and reproduction were more similar for both Ski Run and Tahoe City, then for Stag. Trends for both those stormwaters were similar for those two toxicity metrics when comparing Ski Run and Tahoe City stormwater results. Figure D-3 gives similar results for algae brood size, again with stormwaters from Ski Run and Tahoe City giving more similar results than with Stag. These data suggest 1) hardness and associated variables are affecting stormwater toxicity and 2) stormwaters that are similar with regard to Factor 1 show similar results regarding the ecotoxicity metrics.

Figure D-10 shows stormwaters clump somewhat by Factor 3. Factor 3 is a measure of suspended particles and solids, relating to turbidity, total metals and suspended solids. All stormwaters range from around -4 to +8 for Factor 2. As discussed earlier, these variables do not seem to affect any toxicity metric..

Changes in water quality from dosing

As discussed previously, Table D-11 shows the variables affected during coagulant dosing, while Figure D-7 shows the trends from chemical dosing. Alkalinity, pH and dissolved organic carbon all decrease under coagulant dosing whereas total aluminum and zinc increase. Additional insight into the processes can be obtained by looking at specific analytes across different dosing levels for the different stormwaters.

Figure D-11 shows total aluminum concentrations at dosing levels as multiples of the optimal dosing level, determined by the streaming current detector. Total Al concentrations correlate best with dosing as a multiple of optimum. decreasing with dose up to the optimum and then increasing . The relationships between total Al, soluble Al and dose change as dosing levels rise. Soluble Al decreases with dose from 0 to 0.5 and then increases slightly with dose thereafter (Figure D-12).

TSS and Turbidity are both lowest at doses of 0.5 and 1 times optimum (Figure D-13). TSS tends to increase when stormwater is overdosed, sometimes exceeding non-dosed TSS values. The increase in TSS is likely do to the restabilization of particles and less aggregation as the coagulant provides nearly complete coverage of the particles (Snoeyink and Jenkins, 1980). This results in a reversal of charge in the particles and interferes with aggregation. Turbidity is less effected by overdosing; it remains low in Tahoe City and Ski Run stormwater and increases slightly in Stag stormwater, when dosed above 1 times optimum (Figure D-13). The comparison of total aluminum, TSS and turbidity data show that total aluminum in solution is concentrated in flocculates formed during coagulant precipitation that have not settled from solution. Thus, the formed flocculates have high aluminum concentrations by mass. Figure D-12 shows that under over-dosing conditions, nearly all the dosed aluminum stays in solution and all the soluble aluminum is converted to particulate form.

These trends are similar for the reactive constituents. Dissolved organic carbon and soluble reactive phosphorus are both removed at higher dosing levels (Figure D-14). DOC decreases with increasing dose, along a curve that flattens as the dose increases over one times optimum. Similarly, soluble and total concentrations for the priority metals did not increase with coagulant dosing except for soluble zinc, which has been discussed previously.

These trends thus represent certain phenomena. Reactive dissolved constituents are removed by coagulation, forming precipitates. These precipitates are removed through settling during optimal dosing. However when over-dosing occurs, the formed flocculates that remain in solution are likely composed of the constituents formed during flocculation. In this situation, the formed flocculates are composed of constituents such as aluminum, carbon and phosphorus.

Some of the more general water quality effects resulting from chemical dosing are discussed below.

Alkalinity and pH with Dose

Increased dosing reduces alkalinity, and this relationship is very similar for all waters when dose is expressed as mg coagulant/L. This linear relationship with dose is strong and is expected because a coagulant consumes a specific amount of carbonate alkalinity per unit coagulant (EPA design manual, 1987, Chapter 4, Phosphorus removal by chemical addition). Increased dosing also lowers pH. The drop in pH with dosing is related to the fact that the coagulants consume alkalinity. For the March 2005 stormwaters, relationships between pH and alkalinity were similar for Ski Run and Tahoe City stormwaters and different for Stag This result is consistent with the PCA analyses showing that Ski Run and Tahoe City stormwaters were similar compared to Stag stormwater for March 2005, and they responded similarly to dosing.

Iron and Dose

Soluble Fe drops to below the detection limit when dosed above 0 and does not increase with overdosing. Total Fe decreases with dose above 0 and then increases with dose above 1, especially for Stag stormwater.

D.4.5. Effects of particulate aluminum – October 2005 studies

Table D-12 shows the experimental design for the October 2005 studies. The hypothesis being tested was that filtration of flocculate from solution would reduce zooplankton toxicity. This hypothesis was based upon preliminary data analyses suggesting that elevated total aluminum concentrations were toxic. Results from the March 2005 study showed that the factor related to dosing was also related to several toxicity metrics. Also, data from March 2005 showed that total aluminum concentrations in particulates increased, as the particles remaining in solution under over-dosing conditions were flocculates with high concentrations of carbon and aluminum. This study differed from the earlier studies in that flocculate was removed from solution through both decanting and filtration. Earlier studies just used decanting, which allows small pin-floc to remain in solution. However, under filtration, that pin-floc was removed.

Table D-13 presents the results of a 3-way ANOVA testing the effects of the presence or absence of floc, stormwater, and dosing levels. These results show zooplankton mortality statistically differed for the different tested stormwaters. Mortality was not significantly affected by different dosing concentrations or by different treatment of the floc. Zooplankton reproduction was significantly affected by the different dosing levels and by different treatment of the flocculate.

For October stormwaters, zooplankton toxicity metrics were again related to factors affected by coagulant dosing: pH, alkalinity, soluble aluminum and total aluminum. These relationships are defined by Factor 1 using a PCA analyses (Table D-14). Factor 2 relates turbidity, total suspended and dissolved solids, EC and total iron. The results from this PCA analyses are similar to those for March 2005 analyses. Results were plotted in PCA factor space. Stormwater clumped with Factor 2 and dosing levels clumped with Factor 1. So dosing predictably affected pH, alkalinity, soluble aluminum and total aluminum. Stormwater was characterized by different solids, EC and iron concentrations.

Notably, total aluminum remaining in solution was related to toxicity in the PCA analyses. Table D-15 shows results from ANOVA analyses looking at total aluminum in solution for different floc treatments, stormwaters and dosing levels. Total aluminum varied with floc treatment and dosing levels, with these differences being statistically significant. The factors shown to be statistically significant for total aluminum were also significantly different for zooplankton reproduction. These data suggest that total aluminum may be important with regard to zooplankton reproduction. Zooplankton are filter feeders. Greater abundance of total aluminum in solution through increased particle numbers or through greater concentrations in the precipitate could compromise zooplankton reproduction. Figure D-15 supports that interpretation. At total aluminum concentrations greater then 3 mg/L, zooplankton reproduction precipitously declines.

D.5. Discussions

This project tested several different questions regarding toxicity effects from stormwater:

- March 2005 –

    1. Do different stormwaters have different toxicity effects?
    2. Does optimal coagulant dosing affect stormwater toxicity?
    3. How does over-dosing effect stormwater toxicity?

- October 2005 –

    1. Does removal of flocculate after coagulation change toxicity effects?

Table D-16 summarizes the different experiments conducted in both 2004 and 2005. The following discussion relates to data from both years.

D.5.1. Did different stormwaters have different toxicity effects?

Results from a previous study on 2004 Tahoe stormwaters (Appendix C, this report) were included in this analysis to assess the toxicity of raw non-dosed stormwaters. Stormwater collected in 2004 generally had higher toxicity then the control water. Non-dosed stormwaters from that year generally were generally more toxic to algae and fish, and had mixed effects on zooplankton reproduction (Table D-16). Zooplankton mortality and surviving fish biomass were not affected. Of the metrics affected in 2004, the greatest effects were on algae cell counts, which saw a marked decrease in all non-dosed stormwaters.

The May 2004 storm was a first flush event, occurring after a long period without precipitation. Stormwater from Tahoe City least affected zooplankton reproduction. Ski Run stormwater least affected zooplankton mortality but most affected the fish hatching success. Stag most greatly affected fish mortality. Interestingly, the toxicity metrics for which there were significant effects as compared to the control, also showed significant differences between the different stormwaters as well. These results are covered in more depth in Appendix C. However there are a couple of messages from the 2004 data:

1. Stormwater chemistry and its effect on toxicity varied spatially throughout the Tahoe Basin. These effects can be significantly different for different stormwaters.
2. No single toxicity metric captures or models all toxic effects.

Stormwaters collected for this study in March 2005 expand on those results. These stormwaters were collected in March of 2005 and represent snowmelt runoff. For this event, toxic effects on zooplankton reproduction and fish mortality differed significantly between stormwaters ($p<0.05$, Table D-16). Algae cell count, zooplankton mortality and fish biomass were not significantly different between stormwaters.

These data, when compared to the 2004 data set, show that first flush stormwater can increase toxicity and broaden it to other metrics. The data suggest that typical stormwater runoff is likely to affect zooplankton reproduction and fish mortality, whereas first flush stormwater could worsen those effects and prove toxic to algae as well. Zooplankton mortality and fish biomass were not significantly affected for each collection period.

When comparing data from the two different events, fish biomass generally was in the range of 0.15 to 0.24 mg for 2004 data (Appendix C, Figure C-11) and around 0.25 mg for March 2005 data (Figure D-5). Zooplankton mortality averaged from 5 to 20% in 2004 (Figure C-7) and 0% for March 2005 (Figure D-4). This review shows that even though some toxicity metrics are not spatially variable for any given event, they are likely significantly different ($p<0.05$) temporally. With more sample collection those differences would likely become more evident, because as the number of samples increases the 95% confidence interval becomes smaller, resulting in greater precision for distinguishing statistical differences.

Of the metrics considered when assessing statistical differences for March 2005, zooplankton reproduction was the more sensitive metric, with all the tested stormwaters affecting it and resulting in statistically significant changes ($p<0.05$, Table D-2). Fish biomass was a less sensitive metric though the effects also were significant ($p<0.05$, Table D-2).

From a review of the 2004 and 2005 data taken together, some conclusions can be drawn with regard to toxicity of stormwaters:

1. Stormwater chemistry and its effect on toxicity vary spatially and temporally throughout the Tahoe Basin.
2. Tahoe urban stormwaters are toxic, although the effects may not be consistent across all toxicity metrics.
3. No single toxicity metric captures or models all toxic effects. This is most likely due to different toxic chemicals present in stormwater from different areas.
4. Zooplankton reproduction was the most sensitive toxicity metric, when compared to stormwater chemistry. Fish mortality was a less sensitive metric, showing less magnitude in the differences between stormwaters. Both metrics identified statistical differences in toxicity between stormwaters tested in 2004 and 2005.
5. Fish biomass and zooplankton mortality were the least affected by stormwater, showing no effects ($p<0.05$) for stormwaters tested in 2004 and 2005.
6. Types of runoff events (e.g. first flush rain event, snow melt) and their duration likely affect toxicity.

D.5.2. Does optimal coagulant dosing affect stormwater toxicity?

For the March 2005 storm event, “optimal dosing” based on a streaming current value of 0 V was conducted with PAX-XL9, a polyaluminum chloride tested throughout this study, and with chitosan, a chitin-based coagulant. Toxicity effects on the 3 tested species were analyzed.

The March 2005 study was the first study conducted at dosing levels determined by a streaming current detector. This SCD-based value is an estimated optimal dosing level. In 2004, the dosing level was determined with jar tests and represents a less rigorous method for determining optimal dosing levels.

Data from 2004 showed coagulation can reduce or increase toxicity. Coagulants negatively affected zooplankton reproduction and positively or negatively affected algae cell counts and zooplankton mortality. These results are discussed more in Appendix C and the data are summarized in Tables C-4 and C-5.

For the March 2005 dataset, algae cell counts and zooplankton reproduction improved significantly when dosed at the optimal level as compared to the non-dosed treatment. Algae cell counts improved using both coagulants (Table D-5, Figure D-2) and the improvements were greatest with Stag stormwater (representing predominantly highway runoff). Zooplankton reproduction improved more with Chitosan then with PAX-XL9 (Figure D-3). No statistically significant effects ($p<0.05$) resulted with zooplankton mortality, fish biomass or fish mortality (Table D-16).

Thus, optimal dosing reduced stormwater toxicity as it related to algae and zooplankton. Apparently, dosing removed constituents causing those toxicities. Fish mortality, zooplankton mortality and fish biomass were not affected.

D.5.3. How does over-dosing affect stormwater toxicity?

Over-dosing at 2 and 3 times the SCD-determined optimal dose increased the toxicity response of several metrics (Tables D-5, D-6, D-7, D-16). Over-dosing negatively affected algae cell counts, zooplankton reproduction, zooplankton mortality and fish biomass, and these effects were statistically significant ($p<0.05$). Zooplankton reproduction greatly decreased while zooplankton mortality greatly increased. Fish mortality increased from about 4 to 20%. Algae cell counts showed a general decrease.

Stormwater toxicity becomes less severe as dosing approaches optimal levels (0.5x and 1x optimal dosing level) and then becomes more severe at over-dosing levels (2x and 3x; Figures D-4 through D-6).

D.5.4. What are the mechanisms causing toxicity when stormwaters are over-dosed?

From the March 2005 dataset, possible toxicity mechanisms were investigated using a set of statistical tools: Principal Component Analyses (PCA), correlations, assessment of trends, regressions, and ANOVA. One particular goal of that dataset was to tentatively identify the possible mechanisms or constituents causing toxicity. The follow-up study in October 2005 further investigated possible mechanisms. A number of findings were obtained from these two studies.

Relating variables to toxicity

Several methods were used to investigate relationships between toxicity and the different variables measured. The PCA analyses done on the March 2005 dataset showed zooplankton (reproduction & mortality) and fish (mortality) metrics were related to a number of variables which are affected by chemical dosing: alkalinity, pH, soluble zinc, total aluminum and DOC (Tables D-9 & D-11). This result is not surprising, as over-dosing of stormwater significantly affects these metrics (Table D-16). Another PCA analyses was conducted on the October 2005 data dataset. It provided similar results and included the addition of soluble aluminum.

Several variables were not related to toxicity in the PCA analyses. Hardness and its related variables (e.g. calcium and magnesium), total suspended solids and turbidity, total dissolved solids and EC, and total and soluble priority metals (e.g. Zn, Mn, Pb, Ni, As, Cr, Ag, Cd). Note that some of the priority metals were not analyzed in the PCA analyses because they were below the reporting limits, which were generally at or below the EPA recommended water quality criteria for freshwater systems (Table D-8).

In the PCA analyses, stormwaters clustered according to some of these parameters, including: hardness, alkalinity, turbidity, suspended solids, dissolved solids and EC. Stormwater also grouped with total iron.

A correlation analysis was conducted, looking for strong correlations with different toxicity metrics that were statistically significant ($p<0.05$). All variables were initially included in this analysis. Variables for which relationships to any of the toxicity metrics were not statistically significant were eliminated. For redundant measurements, such as multiple measurements of pH, all but one of the redundant variables were also eliminated. Variables in which there were a greater number of measurements (N) were favored. Table D-17 shows the remaining variables and their relationships with the different toxicity metrics. Shaded values represent statistically significant correlations. Highlighted values represent variables likely causing toxicity.

Toxicity to algae

pH was the only variable that showed clear relationships to algae cell counts in the PCA and correlation analyses. Figure D-16 shows that algae dramatically drops at pH values below 6.8. Cell counts are not clearly related to dosing levels. So the conclusion here is that the resulting pH change in water quality, which is affected by the dosing level and the alkalinity of the water, controls algae cell counts. This relationship is likely not linear given the shape of the data in Figure D-16.

This relationship only accounts for about 40% of the variance in the data. Low algae cell counts were also measured in 2004 experiments, with first flush stormwater from urban sources (Appendix C, this report). Thus, the toxicity to algae could be resulting from variables not measured in these experiments but common to first flush stormwaters, such as oil and grease, priority metals, or organics. The priority metals were not measured in 2004, so it is possible that while they do not show a relationship with the 2005 data set they could have been contributing to the toxicity observed with algae in 2004 stormwaters.

Toxicity to Zooplankton

Toxicity to zooplankton is measured by reproduction and mortality. The variables associated with those metrics based upon the PCA and correlation analyses were graphed to identify trends. A number of relationships stand out for reproduction and mortality.

Zooplankton reproduction decreases with decreasing alkalinity and pH. In Figure D-17, very low reproduction was measured in over-dosed stormwaters from Ski Run and Stag. These stormwaters had a pH below 6.0. Both the toxicity metrics relate to dosing level (Table D-17). Figure D-18 shows that suspended solids and total aluminum in the water column also affect zooplankton reproduction. At total aluminum concentrations greater then 5 mg/L, toxicity greatly increases.

Figure D-12 showed the response of total aluminum concentrations to aluminum dosing. Concentrations can be initially high, such as with the Stag stormwater during March 2005 (Figure D-12). With optimal dosing in the range of 0.5 to 1 times optimal dose, total aluminum decreases; but over-dosing leads to elevated total aluminum concentrations again.

Figure D-18 showed the effects of total suspended solids and total aluminum on zooplankton reproduction. At high total solids, above 80 – 100 mg/L, zooplankton reproduction is always low. Correspondingly, at total aluminum concentrations greater then 3 or 4 mg/L, zooplankton reproduction is never above 10 which is much below the average. At levels above 10 mg/L, zooplankton reproduction is always near zero.

Based on the data from Figure D-18, whenever total aluminum is greater then 3 or 4 mg/L, zooplankton reproduction will be suppressed. And it will be near zero above 10 mg/L. Thus, zooplankton reproduction in Stag stormwater from March 2005 was suppressed initially (Figures D-12 and D-4), and was suppressed again at dosing levels greater then 2 times optimal. This trend was repeated in October 2005 with zooplankton reproduction relatively high for Tahoe City and Ski Run stormwaters but suppressed in Stag samples (Figure D-19). Total aluminum concentrations in the water column increased with dose (Figure D-20). Correspondingly with increasing dosing levels, zooplankton reproduction decreased suggesting total aluminum may indeed be affecting zooplankton reproduction.

Several possible mechanisms could be causing toxicity to zooplankton from total aluminum and particulates. Some are physical and some are chemical. Particulate aluminum from originally suspended solids or precipitated through coagulation can cause stress on organisms by inhibiting respiration (Gensemer and Playle, 1999). In Cladoceran (such as *Ceriodaphnia dubia*), cationic polymers are thought to bind to the surface of the integument and/or to appendages, inhibiting movement and uptake of nutrients (Rosemond and Liber 2004). Cationic particles would be expected to behave similarly. More cationic particles will be present in higher dosed water because PAX-XL9 changes the net ionic and colloidal surface charge in the stormwater from negative to positive.

Soluble aluminum is a known toxicant. In the pH range of 7 to 8 the predominant Al form in solution is likely to be $Al(OH)_3^0$ (an amorphous form of gibbsite that is not toxic). However, $Al(OH)_4$ is toxic and likely to be the second most predominant monomeric form in the pH range of 7 to 8. Conceivably, a chemical equilibrium in C. dubia between soluble and total aluminum could be exposing the grazer to aluminum toxicity from the monomer.

It also seems likely that particulate aluminum could be causing toxicity through physical clogging, chemical adhesion, or some related process. Digestion of the particulate aluminum may then result in the release of soluble aluminum, which has been identified in studies by others as a toxicant. Mixing treated water with natural waters or exposing them to systems in which organic processes are active could possible mitigate this cause of toxicity.

Regardless of the mechanism for aluminum toxicity, these data show that total aluminum concentrations above 3 to 4 mg/L are suppressing zooplankton reproduction. This concentration is above the recommended EPA criteria of 0.75 mg/L.

For the October 2005 studies, we filtered stormwater that was over-dosed with coagulants. Figure D-19 shows that for most over-dosing situations, filtration of the dosed-stormwater and the removal of solids and total aluminum greatly reduced zooplankton toxicity. Table D-19 summarizes those findings.

pH, alkalinity and total aluminum all similarly affect zooplankton mortality. Increased mortality was more common as pH and alkalinity decreased. These trends are related to aluminum dosing, so it is difficult to separate pH and alkalinity effects from dosing effects. Total aluminum above 12 mg/L greatly increased mortality (Figure D-20).

Several conclusions can be drawn from this analysis with regard to causes of toxicity on zooplankton. pH, alkalinity, total aluminum and suspended solids all contribute to toxic effects. The changes in these variables all relate to coagulant dosing, so it is difficult to separate the effects from each variable. However, some conclusions can be drawn with regard to each variable.

From these analyses it can be surmised that total aluminum is certainly resulting in toxicity to zooplankton. Toxicity occurs under different water chemistries and with non-dosed and over-dosed conditions. Possible mechanisms for total aluminum toxicity include physical clogging, adhesion or chemical conversion to soluble and more toxic forms. Whenever total aluminum is above 3 to 4 mg/L, zooplankton health is suppressed. The recommended national water quality criterion for total aluminum is 0.75 mg/L. Therefore, if outflow from basins using chemical dosing can maintain the total aluminum concentrations below that criteria, an important cause of toxicity will be eliminated.

Elevated total suspended solids above 80 mg/L also appear to be a main cause for toxicity. Reducing total suspended solids in the outflow to less then 30 mg/L, should help reduce that toxicity effect.

Finally, more neutral pH and solutions with high alkalinity had lower zooplankton reproduction. It is unclear whether these variables directly increase zooplankton toxicity or indirectly because of the effects of aluminum, suspended solids and other resultant change in water quality from coagulant dosing. The data do, however, suggest that adjusting pH and alkalinity after coagulant dosing to more closely reflect pH and alkalinity of natural waters in the area could further reduce zooplankton toxicity.

Toxicity to Fish

Toxicity to fish is measured by mortality and biomass (of the survivors). Similar methods were used to assess causes of fish toxicity as were used to assess causes of toxicity to algae and zooplankton.

Increases in fish mortality did not increase simply with higher dosing levels. The correlation is poor, and the effect is not statistically significant ($p<0.05$, Table D-19). Nor is the trend clear, as both high and low dosing levels correspond to low and high fish mortality (Figure D-21).

Fish mortalities were recorded above 70% for first flush stormwater in May 2004 experiments (Appendix C, this report), and these mortalities occurred for both dosed and non-dosed stormwaters. In those experiments, a slight increase in fish toxicity corresponded with higher dosing levels.

The PCA analyses of March 2005 stormwater test data showed that fish mortality corresponds greatly with many of the same metrics corresponding to zooplankton toxicity. Figure D-22 shows the relationships with multiple variables and fish mortality. Mortality is always above 10% for alkalinity below 20 mg-Ca/L, and is always below 10% for alkalinity greater then 35 mg-Ca/L. Thus, fish mortality seems to be affected at alkalinity levels somewhere between 20 and 35 mg-Ca/L. DOC concentrations at around 2 mg/L also seem to represent some kind of threshold, below which the fish mortality is nearly always greater then 10% and above which the mortality is nearly always below 10%.

pH and total aluminum concentrations significantly affect mortality. As pH drops, the fish mortality increases, but there is no clear threshold. Increasing aluminum concentrations, on the other hand, increase fish mortality; but at concentrations below 3 to 4 mg/L the fish mortality was always less than 10%.

Some of the same toxicity mechanisms could be affecting both fish and zooplankton. Coagulant dosing could interfere with life functions if cationic colloidal particles bind to negatively charged areas on the organisms. In fish, this may occur on gills, thus blocking respiratory function. It is possible that polymers precipitate as PAX-XL9 binds with food particles. These particles may then clog feeding or respiratory organs. Furthermore, since DOC binds to coagulants, its presence in the stormwater at higher concentrations may mitigate some of the biological toxicity.

Effects of stormwaters and coagulants on fish biomass are less extreme than on fish mortality, but these effects are still statistically significant ($p<0.05$). Soluble calcium has a statistically significant effect on biomass. Higher Ca concentrations resulted in about 10% higher fish biomass in the March 2005 dataset. Increased concentrations of total suspended solids, total iron and total aluminum resulted in statistically significant lower biomass. The reasons for these effects are likely due to the same mechanisms affecting mortality.

From these analyses, several conclusions can be drawn with regard to fish. First, the first flush stormwater in 2004 had the greatest effect on fish toxicity, with mortality exceeding 70% studying those experiments. The stormwaters were from urban sources and mortality was not affected by coagulants. Thus, the constituents that caused mortality during that first flush event were constituents that could not be removed through coagulation. Possible pollutants could have been oil and grease, organics, or unusually high concentrations of priority metals that exceeded levels reported in the 2005 experiments.

Second, although separating dosing and water quality impacts on toxicity is complicated, the data suggest that toxicity thresholds exist for total aluminum, alkalinity and DOC. Total aluminum concentrations at or below the EPA recommended water quality criteria should reduce toxicity to fish. Maintaining alkalinity above 35 mg/L and keeping DOC concentrations above 2 to 3 mg/L may also help to mitigate toxicity. We have hypothesized that coagulant dosing creates positively charged particles that interfere chemically or physically with biological processes. Alkalinity and DOC both react with aluminum during coagulation. These reactions with aluminum may reduce its toxicity by minimizing the physical and chemical interactions. Lower concentrations of alkalinity or DOC may result in higher charged and more reactive flocculates. Finally, higher concentrations of dissolved calcium appear to correlate with improved fish biomass.

At this time we have insufficient information to do more than hypothesize on the mechanisms of toxicity, but these data suggest that certain measures may help to mitigate some of that toxicity, as discussed above.

Ruling out some constituents

Toxicity from some constituents can be ruled out, based on the above discussion.

Soluble aluminum

Soluble aluminum does not seem to be a concern. During coagulation, soluble aluminum concentrations remain relatively constant and low. The PCA and correlation analyses of the 2005 datasets provide little evidence that soluble aluminum had much of an effect on toxicity.

Priority metals

Total and soluble priority metals at the levels reported in this study do not pose a toxicity concern. These metals were near or below EPA recommended water quality criteria, which are very similar to California Toxics Rule requirements. These priority metals are Ag, As, Zn, Pb, Cu, Cr, Mn, and Ni.

First flush had a great effect on fish biomass. We do not know the concentrations of priority metals in those waters. Additional possible toxicants in those stormwaters include oil and grease, or organics such as PAHs.

Factors possibly affecting toxicity

The March 2005 PCA analyses shows that Ski Run and Tahoe City stormwater plotted similarly with regard to Factor 1, an indicator of hardness, while the Stag stormwater plotted differently (Figure D-9). When Ski Run and Tahoe City stormwaters were dosed with different levels of PAX-XL9, the resulting responses with regard to zooplankton reproduction and mortality (Figure D-4), and algae cell count (Figure D-6) were more similar then the responses for dosing of Stag stormwater.

Similar stormwater chemistry effects

The initial chemistry of the Tahoe City and Ski Run stormwater collected during March 2005 was more similar than that of the Stag stormwater, and thus Tahoe City and Ski Run stormwaters responded more similarly to the different dosing levels with regard to toxicity. These data suggest that hardness and related analytes may have affected the response of stormwater to dosing. The results in Table D-10 support this hypothesis, showing a weak but statistically significant relationship between hardness and fish toxicity as measured with fish biomass. In water that is non-dosed or is dosed at 0.5 or 1 times optimal, the lower alkalinity and hardness are associated with higher toxicity. Hardness can ameliorate metal toxicity in aquatic organisms, and is thought to result from the competitive binding of Ca^{+2} at the Ca channels of the cell membrane (Markich et al, 1994).

Alkalinity and pH

Separating dosing effects from the effects of certain constituents with regard to toxicity is difficult. Several toxicity metrics show that dosing, pH and alkalinity affect toxicity. However, pH and alkalinity are themselves affected by dosing. Thus, the data are difficult to interpret.

Nonetheless, our data consistently indicate that pH and alkalinity are important factors related to toxicity. There are possible reasons that these two constituents could affect toxicity. Alkalinity, like hardness, is likely to be associated with calcium. In water that is non-dosed or dosed at 0.5 or 1 times optimal, lower alkalinity was associated with higher toxicity. pH declines with dosing, and although that decline is relatively slight, there are cases in the literature in which even small changes in pH are suspected of having negative ecosystem effects.

D.6. Conclusion

Table D-18 provides a summary of the variables that are suspected of causing toxicity, as measured by the different metrics. Some of these variables depend upon the initial chemical characteristics of the stormwater and can be affected by the coagulants. Toxicity generally varies spatially and temporally for all these metrics throughout the Tahoe Basin. Coagulant dosing within an optimal range reduces stormwater toxicity. But over-dosing can greatly increase toxicity. In this study, total aluminum was identified as a primary toxicant, but pH, alkalinity and DOC may also influence toxicity.

Some measures have been identified to minimize toxicity:

- Keep total aluminum concentrations in treated outflow below the EPA recommended water quality criteria (0.75 mg/L);
- Adjust pH in outflow towards 7;
- Maintain alkalinity above 35 mg-Ca/L; and
- Maintain DOC concentrations above 2 mg/L.

There are many unexplained questions with regard to toxicity. First flush stormwater was very toxic. We do not know what constituents in the first flush stormwater caused that toxicity. We just know that coagulation did not remove those constituents from the stormwater, as the high toxicity persisted after coagulation. Also, stormwaters clustered according to certain PCA factors. These factors represented certain water quality characteristics with regard to hardness, alkalinity and other constituents. Similarly clustered stormwaters reacted similarly with regard to effects on the different toxicity metrics.

D.7. References

Bachand, P.A.M., A. Heyvaert and J. Reuter. 2006. Considering Toxicity When Using Coagulants to Treat Stormwater in the Tahoe Basin – Which Toxicity Metric is the Concern?

Gensemer, R.W. and R.C. Playle. 1999. The bioavailability and toxicity of aluminum in aquatic environments. Critical Reviews in Environmental Science and Technology, 29(4):315–450.

Horne, A.J. and C.R. Goldman. 1994. Limnology, Second Edition. McGraw-Hill, Inc. New York.

Reitzel, K, J. Hansen, H.S. Jensen, F.Ø. Andersen and J.S. Hansen. 2003. Testing aluminum addition as a tool for lake restoration in shallow, eutrophic Lake Sønderby, Denmark. Hydrobiologia 506-509:781-787.

Reuter, J.E. and W.W. Miller. 2000. Aquatic Resources, Water Quality, and Limnology of Lake Tahoe and Its Upland Watershed. In: D.D. Murphy and C.M. Knopp (Eds.) Lake Tahoe Watershed Assessment: Volume 1. Gen. Tech. Rep. PSW-GTR-175. Albany, CA: Pacific Southwest Research Station, Forest Service, US Department of Agriculture.

Rosemond, S.J.C. and K. Liber. 2004. Wastewater treatment polymers identified as the toxic component of a diamond mine effluent. Environmental Toxicology and Chemistry, Vol. 23(9): 2234–2242.

Snoeyink, V.L. and D. Jenkins. 1980. Water Chemistry. John Wiley & Sons. New York.

Swift, T.J., J. Perez-Losada, S.G. Schladow, J.E. Reuter, A.D. Jassby, and C.R. Goldman. 2006. Water clarity modeling in Lake Tahoe: Linking suspended matter characteristics to Secchi depth. Aquat. Sci. 68: 1-15.

Table D-1. Drainage Areas for Sampled Stormwaters

	Percent Coverage by Landscape Classification													**% Erosion Hazard**			**Drainage Area**
	Residential				Com/Ind*		Roads			Other							
Site Name	Single Family- Pervious	Single Family- Impervious	Multifamily- Pervious	Multifamily- Impervious	Commercial-Pervious	Commercial- Impervious	Primary Roads	Secondary Roads	Unpaved Roads	Ski Run	Unimpacted Area	Turf	Percent Impervious Area	Slight	Moderate	High	(m^2)
Shivagiri											100		0	80	20		994591
Tahoe City Wetland	13	7	8	10	4	20	5	16			13	4	59	84	16		228215
Ski Run	25	6	8	6	8	6		26			16		44	100			101031
Stag	47	14			1			19			19		33	57	43		87846

Includes commercial, industrial, communications, utilities

Table D-2. Stormwater toxicity effects as indicated by five metrics. Highlighted values represent highest toxicity when there was statistical significantly ($p<0.05$) differences. Zooplankton reproduction and fish survivor biomass were affected by stormwater. Stag stormwater had most deleterious effects of all the stormwaters.

	Algae			Zooplankton						Fish					
	Cell Count			Reproduction			Mortality			Mortality			Survivor Biomass		
Stormwater Treatment	Mean #	SD #	Stat Sig[1]	Mean #	#	Stat Sig[1]	Mean %	%	Stat Sig[1]	Mean %	%	Stat Sig[1]	Mean mg	mg	Stat Sig[1]
Control	1.42E+06	2.66E+05	a	22.0	3.8	cd	2.5%	15.8%	a	1.7%	3.9%	a	0.273	0.032	b
Shivagiri	1.62E+06	8.16E+04	a	15.6	5.8	bc	0.0%	0.0%	a	2.5%	5.0%	a	0.263	0.022	ab
Ski Run	1.34E+06	8.36E+04	a	18.4	6.1	bcd	0.0%	0.0%	a	2.5%	5.0%	a	0.265	0.006	ab
Stag	1.49E+06	1.28E+05	a	5.0	1.7	a	0.0%	0.0%	a	5.0%	5.8%	a	0.213	0.025	a
Tahoe City Wetland	1.52E+06	1.75E+04	a	27.5	2.6	e	0.0%	0.0%	a	2.5%	5.0%	a	0.260	0.029	ab
p-value			0.300			0.000			0.915			0.814			0.197

1. Different letters represent statistical differences by post-hoc tukey analyses, p<0.05

Table D-3. A factorial-ANOVA analyses of optimally dosed stormwaters on Toxicity. Three stormwaters were tested for three dosing regimes: no dosing, optimally dosed with PAX-XL9 and optimally dosed with Chitosan. Below are shown p-values relating the effects of different treatments on the different toxicity metrics. Stormwater, coagulant and their interactions significantly affected ($p<0.05$) algae count and zooplankton (Cerio) reproduction. Coagulants and their interaction with stormwater did not affect zooplankton or fish mortality, or fish biomass.

	Algae Cell Count	Cerio Reproduction	Cerio Mortality	Fish Mortality	Fish Biomass
Stormwater (Stag, Ski Run, TCW)	0.029	0.000	0.678	0.171	0.005
Coagulant (No Dose, Optimal PAX-XL9, Optimal Chitosan)	0.000	0.000	0.616	0.740	0.053
Stormwater x Coagulant	0.043	0.001	0.745	0.700	0.085

Table D-4. Mean ecotoxicity metric values for different dosing levels. Overdosing of coagulants at 2 and 3 times optimal levels decreased zooplankton reproduction, increased zooplankton mortality and increased fish mortality. Dosing levels near optimal levels (e.g. 0.5 x and 1 x) reduced toxicity to algae, increased zooplankton reproduction and did not affect fish when compared to non-dosed stormwaters. Treatments highlighted in yellow show a reduction in toxicity when compared to the non-dose treatment (0 x). Treatments highlighted in orange show an increase in toxicity when compared to the no-dose treatment.

	Algae			Zooplankton						Fish					
	Cell Count			Reproduction			Mortality			Mortality			Survivor Biomass		
Dosing (Multiple of Optimal)	Mean #	SE #	Stat Sig[1]	Mean #	SE #	Stat Sig[1]	Mean %	SE %	Stat Sig[1]	Mean %	SE %	Stat Sig[1]	Mean mg	SE mg	Stat Sig[1]
0	1.45E+06	4.05E+04	a	17.0	0.9	b	0%	3%	a	3.3	2.0	a	0.25	0.01	a
0.5	1.49E+06	4.05E+04	ab	21.3	0.9	c	0%	3%	a	5.0	2.0	a	0.26	0.01	a
1	1.63E+06	2.87E+04	b	19.0	0.6	bc	2%	2%	a	4.6	1.4	a	0.26	0.01	a
2	1.59E+06	4.05E+04	ab	3.7	0.9	a	13%	3%	b	14.2	2.0	b	0.25	0.01	a
3	1.48E+06	4.05E+04	ab	3.2	0.9	a	67%	3%	c	13.4	2.0	b	0.24	0.01	a
p-value			0.002			0.000			0.000						

1. Different letters represent statistical differences by post-hoc tukey analyses, p<0.05

Table D-5. Toxicity Effects of Stormwater and Coagulants on Algae Cell Count.

Stormwater	Coagulant	N	Dose	Algal Cell Count		
				Means	Std.Dev.	Std.Err.
Control						
	None	12	0	1424378	266386	76899
Shivagiri						
	None	4	0	1622807	81612	40806
Ski Run						
	None	4	0	1340687	83649	41824
	Chitosan	3	1	1549893	252129	145567
	PXXL9	4	0.5	1666787	38343	19172
		8	1	1673530	145456	51427
		4	2	1475200	111874	55937
		4	3	1407833	195243	97622
Stag						
	None	4	0	1493280	127889	63945
	Chitosan	4	1	1721407	57911	28956
	PXXL9	4	0.5	1393227	85286	42643
		8	1	1514063	156661	55388
		4	2	1630847	105428	52714
		4	3	1483633	245007	122504
Tahoe City Wetland						
	None	4	0	1521367	17464	8732
	Chitosan	4	1	1768287	41887	20944
	PXXL9	4	0.5	1412460	85558	42779
		8	1	1703263	150797	53315
		4	2	1678800	38514	19257
		4	3	1561127	227329	113664

Table D-6 . Toxicity Effects of Stormwater and Coagulant on Zooplankton.

Storm Water	Coagulant	Dose	N	Cerio Brood Size			Mortality		
				Means	Std. Dev.	Std. Err.	Means	Std. Dev.	Std. Err.
Control									
	None	0	40	22.03	3.82	0.60	3%	16%	3%
Shivagiri									
	None	0	10	15.60	5.78	1.83	0%	0%	
Ski Run									
	None	0	10	18.40	6.13	1.94	0%	0%	
	Chitosan	1	10	25.30	5.93	1.87	0%	0%	
	PXXL9	0.5	10	20.90	6.77	2.14	0%	0%	
	PXXL9	1	20	21.30	6.80	1.52	0%	0%	
	PXXL9	2	10	4.70	2.36	0.75	0%	0%	
	PXXL9	3	10	0.00	0.00		100%	0%	
Stag									
	None	0	10	5.00	1.70	0.54	0%	0%	
	Chitosan	1	10	21.60	5.85	1.85	0%	0%	
	PXXL9	0.5	10	19.60	5.50	1.74	0%	0%	
	PXXL9	1	20	11.40	4.90	1.10	5%	22%	5%
	PXXL9	2	10	1.40	1.58	0.50	20%	42%	13%
	PXXL9	3	10	9.60	3.10	0.98	0%	0%	
Tahoe City Wetland									
	None	0	10	27.50	2.64	0.83	0%	0%	
	Chitosan	1	10	28.80	2.70	0.85	0%	0%	
	PXXL9	0.5	10	23.40	4.33	1.37	0%	0%	
	PXXL9	1	20	24.40	8.03	1.80	0%	0%	
	PXXL9	2	10	4.90	4.51	1.43	20%	42%	13%
	PXXL9	3	10	0.00	0.00		100%	0%	

Table D-7 . Toxicity Effects of Stormwater and Coagulant on Fathead Minnows.

Stormwater	**Coagulant**	**Dose**[1]	**N**	**Mortality**			**Biomass Per Survivor ,mg**		
				Means	**Std.Dev.**	**Std.Err.**	**Means**	**Std.Dev.**	**Std.Err.**
Control									
	None	0	12	1.67%	0.0389	0.0112	0.2725	0.0322	0.0093
Shivagiri									
	None	0	4	2.50%	0.0500	0.0250	0.2625	0.0222	0.0111
Ski Run									
	None	0	4	2.50%	0.0500	0.0250	0.265	0.0058	0.0029
	Chitosan	1	4	0.00%	0.0000		0.3075	0.0479	0.0239
	PXXL9	0.5	4	2.50%	0.0500	0.0250	0.3025	0.0171	0.0085
	PXXL9	1	8	5.00%	0.0756	0.0267	0.2775	0.0369	0.0131
	PXXL9	2	4	17.50%	0.0500	0.0250	0.27	0.0216	0.0108
	PXXL9	3	4	12.50%	0.0957	0.0479	0.2425	0.0443	0.0221
Stag									
	None	0	4	5.00%	0.0577	0.0289	0.2125	0.0250	0.0125
	Chitosan	1	4	7.50%	0.0957	0.0479	0.2775	0.0299	0.0149
	PXXL9	0.5	4	7.50%	0.0500	0.0250	0.2525	0.0050	0.0025
	PXXL9	1	8	5.00%	0.0535	0.0189	0.245	0.0283	0.0100
	PXXL9	2	4	15.00%	0.0577	0.0289	0.245	0.0208	0.0104
	PXXL9	3	4	10.25%	0.0818	0.0409	0.215	0.0129	0.0065
Tahoe City Wetland									
	None	0	4	2.50%	0.0500	0.0250	0.26	0.0294	0.0147
	Chitosan	1	4	0.00%	0.0000		0.245	0.0332	0.0166
	PXXL9	0.5	4	5.00%	0.0577	0.0289	0.235	0.0129	0.0065
	PXXL9	1	8	2.50%	0.0707	0.0250	0.26875	0.0210	0.0074
	PXXL9	2	4	10.00%	0.1155	0.0577	0.2475	0.0236	0.0118
	PXXL9	3	4	17.50%	0.0957	0.0479	0.2525	0.0597	0.0298

[1] Multiple of optimum

Table D-8. Analytes Measured for 2005 Stormwater Toxicity Tests. Analyses were conducted on filtered (F) and unfiltered (U) subsets of samples (see text for details).

Analyte[2]	Data did not exceed RL	RL > NTR stds	RL < NTR stds	Reporting Limit	Freshwater Stds[1]	
					CMC	CCC
InitTemp						
InitDO						
InitpH						6.5 - 9
InitEC						
InitHardness						
InitAlk						
FpH						6.5 - 9
UpH						6.5 - 9
Ualkalinity, meq/L						
FHardness, grains/gal						
Uhardness, grains/gal						
FAg (Soluble), mg/L	X	X		0.005	0.0032	
FAl (Soluble), mg/L				0.05		
FAs (Soluble), mg/L	X		X	0.01	0.34	0.15
FCa (Soluble), meq/L						
FCd (Soluble), mg/L	X	X	X	0.001	0.002	0.00025
FCu (Soluble), mg/L	X	X	X	0.01	0.013	0.009
FCr (Soluble), mg/L	X		X	0.005	0.57	0.074
FFe (Soluble), mg/L				0.1		
FMg (Soluble), meq/L				0.1		
FMn (Soluble), mg/L	X			0.1		
FNi (Soluble), mg/L	X		X	0.02	0.47	0.052
FPb (Soluble), mg/L	X	X	X	0.005	0.065	0.0025
FZn (Soluble), mg/L			X	0.02	0.12	0.12
FAg (Total), mg/L	X			0.02		
FAl (Total), mg/L				0.5		
FAs (Total), ug/L				1		
FCa (Total), mg/L						
FCd (Total), mg/L	X			0.01		
FCr (Total), mg/L	X			0.01		
FCu (Total), mg/L	X			0.2		
FFe (Total), mg/L				0.1		
FMg (Total), mg/L						
FMn (Total), mg/L	X			0.1		
FNi (Total), mg/L	X			0.1		
FPb (Total), mg/L	X			0.1		
FZn (Total), mg/L	X			0.1		
UCa (Total), mg/L						
UMg (Total), mg/L						
UZn (Total), mg/L	X			0.1		
UMn (Total), mg/L				0.1		
UFe (Total), mg/L			X	0.1		1
UCu (Total), mg/L	X			0.2		
UAl (Total), mg/L		X	X	0.5	0.75	0.087
UAs (Total), ug/L				1		
UCd (Total), mg/L	X			0.01		
UCr (Total), mg/L				0.01		
UPb (Total), mg/L	X			0.1		
UNi (Total), mg/L	X			0.1		
UAg (Total), mg/L	X			0.02		
TDS, mg/L						
TSS, mg/L				4		
Turbidity, NTU						
DOC, ug/l						

1. Standards shown are based upon EPA National Recommended Water Quality Criteria, 2002. EPA-822-R-02-047.
2. Highlighted values represent data collected above the reporting limits.
3. RL = Reporting Limit.

Table D-9. Factor Coordinates for PCA Analyses for March 2005 Stormwater. Analyses were conducted on filtered (F) and unfiltered (U) subsets of samples (see text for details).

	Factor 1	Factor 2	Factor 3
Dose mg-Me/L	-0.20	0.94	0.00
AlgaeAvgCellCount	-0.11	-0.22	0.25
CerioAvgReproduction	-0.42	-0.79	0.14
Cerio%Mortality	-0.10	0.83	-0.15
AvgFHBiomassPerSurvivor mg	-0.61	-0.21	0.23
AvgOf%FHMortality	0.24	0.81	0.05
InitpH	-0.27	-0.51	-0.22
InitEC	-0.33	0.61	-0.15
InitHardness	-0.96	0.08	-0.22
InitAlk	-0.58	-0.68	-0.27
FpH1	-0.15	-0.81	-0.05
UpH1	-0.15	-0.90	0.01
Ualkalinity, meq/L1	-0.60	-0.75	-0.20
FHardness, grains/gal	-0.95	0.17	-0.23
Uhardness, grains/gal1	-0.95	0.14	-0.24
*FAl (Soluble), mg/L	0.27	-0.33	-0.86
FCa (Soluble), meq/L1	-0.93	0.24	-0.25
*FFe (Soluble), mg/L	0.43	-0.22	-0.85
*FMg (Soluble), meq/L	-0.94	0.11	-0.20
*FZn (Soluble), mg/L	-0.29	0.67	-0.51
*FAl (Total), mg/L	-0.04	0.57	-0.29
*FAs (Total), ug/L	-0.16	-0.31	-0.33
FCa (Total), mg/L1	-0.93	0.22	-0.25
*FFe (Total), mg/L	0.41	-0.12	-0.89
FMg (Total), mg/L	-0.91	0.06	-0.21
UCa (Total), mg/L1	-0.83	0.21	-0.47
UMg (Total), mg/L1	-0.84	0.05	-0.41
*UFe (Total), mg/L	0.66	-0.09	-0.67
*UAl (Total), mg/L	0.24	0.80	-0.40
*UAs (Total), ug/L	0.16	-0.29	-0.79
*UCr (Total), mg/L	0.51	-0.12	-0.76
TDS, mg/L1	-0.36	0.54	-0.25
*TSS, mg/L	0.58	0.26	-0.70
Turbidity, NTU1	0.59	-0.13	-0.76
DOC, ug/l	-0.34	-0.66	-0.40
% Variance Explained	33	25	20
% Cumulative Variance	33	58	78

Table D-10. Correlation of Hardness, Calcium and Magnesium to Zooplankton and Fish Toxicity Metrics.

Stormwater from March 2005 shows that measures of hardness are only weakly correlated to zooplankton and fish toxicity. However, some relationships with fish toxicity are statistically significant ($p<0.05$).

	Cerio Reproduction	Fish survivor biomass (mg)
InitHardness	0.29	0.49
FHardness, grains/gal	0.21	0.44
Uhardness, grains/gal1	0.23	0.45
FCa (Soluble), meq/L1	0.17	0.46
*FMg (Soluble), meq/L	0.23	0.43
FCa (Total), mg/L1	0.17	0.48
FMg (Total), mg/L	0.27	0.35
UCa (Total), mg/L1	0.11	0.4
UMg (Total), mg/L1	0.22	0.28

Red signifies statistical significance ($p<0.05$)

Table D-11. Dosing Related Variables and their Correlations with Zooplankton and Fish Toxicity Metrics.

Cerio reproduction and mortality, and fish mortality are correlated to different dosing related variables. Coagulant dosing affects pH, alkalinity, DOC concentrations and total aluminum (under over-dosing conditions). Correlations with these toxicity metrics are statistically significant ($p<0.05$).

	Cerio Reproduction	Cerio Mortality	Fish Mortality
Dose mg-Me/L	-0.68	0.81	0.73
InitAlk	0.74	-0.39	-0.71
FpH	0.66	-0.72	-0.61
UpH	0.72	-0.66	-0.75
Ualkalinity, meq/L	0.84	-0.51	-0.80
FZn (Soluble), mg/L	-0.42	0.70	0.40
UAl (Total), mg/L	-0.74	0.84	0.67
DOC, ug/l	0.67	-0.40	-0.57

Red signifies statistical significant ($p<0.05$)

Table D-12. Experimental Design for October 2005 stormwater.
Experiment to test the effects of precipitate in solution on zooplankton toxicity metrics: reproduction and mortality. Tested those metrics for three different stormwaters at three different dosing levels with resulting floc either decanted or filtered from solution. Decanting was standard practices used in previous studies.

Independent variables	Treatments
Stormcode	Ski Run (SR) Stag (S) Tahoe City Wetland (T)
Floc	Decanted Filtered
Dose (multiple of optimum as determined by SCD)	1 2 3

Table D-13. ANOVA results for October 2005 stormwater.
Red text shows statistically significant results. Stormwater affected zooplankton mortality but not reproduction. Filtration of the flocculate from solution resulted in a statistically significant increase in zooplankton reproduction. Progressively higher dosing levels decreased zooplankton reproduction.

Factor	Level of Factor	N	Reproduction (#)			% Mortality		
			Mean	Std.Dev.	p	Mean	Std.Dev.	p
Total		20	16	12		30	43	
Stormcode	SR	6	12	13	0.126	55	50	0.029
	S	6	13	13		43	48	
	T	8	22	10		1	4	
Floc	Decanted	11	11	12	0.040	43	48	0.212
	Filtered	9	23	9		14	32	
Dose (multiple of optimum)	1	7	26	4	0.033	4	8	0.134
	2	7	13	11		39	45	
	3	6	9	14		50	55	

Table D-14. Factor coordinates for PCA analyses for October 2005 stormwater

	Factor 1	Factor 2	Factor 3
Dose mg-Me/L	-0.53	0.00	0.39
CerioAvgReproduction	0.81	0.09	-0.39
Cerio%Mortality	-0.86	0.14	0.28
InitpH	0.88	-0.32	-0.09
InitEC	-0.17	-0.78	0.18
InitHardness	-0.39	0.39	-0.20
InitAlk	0.66	-0.26	-0.40
FpH1	0.88	-0.17	-0.15
Ualkalinity, meq/L1	0.74	-0.22	-0.44
*FAl (Soluble), mg/L	-0.67	0.45	-0.26
*FFe (Soluble), mg/L	-0.40	0.19	-0.80
*FZn (Soluble), mg/L	-0.36	0.70	0.22
*FAl (Total), mg/L	-0.64	0.48	-0.23
*FFe (Total), mg/L	-0.58	0.36	-0.66
*UFe (Total), mg/L	-0.49	-0.81	-0.20
*UAl (Total), mg/L	-0.81	-0.44	0.13
*UAs (Total), ug/L	-0.42	-0.76	-0.37
TDS, mg/L1	-0.34	-0.78	0.06
*TSS, mg/L	-0.62	-0.72	-0.06
Turbidity, NTU1	-0.45	-0.78	-0.29
DOC, ug/l	-0.46	0.33	-0.57
% variance	37	26	13
% Cumulative variance	37	63	76

Table D-15. ANOVA analyses of Total Aluminum.

Total aluminum varied with floc treatment and dosing levels with these differences significantly different. The factors shown to be statistically significant for total aluminum were also significantly different for zooplankton reproduction.

Factor	Level of Factor	N	Total Aluminum (mg/L)		
			Mean	Std.Dev.	p
Total		20	7	11	
Stormcode	SR	6	6	9	0.130
	S	6	12	16	
	T	8	3	5	
Floc	Decanted	11	12	12	0.014
	Filtered	9	0	0	
Dose (multiple of optimum)	1	7	1	0	0.040
	2	7	7	11	
	3	6	14	14	

Table D-16. Summary of toxicity tests.

Goal	ANOVA	Treatments			Stormwater Effects					Coagulant Effects					Floc	
	Test	Storm water[3]	Coag.[2]	Floc[4]	Algae	Zooplankton		Fish		Algae	Zooplankton		Fish		Zooplankton	
					Count	Repro.	Mort.	Bio.	Mort.	Count	Repro.	Mort.	Bio.	Mort.	Repro.	Mort.
May 2004																
1 Differences between non-dosed stormwaters and a control.	2-way, post hoc analyses	SR,S, TCW, C	none	De	Y -[10]	Y +/-[10]	N	N	Y -[10]							
2 Differences between non-dosed stormwaters	2-way, post hoc analyses	SR,S, TCW	none	De	Y	Y	N	N	Y							
3 Test the effects of different coagulants on dosing	2-way	SR,S, TCW, C	none, PAX, SUM, JC[7,8]	De	Y	Y	Y	Y	Y	Y +/-[9]	Y -	Y +/-[9]	N	N		
Mar 2005																
1 Differences between non-dosed stormwaters	1-way	SR, S, TCW	0x	De	N	Y	N	N	Y							
2 Effects of optimal dosing on stormwaters with a polyaluminum chloride (PAX-XL9) and a chitin based coagulant (Chitison)	2-way factorial	SR, S, TCW	0x, 1x[6]	De	N	Y	Y	N	Y	Y +	Y +	N	N	N		
3 Effects of over-dosing on stormwaters	2-way factorial	SR, S, TCW	0x, 0.5x, 1x, 2x, 3x	De	N	Y	Y	N	Y	Y -[1]	Y -[1]	Y -[1]	Y -[1]	N		
October 2005																
1 Effects of over-dosing on stormwaters and testing if floc removal reduces toxicity.	3-way factorial	SR, S, TCW	1x, 2x, 3x	De, Fi		N	N				Y -[1]				Y+[5]	Y+[5]

1. At over-dosing of 2x and 3x optimal dose
2. Multiple of dose determined for SCD = 0 V.
3. SR = Ski Run, S= Stag, TCW = Tahoe City Wetland, SHV = Shivagiri, C= Control
4. Floc treatment: De = decanted after coagulation and settling. Fi = Filtered after coagulation and settling.
5. Zooplankton reproduction improved and mortality decreased when flocculate was removed through filtration.
6. Dosed at 1x with Chitosan and PAX-XL9
7. PAX = PAX-XL9, SUM = Sumachlor 50, JC = Jenchem 1720.
8. Coagulant dosing was not optimized using SCD. Dosing was estimated using jar tests.
9. Increased or decreased toxicity effect depending upon coagulant and dosing level.
10. Toxicity metric measured in stormwater when compared to control (- means worsened, + means improved).

Table D-17. Correlation between toxicity metrics and measured water quality parameters.

Bolded values show correlations that were statistically significant. Highlighted values represent variables expected to be causing toxicity based upon review of trends. On the right of the tables, the possible sources for each variable are shaded.

	Correlation, number and probability[2]					Source[1]	
	Algal Cell Count	Cerio Reproduction	Cerio Mortality	Fish Biomass (Survivor)	Fish Mortality	Coag.	StormW.
Dose mg-Me/L	-0.31 N=25 p=.130	**-0.58** **N=49** **p=.000**	**0.68** **N=49** **p=.000**	-0.02 N=24 p=.942	0.27 N=25 p=.190	🟩	
Algal Cell Count	1.00 N=25 p= ---	0.06 N=25 p=.769	0.12 N=25 p=.564	**0.38** **N=24** **p=.070**	**-0.75** **N=25** **p=.000**		🟩
Cerio Reproduction	0.06 N=25 p=.769	1.00 N=49 p= ---	**-0.66** **N=49** **0.000000**	0.06 N=24 p=.796	0.00 N=25 p=1.00		🟩
Cerio Mortality	0.12 N=25 p=.564	**-0.66** **N=49** **0.000000**	1.00 N=49 p= ---	-0.03 N=24 p=.893	0.00 N=25 p=.991		🟩
Fish Biomass	**0.38** **N=24** **p=.070**	0.06 N=24 p=.796	-0.03 N=24 p=.893	1.00 N=24 p= ---	-0.27 N=24 p=.203		🟩
Fish Mortality	**-0.75** **N=25** **p=.000**	0.00 N=25 p=1.00	0.00 N=25 p=.991	-0.27 N=24 p=.203	1.00 N=25 p= ---		🟩
pH	**0.64** **N=25** **p=.001**	**0.46** **N=45** **p=.001**	**-0.63** **N=45** **0.000000**	0.18 N=24 p=.399	**-0.65** **N=25** **0**	🟩	
Hardness	0.04 N=19 p=.864	0.05 N=39 p=.745	0.24 N=39 p=.148	0.49 N=19 p=.032	-0.15 N=19 p=.540		🟩
Alkalinity	0.10 N=19 p=.685	**0.62** **N=39** **0.000000**	**-0.55** **N=39** **0.000000**	0.35 N=19 p=.139	**-0.71** **N=19** **p=.001**	🟩	
FAl (Soluble), mg/L	-0.25 N=19 p=.308	-0.28 N=39 p=.080	**0.41** **N=39** **p=.010**	-0.29 N=19 p=.232	-0.22 N=19 p=.361		🟩
FCa (Soluble), meq/L	-0.02 N=19 p=.928	0.17 N=19 p=.493	0.29 N=19 p=.225	**0.46** **N=19** **p=.050**	-0.06 N=19 p=.797		🟩
FZn (Soluble), mg/L	-0.13 N=19 p=.583	-0.29 N=39 p=.070	**0.51** **N=39** **p=.001**	0.13 N=19 p=.597	0.40 N=19 p=.088	🟩	
UFe (Total), mg/L	-0.14 N=19 1	**-0.38** **N=39** **p=.019**	0.15 N=39 p=.359	**-0.46** **N=19** **p=.047**	0.06 N=19 p=.800		🟩
UAl (Total), mg/L	-0.27 N=19 p=.258	**-0.71** **N=39** **0**	**0.70** **N=39** **0**	**-0.41** **N=19** **p=.079**	**0.67** **N=19** **p=.002**	🟩	🟩
TSS, mg/L	-0.17 N=19 p=.474	**-0.52** **N=39** **0**	**0.37** N=39 p=.020	**-0.52** **N=19** **p=.024**	0.32 N=19 p=.177	🟩	🟩
Turbidity, NTU	-0.14 N=19 p=.575	**-0.32** **N=39** **p=.049**	0.08 N=39 p=.624	-0.44 N=19 p=.058	-0.01 N=19 p=.963	🟩	🟩
DOC, mg/l	0.01 N=19 p=.976	0.04 N=39 p=.800	0.27 N=39 p=.095	0.24 N=19 p=.333	**-0.57** **N=19** **p=.011**	🟩	🟩

1. Shaded area indicates possible source of analyte affecting toxicity.
2. **Bolded items represent relationships are statistically significant (p<0.05).**
3. Highlighted items are those expected to be most likely affecting the toxicity metric based upon a review of the data.

Table D-18. Summary of variables implicated in toxicity

	Correlation, number and probability[2]					Source[1]	
	Algal Cell Count	Cerio Reproduction	Cerio Mortality	Fish Biomass	Fish Mortality	Coag.	StormW.
Dose mg-Me/L		🟨	🟨			🟩	
pH	🟨	🟨	🟨		🟨	🟩	
Alkalinity		🟨	🟨		🟨	🟩	
Soluble Ca				🟨			🟩
Total Fe		🟨		🟨			🟩
Total Al		🟨	🟨	🟨	🟨	🟩	🟩
TSS		🟨		🟨		🟩	🟩
Turbidity		🟨				🟩	🟩
DOC					🟨	🟩	🟩

1. 🟩 Shaded area indicates possible source of analyte affecting toxicity.
2. 🟨 Highlighted items are those expected to be most likely affecting the toxicity metric based upon a review of the data.

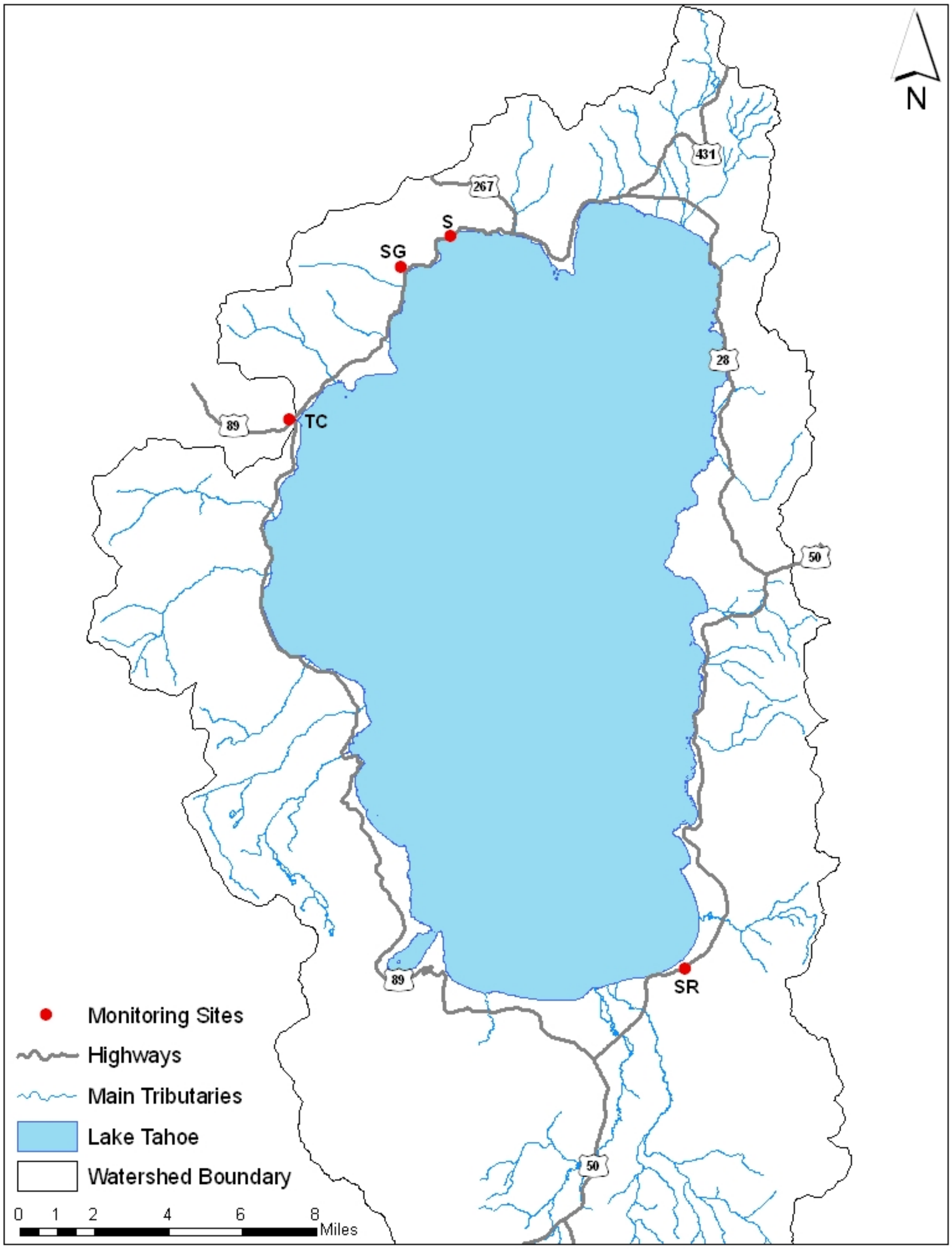


Figure D-1. Map of locations from which stormwater was sampled.
S=Stag, SG=Shivagiri, TC=Tahoe City, SR=Ski Run.

Figure D-2. Algae cell reproduction for optimally dosed stormwaters

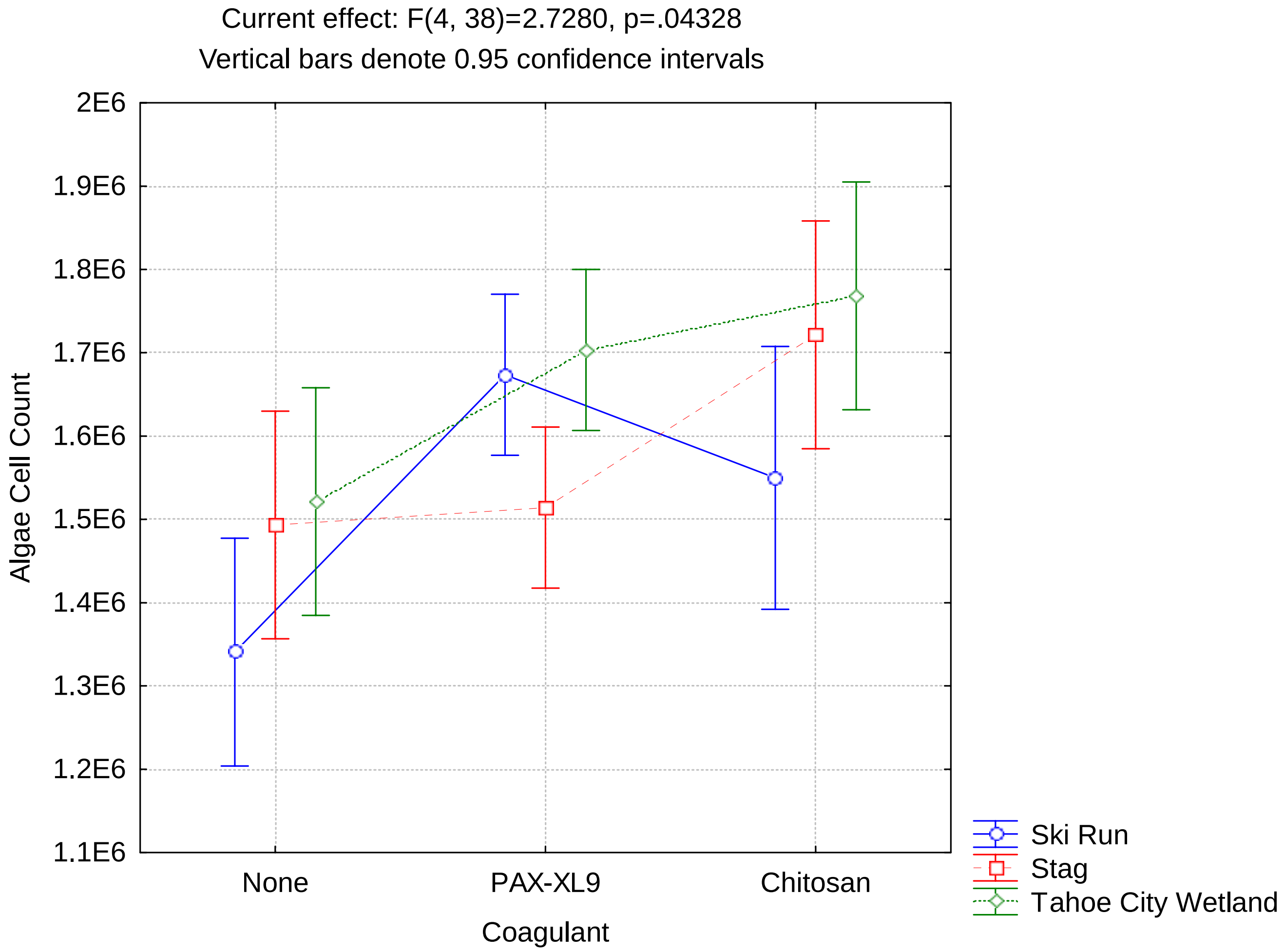


Figure D-3. Brood Sizes for Optimally Dosed Stormwaters

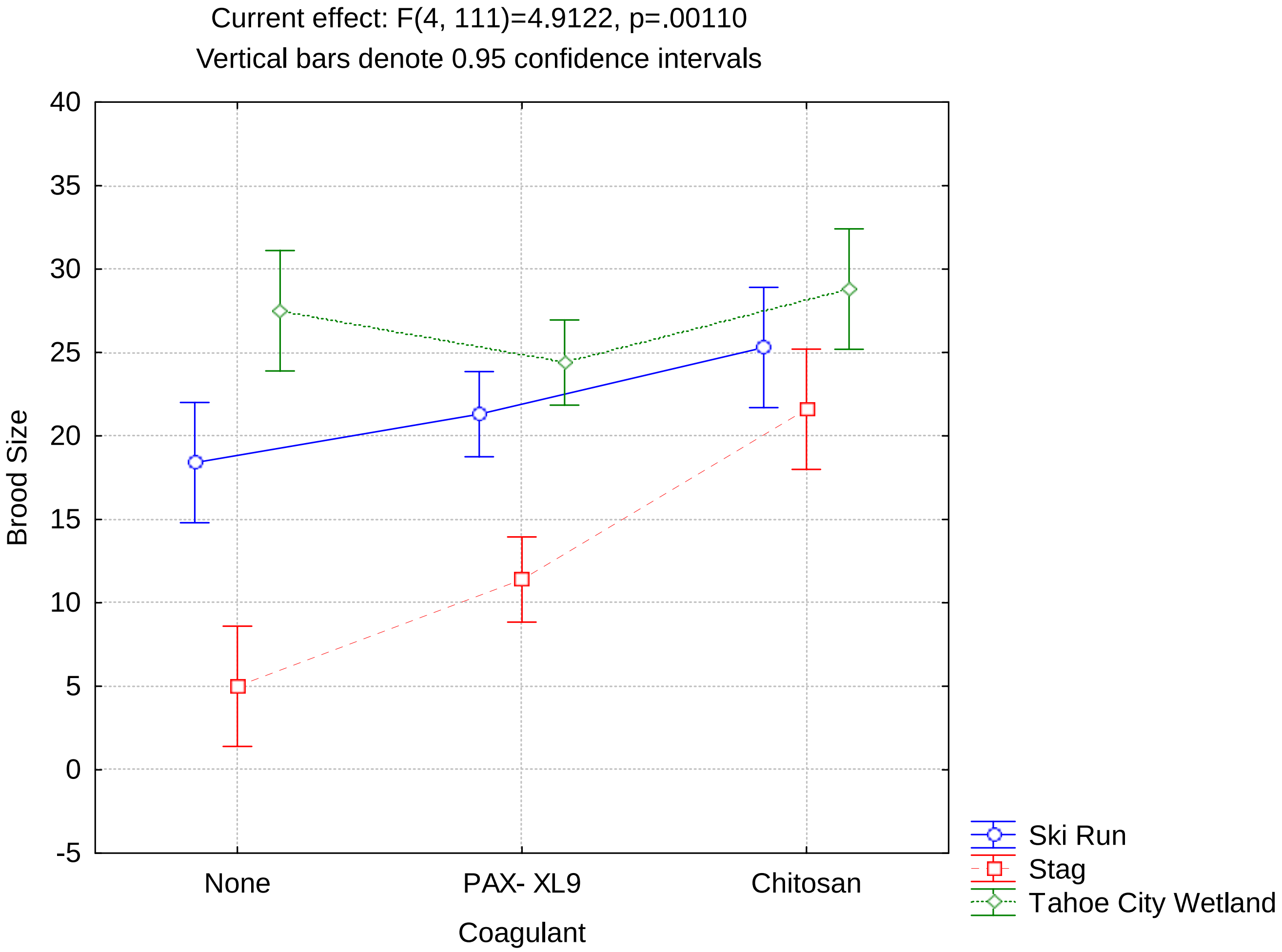
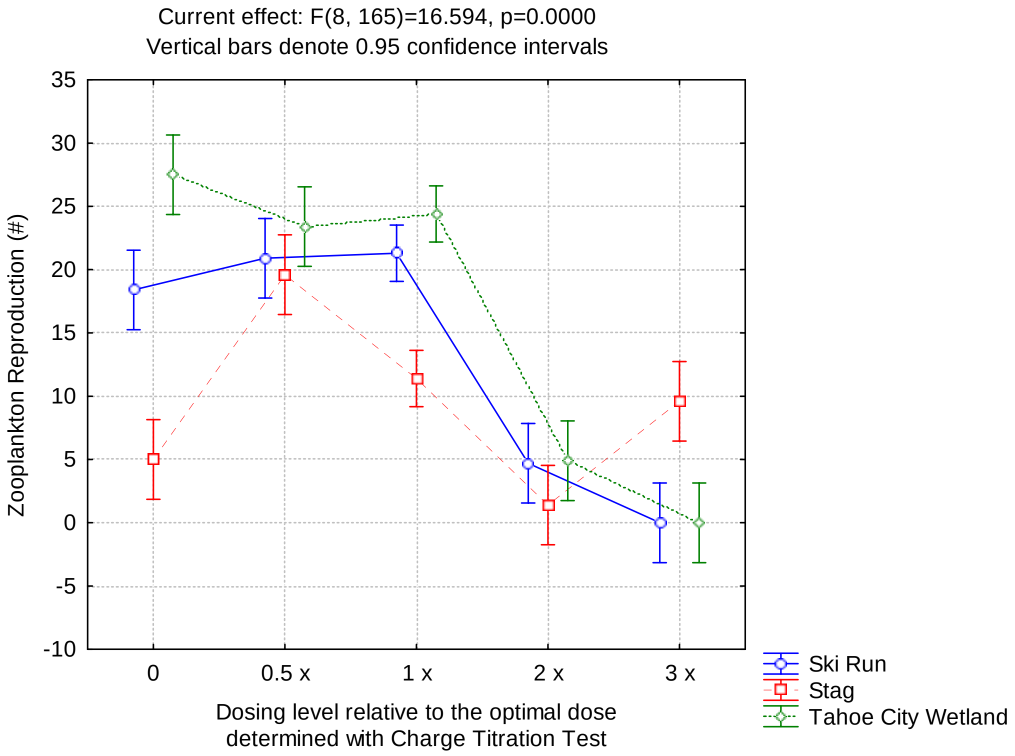


Figure D-4. Effects of Over Dosing on Zooplankton

a) Reproduction



b) Mortality

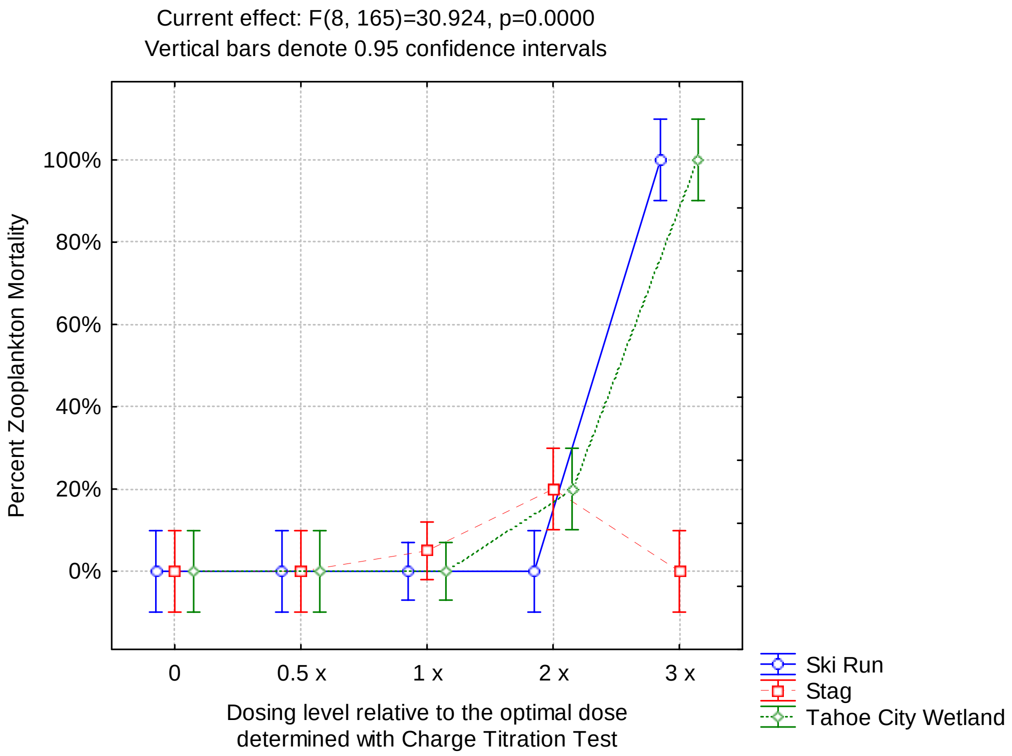
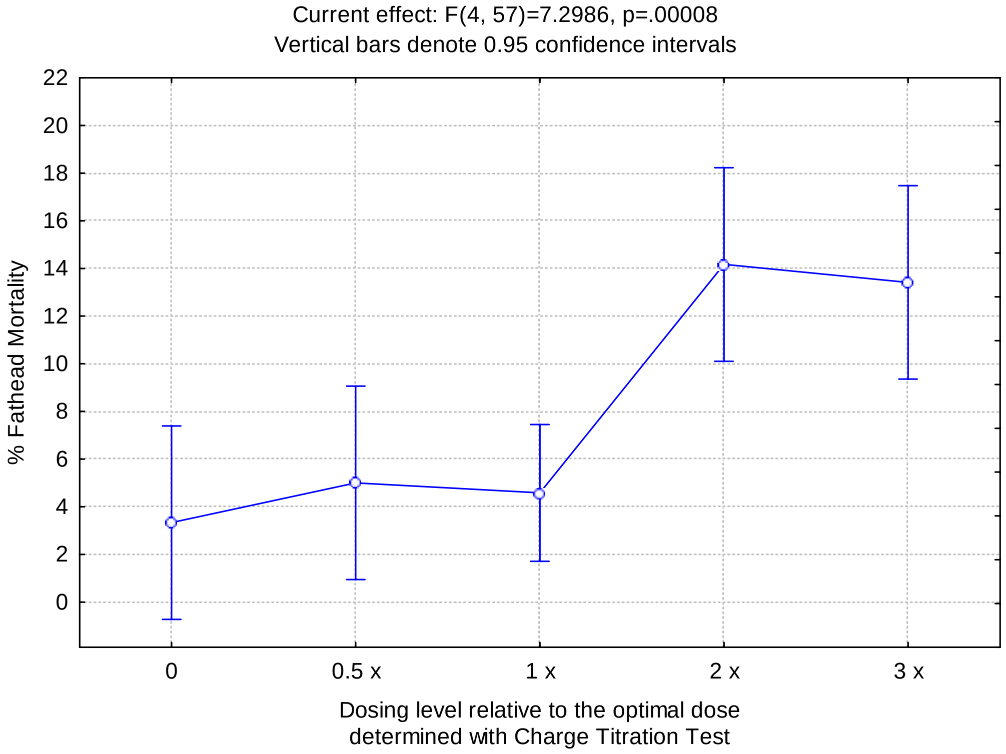

Current effect: F(8, 165)=30.924, p=0.0000
Vertical bars denote 0.95 confidence intervals
Percent Zooplankton Mortality
100%
80%
60%
40%
20%
0%
0
0.5 x
1 x
2 x
3 x
Dosing level relative to the optimal dose
determined with Charge Titration Test
Ski Run
Stag
Tahoe City Wetland

Figure D-5. Effects of Over-dosing on Fathead Minnows

a) Mortality



b) Survivor Biomass

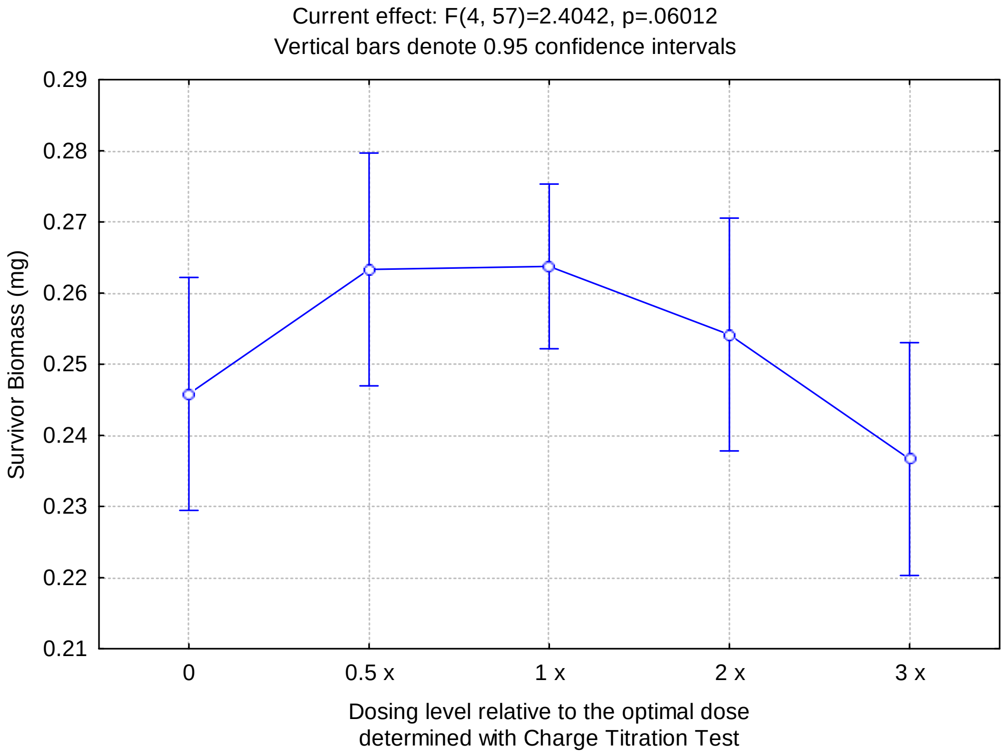

Current effect: F(4, 57)=2.4042, p=.06012
Vertical bars denote 0.95 confidence intervals
Survivor Biomass (mg)
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0
0.5 x
1 x
2 x
3 x
Dosing level relative to the optimal dose
determined with Charge Titration Test

Figure D-6. Effects of Over-dosing on Algae Cell Count

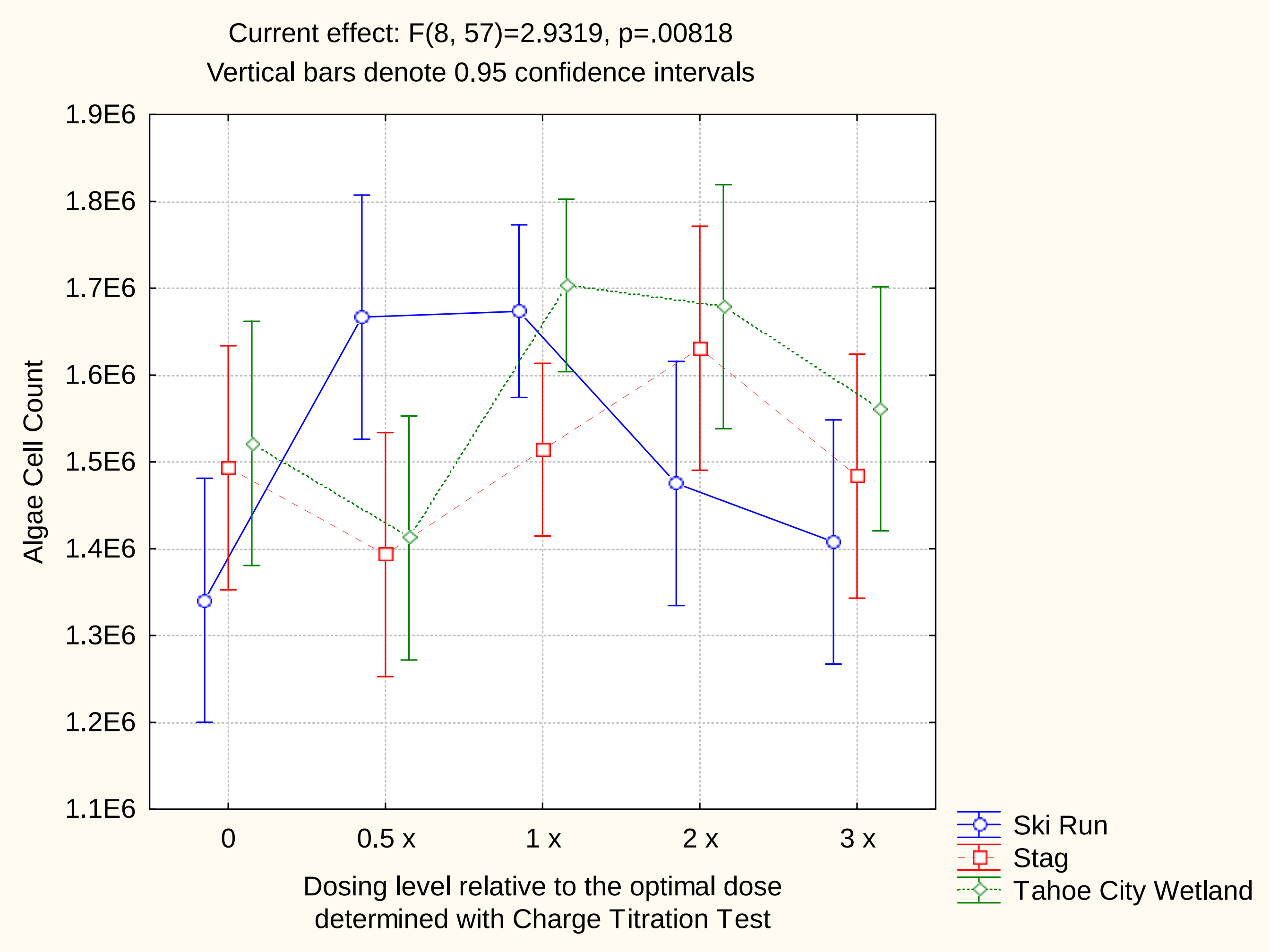


Figure D-7. Correlations between dosing level and water quality variables. Dosing predictably affects alkalinity, pH and DOC. Total aluminum increases in the water column under over-dosed conditions. Soluble zinc is the only priority metal significantly affected ($p<0.05$) by coagulant dosing at the dosing levels used in this study.

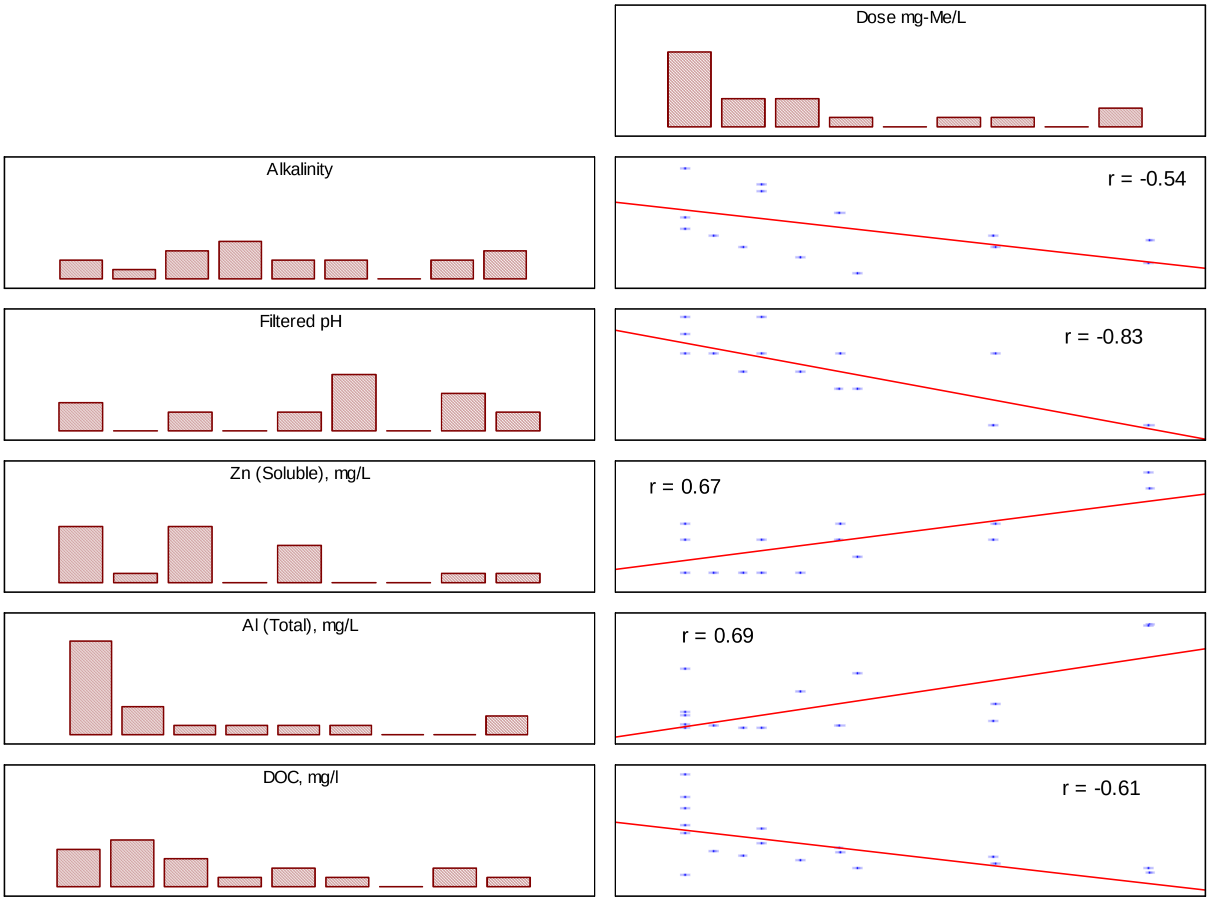


Figure D-8. Turbidity correlates with some metals and suspended solids.
Total suspended solids and total iron have the most consistent correlation with turbidity. Total chromium and arsenic are more affected by overdosing levels.

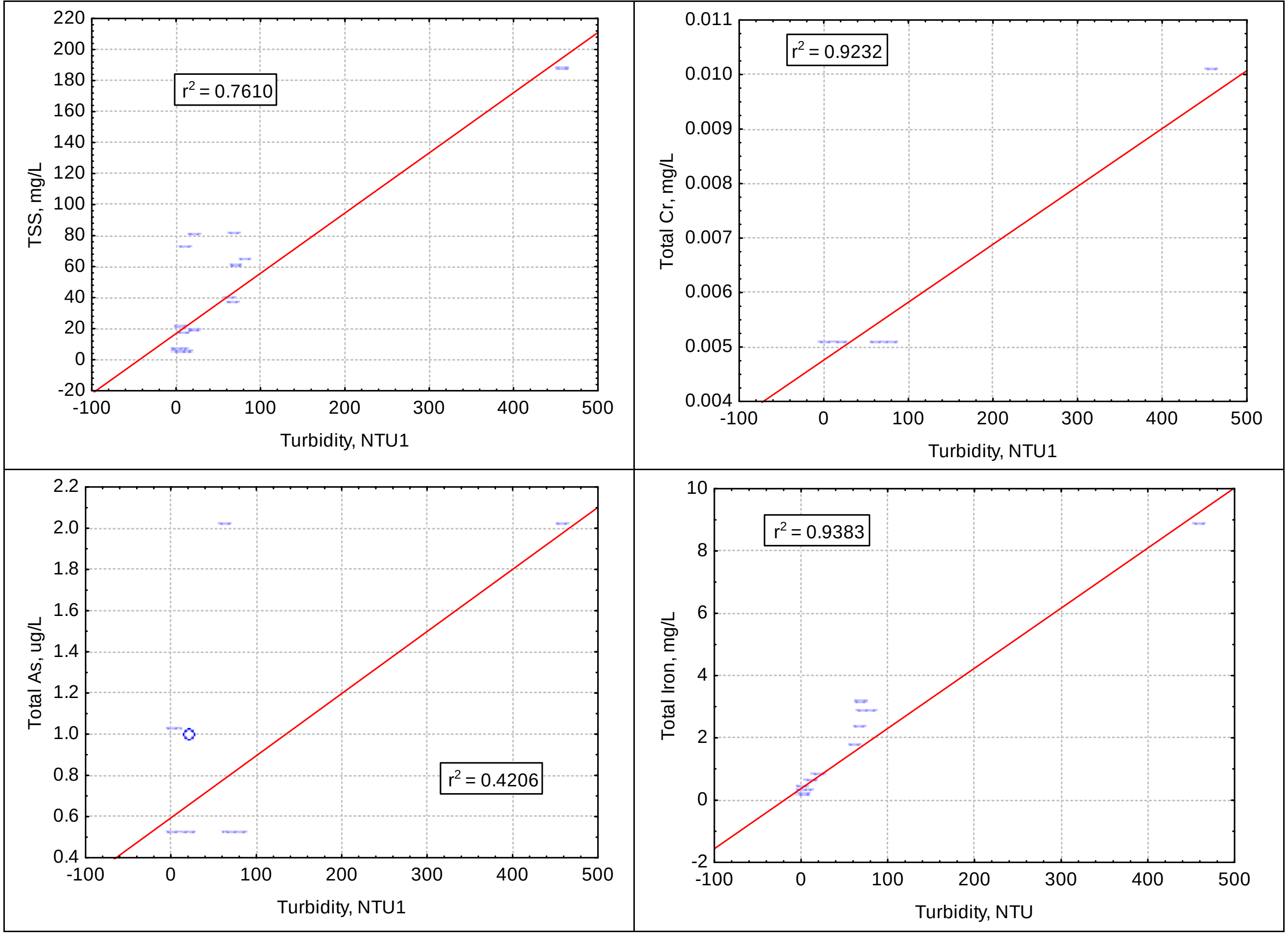


Figure D-9. Stormwaters described by Factor 1.
Both Ski Run and Tahoe City stormwaters correspond to a Factor 1 value in the range of -2 to -4. Stag stormwaters correspond to Factor 1 at a value near 4. Factor 1 is primarily characterized by its hardness. All stormwaters range from around -4 to +8 for Factor 2.

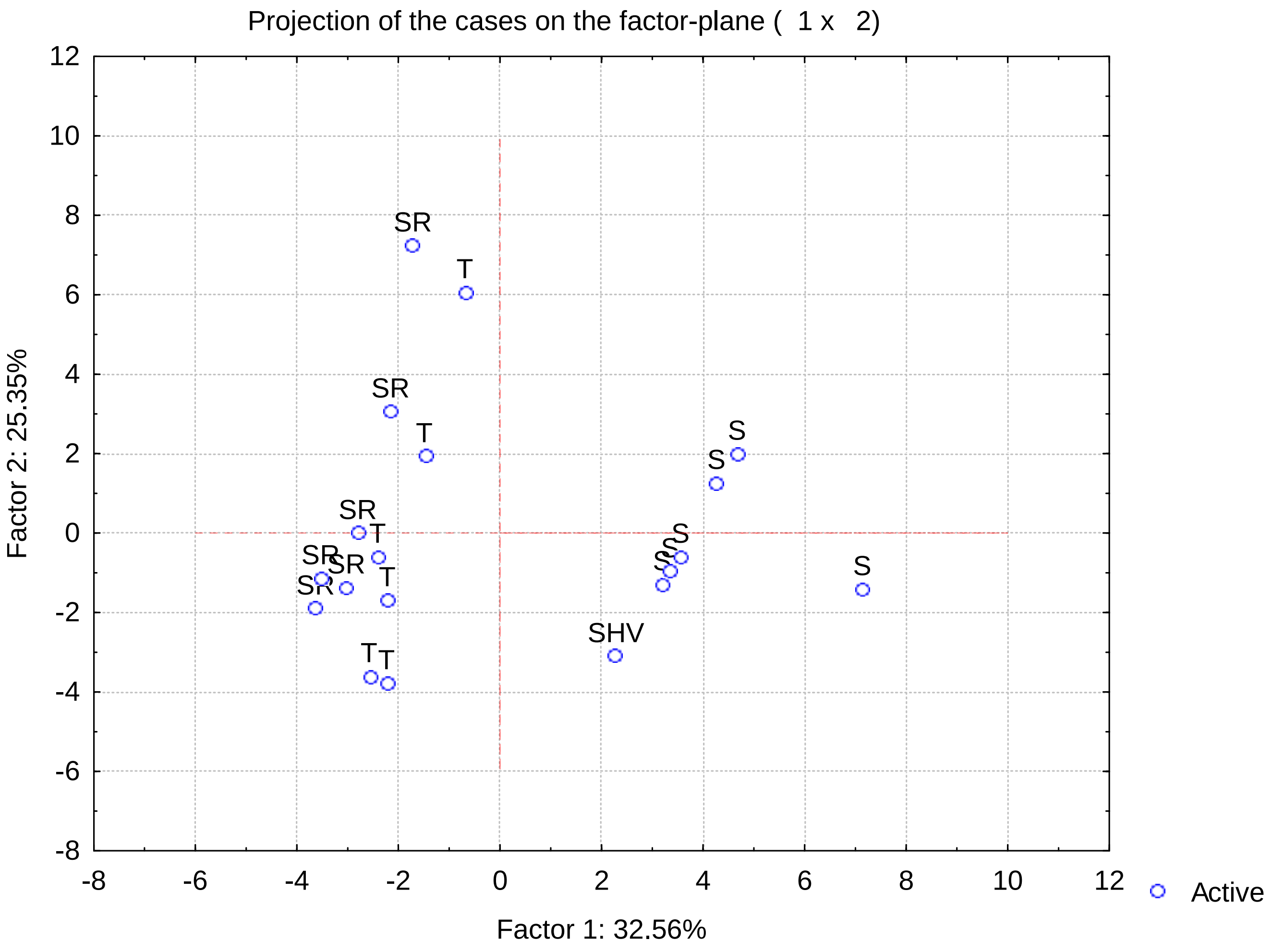


Figure D-10. Stormwaters show slight correspondence with Factor 3.
Factor 3 characterizes particulates and negatively corresponds with turbidity an suspended solids. Ski Run and Tahoe City stormwaters would appear to have similar turbidity and suspended solids and those values would seem to be higher then for Stag.

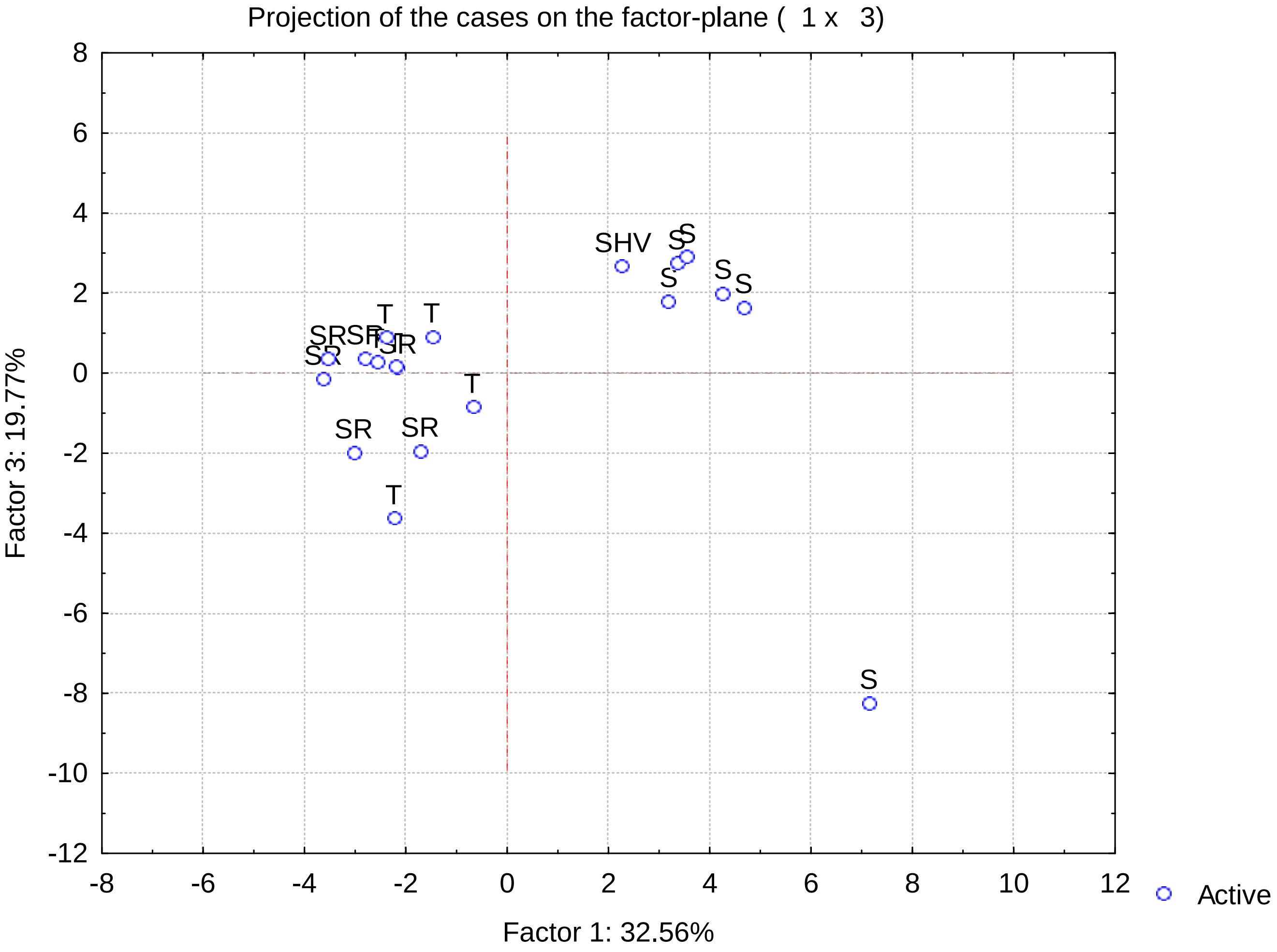


Figure D-11. Total Aluminum Forms Flocculate but Remains in Water Column when Over-Dosing Occurs.

Flocculate forms and settles under optimal dosing conditions. When over-dosing occurs, formed flocculates may not be removed from the water column. The formed flocculates are composed largely of aluminum and so the concentrations of total aluminum in solution can approach the dosing concentration.

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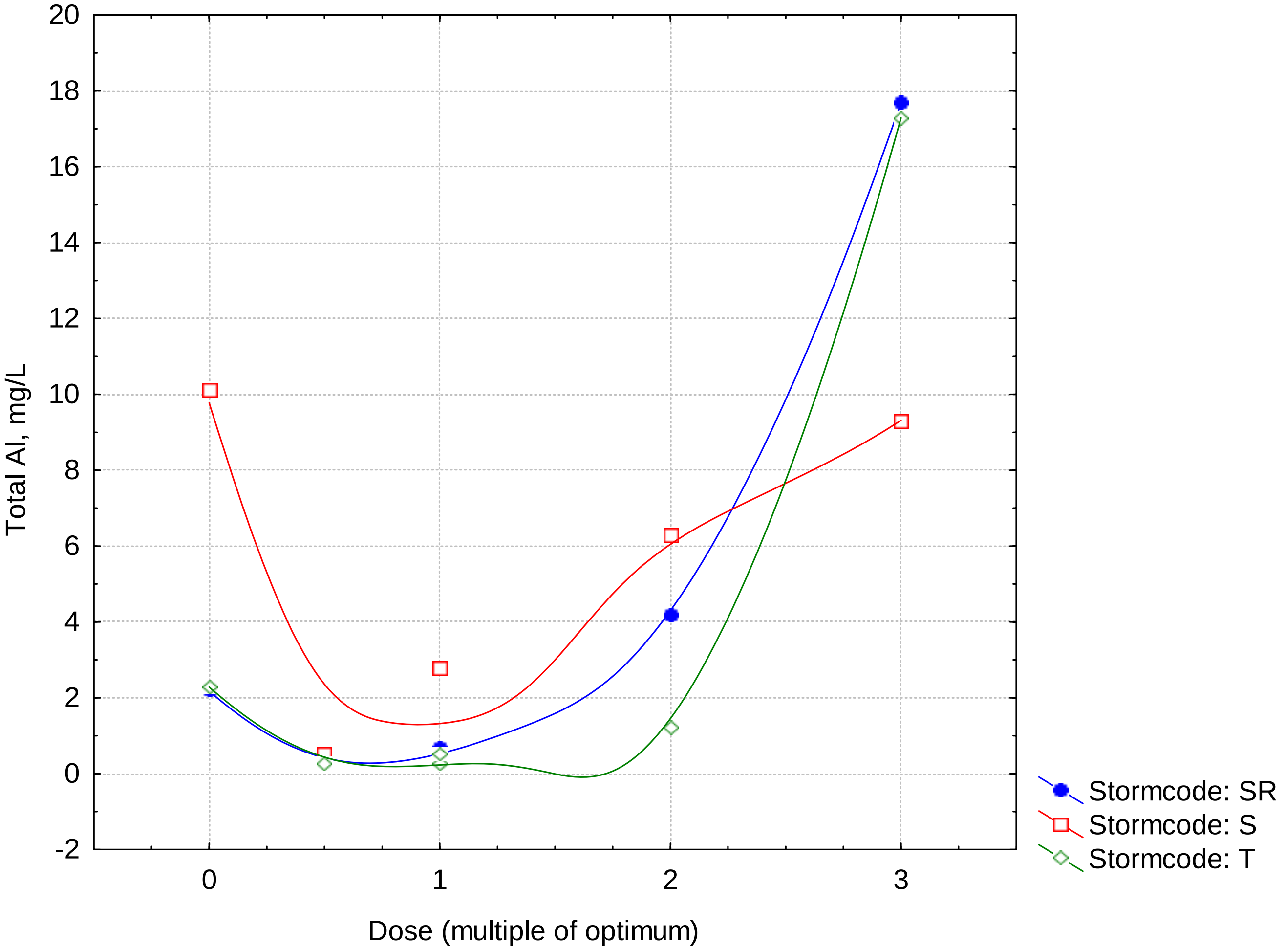
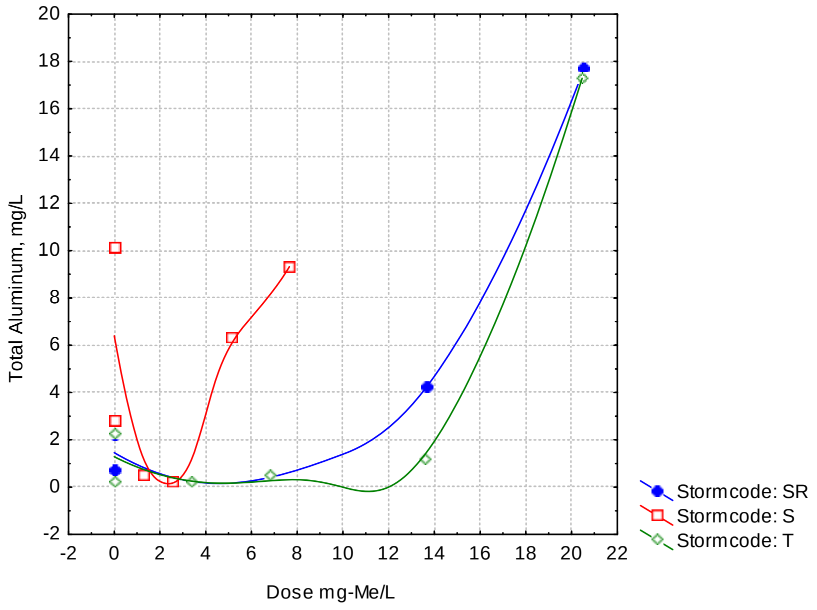


Figure D-12. Fate of Aluminum for range of coagulant dosing.
Formed flocculates are composed of aluminum and under over-dosing conditions, much if not all of the total aluminum may remain in solution. Soluble aluminum is eliminated during the dosing process and remains low under the full range of dosing levels that were conducted for this study.

A. Total Aluminum



B. Soluble Aluminum

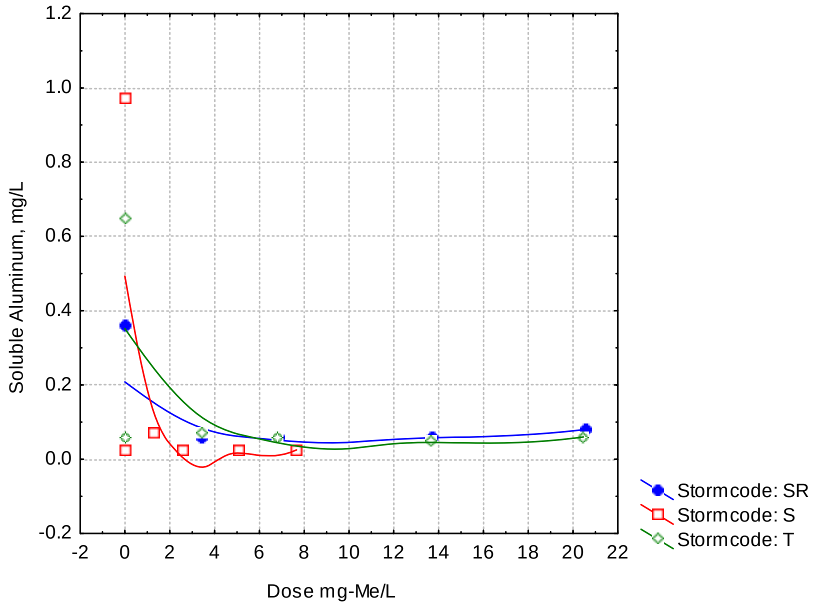


Figure D-13. Resuspension and Turbidity Increases with Over-Dosing.
Turbidity and suspended solids are removed through coagulation. When over-dosing occurs, turbidity can increase or remain steady.

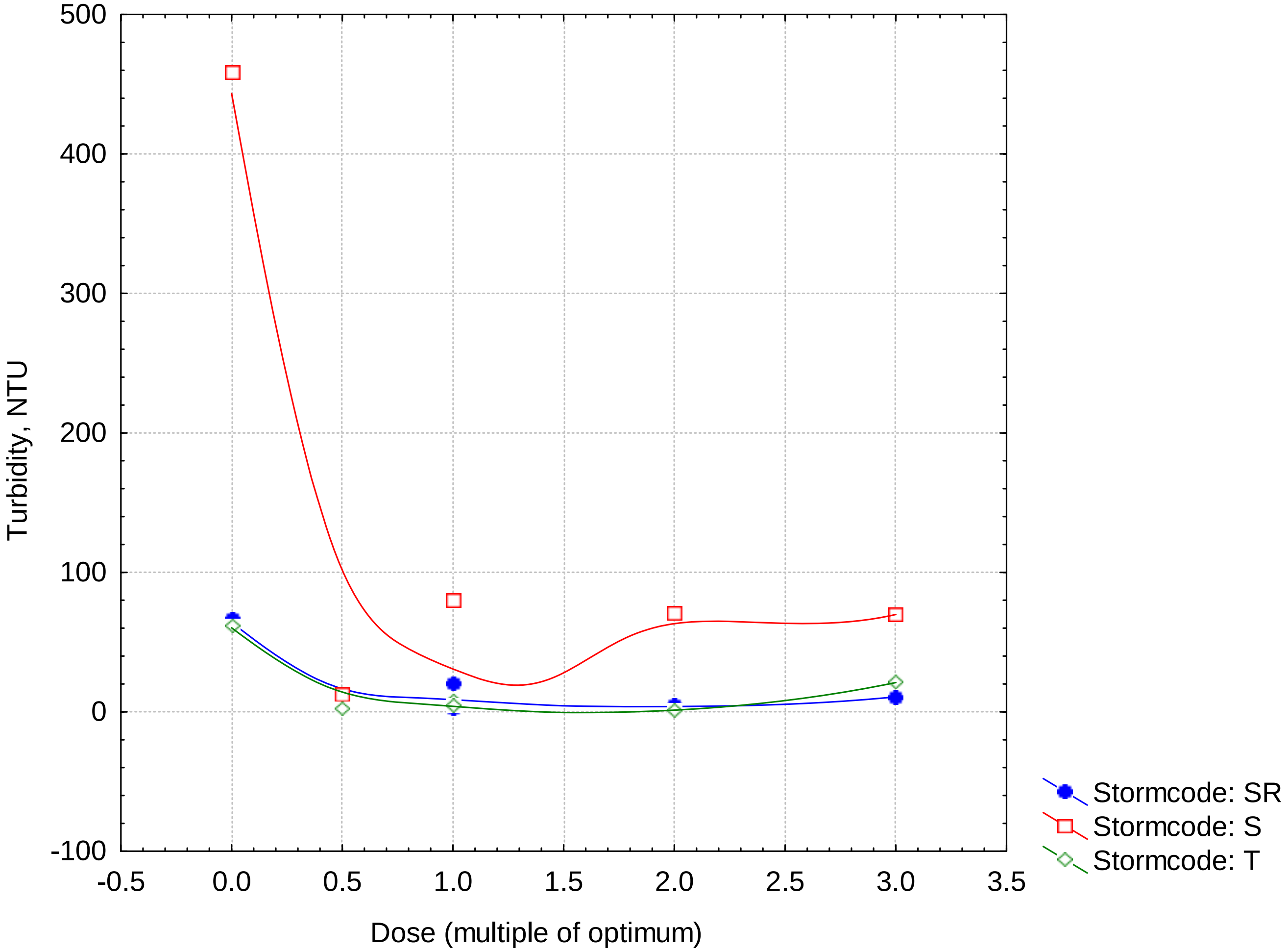
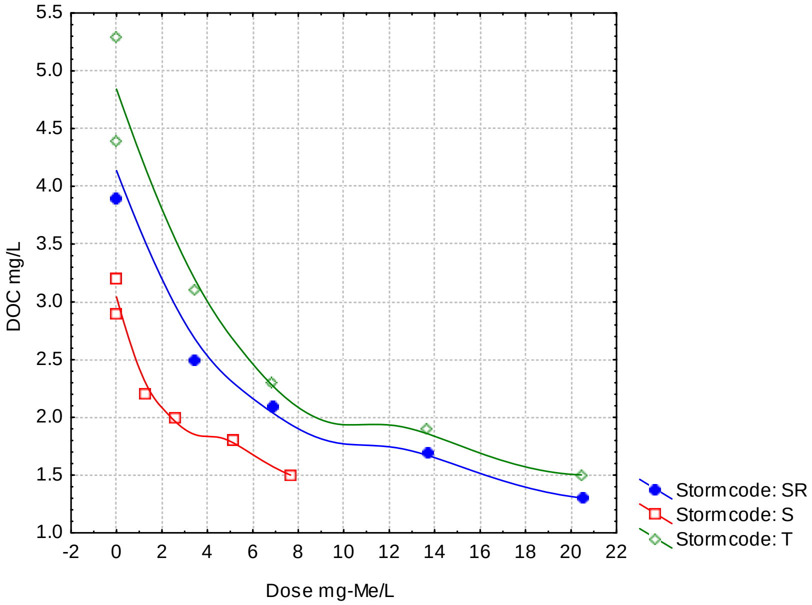


Figure D-14. Effects on dissolved carbon and phosphorus under coagulant dosing
Dissolved organic carbon and phosphorus continues to be removed under over-dosing conditions.

A. DOC



B. Soluble Reactive Phosphorus

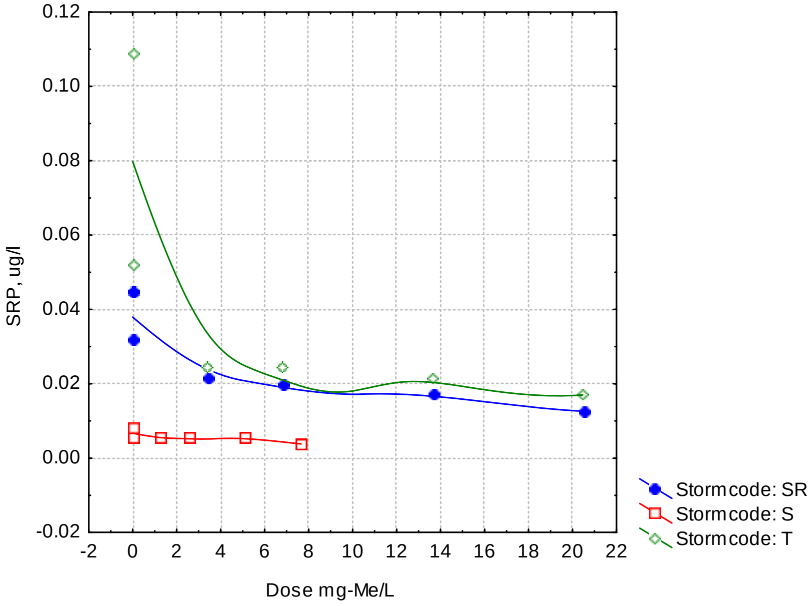


Figure D-15. Zooplankton reproduction inversely relates to total aluminum concentrations.

At total aluminum concentrations greater then about 3 mg/L, zooplankton reproduction dramatically falls. At total aluminum concentrations less then 3 mg/L, reproduction is about 20. At greater aluminum concentrations, it falls to a range of 0 to 7.

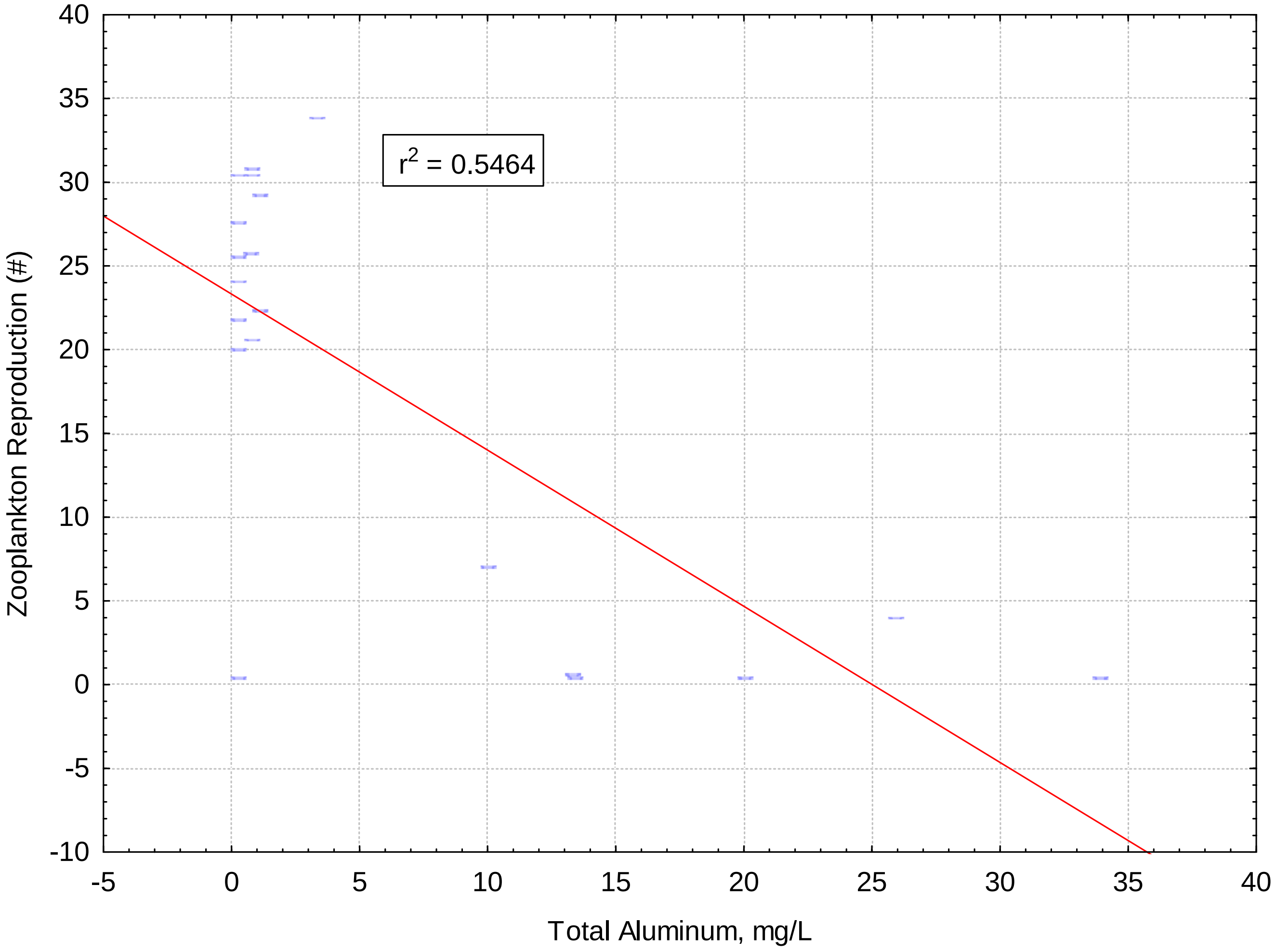


Figure D-16. pH reduces algae cell counts.
Cell counts dramatically decrease at pH below 6.8. Response is probably not linear and may relate to changes in aluminum speciation.

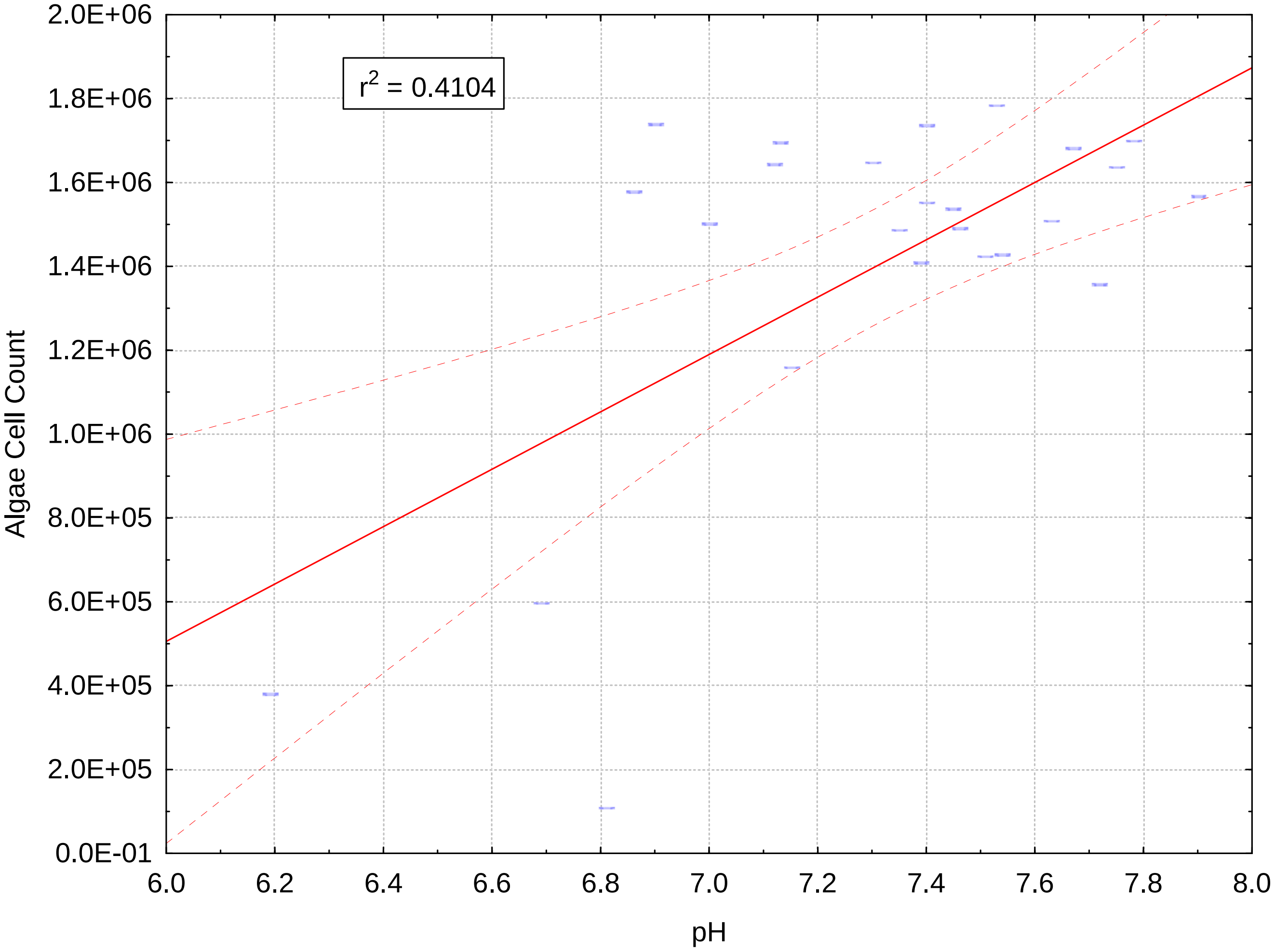
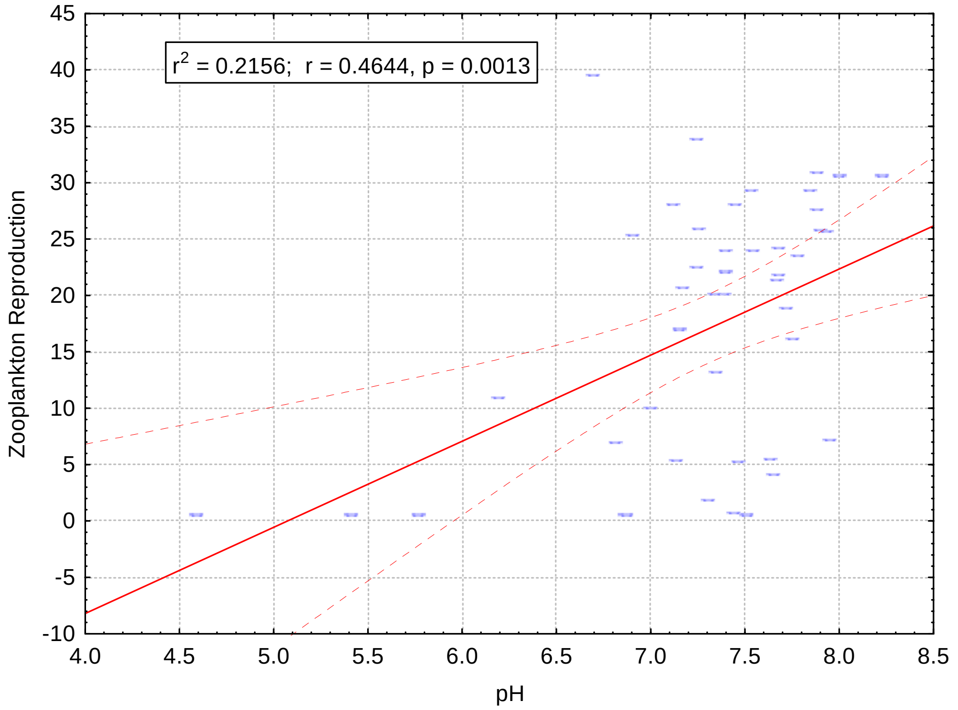


Figure D-17. The response of zooplankton reproduction to changes in pH and alkalinity

A. pH



B. Alkalinity

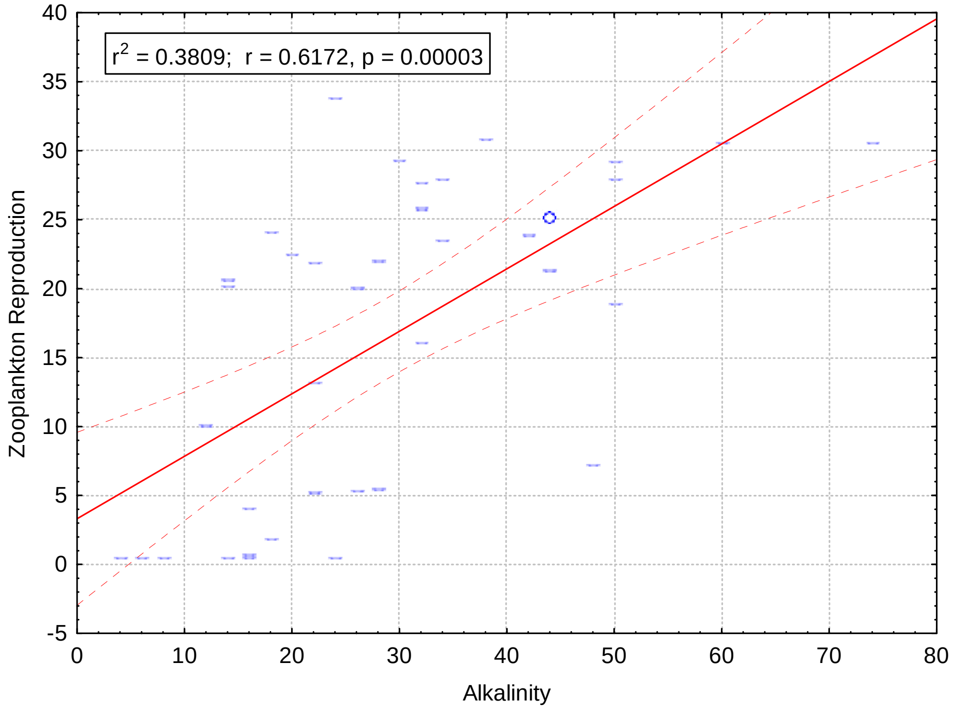
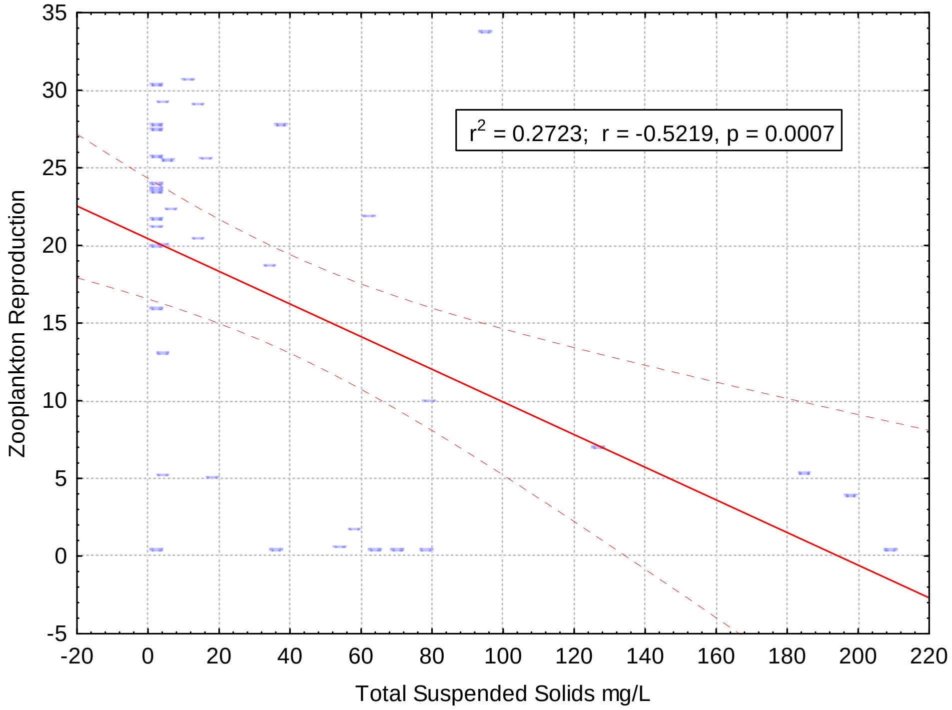


Figure D-18. Effects of Particles and Total Aluminum on Zooplankton Reproduction

A. Response to TSS



B. Response to Total Aluminum

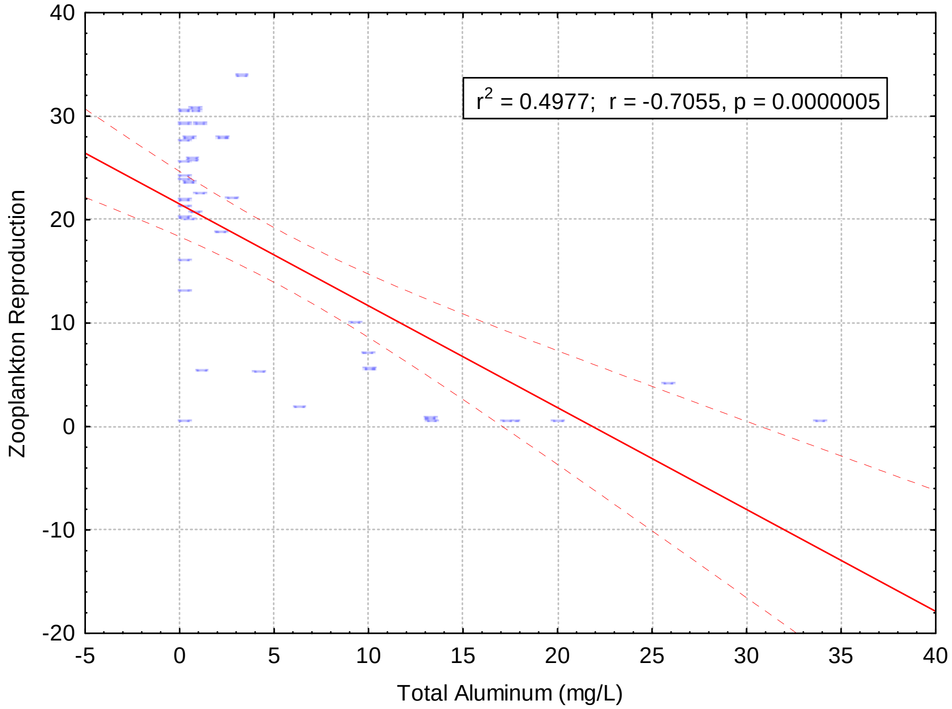


Figure D-19. Zooplankton reproduction response to high total aluminum concentrations.

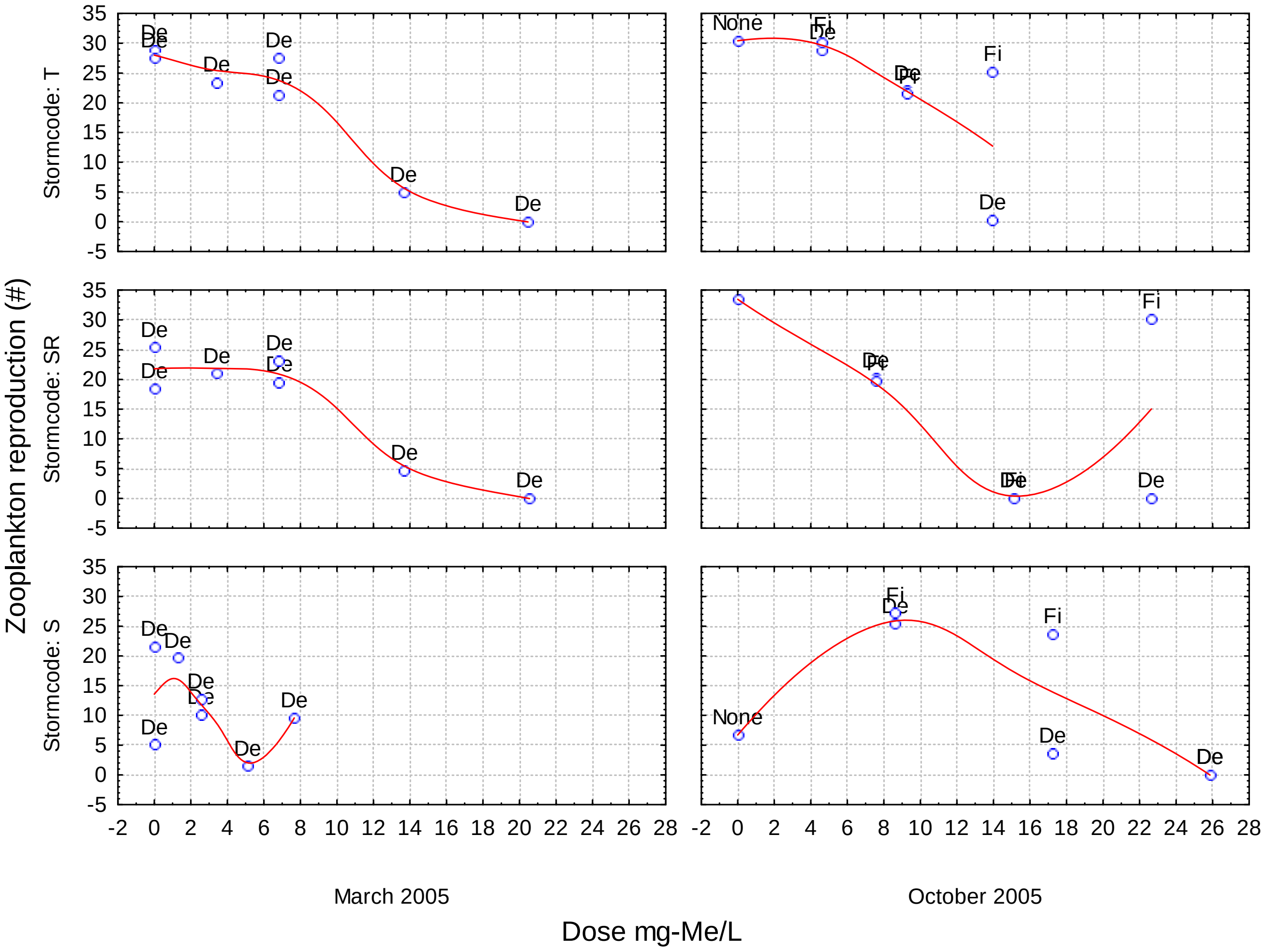


Figure D-20. Effects of Filtration on total aluminum concentrations

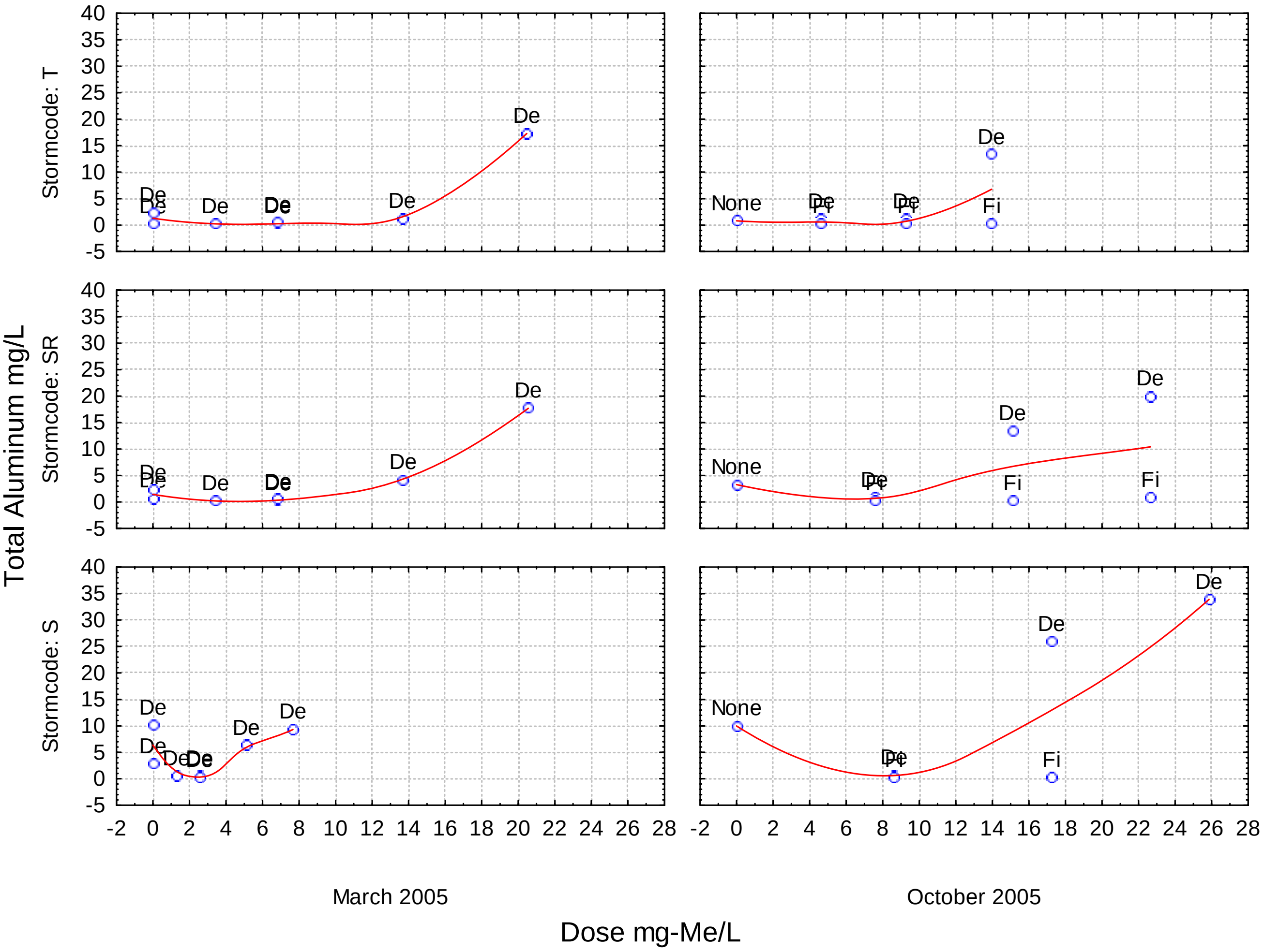


Figure D-21. Dosing alone does not greatly affect fish mortality.
The high fish mortalities (>70%) were recorded for dosed and non-dosed stormwaters collected in May 2004 from Stag and Ski Run. These sites receive urban runoff. May 2004 was a first flush event. Excluding those points, one can see a slight increase in fish mortality as coagulant dosing increases.

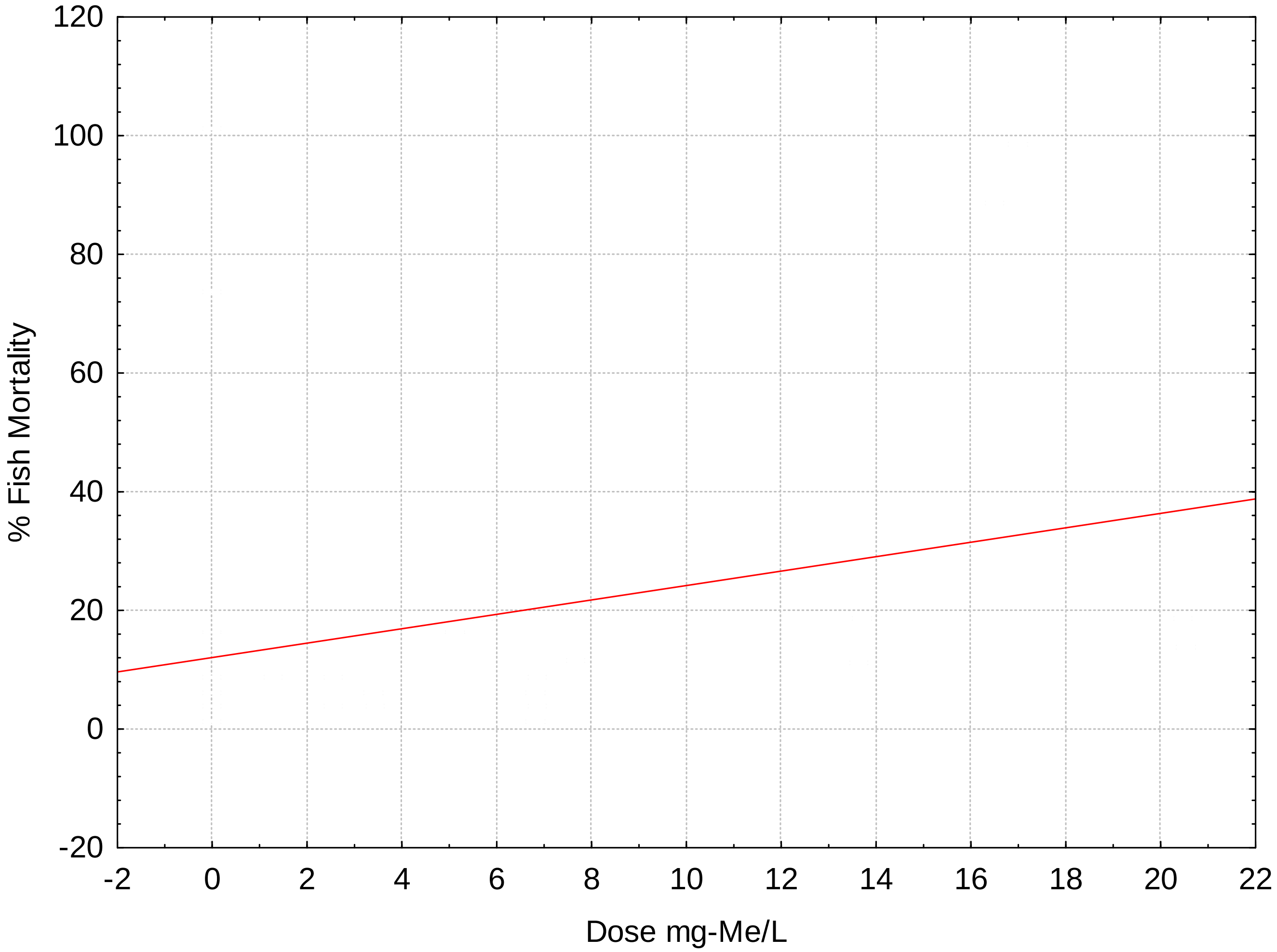
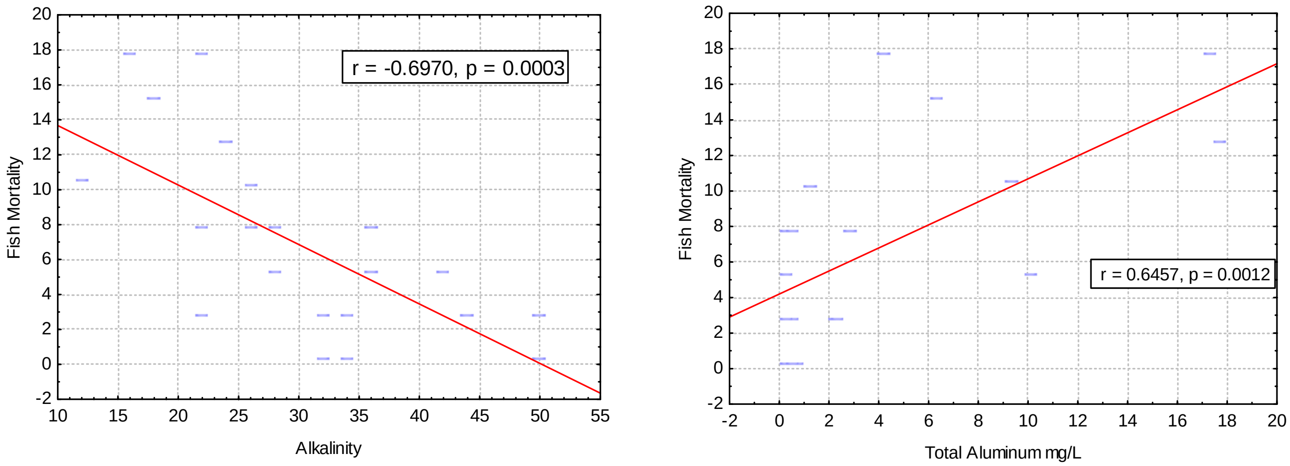
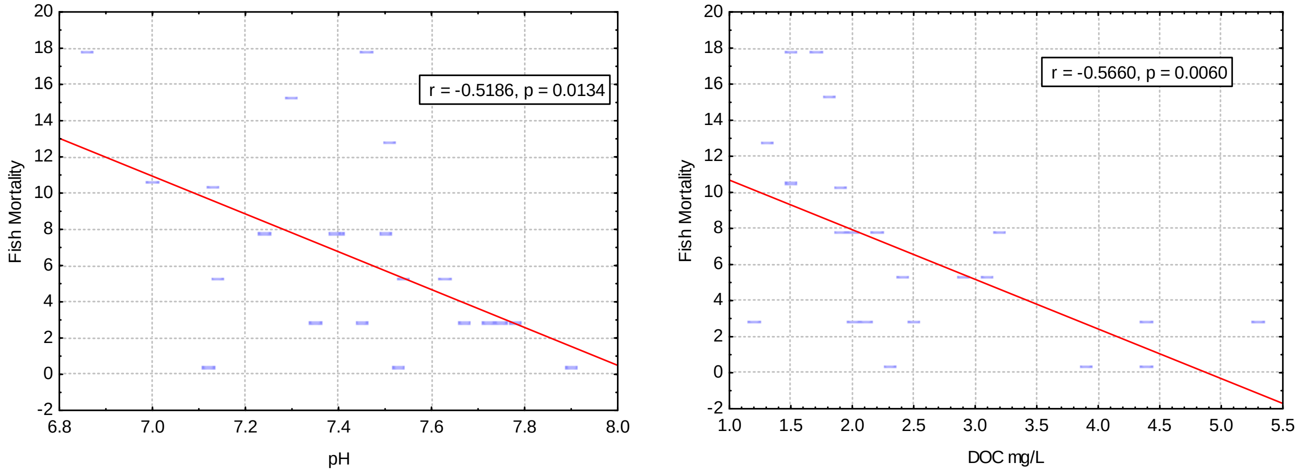


Figure D-22. Factors affection Fish Biomass


A. Alkalinity –

B. Total Aluminum –


C. pH –

D. DOC –

E. Site Selection

This chapter describes the process used to select a technically feasible and desirable site for implementing a Chemical Treatment Mesocosm Study (CTMP) to test low intensity coagulant dosing. The study would be the next step in testing this technology and would be a field scale replicated study. Six to nine treatment cells are planned for this study and each cell would be on the order of a few hundred to a few thousand square feet each. This process was an iterative process with Placer and El Dorado County, the City of South Lake Tahoe and the U.S.D.A. Forest Service. Sites were initially only considered in the City's jurisdiction though in 2004 additional jurisdictions were considered. The most promising jurisdictions aside from the City were El Dorado and Placer Counties.

E.1.Site Selection Criteria

Site selection criteria were developed in October 2003 in a meeting with S. Peck of the City of South Lake Tahoe, Dr. Roger Fuji of the USGS, Dr. Alan Heyvaert of the UC Davis Tahoe Research Group and Dr. Philip Bachand of Bachand & Associates. The criteria are shown in Table 7-1. The criteria addressed issues associated with availability of historical data, implementation logistics, environmental issues and concerns, experimental design considerations and community support.

E.2.Considered Sites and Selection Process

Twenty seven possible sites were identified through surveying the City of South Lake Tahoe, Placer County, El Dorado County and the Nevada Resource Conservation District. Various meetings were set up with representatives of those jurisdictions to discuss and visit the sites.

In October 2003, Steve Peck of the City of South Lake Tahoe discussed with Drs. Alan Heyvaert, Dr. Roger Fujii, and Alan Heyvaert the possible sites located in the City's jurisdiction. The sites were ranked during the meeting and a tour was give by Mr. Peck of the top sites: Glorene and Eighth, Eloise, Osgood at Ski Run, and Stateline. Within the City's jurisdiction, the most opportunities were identified for the Osgood site and this site was considered the top site for studies in the City:

- Treat high volumes,
- Urban watershed,
- Plenty of room for experiments and flexibility for their implementation,
- Opportunities to test variable stormwater quality,
- Good site for showcasing redevelopment activities and progress in addressing stormwater, and
- Twelve EIP projects in the Watershed Master Plan study.

Subsequent meetings were held with Placer and El Dorado County. Placer County gave Dr. Bachand a tour of a number of basins during March 2004: Fox St, Fox St II, Coon St, Cutthroat, Beaver St., Upper and Lower Nile, Barton Creek, Bear St., Brockway Vista and a wetland located outside of Kings Beach. The top opportunities in Placer County were the basins at Fox St. and at Coon St. in Kings Beach. These basins treated urban runoff and were sites of current research and studies. However, neither of these sites was considered to provide the number of overall opportunities as the Osgood site at Ski Run.

Jennifer Quickel of El Dorado County discussed opportunities for possible sites with Drs. Alan Heyvaert and Phil Bachand at a meeting in July 2004 and provided subsequent information in our survey on possible opportunities. A number of sites were identified with the most highly considered sites Cattleman’s Pioneer Trail Basins and the Appalachee Basin Nottawa.

A meeting was held in December 2004 with Jennifer Quickel of El Dorado County, Russ Wigard and Brad Vitro of the City of South Lake Tahoe, Sue Norman of the U.S.D.A. Forest Service, Robert Erhlich of the Regional Water Quality Control Board and Phil Bachand of Bachand & Associates to discuss the top possible sites being considered: Osgood at Ski Run, Cattleman’s Pioneer Trail Basins and the Appalachee Basin Nottawa.

The top site identified in that discussion was the Osgood Basin at Ski Run. This site was selected for any subsequent pilot study if potential toxicity issues could be addressed. Further studies on toxicity were approved to address the City’s concerns. Coagulants to be considered in the toxicity assessment were to be polyaluminum chlorides and chitosan. Table E-1 summarizes the results of the site selection process. A detailed matrix which includes the data compiled for this assessment is in Appendix I.

The U.S.D.A. Forest Service considered this meeting the final step in the site selection process.

Table E-1. Site Selection Criteria Developed October 2003.

	Historical Data	Implementation Logistics	Environmental Issues and Concerns	Experimental Design	Community Support
* Background Data for site such that there is a history of hydrologic and nutrient loading to the site.	X				
* High nutrient loading to the site as indicated by historical data or land use. For land use assessment there is sufficient watershed characterization to predict or estimate nutrient and hydrologic loads.	X				
* Site expected to be online by no later than Fall 2005.		X			
* Experimental design can be easily implemented at site through either integration into current design or through retrofit. Site will accommodate at least 3 treatment cells that will cover only a portion of the site.		X		X	
* No endangered species isssues. Minimial EIR issues.		X	X		X
* Outflow from experimental site will not discharge directly to lake.			X		X
* Current or planned basin design (w/o LICD or other more sophisticated modifications) has potential to be inadequate for future nutrient and hydrologic loads to the site.			X		
* Easy flow monitoring with no backflow at inflow and outflow.		X			
* Enthusiasm from interested local, state and federal agencies.		X	X		X
* Enthusiasm from the City of South Lake Tahoe with likely benefits to the City.		X	X		X

Table E-2. Site Selection Summary

Site Name	Step 1 - Fatal Flaw Based on Water supply or quality, Design, Logistics or Availability	Step 2 & 3 - Qualitative Ranking Criteria and Assessment[1]	Step 4 - General Watershed Assessment
City of South Lake Tahoe			
Stateline		Ranking score, low inflow	
Osgood			
Glorene and 8th		Ranking score, availability	
Eloise			Water supply[5]
West Sierra Track		Ranking score	
Rocky Point		Ranking score[2]	
El Dorado County			
Christmas Valley 2 Industrial Area		Ranking score, availability	
DOT yard in Christmas Valley		Insufficient room	
Cattleman's			Env. Issues & Availability
Pioneer Trail Basins (Kokohnee)	Design & Logistics		
Cole Creek Basin	Design		
Apalachee Basin - Nottawa			Limited Opportunities
Apalachee 2		Design & Logistics - steep	
Black Bart		Ranking Score	
Hekpa		Ranking Score	
Silvertip	Availability - lawsuits		
Patlowe Bike Trail	Design & Logistics		
Placer County			
Fox St			Ranking Score, Limited Opp[4]
Coon Street			Ranking Score, Limited Opp[4]
Bear Street		Ranking Score	
Fox St II/Brockway Vista		Ranking Score	
Cut-throat	Availability		
Beaver	Water supply/quality		
Chipmunk		Ranking Score	
Lower Nile Basin	Water supply/quality		
Upper Nile Basin	Water supply/quality		
Barton Creek	Water supply/quality		
Nevada Resource Conservation District[3]			

[1] Ranking score means in ranking against criteria, site did not score in the top group.
[2] Forest Service interest in site but City saw complications (environmental, logistics)
[3] No highly rated opportunities for urban sites.
[4] Not considered as desirable as top sites in the City of South Lake Tahoe. Fewer opportunities in watershed.
[5] Often dry and may not support longterm studies.

F. Conceptual Design for Implementing LICD at the Basin Scale

The proposed location for implementing the test cells for chemical treatment mesocosm pilot studies are the Ski Run Basins at Ski Run Boulevard and Osgood Street (Figure F-1). This chapter provides background information on the watershed and the basin and develops design concepts for implementing full-scale LICD at this location. This design was developed under a number of considerations:

- Completely passive stormwater treatment systems are unlikely to remove P and fine particles sufficiently to address the regulatory and environmental requirements in the Tahoe Basin (Bachand et al. 2005);
- Economies of scale will become possible with the implementation of the TMDL because resources and manpower will be able to be focused on watershed areas that have greater load discharges and thus through treatment hold the potential for greater load removal;
- Treatment plants can be designed to meet discharge requirements though they are an expensive alternative.

The approach of LICD is to provide a middle opportunity between the completely passive approach and the advanced treatment approach. The goal is to keep costs more modest but provide more effective treatment.

This proposed design presents one possible vision for implementing this technology. We do not recommend moving forward immediately to this scale of implementation as many logistical and technical issues remain. These issues should be addressed at more controlled scales. However, this conceptual design is presented to provide a context to justify the smaller-scale studies and serves as a target design that can evolve with the findings of the smaller-scale controlled studies and with the specific needs of the agencies that might implement this technology.

F.1. Background Watershed and Site Information

Background information on the watershed and the basin is mainly synthesized from the *East Pioneer Trail Watershed Hydrology Study* (Lumos and Associates, 2005). Information in this section is from that source unless otherwise noted. For more detailed background information please see the above report.

F.1.1. Watershed characteristics

Two watersheds contribute to the Ski Run Basins located at Ski Run Boulevard and Osgood Street (Figure F-1)): Keller Canyon Drainage and the Bijou Park Drainage. The Keller Canyon Drainage commences east of the Heavenly Ski Resort and travels northward through residential neighborhoods and densely wooded areas towards Lake Tahoe. It contributes to the basins through conveyance by storm drains. The adjacent commences at the Heavenly Ski Resort parking lot and runoff is conveyed into the Bijou Park Creek, finally entering the City storm drain system. It enters the basins through overland runoff from surrounding roads and from storm drains collecting local runoff. Both watersheds are quite different.

Keller Canyon drainage commences east of the Heavenly Ski Resort and travels northward through residential neighborhoods and densely wooded areas towards Lake Tahoe. It is characterized by steep mountainous slopes, moderate to highly permeable soils, Jeffrey Pine and mixed conifer forest, and relatively clean runoff. Lumos and Associates predicted storm flows from the watershed of 28 cubic feet per second (cfs) for a 2-year storm event, 141 cfs for a 10-year storm event and 300 cfs for a 100-year storm event. The entire Keller Canyon watershed discharges into the northeast outfall of the Ski Run Marino through the Wildwood Basins between Osgood Ave and Lake Tahoe Boulevard (Highway 50) and the Ski Run basins to the west at Osgood Ave, Paradise Avenue and Ski Run Boulevard.

The Bijou Park Drainage is adjacent to the Keller Canyon drainage. It commences at the Heavenly Ski Resort parking lot and runoff is conveyed into the Bijou Park Creek and then into the City storm drain system. Approximately 58 % of the watershed is characterized as high density residential and commercial wit the remaining characterized as low to medium residential. The Bijou Park drainage comprises numerous soil types, all generally well drained with permeabilities up to 13" per hour. It is mostly covered with Jeffrey Pine with the remaining area wet meadows, mixed conifers, aspen and other species. Roads, including Ski Run Boulevard and Highway 50, and paved areas create connected impervious surfaces for surface flows. This characteristic is termed "connectivity" in the Pioneer Trail report (Lumos and Associates, 2005). The Bijou Park Drainage has the highest level of connectivity of the three watersheds that define the South Lake area. A storm drain collects runoff the length of Ski Run Boulevard from Pioneer Trail to the outfall of at the Ski Run Marina, including runoff from the Keller Canyon Drainage. In this watershed, the primary pollutant sources are from heavily used road shoulders and parking lots, specifically at Heavenly Valley. Lumos and Associates predicted storm flows of 68 cfs for a 2-year storm, 380 cfs for a 10-year storm, and 822 cfs for a 100-year storm.

F.2. Ski Run (Osgood) Basins' Characteristics and Nearby Contributing Areas

The two Ski Run (Osgood) Basins are bordered by Osgood Avenue to the east, Paradise Avenue to the south, Ski Run Boulevard to the west and commercial development along Highway 50 to the north (Figure F-1). Together, these basins cover just over 3 acres. Both Keller Canyon and Bijou Park Drainages contribute stormwater to these basins. The westerly cell was planned as a detention basin for the Ski Run area. Water collected in the Ski Run Boulevard drainage system enters the westerly cell. The easterly cell was constructed as SEZ mitigation. It receives stormwater collected in storm drains from the general vicinity and runoff from local streets. The westerly cell has low capacity as water spreads out as overland flow until it reenters the drainage system for conveyance to the Ski Run Marina outfall. An 8" pipe connects the two cells though observations suggest the hydraulic connection is minimal if at all. These two basins are heavily overused. And during large storm events, outflows from the basins feed the Ski Run Marina outfall during large storm events.

The basins are at approximately 6240 ft-NAVD. The basins and the areas to the east and northeast have been defined by the TRPA as SEZ. The local area is defined by loamy coarse sand; residential and commercial development with very few vacant lots; high connectivity along Ski Run Boulevard; and medium to high pollution potential from the immediately surrounding areas.

F.2.1. Pollutants

Pollutants sources along the watershed and to these basins include sediment erosion from Heavenly Valley trails, ski runs, access roads and chairs; de-icing, snow making and mechanical practices in Heavenly Valley; and pollution from heavily used road shoulders and parking lots. High connectivity along the residential and commercial areas along Ski Run is a concern with regard to channeling and loading pollutants to the storm drain system and these basins. Heyvaert et al. (2004) determined that residential and commercial runoff typically exceeds Lake Tahoe discharge standards (Table F-1). Lumos and Associates (2005) showed typical stormwater entering the Ski Run Basins is actually more characteristic of highway runoff, the stormwater with the worst water quality (Table F-2).

F.2.2. Groundwater

A nearby observation well (USGS Site 22) approximately 500 feet north of the Ski Run and Highway 50 intersection shows groundwater on October 2003 was approximately 8 feet below land surface elevation at 6,228.8 ft-NAVD. High water levels in the lake are 6229.3 ft-NAVD, near the water level recorded in the groundwater during October 2003. This information suggests groundwater levels at this location are very near those of the lake and largely controlled by lake levels.

F.2.3. Hydraulic Loading

Table F-3 shows that hydraulic loading to the Ski Run Basins under current and the rerouting conditions suggested by Lumos and Associates (2005). Currently for a 2-year storm, Lumos and Associates (2005) predict flows of 28 cfs and a volume of 14 ac-ft. Lumos and Associates has recommended diverting flows throughout the watershed for a number of reasons. These reasons for diverting flows include providing higher quality stormwaters to Tahoe Meadows to reinvigorate the meadows and reducing erosive stresses in the Heavenly Valley parking lot and the resultant loading to downstream Bijou Park Creek. However, specific to this site diverting flows would reduce the hydraulic loading to these basins but also reduce the water quality of the stormwater entering the basins. Thus, the predicted flow for a 2-year storm event under the conditions of diverted flows would be 6 cfs with a total volume of 4 ac-ft. Similar predictions are made for the 10- and 100-year storm event. Under conditions where flows were diverted, the predicted flows and water volume requiring treatment are about 25 % of the flows predicted under the current conditions.

In reviewing the model results from Lumos and Associates (2005) and understanding the weather in Tahoe, several key characteristics need noting:

- Maximum flows are over four times higher then flows when averaged over a 24-hr period;
- Maximum flows and average flows are about an order of magnitude higher or more for the 100-yr storm event as compared to the 2-year storm event;
- During spring runoff events, flows will be more relatively constant with variations occurring on a diel basis;
- During rain on snow events or during thunderstorms, runoff will be flashy and localized.

F.3. Key Design Issues

Several key design issues we have identified that follow from the watershed and basin description.

F.3.1. Water quality

Stormwater collected in 2004 as inflow to Osgood Basin was relatively poor and characteristic of commercial and highway runoff stormwaters. The surface water discharge standard for turbidity is 20 NTU. The median total suspended solids loading to the Osgood Basins is approximately 150 mg/L and the mean is approximately 200 mg/L. Caltrans (2003) stormwater assessment shows for highway runoff that mean turbidity values measured in NTUs are about 60 to 66 % of mean TSS measured in mg/L, depending upon location and type of runoff (snowmelt, early rain, rain/snowmelt mix). Thus, typical stormwater into the Osgood Basins likely has turbidity in the range of 100 to 125 NTU. This is five to six times higher then surface water discharge standards for turbidity. The basin would need an average removal rate of over 80% to meet surface water discharge standards. This rate is unlikely to be achieved with settling basins alone, given the particle size distribution of stormwaters in the Tahoe Basin and the settling velocities of those particles (Appendix B, this report).

The story for phosphorus is probably worse. Mean and median total phosphorus levels to Osgood are eight to nine times greater then surface water discharge standards.

F.3.2. Flow

Surface water flows to the Osgood Basins are highly variable and can vary by orders of magnitude. Flows during spring runoff events are relatively more constant. Accommodating variations in flows being treated is likely the number one issue for effective treatment.

F.3.3. Groundwater issues

Groundwater levels appear to be very close to surface water levels in the lake during the summer and fall based upon information from Lumos and Associates (2005). Groundwater was approximately eight feet below ground surface elevations in October 2003. Thus, surface water likely infiltrates to groundwater at least during the summer and fall. Groundwater may become raised during the winter and spring in response to infiltration from runoff. In any case, surface water likely infiltrates to groundwater at these locations.

F.3.4. Space

The Osgood Basins are approximately 3 acres allowing for sufficient area for setting up experimental systems. However, the acreage is insufficient for treating storm water volumes predicted for larger events. Table F-3 shows for a 2-year storm event, the basin currently sees 14 ac-ft. Under scenarios where flow is diverted, the volume being delivered to the basin during a 2-year storm event is about 4 ac-ft. Assuming water levels of about 1 to 1.5 feet throughout the entire acreage, if 4 ac-ft is delivered to the basin in 24 hours, that volume is near the maximum treatable with the available acreage.

F.3.5. Toxicity issues

Coagulant dosing will affect toxicity, sometimes increasing toxicity and sometimes decreasing toxicity, depending upon the stormwater and the toxicity metric used (Chapter 3 and Appendices C and D, this report). Surface water outflows from the Osgood Basins are discharged into Lake Tahoe. The basin also likely infiltrates to ground water. Mitigating toxicity will be required for coagulant dosing to be an effective stormwater treatment option.

F.3.6. Integrating Design Changes at Osgood Basins with Overall Improvements to the E. Pioneer Trail Watershed.

The East Pioneer Trail Watershed Hydrology Study (Lumos and Associates, 2005) states many recent erosion control and watershed restoration projects in the E. Pioneer Train Watershed area fall short of current discharge standards for dissolved nutrients and fine particles. Table F-5 shows the report’s recommendations to improve stormwater discharged from the watershed (Lumos and Associates, 2005). The report recommends actions that could be taken to improve stormwater quality entering the lake including stabilizing creeks, restoring SEZs, purchasing priority parcels, and eliminating the Bijou Creek golf course. To improve treatment capabilities of existing basins, the report recommends diverting cleaner stormwaters away from the basins to either Tahoe Meadows or directly to the Lake, and increasing overland flows over meadows. A number of recommendations directly affect the Osgood Basins:

- Expanding Osgood Basins for more treatment potential;
- Consider using adsorptive media in infiltration areas; and
- Implementing low intensity chemical dosing along the commercial corridor.

The report also states that the basin area is inadequate for treating high storm flow events being up to an order of magnitude too small.
Three considerations need to be addressed for implementing LICD at the full-scale:

1. Technical feasibility of coagulant dosing for removing fine particles and phosphorus under in situ conditions;
2. Mitigating potential toxicity issues associated with coagulant dosing; and
3. Logistics of implementing coagulant dosing (or any other stormwater BMP) to meet capacity requirements.

This report and the Caltrans report (Bachand et al., 2006; Appendices A and H) discuss the technical feasibility of coagulant dosing. Coagulant dosing can greatly increase settling times of fine particles and can effectively precipitate phosphorus. This concept has been tested under in situ conditions in the Florida (Bachand et al., 2000) and demonstrated mean total P concentrations in the 20 to 30 µg/L range can be achieved. Others have shown that chemical dosing can effectively remove fine particles from stormwater being discharged from construction sites, and alum effectively decreases nutrient concentrations in lakes. These studies suggest coagulant dosing can be implemented effectively to remove phosphorus and fine particles. The results of the studies on stormwater in the Tahoe Basin and elsewhere suggest coagulants can effectively be used to remove fine particles and phosphorus.

Potential toxicity is the second issue and this issue has been discussed in Chapter 3 and Appendices C and D of this report. Both chemically treated and non-treated stormwaters can be toxic. The use of coagulants to reduce turbidity and phosphorus from stormwaters can decrease or increase toxicity depending upon the stormwater, the coagulant and the dosing level. In situations where coagulants increase toxicity, stormwater wetlands may mitigate toxicity. This hypothesis should be tested under in situ conditions in the Tahoe Basin.

Finally, logistics are an important consideration, some of which are identified below:

- Temperature effects on coagulant performance;
- Freezing and thawing effects on equipment operation, design and specifications;
- Capacity of the system to accommodate order-of-magnitude variations in flows and volumes.

F.4. Conceptual Design for Full-Scale Implementation of LICD – A Target for Experimental Investigations

Figure F-2 presents a conceptual design for implementing coagulant dosing at a large-scale. This design serves as one option towards which smaller-scale studies can be focused. Under this conceptual design, an equalization wetland basin receives and provides storage for stormwater from the watershed and a stormwater treatment wetland subsequently treats the stormwater. A static mixer between the wetlands provides rapid mixing to blend the coagulants and a subsequent raceway provides a slow mixing environment to improve aggregation. These raceways can be fairly simple to construct and can be constructed potentially from wood (Figure F-3). At the outflow of the treatment wetland is a simple filtration system. The exact design of this filtration area is not defined and could be from geotextile fabrics. Another alternative could be using more natural materials such as woven jute (Figures F-3 and F-4). Jute has been used in conjunction with polyacrylamide dosing to remove turbidity in stormwater systems in the south (Iwinski, 2004). The equalization basin could be lined with an adsorptive media specifically for phosphorus removal to minimize export of phosphorus to groundwater (Bachand and Heyvaert 2006).

Table F-4 presents different possible configurations. The configurations are grouped into different scenarios: A, B1, B2, B3 and C. Scenario A represents a treatment wetland without an upstream equalization basin and this represents the typical dry or wet basin or wetland design. Scenarios B1 through B3 represent separate equalization and treatment wetlands, all located at a 4-acre site, which for the purposes of the report is assumed to be the Osgood Basins. Scenario C represents equalization and treatment basins occupying a larger area which for the purposes here are the Wildwood Basis for an equalization basin and the Osgood Basins for the treatment wetlands.

For all the configurations in which an equalization basin is included, the maximum depth for the equalization basin is 6 feet. Also, for all the configurations the maximum and operational depth for the treatment wetland is 1.5 feet, and the assumed treatment time designed for in the treatment wetland is 24 hours.

Scenarios B1 through B3 differ in only the ratio of equalization wetland to treatment wetland. For B1, each basin occupies the same area. For scenario B2, the equalization basin occupies twice the area and for scenario B3 three times the area.

The comparison shows using an equalization wetland greatly increases capacity for the same area used. Equalization wetlands result in an increase capacity of 220 to 290 %. Because the equalization wetlands provide storage, all the water does not need to be treated in the amount of treatment time planned for the treatment wetland. So whereas without an equalization wetland all the stormwater is designed here to be treated in one day, the use of an equalization wetland spreads the amount of time allowable to treat the stormwater to five to thirteen days, depending upon the area ratio.

With the equalization wetlands, the 2.9 acres can treat up to 11 ac-ft of stormwater volume. This is equivalent to a 10-year storm event under the rerouting conditions described in the East Pioneer Trail Hydrologic Study (Lumos and Associates 2005). If the basin configurations are enlarged to include both the Wildwood and Ski Run basins, with the Wildwood Basins used as for the equalization wetlands, the system can the treat up to a 100-yr storm event under the rerouting conditions and a 2-year storm event under current conditions.

In the design shown in Figure F-2, we identify some components considered necessary for implementing LICD under this configuration:

- A pump to move water from the equalization basin to the treatment wetland;
- A pump to dose coagulants;
- A controller and data logger to control the operation of the systems; and
- Necessary sensors to help control the dosing system and properly dose.

The design in Figure F-2 addresses many of the design issues raised earlier.

F.4.1. Water Quality

The conceptual design likely provides a means to remove fine particles and dissolved phosphorus. Coagulation can precipitate dissolved phosphorus and can aggregate fine particles to increase settling velocities by an order of magnitude. Coagulation is a proven technology and should be able to be implemented to meet those goals. Cost, robustness and the logistics of implementation are the likely challenges for implementing coagulant dosing.

F.4.2. Flow

The equalization basins will dampen flow peaks and will extend the period to allow for treatment. When operated at full capacity, the hydraulic retention time in the equalization basin will be in the general range of 4 to 10 days depending upon the exact configuration (Table F-4), allowing time for removal of particles with settling velocities in the range of 0.002 to 0.005 cm/s. Stormwater to the treatment wetlands would be treated with coagulants to precipitate dissolved phosphorus, and aggregate and removal fine particles.

F.4.3. Groundwater Issues

Both wetlands shown in Figure F-2 are designed to minimize infiltration of phosphorus to groundwater. The equalization wetland is lined with an adsorptive media to take up phosphorus and minimize its movement through soils. The treatment wetland will have the formation of coagulated sediments which are likely to have excess capacity for phosphorus uptake (Bachand et al, 2000).

F.4.4. Space

The combination of the equalization and treatment wetlands greatly increase capacity using limited space. Much larger storm events can be accommodated (Table F-4).

F.4.5. Toxicity Issues

Wetlands have been shown to mitigate toxicity and this concept could be tested. Coagulants change stormwater toxicity but as discussed in the preceding chapters, those changes can be positive or negative (Chapter 3 and Appendices C and D, this report).

F.4.6. Other Issues: Safety and Aesthetics

Two other issues need to be addressed with this conceptual design: safety and aesthetics. The equalization basins can be operated in the design shown at 6 feet deep. These depths provide a safety issue at high flows and would need to be addressed.

The equalization basin could be constructed in many ways. One way would be to have it deeper into the soils. This is likely to increase damper conditions in the equalization basin as compared to the treatment wetland. Thus, the equalization wetland and treatment wetland would be expected to have different vegetation conditions. Both would be expected to be wetlands. Even with potential operating depths of six feet, wetland vegetation would be expected to persist because of the relatively short duration of those deep water conditions.

F.5. Estimated Costs for Implementing Chemical Dosing

Table F-6 presents an estimate for costs to implement Option C from Table F-4 and as discussed previously. Table F-6 shows the assumptions used for developing the cost estimates and some important assumptions are listed below:

- *Costs for the chemical dosing system are based upon Harper et al. (1999). Harper et al (1999) is a review of the systems built to treat stormwater with alum, detailing the successes, issues, feasibility and costs. Harper et al (1999) was used to estimate both the capital costs associated with construction as well as the O&M costs.*
- *Wetland and pond costs are based upon costs for the Bay Area.*
- *A 20% contingency was applied to all estimates.*
- *Capital costs included estimates for the chemical dosing system, for building of the ponds and for demolition.*
- *Land costs were not included in the capital costs.*
- *O&M costs included those O&M costs associated with the ponds/wetlands and with the chemical dosing system.*
- *Monitoring costs were for bi-weekly sampling of the system at two locations. Analytes sampled for were P, turbidity and pH. An additional lump sum was applied to account for other monitoring needs. In addition to water quality monitoring, flow monitoring at one location was also assumed.*
- *Construction of the ponds was for the design shown in Figure F-2 and included raceways and filter zones constructed to improve pond performance.*
- *Technician support assumed an annual salary of about $46K with 25% benefits and a 200% overhead multiplier.*
- *All costs have been converted to 2007 dollars using a 3% annual increase.*
- *Engineering costs were assumed to be 15% of the construction costs.*

Based upon the above assumptions, the capital costs estimated for this project were about $406K for construction of the treatment ponds and wetlands, the stormwater dosing system and the electrical power modifications. Instrumentation installation was an addition $15K. Including contingencies and engineering and design costs, the total capital costs were estimated at about $600K.
Associated Operation and Maintenance (O&M) costs are estimated at about $50K. These costs are for all O&M costs associated with the treatment ponds and wetlands, and the chemical dosing system. O&M costs are essentially split down the middle between the ponds and wetlands, and the dosing system.

Annual monitoring costs are estimated at about $40K. These costs include regular sampling of regulated discharge parameters (e.g. phosphorus, turbidity, pH), flow monitoring, and an additional lump sum for other water quality parameters, not defined here.

Assuming a 3% interest rate, the 20-year Present Worth is about $2 Million.

F.6. References

Army Corp of Engineers (ACOE). 2003a. Lake Tahoe Basin Framework Study, Groundwater Evaluation. US Army Corps of Engineers, Sacramento District. Draft Final Report, June 2003.

Bachand, P.A.M, A. Heyvaert, J. Darby, S. Crawford. 2006. Using coagulants to dramatically increase settling rates of fine particles in Tahoe stormwaters and their implications on basin design and water quality. Chapter 3 this report prepared for publication.

Bachand, P.A.M., S.M. Bachand, A. Heyvaert and OWP. 2005. Task 2. BMP treatment technologies, monitoring needs, and knowledge gaps: Status of the knowledge and relevance within the Tahoe Basin. By Bachand & Associates, UC Davis Tahoe Research Group and Office of Water Programs at CSUS. In: Stormwater Best Management Practices in the Tahoe Basin, Review of Current and New Technologies in Stormwater Management By M.L. Johnson, John Muir Institute of the Environment, Aquatic Ecosystem Analysis Laboratory, University of California, Davis. Prepared for El Dorado Department of Transportation, October 31, 2005.

California Department of Transportation (Caltrans). 2003b. Caltrans Tahoe Highway Runoff Characterization and Sand Trap Effectiveness Studies. 2000-03 Monitoring Report. June 2003. CTSW-RT-04-054.36.02.

Harper , H.H.; H err, J.L.; and L ivingston, E.H . (1999) Chapter 9 : Alum Treatment of Stormwater: the First Ten Y ears. In: *New Applications in Modeling Urban Water Systems.* Monograph 7 in the series. W. James, Ed. Pub. by CHI, Guelph, Canada,159.

Heyvaert, A.C., J.E. Reuter and E. Strecker. 2004. Evaluation of Selected Issues Relevant to the Design and Performance of Stormwater Treatment Basins at Lake Tahoe. Draft Final prepared by the Tahoe Research Group and Geosyntec Consultants. September 10, 2004.

Iwinski, S.R. 2004. Soil Specific Polymer Blend, Applications and Corresponding BMPs. Presentation at the CONFERENCE ON ADVANCED TREATMENT FOR CONSTRUCTION SITES, October 21, 2004, California State Water Resources Control Board Water Quality Storm Water Program. http://www.swrcb.ca.gov/stormwtr/advtreatment.html, http://www.swrcb.ca.gov/stormwtr/docs/advtreat/appliedpolymer.pdf.

Lumos and Associates, Inc. 2005. East Pioneer Trail Watershed Hydrology Study Final Report. Submitted to City of South Lake Tahoe and California Tahoe Conservancy. October 2005. Prepared by Lumos and Associates, Inc., Carson City, NV 89706. cc@lumosengineering.com

Reuter, J.E., A.C. Heyvaert, M. Luck, S.H. Hackley, E.C. Dogrul, M.L. Kavvas, and H. Askoy. 2001. Investigations of Stormwater Monitoring, Modeling and BMP Effectiveness in the Lake Tahoe Basin. 205j grant technical report to the Tahoe Regional Planning Agency, Stateline, NV and to the California State Water Resources Control Board, Sacramento, CA. November 30, 2001.

Strecker, E. and J. Howell. 2003. Preliminary Water Quality Evaluation for Lake Tahoe TMDL. Draft Technical Report prepared by GeoSyntec Consultants for Lahontan Regional Water Quality Control Board. South Lake Tahoe, CA. October 10, 2003.

Table F-1. Estimate for selected pollutants from different land uses.

Shaded cells indicate where current surface water discharge standards are exceeded for specific PoC (e.g. TN, TP, TSS, turbidity). Darkly shaded areas show where the surface water discharge standard is for specific PoC that are regulated (e.g. TN, TP and turbidity). Lightly shaded areas show where particular specie for a PoC exceeds the surface water discharge standard. For instance, TKN alone exceeds the TN surface water discharge standard. In some cases, infiltration standards are also exceeded. The infiltration standard for TP is 1 mg/L and that standard is exceeded by Highway runoff, which has an average TP concentration of 1.21 mg/L. TSS is one measure for monitoring the discharge of solids. Turbidity is another metric and the relationship between TSS and turbidity depends upon the source. The data presented for turbidity is from Caltrans (2003b). In the Tahoe Basin, the TSS/turbidity ratio is approximately 1.4. The table presented is modified from Heyvaert et *al.*, 2004 (with data from Strecker and Howell 2003, ACOE 2003a, Reuter et *al.* 2001) and includes data from Caltrans 2003b.

Source [1]	**Pollutants of Concern**[3]						
	NO3-N (mg/L)	**TKN** (mg/L)	**TN**[2]	**SRP** (mg/L)	**TP** (mg/L)	**TSS** (mg/L)	**Turbidity** NTU
Surface Water Discharge Std			0.5		0.1		20
Runoff, undisturbed forested area	0.01	0.14	0.15	0.01	0.02	3	
Residential area runoff	0.05	1.41	1.46	0.03	0.26	431	464[4]
Commercial area runoff	0.2	2.16	2.36	0.14	0.54	178	503[5]
Highway runoff	0.25	1.84	2.09	0.11	1.21	1133	
Forested area groundwater	0.12	0.06	0.18	0.05	0.07	--	
Residential area groundwater	0.37	0.26	0.63	0.08	0.11	--	
Commercial area groundwater	0.51	0.16	0.67	0.09	0.12	--	
Recreational use area groundwater	0.42	1.26	1.68	0.07	0.1	--	
Precipitation at Tahoe	0.2	0.2	0.4	< 0.03	0.04	13	3.8

1. Groundwater NO_3-N includes nitrite, and groundwater TP represents total dissolved phosphorus as reported in ACOE (2003a).
2. Calculated value from the addition of nitrate and TKN.
3. Light shading shows that one specie of pollutant exceeds surface water discharge std. Dark shading shows that pollutant total (e.g. TP, TN, TSS) exceeds the surface water discharge standard.
4. Rural (Caltrans 2003b)
5. Urban (Caltrans 2003b)

Table F-2. Water Quality to Osgood Basins during 2004 Water Year (Lumos, 2006).

		Median	Mean	Stdev	N
TKN	mg-N/L	2.06	2.1	1.07	9
NO3-N	mg-N/L	0.06	0.1	0.09	8
NH4-N	mg-N/L	0.04	0.14	0.15	9
TP	ug/L	880	950	850	9
TDP	ug/L	90	100	60	9
SRP	ug/L	60	80	50	9
TSS	mg/L	156	197	190	9

Table F-3. Existing and Predicted Flows (cfs) to Osgood Basins.

Predicted flows are under conditions where less polluted runoff from upper watersheds is routed to (from Keller Canyon) to Lake Tahoe and (from upper Bijou Park Drainage) to Bijou Meadow.

Storm Event[2]	Current Conditions			Rerouted Flows[1]		
	High Flow (cfs)	Volume (ac-ft)	Average 24-hr Flow (cfs)	High Flow (cfs)	Volume (ac-ft)	Average 24-hr Flow (cfs)
Q_2	28	14	7	6	4	2
Q_{10}	168	44	22	49	11	6
Q_{100}	363	88	44	90	24	12

[1] Rerouting cleaner flows from upper watershed.

[2] For 2-, 10- and 100-year storm event

[3] Volumes are estimated from HEC model difference of "CP 61B_1" minus 'CP 74B_1'

Table F-4. Design options for stormwater treatment basins at Osgood and Wildwood Basins

Scenario		**A**	**B1**	**B2**	**B3**	**C**
Parameter	**Unit**	**Value**				
Eq:Tr Area[1]	Ratio	0:1	1:1	2:1	3:1	1.7:1
Locations used[3]						
Osgood Basins		T	T & E	T & E	T & E	T
Wildwood Basins						E
Total Wetland Area[2]	Acres	2.9	2.9	2.9	2.9	8.1
Assumed wetland area to parcel area		85%	75%	75%	75%	75%
Total Wetland Area for Stormwater Processing[4]	Acres	2.5	2.2	2.2	2.2	6.1
Equalization Wetland Specifications						
Max Depth	Ft	6	6	6	6	6
Area	Acres	0.0	1.1	1.5	1.6	3.8
Capacity	Ac-ft	0.0	6.5	8.7	9.8	23.0
Treatment Wetland Specifications						
Operating Depth	Ft	1.5	1.5	1.5	1.5	1.5
Area	Acres	2.5	1.1	0.7	0.5	2.3
Capacity	Ac-ft	3.7	1.6	1.1	0.8	3.4
HRT	days	1	1	1	1	1
Flow	ac-ft/d	3.7	1.6	1.1	0.8	3.4
	cfs	1.9	0.8	0.5	0.4	1.7
Combined System Specifications						
Total Capacity	Ac-ft	3.7	8.2	9.8	10.6	26.3
Time to treat all stored water		1.0	5.0	9.0	13.0	7.8
Treatable Storm Event by Volume (ac-ft)						
Current Conditions						
Q_2 14	%	26%	58%	70%	76%	188%
Q_{10} 44	%	8%	19%	22%	24%	60%
Q_{100} 88	%	4%	9%	11%	12%	30%
Q_2 4	%	92%	204%	245%	265%	658%
Q_{10} 11	%	34%	74%	89%	96%	239%
Q_{100} 24	%	15%	34%	41%	44%	110%
Estimated maximum depth of Equalization Basin						
Current Conditions[5]						
Q_2 14	ft	NA	6.0	6.0	6.0	3.2
Q_{10} 44	ft	NA	6.0	6.0	6.0	6.0
Q_{100} 88	ft	NA	6.0	6.0	6.0	6.0
Rerouted Conditions[5]						
Q_2 4	ft	NA	2.9	2.5	2.3	0.9
Q_{10} 11	ft	NA	6.0	6.0	6.2	2.5
Q_{100} 24	ft	NA	6.0	6.0	6.0	5.5

[1] Equalization to Treatment Area

[2] Based upon basins identified for use

[3] T = Treatment Wetland; E = Equalization Wetland

[4] Processing defined as storage and treatment

[5] Lumos and Associates hydrologic scenarios

Table F-5. Opportunities and Constraints Matrix (From Lumos and Associates, 2005)

Item #	Opportunity Description	Watershed Area	Benefits	Constraints	Feasibility
1	Acquisition and restoration of sensitive (SEZ) parcels, both developed and un-developed	Entire watershed	Restoration of sensitive areas (SEZs); creation of open space; reduction of impervious coverage; Highest water quality benefit; additional water quality treatment area; protection of sensitive lands	Cost; willingness of owners to sell developed parcels	Medium-High
2	Construction of water quality treatment basins using filtration materials, such as dolomite.	Entire watershed	Improved water quality treatment effectiveness in difficult areas	Cost; maintenance; effectiveness not "definitely" known.	Medium-High
3	Stabilization of road shoulder and elimination of road shoulder disturbance by parking in all lower watersheds (higher density residential areas)	Entire watershed	Improved water quality at the source; source control	Difficulty in stabilization and elimination of parking w/o creating connectivity; public reaction to reduced parking areas	Medium-High
4	Elimination of coverage (soft and hard); elimination of roadways	Entire watershed	Improved water quality; increase infiltration; restore to more "natural" condition; ease downstream treatment pressure	Elimination of roadways reduces/restricts fire protection	Medium-High

Item #	Opportunity Description	Watershed Area	Benefits	Constraints	Feasibility
5	Installation of private property BMPs to reduce impact of private properties on City drainage system	Entire watershed	Improved water quality; reduced flows; less "strain" on City system, in particular Bijou Park Creek	CTC funds not able to be used on private property projects; TRPA/Lahontan can not "force" the issue until 2006; outside of the control of City/CTC	Low-Medium
6	Installation of new water quality treatment technologies, such as, low intensity chemical dosing, in small areas with high pollution concentrations	Entire watershed (Commercial Corridor)	Improved water quality treatment; area required for treatment facilities educed, thus lowering need for acquisition	Treatment efficiency unknown at this time; cost of installation and maintenance; public perception of "chemicals" used for treatment	Medium
7	Re-routing of Keller Canyon Drainage to the meadow, between Beach and Meadow Road, in the Tahoe Meadows Subdivision; construction of water quality treatment basin, and/or restored SEZ in the Tahoe Meadows	Keller Canyon	Reduced runoff and treatment pressure on Osgood Basins, improving performance; provide irrigation for dry and dying meadow; reduce flood hazard in Bijou Park	Costs associated with conveyance to the meadow; coordination and permission with the Tahoe Meadows Subdivision and home owners; potential utility conflicts	Medium - High
8	Re-establish Drainage Path near access road at the terminus of the Keller Canyon surface flow, near Tahoe Tyrol	Keller Canyon	Minimized potential for future failure of channel in its current location; restore channel to its original/natural condition for water quality benefits	Sanitary Sewer line existing in the vicinity along with utilizing existing easements and right-of-ways; area available for restoration may be limited due to adjacent property encroachment	High

Item #	Opportunity Description	Watershed Area	Benefits	Constraints	Feasibility
9	Reconstruction/modifications to the Osgood Basin area	Keller Canyon	Improved water quality treatment capacity in the area; remove outfall to Ski Run Marina and route to under-utilized wildwood basin system decreasing stress on the outfall	No apparent constraints	High
10	Reconstruction of the Ski Run Marina Outfall to provide capacity for watershed and relocate out of Marina area	Keller Canyon	Provide adequate capacity for outfall; removal of outfall from the Marina will increase water quality by not "disturbing" dirty water in Marina; reduced flood hazard	Proposed location of new outfall limited to few locations; size of outfall very large; cost	Medium-High
11	Expansion of Wildwood basins, above Highway 50 for additional water quality treatment area	Keller Canyon	Improved water quality by additional residence time and more "wetland" treatment	Cost of acquisitions of Highway 50 and residential properties; willingness of property owners to sell	Medium
12	Re-route of eastern Heavenly Valley flow to Keller Canyon	Keller Canyon & Bijou Park	Reduced flows in the Bijou Park drainage, thus improving water quality efficiency in the drainage and reducing pressure on outfall at Ski Run; reduced flooding potential upstream of Super 8	Cost; potential utility conflicts; easement/right-of-way acquisition potential; alteration of existing drainage paths	Medium
13	Heavenly Valley Ski Area installation of BMPs on upland areas and parking lot to eliminate or reduce stormwater to City drainage system	Bijou Park	Improved water quality; reduced flows; less "strain" on City system, in particular Bijou Park Creek; reduced flood hazards	CTC funds not able to be used on private property projects; TRPA/Lahontan can not "force" the issue until 2008; outside of the control of City/CTC	Low-Medium

Item #	Opportunity Description	Watershed Area	Benefits	Constraints	Feasibility
14	Installation of water quality treatment basins in the lower Bijou Park Creek Drainage	Bijou Park	Improved water quality treatment capacity in the area	Property acquisition necessary, cost	Medium
15	Creation of a "flow through" system in the drainage between Pioneer Trail and Super 8	Bijou Park	Improved water quality treatment effectiveness by dispersing flows in a "natural" fashion (overflow bank method similar to flood plains in streams/rivers); restore SEZ and sensitive lands	Property acquisition necessary; cost	Medium-High
16	Relocation of Super 8 Motel to the northwest corner of Ski Run Boulevard and Highway 50 (vacant lot); restoration of SEZ in current Super 8 location; construct water quality treatment system	Bijou Park	Improved water quality treatment; restoration of SEZ; elimination of drainage system "under" a structure	Cost; willingness of Super 8 owner to relocate; willingness of Embassy Vacation Resort to "sell" property for construction of new Super 8	Low
17	Reconstruction of the Bijou Park drainage system between Super 8 and lower Ski Run Boulevard Drainage	Bijou Park	Elimination of "forced" flow in system; elimination of old system, in an unknown location; provide a maintainable system; provide adequate capacity; reduce flooding potential upstream of Super 8	Cost; easement/right-of-way acquisition; Caltrans encroachment; potential jack-and-bore work required	Medium

Item #	Opportunity Description	Watershed Area	Benefits	Constraints	Feasibility
18	Diversion of Bijou Park Creek Drainage, above Needle Peak Road, to the Bijou Creek Watershed	Bijou Park & Bijou Creek	Reduced flows within the lower Bijou Park Creek Drainage and flows to the Ski Run Marina Outfall; increase efficiency of SEZ treatment in the lower Bijou Park Creek Drainage; provide additional moisture (stormwater) for Bijou Meadow; reduced flood hazard in Bijou Park	Cost; deep excavation for rerouting on Needle Peak Road west of Ski Run; potential utility conflicts; alteration of historic drainage paths	Medium
19	Installation of Water Quality Treatment Basins - Walk-up, Becka, Glenwood area	Bijou Park & Bijou Creek	Restoration of sensitive areas (SEZs); removal of sediment and nutrients; overall water quality treatment improvement	Cost to acquire land; acquisition of enough land to build enough treatment area; exiting utility conflicts unknown	Medium
20	Installation of water quality treatments in the upper Bijou Meadow and Upper Bijou Park Drainage systems (below Pioneer Trail) on public land	Bijou Park & Bijou Creek	Improved water quality; restore sensitive lands; cost effective due to land already under public control	"Getting" appropriate amount of runoff to these areas; potential utility conflicts unknown	High
21	Coordinated water quality treatment system between City, Caltrans and Bijou Center property owners	Bijou Creek	Improved water quality treatment, from the worst point source in the Tahoe Basin; eliminate direct discharge to Lake Tahoe from Highway and commercial uses; upgrade outfall capacity and reduce flood potential	Cost; coordination of Caltrans and private property owners; acquisition of enough land to provide adequate treatment area	Low

Item #	Opportunity Description	Watershed Area	Benefits	Constraints	Feasibility
22	Water quality treatment basin adjacent to Don Cheapo's outfall	Bijou Creek	Provides water quality treatment for an outfall that currently has none; constructed on CTC controlled land	Elevation of existing drainage system; land capability; visual corridor considerations	High
23	Elimination of the Bijou Golf Course	Bijou Creek	Elimination of fertilizer application; use of golf course area for water quality treatment basins	Loss of revenue to City; loss of recreation in South Shore	Low
24	Relocation of Bijou Golf Course to a location "higher" in the meadow	Bijou Creek	Relocation of fertilizer application to an area "higher" in the meadow and further away from the Lake; "freeing" up area where water quality treatment basins can be built near the lower end of the watershed	Permitting difficulties; funding difficulties; public perception	Low
25	Stormwater lift station to relocate highly polluted stormwater from intense use areas to high capability land (in particular Bijou Shopping Center area)	Bijou Creek	Reduced amount of acquisition required; minimal groundwater/stormwater interaction	Utility conflicts unknown; cost; need to separate highly polluted runoff from typical residential and cleaner runoff	Low

Table F-6. Estimated costs for chemical dosing system.

Description			Unit	Unit cost	Quantity	Costs
Direct Capital Costs				**$**		
A	**General**					
		mobilization and demobilization	$	$10,000	LS	$ 10,000
B	**Construction**					
	1	Ponds and Constructed Wetlands (Option C)[16]				
	a	Excavation, placement and compaction of sediments. Includes levee construction.[1]	$/cubic yd	$4.92	11062	$ 54,422
	b	Baffled raceway for slow mixing	$	$20,000	LS	$ 20,000
	c	Outflow jute filter	$	$20,000	LS	$ 20,000
		Pond subtotals				$ 94,422
	2	Stormwater dosing system[17]	$	$302,547	LS	$ 302,547
	3	Electrical power distribution[7]	$/mile	$98,390	0.10	$ 9,839
		Construction Subtotal				***$ 406,807***
C	**Land Purchases**					
		Pond and wetland area	$/acre			Not included
D	**Instrumentation**					
		Flow Monitoring equipment and installations	$	$15,000	LS	$ 15,000
Total Direct Capital Costs						**$ 431,807**
Contingency			%	$0.20		$ 86,361
Total, Direct Costs with Contingency						**$ 518,169**
Indirect Capital Costs						
		Engineering and Design costs[9]	%	$0.15	LS	$ 77,725
Total Direct and Indirect Capital Costs including 20% contingency						**$ 595,894**
Annual Operating and Maintenance (O&M) Costs						
	1	***Ponds and Wetlands***				
	a	Water Level Management and Control	$/hr[13]	$55.00	40	$ 2,200
	b	Vegetation Control	$/hr[13]	$55.00	80	$ 4,400
	c	Mosquito Control	$/hr[13]	$55.00	120	$ 6,600
	d	Levee Repair[14]	$/foot	$9.84	330	$ 3,244
	e	Oversight and Management[13]	$/hr[13]	$55.00	40	$ 2,200
	f	Miscellaneous	% Annual Operating Costs	$0.20		$ 3,729
		Subtotal Ponds and Wetlands				***$ 22,373***

2 Chemical Treatment System chemical, power, manpower for routine inspections, and equipment renewal and replacement costs[17]		$21,285	LS	$	21,285
Total Annual O&M Costs				**$**	**43,658**
Contingency	%	$0.20		$	8,732
Total O&M Cost s with Contingency				**$**	**52,390**
Water Quality and Flow Sampling and Monitoring					
a Sampling and monitoring, Labor[10]	$/hr	$55.00	104	$	5,720
b Sample analyses (turbidity, TP, ortho-P, pH, total Al, soluble Al); Two sample locations	$/analyte	$25.00	312	$	7,800
c Miscellaneous Analyses	$	$10,000	LS	$	10,000
d Flow data calibration and maintenance	$/hr	$55.00	120	$	6,600
e Data analyses	$/hr	$100.00	40	$	4,000
Subtotal Water Quality and Flow Sampling and Monitoring				***$***	***34,120***
Total Annual Monitoring Costs				**$**	**34,120**
Contingency	%	$0.20		$	6,824
Total Monitoring Cost s with Contingency				**$**	**40,944**
20-yr Present Worth (2007 dollars, 3% interest rate)				**$**	**1,984,467**

Notes

1 Roger Leventhal. Montezuma bid information. $4/LF plus corrected with 3% annual interest. July 2001.

7 Cost estimated by CRA (2000). Corrected for 2007 $'s.

9 Based upon % construction costs

10 Sampling every other week requiring 4 Hrs per day of sampling for prep, sample collection and necessary paperwork.

13 55 $/hr is equivalent to about $46K per year with 25% benefits and a 200% OH multiplier.

14 Assumes levees are repaired on a 10 year cycle. $8/ft (CDFG)

16 Includes wetlands/ponds at both Osgood and Wildwood using Option C.

17 Harper et al (1999). Corrected for 2007 $'s.

18 Assumes treatment system will be retrofit of existing system

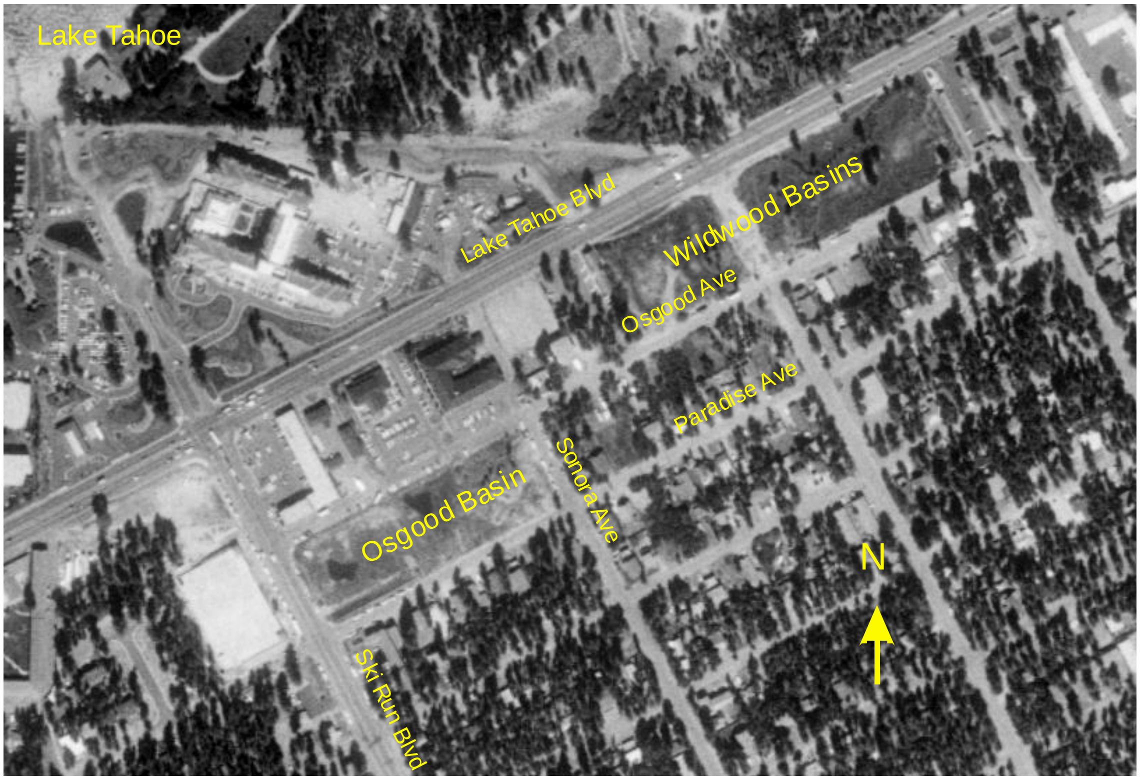


Figure F-1. Aerial photograph of Osgood and Wildwood Basins along the south shore of Lake Tahoe.

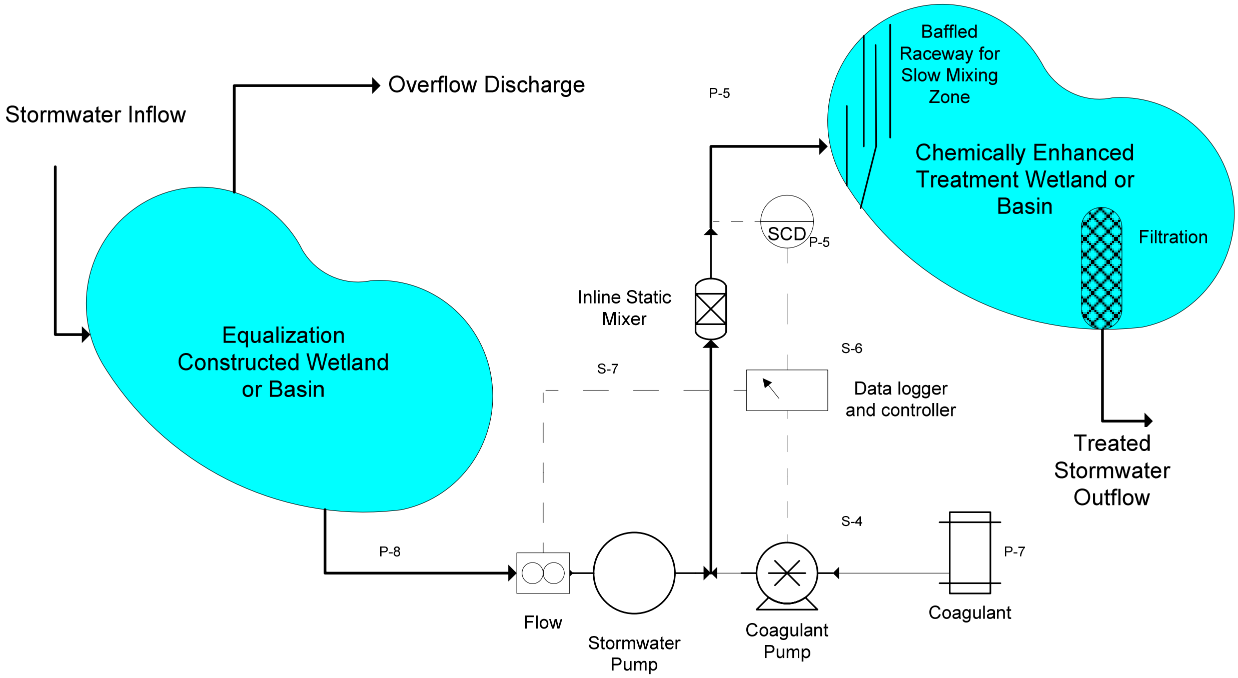


Figure F-2. Conceptual Process Flow Diagram for Stormwater LICD System.

Figure F-3. Particle curtains of woven jute on wood frames (Iwinski, 2004).

Figure F-4. Baffle grids used for filtering treated stormwaters (Iwinski, 2004).

G. Pilot Study Conceptual and Experimental Design

This chapter focuses on the proposed conceptual and experimental design for in situ mesocosm and pilot studies to test and optimize Low Intensity Chemical Dosing. The approach planned for testing this technology is by using two complementary experimental systems. The first recommended system is a small-scale mobile system to optimize coagulant dosing methods at a scale-more representative of full-scale studies. These tests are all based upon processes that are energy or flow dependent, such as mixing regimes and methods to improve flocculate aggregation. The second recommended system is a replicated mesocosm systems. These systems would test processes that are time dependent, such as the time to settle flocculates, changes in water quality or sediment chemistry overtime and time effects on toxicity.

G.1. Small-scale mobile pilot study

The small-scale mobile pilot study will be conducted to test processes that are scalable based upon dynamic processes such as velocity and energy. For this technology, these processes include selecting and understanding static mixers that will provide sufficient energy to initially mix coagulants with stormwater at a larger-scale; and modeling velocities and times that provide sufficient slow mixing for flocculate aggregation in order to better design the slow mixing region in the full-scale system. Additionally, this study could also be used to assess the initial toxicity of non-dosed and dosed stormwaters under in situ conditions.

The process flow diagram for this mobile pilot is shown in Figure G-1. Stormwater is pumped from a stormwater source through a static mixer where it is dosed with coagulant. Some of the dosed coagulants are slip-streamed to a slow mixing tank where flocculate aggregation is monitored. Water samples are expected to be collected to measure performance indicators such as ortho-phosphorus and turbidity, but also for a subset of samples to measure additional metrics such as particle size distribution (PSD), streaming current value (SCV) and toxicity metrics such as the toxicity to zooplankton.

This study would have a number of hypotheses and goals as shown in Table G-1. These goals and hypotheses related to determining operational parameters and also determining initial water quality effects.

G.2. Mesocosm Study

The mesocosm study will enable studying time-dependent processes such as phosphorus and fine particle removal in the water column, changes in sediment over time, changes in toxicity over time and soil accretion (Table G-1). Figure G-2 presents the process flow diagram for the mesocosm study. Stormwater is stored on site to provide a volume for experimentation. Treatment stormwater can either be chemically dosed stormwater or non-dosed stormwater depending upon the treatment. Treatment stormwater enters the mesocosm and flows at low velocities through a raceway to allow for flocculate aggregation. Stormwater then passes

through the mesocosm for a defined hydraulic residence time, eventually flowing through a particle curtain to help capture any remaining flocculate before being discharged.
At the Osgood Basin, there is infiltration to groundwater. To assess groundwater effects, the mesocosm cells are lined (Figure G-3) and groundwater is captured from the underlying soils. Analyses of groundwater will show how the different treatments affect groundwater transport of phosphorus and other constituents.

The treatments planned are two chemical dosing treatments, one control and one in which no dosing is conducted of surface waters but adsorptive media is blended with the soils (Table G-2). These treatments would test chemical dosing of both a polyaluminum chloride and of chitosan. Polyaluminum chlorides have been determined to be the more effective coagulants for removing P from Tahoe stormwaters (Bachand et al. 2006). The community in the Tahoe Basin still is interested in chitosan because of concerns about using chemicals in the Tahoe Basin and potential toxicity and environmental issues. The treatment in which adsorptive media is blended with the soils is intended to simulate the equalization basin concept discussed in Chapter 8. Adsorptive media could be blended with the equalization wetland's soils to help retard the movement of surface water P to groundwater (Bachand and Heyvaert, 2006).

This design will address both surface and groundwater effects for a number of issues (Table G-1):

- Fate and transport of phosphorus and aluminum
- Temporal wetland effects on toxicity
- Changes in soil and groundwater chemistry
- Effects on vegetation
- Diel effects on surface water and flocculate sequestration

G.3. Planned Scope of Work

Several goals are planned for the next phase:

1 Validate the effectiveness of LICD for removing phosphorus and fine particles under *in situ* conditions at a realistic scale and identify the variables affecting performance and robustness;
2 Identify how temporal variance in stormwater flow and quality affects performance and develop strategies to accommodate the variance;
3 Separate out biotic and abiotic factors controlling P and fine particle removal;
4 Characterize the retardation of dissolved P in the sediments and describe how the sediments may affect P transport to subsurface groundwater;
5 Identify resulting changes in soil biogeochemistry and define the fate of flocculates and their associated P and fine particles formed during chemical dosing;
6 Assess ecotoxicity affects from treated and non-treated stormwaters and quantify how the basins affect ecotoxicity through biotic and abiotic processes;
7 Extrapolate findings to other regions in the Tahoe Basin; and

8 Develop recommended standards for implementation and monitoring of this technology at a demonstration scale.

To accomplish these goals, the Scope of Work would need to include a number of components:

1. Design and construction of mobile pilot study;
2. Optimizing LICD operation with mobile pilot study and assessing initial in situ toxicity effects;
3. Design and construction of mesocosms including an assessment of most state-of-the-art stormwater treatment;
4. Mesocosm studies to assess a number of issues:
    a. Determine residence time for optimal performance,
    b. Characterize changes in particle size distribution and density of formed precipitates;
    c. Assess biotic effects on toxicity and toxicity changes over time,
    d. Determine fate and transport of phosphorus and aluminum,
    e. Determine accretion rates,
    f. Characterize changes in vegetation and soil chemistry;
5. Outreach;
6. Recommendations for demonstration or full-scale implementation; and
7. Reports and manuscripts.

Table G-3 presents analytical methods likely to be used.

G.4. Estimated implementation Costs for Experimental Study Components

Costs for similar studies have been developed in earlier proposals (Bachand et al.). Cost estimates for the mesocosm systems are approximately $2 million dollars over a duration of 3 to 4 years (Bachand et al..). These experiments would test performance as well as toxicity. Cost estimate worksheets are provided in Appendix K.

G.5. Key Management Questions (KMQ) Addressed

Several KMQs will be addressed as they relate to LICD and related CEMP/AT technologies. This project will be a process based, replicated assessment of both biotic and abiotic treatment processes. It will identify and measure the removal of specific pollutants (e.g. dissolved and particulate P, turbidity, particle size distribution) and will manipulate the operation of the pilot studies such that specific design and performance criteria such as dosing requirements, wetland/basin characteristics and design can be identified (KMQ 1.2.3).

This project will move beyond a simple black-box analyses and investigate biogeochemical processes controlling P and fine particle removal and the fate of these particles. These analyses will be conducted for all treatments including the control and thus it will provide mechanistic and process information that will be helpful in understanding the removal that can be expected in more natural systems and what effluent limits can be achieved (KMQ 1.2.4, 1.2.6). For instance, how do floc/sediment interactions affect the fate of flocculates. During this project, we will measure accretion that occurs, measure changes in sediment, and assess the practical application of this technology. These steps will be important in addressing additional KMQs with regard to this CEBMP as well as standard wetland or basin treatment (KMQs 1.2.2, 1.2.5). For instance, what are the O&M requirements on these basins and dosing equipment and how does it affect performance; what is the predicted lifespan for the basins before dredging or sediment removal might be necessary; what is the longer-term fate of pollutants removed in these basins and are they mobile?

This project will address the long term impact of infiltrating stormwater at this location and other locations where soil characteristics are similar (KMQ 1.2.10). This information will be useful in predicting subsurface movement of phosphorus in relation to groundwater flow addressing an additional KMQ:

Because of the scientific breadth of this project and the extended experimental period, we will be able to systematically identify success criteria for this project and related projects (KMQ 1.2.9).

In addition to addressing the above KMQs, this project addresses additional technical issues and should help with future planning in the Tahoe Basin:

- Provide insight into the physical, chemical and biological processes controlling P and fine particle removal and cycling and enable local agencies to utilize that information in managing other BMPs in which similar processes may be occurring. This assessment will be from all the treatments and thus enable a better understanding of wetlands or basins alone and in combination with chemical treatment.
- Quantify the retardation characteristics of basin soils and sediments and enable a better understanding of management activities that will retard subsurface P movement.
- Provide important toxicity information on both treated and non-treated stormwater, enabling a better understanding on how stormwater affects the Lake; and

G.6. References:

Bachand, P.A.M., P. Vaithiyanathan and C.J. Richardson. 2000. Phase II Low Intensity Chemical Dosing (LICD): Development of Management Practices. Final Report submitted to Florida Department of Environmental Protection in fulfillment of Contract No. WM720. Report available at www.bachandassociates.com.

Bachand, P., J. Trejo, J. Darby and J. Reuter. 2004. Draft Final Report: Low Intensity Chemical Dosing (LICD) for Treatment of Urban Runoff. Bench-Scale and Small-Scale Investigations. In partial fulfillment of Caltrans Contract No. 43A0073 of Task Order Number 13, University of California Davis. For copy of draft contact *phil@swampthing.org*.

Bachand, P., J. Reuter, A. Heyvaert, R. Fujii and J. Darby. 2002. Chemical Treatment Methods Pilot (CTMP) for Treatment of Urban Runoff, Phase 1. Feasibility and Design. Proposal submitted to the City of South Lake Tahoe (City) in response to request for Proposal by the U.S. Forest Service

Bachand and Reuter, unpublished data. Ecotoxicity results for chemically treated and non-treated stormwater.

Crawford, S. unpublished data. Thermal, x-ray diffraction and NMR analysis of flocculate formed during LICD.

Delaney, T. Personal correspondence. Visual observations of stormwater collected from three different sites during May 2004 for use in ecotoxicity testing. Stormwater was collected through a 2 hour period at each site and differences in stormwater could be visually identified (turbidity, color).

Heyvaert, A., P. Bachand and J.M. Thomas. 2004. Phosphorus Sorption Characteristics of Soils from Selected Stormwater Infiltration Sites in the Lake Tahoe Basin. DRAFT FINAL. September 20, 2004. Prepared for: Tahoe Regional Planning Agency

Heyvaert, A. Unpublished data from Tahoe storm events.

Trejo-Gaytan, J., P.A.M. Bachand and J.L. Darby. 2004. Low Intensity Chemical Dosing Treatment of Urban Runoff at Lake

Table G-1. Experimental Design

Variable	Hypothesis/Goal	Scale Issues Variable	 Comment	Proposed metrics
1. Portable Batch Studies to Test Coagulation and Chemical Dosing[1]				
Operational				
Slow Mixing	G: Determine slow mixing and water velocities for near optimal flocculate formation	Velocity	Simulate velocities for full-scale implementation	PSD, Bulk Density, total and dis P, SCV, total and dis Al
Rapid Mixing	H: Static mixers will provide sufficient energy for precipitation.	Energy	Simulate turbulence for full-scale implementation	
Initial Surface Water Quality Effects				
Dissolved P removal	H: Dissolved P is reduced to < 10 ppb	Energy	In situ conversion from dissolved to particulate P	Dissolved P
Dissolved Aluminum	H: Proper dosing levels result in dissolved Aluminum levels below water quality standards	Energy	Efficiency of Al utilization	Dissolved Al
Toxicity	G: Spot checking of toxicity	Energy	Initial toxicity of treated and non-treated stormwaters	Toxicity metric
2. Replicated Mesocosm Sites to Test				
Longer-term Surface Water Quality Effects				
P and fine particle removal	H1: TP values below 30 ppb can regularly be achieved. H2: Turbidity can be reduced regularly below discharge standards. G: Determine optimal HRT for operation.	Time	Use replicated results across mesocosms compared to control (no chemical dosing)	P, turbidity, PSD
Toxicity Changes	G: Assess toxicity changes through mesocosms. H: Toxicity is mitigated by the biotic conditions in the wetland.	Time	Subset of samples from replicated mesocosms	Toxicity metric
Groundwater and Soil Effects				
Phosphorus and aluminum transport through sediments	G: Assess movement of water quality constituents through groundwater. H: P transport is greatly retarded because of the formed flocculates combining with sediments and through use of adsorptive media.	Time	Groundwater extracted from replicated mesocosms	dissolved P, dissolved Al
Soil accretion and changes in sediment	G: Estimates of soil accretion rates and resulting soil quality from floc and biomass accumulation.	Time	In situ measurements of accretion	Bulk density, wet and dry weight, total P, total Al, organic carbon
Other effects				
Effects on vegetation biomass and chemistry	G: Changes in vegetation C/N/P/Al ratios.	Time	annual sampling in mesocosms	total Al, C, N and P
Temperature mixing effects	H: Temperature gradients do not resuspend P or fine particles after removal by flocculation	Time	diel studies	Total P and turbidity

[1] Temporal replication using different stormwaters from different locations and times

[2] Spatial replication using multiple mesocosms

Table G-2. Planned Treatments for Mesocosm Studies

Treatment	Justification
PACl	Polyaluminum chlorides have been found to be the most robust and effective coagulants for removing phosphorus
Chitin	There is much interest in the Tahoe Basin with regard to chitin, based upon concerns about using chemicals and their potential toxicity. Chitosan is considered a safer alternative.
Control	Provides baseline comparison
Adsorptive media blended with soils	Adsorptive media used in equilization basins (See Chap 8) should help retard P movement to groundwater

Table G-3. General summary of analytical methods.

Analyte	**Units**	**Method of Analysis**
Lab Analyses - Water		
DOC	µg/L	Standard Methods 5310-C, Phoenix 8000 (Teledyne-Tekmar, Mason, OH)
Nitrate + Nitrite	mg N/L	Standard Methods 4500-NO3- I, Flow Injection Analysis Colorimetry, QuikChem Method 10-107-04-1-B
Ammonia	mg N/L	Salicylate method. From methods for the Chemical Analysis of Water and Wastes, March 1979, Method 351.2.
DON	mg N/L	Standard Methods, 4500-N C
Total Nitrogen	mg N/L	Standard Methods, 4500-N C,
Total Phosphorus, Total dissolved phosphorus and ortho-phosphorus	ug/L	TRG SOP (standard operating procedures) modification to Standard Methods 4500
Aluminum	mg/L	AA
Molecular structure		X-ray diffraction, thermal combustion, NMR
Lab Analyses - Soils		
TN/TC	mg/L	Dry combustion/GC
Total Aluminum	mg/L	UC DANR 835 or equivalent[1]
Isotherm analyses		Published scientific methods
bulk density	g/cc	gravimetric
Field Measurements		
EC	µS/cm	CDM83 Conductivity Meter
pH	range	EPA 150.1
Temperature	deg C	EPA 170.1
DO	mg/L	EPA 360.1
Flow		pressure transducer correlated with flow over a weir; flow meters
Toxicity		Standard 3-specie EPA test
		Supplemental organic and metals analyses of stormwater
Notes		
1. Division of Agricultural and Natural Resources, UCD		

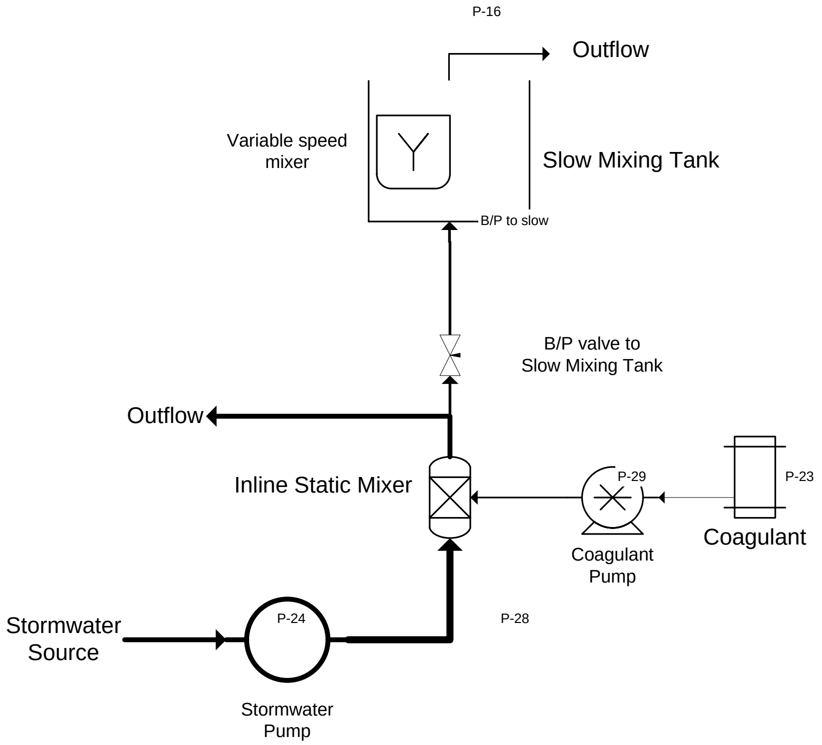


Figure G-1. Mobile Pilot Testing System
Mobile system is for testing dynamic processes in which scale is a function of velocity and energy. Mobile system would develop dosing and mixing protocols and methods to implement at the larger scale.

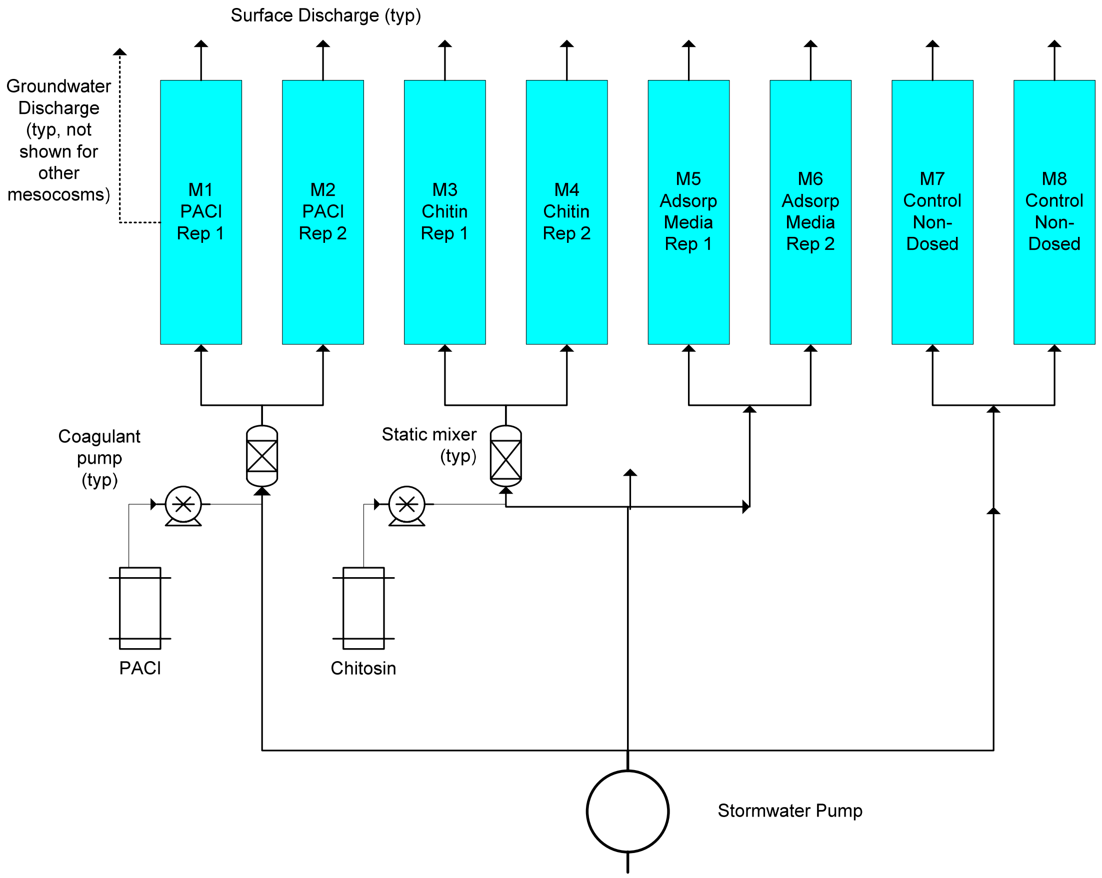
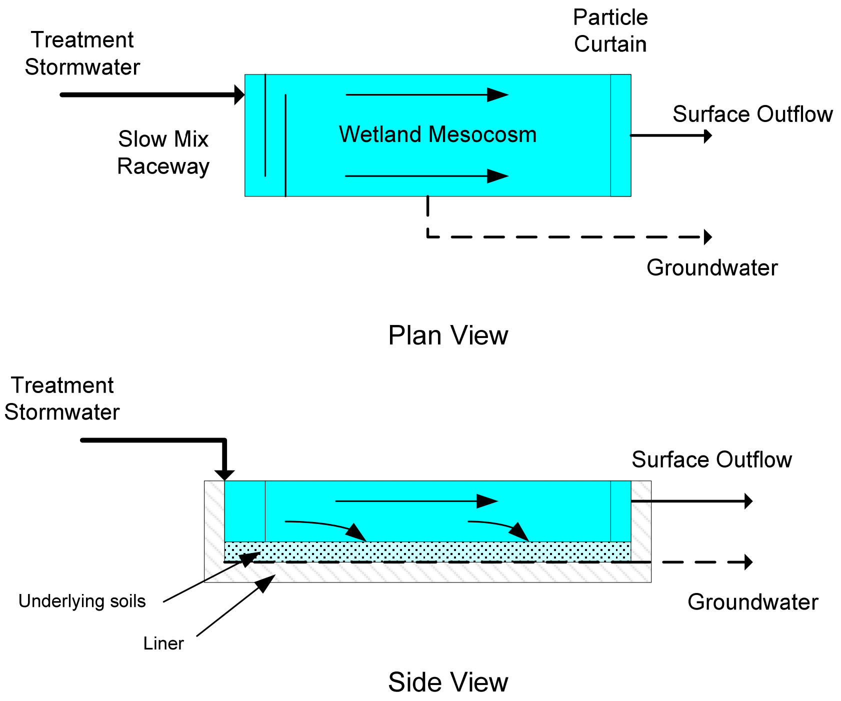


Figure G-2. Mesocosm Process Flow Diagram



Notes
1. Each basin is lined to allow groundwater collection.
2. Not to scale.
3. Preliminary conceptual design.

Figure G-3. Plan and Side Views for Mesocosms

H. Caltrans Report

The Caltrans reports follows from this page.

Final Report:

Small-Scale Studies on Low Intensity Chemical Dosing (LICD) for Treatment of Highway Runoff

April 19, 2006

P. Bachand[1], J. Trejo-Gaytan [3], J. Darby[3], J. Reuter[2]

[1]Bachand & Associates; [2]U.C. Davis Tahoe Research Group (TRG); [3]U.C. Davis Civil and Environmental Engineering

in partial fulfillment of Contract No. 43A0073 of Task Order Number 13

EXECUTIVE SUMMARY

In the Tahoe Basin, strict surface water discharge limits of 20 NTU for turbidity and 0.1 mg/L for total phosphorus are due to come into effect in 2008. The main concern in terms of water quality is the discharge of fine particles and nutrients into Lake Tahoe. The overall goal of this project was to determine the feasibility of low intensity chemical dosing (LICD) for improving highway storm water runoff quality in the Lake Tahoe Basin. A primary objective was to identify promising coagulant chemistries for turbidity and phosphorus reduction that could be tested further in small-scale and full-scale pilots. This project combined literature reviews, laboratory studies (charge titration and jar test experiments using synthetic and actual storm water runoff) and settling column studies to assess treatment performance and feasibility. A related project funded by the U.S.D.A. Forest Service (through the City of South Lake Tahoe) for which the Caltrans funds for this study provided the match has investigated ecotoxicity issues associated with coagulant treated storm waters in the Tahoe Basin.

Summary of Experiments and Methods

An initial list of 25 coagulants was selected based upon a literature review and information obtained from manufacturers. These coagulants represented a wide-range of available coagulant types:

- Proprietary and non-proprietary products
- Alum, aluminum chlorohydrates and poly aluminum chlorides (PACls; inorganic aluminum-based polymers)
- Ferric sulfate, ferric chloride and poly ferric sulfate (inorganic iron-based polymers)
- Organic polymers
- Inorganic/organic polymer blends
- Chitosan-based coagulants

The goal of this effort was to test a broad range of coagulants (which represent a broad range of chemistries) and determine their overall effectiveness and their robustness to variations in environmental and operational factors. This effort was not to endorse any specific product but to better understand the differences in performance for different coagulant chemistries.

We then narrowed the 25 coagulants down to nine coagulants using charge titration studies. These studies identified the relative dosing levels required by the different coagulants for synthetic storm water produced from Tahoe Basin sweepings, and the turbidity levels that could be achieved for that synthetic storm water.

These nine coagulants were subsequently narrowed to four for further testing based upon the robustness of the different coagulants to variations in dose. Synthetic storm water was dosed with the different coagulants in laboratory charge titration and jar studies. From these tests, four coagulants were chosen for further testing. The selection process used was based on a general model that considered performance, cost and environmental measures. The model used (and weighted) different measures of performance, including turbidity and phosphorus removal performance and robustness to varying dosing levels; dosing levels required for good removal; settling characteristics of flocculates; and effects on pH of the treated water.

In the final set of laboratory studies, the selected four coagulants were further tested in jar test experiments with one synthetic and two real storm waters, and in settling column experiments with one real storm water:

- JenChem 1720
- Pass-C
- PAX-XL9
- SumaChlor 50

JenChem 1720 is a complex product in which organic polymers are blended with inorganic polymers. Pass-C and PAX-XL9 are polyaluminum chlorides (PACls). Pass-C, which is a sulfinated PACl that has been tested extensively by the California Department of Transportation (Caltrans), was used as a standard of comparison. SumaChlor 50 is essentially a straight aluminum chlorohydrate (ACH) and thus equivalent products can be found amongst all manufacturers. The four selected coagulants did not necessarily represent the most effective coagulants in the screening tests, but they did represent diverse coagulant chemistries that provided relatively robust performance for different dosing levels with regard to turbidity and phosphorus removal. Reference to the specific products used in this study does not constitute an endorsement. Stormwater chemistry is likely to affect coagulant selection and the robustness of treatment provided by coagulants. And coagulants with similar chemistries are assumed to perform similarly.

Summary of Main Findings

The findings from this study are diverse and can be categorized by their emphasis:

A. Feasibility of coagulants to help meet current and future Tahoe Basin phosphorus and turbidity storm water discharge limits;
B. Coagulant effects on water quality;
C. Robustness of coagulation with regard to changes environmental and operational conditions;
D. Dosing levels; and
E. Cost issues.

These are presented below.

A. Feasibility of coagulants to help meet current and future Tahoe Basin phosphorus and turbidity storm water discharge limits

1. Chemical dosing shows promise in helping meet current Tahoe Basin storm water discharge limits of turbidities less than 20 NTU and phosphorus less than 0.1 mg/L. All four coagulants in the final selection for full testing were effective at meeting the surface water discharge limits for total phosphorus and turbidity in the laboratory studies. These coagulants were also effective in reducing total phosphorus and

turbidity loads. These four coagulants represented effective coagulant chemistries for the storm waters tested.

2. Coagulants generally reduced mean dissolved phosphorus concentrations to less then 0.01 mg/L in storm waters where initial dissolved phosphorus levels were higher.
3. Turbidity discharge limits were generally more difficult to meet than the total phosphorus discharge limits.
4. Settling column experiments suggest that treated storm waters will have less stratification of fine particles in the water column and much more rapid removal of turbidity than non-dosed storm waters. Thus, chemical dosing should either reduce the needed treatment footprint or increase the capacity of an existing footprint. Moreover, because chemical dosing aggregates and settles fine particles, outflow from a chemically treated system should have relatively fewer fine particles then outflow from a non-treated system.
5. Streaming current meters were useful for predicting an optimal dosing range for different coagulants and different storm waters.
6. Inorganic/organic blends were generally less effective in removing phosphorus and reducing turbidity.

B. Coagulant effects on water quality

1. Overdosing increased soluble concentrations of dosed metal and this increase did not occur under more optimal dosing conditions. In this report, overdosing is defined as dosing above a point of zero charge on a streaming current detector, which for practical purposes represents the point of charge neutralization. This result is more important for coagulants that require higher dosing levels of aluminum to achieve charge neutralization. For instances, for the inorganic/organic blends, the increases in soluble aluminum were small because such low doses of aluminum were used. But for coagulants such as PAX-XL9 and Pass C which required higher aluminum dosing levels to neutralize charge, soluble aluminum concentrations increased from around 0.25 mg/L to over 1 mg/L for a dosing increase of about 2 to 3 mg-Aluminum/L above the zero charge dosing level.
2. The PACl coagulants minimally affected alkalinity, pH and concentrations of nitrogen, iron and aluminum. Dosing levels were the main variable affecting decreases in alkalinity. Nitrogen, total iron and total aluminum concentrations also decreased, likely because of precipitation, and improved particulate aggregation and settling.

C. Robustness of coagulation with regard to changes environmental and operational conditions

1. Coagulant selection, and not mixing, temperature or dosing level, was found to be the most important variable determining phosphorus and turbidity removal. Selection of an effective coagulant can help overcome the effects of temperature, mixing, water quality and dosing on coagulant performance.

2. For the storm waters tested in this study, PAX-XL9 and Pass-C were the most effective and most robust coagulants. These coagulants are sulfinated, medium to medium-high basicity coagulants. The performance of these coagulants with regard to phosphorus and turbidity removal was minimally affected by changes in temperature, mixing regimes, storm water quality and dose. These coagulants represent coagulant chemistries that appear to be both effective and robust with regard to treating Tahoe Basin storm waters.
3. The performance of the less effective coagulants in reducing phosphorus and turbidity was more affected by changes in temperature, mixing regime, water quality and dosing.
4. The most robust coagulants (PAX-XL9 and Pass-C) were less affected by different rapid or slow mixing specifications. For those coagulants affected by mixing regimes, the latter step of slow mixing appeared to more greatly affect coagulant performance in terms of turbidity and phosphorus removal than the initial step of rapid mixing.

D. Dosing levels

7. Many PACls had very good performance over a broad dosing range, and inorganic/organic polymer blends appear to be the most difficult to overdose. However, more optimal dosing was found to improve coagulant performance. This result became evident in the study in which we narrowed the studied coagulants from nine coagulants to four coagulants. In those tests, mean removal of turbidity and total phosphorus improved by 25 % when an optimal dosing range was used (based upon Streaming Current Detector results) rather then a full-dosing range.
8. Though inorganic/organic blends (e.g JENCHEM 1720) were relatively less effective in removing phosphorus and reducing turbidity, they required lower dosing levels (sometimes an order of magnitude lower) than PACls and had little effect on water pH.
9. Overdosing was found to lead to increased soluble concentrations of dosed metal that does not occur under more optimal dosing conditions. Overdosing is defined in this report as dosing above a point of zero charge on a streaming current detector, which for practical purposes represents the point of charge neutralization. Inefficient metal utilization due to overdosing will likely lead to increased coagulant and maintenance costs, and may also lead to greater environmental issues. This is more important for coagulants that require higher dosing levels of aluminum to achieve charge neutralization. For instances, for the inorganic/organic blends, the increases in soluble aluminum were small because such low doses of aluminum were used. But for coagulants such as PAX-XL9 and Pass C which required higher aluminum dosing levels to neutralize charge, soluble aluminum concentrations increased from around 0.25 mg/L to over 1 mg/L for a dosing increase of about 2 to 3 mg-Aluminum/L above optimal dosing levels.
10. Streaming current meters were useful for predicting an optimal dosing range for different coagulants and different storm waters.

E. *Costs issues*

1. Of the four coagulants tested, the inorganic blend (JenChem 1720) is the most expensive coagulant to purchase by weight at more than double the costs of PAX-XL9 and about 60% more than Pass-C. However, use of an inorganic/organic blend may reduce other costs. During the laboratory studies, JenChem 1720 was dosed at a level an order of magnitude less than Pass-C or PAX-XL9 (Table 7-2). In the settling studies, dosing levels for JenChem 1720 continued to be the lowest, with dosing levels one third that of PAX-XL9. Thus, both coagulant cost and the expected dosing level required are important when considering the costs of coagulants for treating storm water volumes. Dosing levels has other considerations as well such as logistical, equipment and other O&M considerations associated with floc accumulation. Floc accumulation rates are dependent upon dosing levels used, with higher dosing levels resulting in more floc produced.
2. Coagulation will reduce the basin size and footprint to treat the design storm event because settling rates are greatly increased and because dissolved phosphorus is converted to particulate phosphorus. Conversely, a basin of a given size should be able to treat the storm water from a greater contributing area when chemical dosing is used then when it is not. This technology thus potentially offers cost savings when developing strategies to remove a given turbidity or phosphorus load from a watershed.

Summary

This study has shown that chemical dosing may be an effective storm water treatment approach for the Tahoe Basin. The results of this study suggest that chemical treatment of highway storm water runoff, when properly implemented, may markedly improve storm water quality in terms of reduced turbidity and lower phosphorus concentrations. Based upon these results, further testing of this technology should be continued at small-scale with a much larger number of real storm waters. Although PAX-XL9 and Pass-C (both polyaluminum chlorides) showed the best treatment performance, SumaChlor 50 (an aluminum chlorohydrate) and JenChem 1720 (an inorganic/organic blend) should also be considered for further testing. Both SumaChlor 50 and JenChem 1720 required lower dosing levels than PAX-XL9 and Pass-C and are therefore likely to have lower potential environmental and maintenance costs. Dose optimization should also be considered in future studies. Inefficient metal utilization when dosing is not optimized can lead to increased coagulant costs, increased basin maintenance costs for flocculate management, and increased soluble concentrations of the dosed metal.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. BACKGROUND AND METHOD SUMMARY

1 Study Goal and Background

The overall goal of this project was to determine the feasibility of low intensity chemical dosing (LICD) to improve the quality of highway storm water runoff flowing into Lake Tahoe. A primary objective was to identify coagulants that showed promise for reducing turbidity and phosphorus in storm water runoff. Meeting this goal required an understanding of the potential and limits of several different technologies:

- Storm water detention basin and wetland
- Improving water quality with coagulants
- The Low Intensity Chemical Dosing (LICD) model

Each of these technologies and the guiding principles behind the feasibility analysis of this approach is discussed below.

1.1 Storm Water Detention Basin and Wetland Performance

Dry and wet detention ponds and wetlands remove on average about 15 – 50% total phosphorus and 45 – 80% total suspended solids (TSS) when utilized in storm water systems (Bachand *et al.*, 2005; Schueler, 2000). In detention ponds, detention basins and wetlands, much of this removal is through the settling of larger particles as detention time is often limited in these basins and particle settling rates are dependent upon particle size, with particles sized at 20 microns settling at rates an order of magnitude greater than those at 7 microns (Wong and Geiger, 1997).

Wetlands also remove phosphorus through a number of short- and long-term processes including biological uptake and cycling, algal uptake, adsorption and peat accretion and burial (Richardson and Craft, 1993). Phosphorus uptake in wetlands has been empirically modeled by Kadlec and Knight (1996) using an areal first-order rate constant. First-order rate constants for phosphorus from these models are low as compared to those for other pollutants such as biological oxygen demand (BOD) or nitrogen.

Thus, wetlands, wet basins and dry basins will remove phosphorus and fine particles as is needed at the Tahoe Basin. Limited available land and variable (and sometimes high storm water flows) create problems with regard to designing systems that will provide sufficient residence times for removal of both these important pollutants to levels needed in the Tahoe Basin. Biologically active systems such as wetlands and wet ponds are expected to more effectively remove phosphorus and this assumption is supported by a review of the different national datasets (Bachand *et al.*, 2005). However, all these systems will have difficulty meeting Tahoe Basin discharge standards (Bachand *et al.*, 2005).

1.2 Utilizing Coagulants for Improving Water Quality

In situ chemical addition of iron or aluminum based coagulants or possibly nitrogen based organic coagulants may improve removal rates of both phosphorus and fine particles in storm water systems in the Tahoe Basin. Precipitation techniques are highly effective in reducing phosphate to very low concentrations (Leckie and Stumm, 1970). Historically, aluminum, ferric iron, and, only occasionally, calcium ions have been used for this purpose. All of these ions can form quite insoluble compounds with phosphate ions although the dominant solid phase varies with pH. Fe(III) ion can form strengite ($FePO_4.2H_2O$) with phosphate ion while aluminum (III) ion can form variscite $AlPO_4.2H_2O$ or wavellite $Al_3(OH)_3(PO_4)_2$.

There is much evidence on the effectiveness of both alum and iron based coagulants in removing phosphorus. Up to 90 to 95% phosphorus removal efficiency has been achieved in wastewater treatment using alum, iron chloride and lime (Narasiah *et al.*, 1994). The addition of alum, iron chloride and lime directly to lakes and reservoirs to regulate phosphorus availability has become an increasingly popular method to control eutrophication (Hall *et al.*, 1994). The City of Orlando injects alum on a flow proportional basis into storm water entering two natural lakes, Lake Dot and Lake Lucerne, to control eutrophication (Harper, 1994). Results showed that in-lake total phosphorus and chlorophyll concentrations were reduced by 90% in Lake Dot and by 25% in Lake Lucerne. Slower water quality improvements in Lake Lucerne were attributed primarily to internal nutrient recycling from nutrient-rich sediments. Welch and Schreive (1992) evaluated the success of alum additions to six natural lakes in Washington during the 1980s and found single alum treatments were generally effective in reducing eutrophic conditions with effects lasting for at least five years (as of 1992). Aluminum was effective in blocking phosphorus release from sediments in stratified lakes with anoxic bottoms. In 1991, another shallow lake in Seattle, Green Lake, was treated with a mixture of alum and sodium aluminate to a dose of 8.6 mg-Al L^{-1} (Jacoby *et al.*, 1994). Total phosphorus concentrations decreased from 40 to 14 $\mu g\ L^{-1}$ after treatment and remained below the goal of 30 $\mu g\ L^{-1}$ for two years. Likewise, Lake Morey in Vermont, was treated with a mixture of alum and sodium aluminate in 1986 (44 g Al m^{-2}) with reduction in eutrophic conditions for at least 4 years (Smeltzer, 1990). The shallow Mohawk Lake in New Jersey was treated with alum to form a sediment “blanket” of alum to block internally recycled sediment phosphorus. Then, continuous alum diffusers were added at various points in the lake to inactivate externally generated phosphorus (Souza *et al.*, 1994). In 1986, alum was added to Eau Galle Lake in Wisconsin resulting in a temporary reduction in phosphorus regeneration and chlorophyll, but heavy external phosphorus loading later negated these improvements (James *et al.,* 1991).

The Wahnbach reservoir plant in Germany has been reducing phosphorus from 60-210 $\mu g\ L^{-1}$ to 5 $\mu g\ L^{-1}$ using an iron dose of 4 to 10 mg L^{-1} (Bernhardt and Schell, 1993). To control eutrophication in lakes serving the St. Paul, MN, water supply, iron chloride has been injected into river water entering into the lake, resulting in 60 to 70% removal of orthophosphate with iron dosages of less than 1 mg L^{-1} (Walker, 1989). Walker (1989) concluded that the long-term success would depend on the redox conditions in the lake sediments since phosphate can be released as iron is reduced.

There is evidence that chemical coagulants can be used in wetlands for phosphorus removal. Bachand *et al.* (2000) demonstrated in mesocosm studies that total phosphorus concentrations below 30 $\mu g\ L^{-1}$ could be achieved by dosing low concentrations of iron and aluminum based coagulants within a storm water wetland system. Phosphorus removal occurs through processes of both precipitation and adsorption when iron and aluminum based coagulants are used. Ann (1996) in a series of experimental studies showed that both iron and aluminum dosing enhanced retention of soluble phosphorus in organic wetland soils.

In applying coagulants to basin or wetland systems, a number of choices exist. Caltrans (2001b) reviewed the possible use of alum, ferric salts, polyaluminum chlorides (PACls) and anionic polyacrylamides (PAMs). Their review states that PACls are generally more effective at lower doses than for alum for suspended solid and organic matter removal, with relative advantages in effectiveness increasing as temperatures decrease. Several issues are raised by Caltrans (2001b) and others in assessing the potential applicability of coagulants for improving storm water quality in the Tahoe Basin:

- **Optimal pH for application.** Optimal pH for alum is 5.8 – 6.5 (Muser, personal communication) and for ferric salts is 6 – 8 (Caltrans, 2001b). PACls have a much broader range of pH for which they are optimal. Some PACls have been shown to be effective for waters with pH ranging from 6 – 8 and relatively effective up to a pH of 10 (Muser, personal communications).
- **Alkalinity consumption and changes in pH from coagulant application.** 10 mg L^{-1} of ferric chloride consumes 10 mg L^{-1} of alkalinity as $CaCO_3$ and 10 mg L^{-1} of ferric sulfate consumes 7.5 mg L^{-1} alkalinity (Caltrans, 2001b). Greater drops in pH will result from the addition of iron salts over aluminum salts (Lind, personal communications; Muser, personal communications). Reduction in pH from applying PACl can range from as high as 1 pH unit to a low of 0.1 pH units depending upon the formulation of the PACl.
- **Temperature.** The ensuing reactions to various hydroxides and phosphates are temperature dependent (Caltrans, 2001b). PACls have been found to be less affected by temperature than alum (Van Benschoten and Esdzwald, 1990). Thus, PACls may be more robust with regard to temperature effects than either alum or iron salts (Muser, personal communications).
- **Quality and heavy metal contents.** Iron salts as a rule have a higher content of heavy metals and contaminants than do aluminum salts. Ferric chloride tends to be the dirtiest because it is a byproduct of other production processes. PACls are the cleanest as they are produced specifically for improving water quality and are highly engineered (Lind, personal communications).
- **Efficiency.** PACls are engineered polymers designed for optimum charge neutralization and bridge binding. Precipitates formed by alum and ferric salt application are amorphous hydroxides and the exact characteristics of those products and the efficiency of the chemicals used are dependent upon a number of variables such as temperature and mixing energy (Van Benschoten and Edzwald, 1990). Engineered polymers tend to be more efficient and robust with regard to achieving coagulation goals because their precipitates are less variable.
- **Flocculate production.** PACls typically produce less flocculate than alum (Muser, personal communications).
- **Residual dissolved metals in solution.** PACls reportedly have ten to twenty times less dissolved aluminum in solution after the coagulation process is completed than does alum (Muser, personal communications).

Based upon this literature review and the cited communications with industry experts, there is strong rationale for investigating PACls for applications in the Tahoe Basin. Caltrans investigated a number of coagulants including alum, ferric chloride and PACls in a series of jar test experiments in which reduction of a range of constituents was investigated (Caltrans, 2002a). They concluded that the PACl Pass-C was the most effective at improving storm water quality, and that all selected PACls outperformed alum and ferric chloride. This study was followed by a pilot project in which storm water runoff was dosed with Pass-C at 100 mg L^{-1} (Caltrans, 2002b).

There are, however, a number of unresolved issues from the Caltrans coagulant studies (Caltrans 2002a and 2002b), especially when considering the two main constituents of concern in the Tahoe Basin with regard to Lake clarity, phosphorus and fine particles:

Preliminary screening of data from the Caltrans jar test experiments with Lake Tahoe storm water suggests that Pass-C at a dose of 100 mg L^{-1} may not always be the best choice when low dosing levels and removal of fine particles are the goal (Caltrans, 2002a). Turbidity was found to be a poor parameter for identifying the optimum dosing range and for evaluating the ability of coagulants to meet Tahoe Basin regulatory standards for phosphorus.

The Caltrans jar test experiments (Caltrans 2002a) do not make any distinction between PACls based upon their fundamental properties. PACls have a number of general properties around which they are designed (Lind, personal communications; Muser, personal communications):

- Aluminum content
- Molecular weight
- Basicity
- Cationic charge density

Industry representatives state that these properties affect PACl performance in terms of removing fine particles and precipitating dissolved phosphorus (Lind, personal communications; Muser, personal communications). For instance, higher basicity PACls are considered better at removing fine particles because of a higher charge density that allows more rapid charge neutralization and scavenging of colloids (Muser, personal communications). Lower basicity PACls are considered better at precipitating dissolved phosphorus though this process can be compromised by turbidity. Thus, all PACls are unlikely to be equal and understanding their properties in the context of storm water treatment may aid in selecting and testing the different coagulants.

Additionally, a number of other coagulants exist that have not been tested for storm water treatment. Polyferric sulfate is widely produced and used in Europe as a coagulant though historically not available in the US (Sims, personal communication). PFS is now available and may show similar improvements in performance over iron salts as PACls do over aluminum salts. Organic polymers have also not been considered. The primary cationic organic polymers being blended with inorganic polymers are polydiallydimethyl ammonium chloride (Poly-DADMAC) and epichlorohydrin dimethylamine polymers (Epi/DMA) (Lind, personal communications). These organic coagulants can have very high molecular weights that can lead to larger, stronger and faster settling flocculate (Ashland Chemical, 2002). Organic coagulants tend to have higher supernatant turbidity, be less economical, have more rapidly settling flocculate, lower sludge volume, be less pH sensitive and consume less alkalinity than inorganic coagulants (Ashland Chemical 2002). Organic and inorganic coagulants are often blended because of their specific advantages and disadvantages. Cationic organic coagulants were not tested by Caltrans (Caltrans, 2002a).

Table 1-1 lists a broad range of coagulant types that are considered in this study based on a review of the literature and information from manufacturers. These coagulants are narrowed to progressively more manageable subsets through a series of screening and validation studies that include charge titration tests, coagulation studies (jar tests) and settling studies.

Table 1-1 Coagulant Blends for Initial Pre-screening

Coagulants	Description
Metal-based (inorganic)	
Ferric Chloride	Iron-base metal salt
Polyferric sulfate	Iron-based inorganic polymer
Alum	Aluminum-based metal salt
Aluminum chlorohydrate	Aluminum-based inorganic polymer
Polyaluminum Chloride	Aluminum-based inorganic polymer
Organic polymers	
Poly-DADMAC	nitrogen-based organic polymer (polydiallydimethyl ammonium chloride)
Epi/DMA	nitrogen-based organic polymer (epichlorohydrin dimethylamine)

1.3 Low Intensity Chemical Dosing

Low Intensity Chemical Dosing, a concept first put forth by Peer Consultants, P.C./Brown and Caldwell (1996), is based on the use of low concentrations of chemical coagulants in a storm water wetland treatment system to enhance and accelerate the rate of phosphorus removal. Bachand *et al.* (2000) tested this approach in a series of mesocosm studies in the Everglades Nutrient Removal Project and found that this technology could achieve mean total phosphorus concentrations in the range of 15 to 30 μg L^{-1}.

In LICD, coagulants are used to precipitate dissolved phosphorus and aggregate flocculates. Treatment wetland processes are used to enhance particle settling and retention. Numerous wetland processes contribute to enhanced settling and retention:

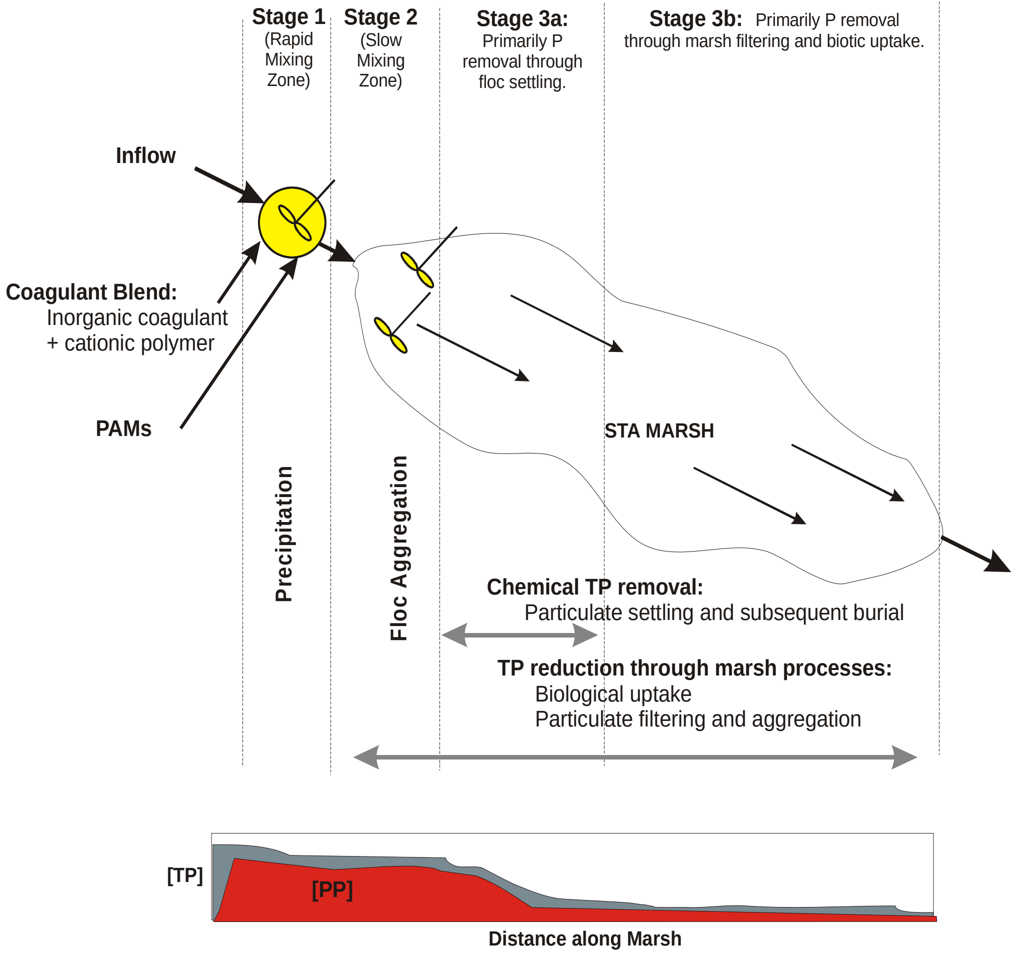
- Increased surface roughness leading to improved filtering, flow buffering and dispersion, and more quiescent waters;
- Biotic activity in the water column and sediments; and
- Wet and dry cycling.

Eventually, settled flocculates are incorporated into basin sediments. LICD would be most effective when flocculates settle at a rate that will not be affected by diel processes such as wind and temperature mixing. Thus, having a maximum settling rate such that settling occurs on the order of one day is likely to be advantageous, and larger flocculates are preferred because of their improved settling characteristics over smaller flocculates.

Minimizing coagulant dosing should reduce potential environmental effects because flocculate will be incorporated into basin sediments and soil. Thus, in LICD, selected chemicals need to be efficiently used in order to minimize their application and limit potential environmental effects. This requires that the most appropriate chemicals are selected and that the requirements for their application (e.g. mixing rate and duration, dose, pH) be met.

Figure 1-1 shows the proposed model of the LICD process. LICD can be broken into several different stages. Stage 1 represents a rapid mixing zone that may be required for efficient chemical utilization by allowing maximum collisions and reactions between ions and particles in solution and the added coagulant. During coagulant addition, the initial reactions that occur and dictate performance and efficiency occur rapidly on the order of tenth of a second to seconds. Stage 2 represents a period of flocculate aggregation. Slow mixing processes enhance flocculate aggregation. This zone of slow mixing could potentially be created by mechanical mixing or aeration, or through baffling flows in the inflow area of the pond or wetland. The degree of both rapid and slow mixing energy and duration will be dependent upon the coagulant selected. Stage 3 represents phosphorus removal through both settling and biological uptake. Phosphorus removal by settling is more rapid (Bachand *et al*, 2000), though biological phosphorus removal will also lead to a reduction in water column phosphorus levels.

Figure 1-1 Phosphorus Removal Model for Storm Water Basin or Wetland using LICD.
(STA is Storm Water Treatment Area).



1.4 Guiding Principles

The experimental studies presented here have been developed in the context of their potential application in earthen basins and storm water wetlands. In such environments, there are important considerations and needs not typical of wastewater and drinking water applications:

- On-site storage, aging and drying of formed flocculates;
- Wet and dry cycling, with total drying in the summer;
- Flows varying by orders of magnitude;
- Large temperature variations in storm water depending upon season;
- Simple operation and controls for dosing systems;
- Minimal infrastructure and minimal maintenance;
- Minimally trained maintenance personnel who will likely have a high turnover rate; and
- Biotic activity effects on flocculates over time
- Toxicity due to potential overdosing.

These considerations are fundamental when developing an evaluation criterion to assess the feasibility of LICD. Fundamentally, the variability in field conditions requires a robust chemical dosing regime, the development of flocculates that settle rapidly and do not re-suspend or re-dissolve, and a need for minimal infrastructure. In these studies, several principles guided development of experimental plans and data analyses:

- Focus on phosphorus and turbidity removal. Tahoe Basin effluent limits for total phosphorus and turbidity are 0.1 mg/L and 20 NTU, respectively. Final phosphorus concentrations and turbidity from this process will not only depend upon the chemical applied for coagulation and flocculate aggregation, but also on the downstream settling device.
- Minimize coagulant dosing. Lower coagulant utilization should minimize environmental effects.
- Consider factors that will help minimize capital, and operation and maintenance (O&M) costs. An important factor here is settling time. Basins will experience flows varying by several orders of magnitude and are typically designed for a 24-hour settling time for a 1-hour 10-year storm (1”). Rapid settling will be required in the field for coagulants to be effective.
- Focus on coagulants that show robust performance for varying operational and environmental conditions. Although chemical dose can be regulated based upon flow or other parameters, minimizing need to adjust dose when water conditions such as quality, temperature, and hydraulics change will provide a simpler, more robust and more reliable system.
- Minimize need to adjust pH and alkalinity.
- Minimize secondary contamination of the treated water through inadequate uptake of dissolved ions or through dissolution or re-suspension of metals.

2 Methods

This project focused on screening and testing coagulants through the following successive tasks:

- Literature and industry review;
- Laboratory studies consisting of jar tests and charge titration studies; and
- Settling columns.

This chapter details the methods for each task. A related project funded by the U.S.D.A. Forest Service (through the City of South Lake Tahoe) for which the Caltrans funds for this study provided the match has investigated ecotoxicity issues associated with coagulant treated storm waters in the Tahoe Basin (Bachand et al., 2006).

2.1 Literature and Industry Review

The survey of initial coagulants was based upon a scientific literature review and discussions with industry representatives. Scientific literature review details, which include a review of Caltrans reports and other gray literature, can be found in the Research Plan (Bachand *et al.*, 2003). Most relevant scientific literature concentrates on the performance and application of aluminum and iron salts such as ferric chloride, ferric sulfate and alum. Polyaluminum hydroxyl chlorides (PACls), polyferric sulfate and nitrogen-based organic cationic polymers such as Poly-DADMACs (polydiallydimehtyl ammonium chlorides), and Epi/DMA (epichlorohydrin dimehtylamine) were also included in this review. The coagulation industry has focused considerable resources on developing these more sophisticated coagulants though the scientific literature has little information or data on these coagulants and their effectiveness under varying conditions. The goals of this review were twofold:

1. Assess industry and published literature on various coagulant options for phosphorus and turbidity removal; and
2. Identify a subset of coagulants for laboratory testing.

2.2 Laboratory Studies

The exact experimental plan and implementation of the laboratory studies evolved over the course of this study, though the primary goals for these studies remained the same:

1. Progressively narrow the list of coagulants from a list of 20 to 30 coagulants to under five for intensive testing focusing on phosphorus and turbidity removal;
2. Assess both steady state coagulant performance and settling characteristics of flocculates formed by coagulants and use that assessment in evaluating coagulants;
3. Evaluate the robustness of coagulants regarding performance for different dosing levels and for different environmental conditions;
4. Evaluate effectiveness of coagulants regarding nitrogen removal and affect on iron and aluminum concentrations in treated waters.

Laboratory studies were conducted through a combination of charge titration studies and standard jar tests in which successive experiments and approaches were based upon the data and results of preceding experiments.

2.2.1 Charge titration procedures

The purpose of charge titration studies was to identify the range of acceptable doses for each storm water and coagulant combination in the jar tests. Essentially, charge titration studies preceded and better identified the dosing requirements for each jar study. Together, these combined studies provided an integrated and efficient approach that allowed rapid determination of chemical requirements and corresponding treatment effectivness. Charge titration studies identified at which doses particle neutralization occurred and jar studies provided information on the removal of particles and pollutants at those near optimum doses.

The charge titration experiments were performed using an electrokinetic charge analyzer or streaming current detector (ECA 2100, Chemtrac, Norcross, GA; SCD) based upon procedures described by Briley and Knappe (2002). Streaming current meters have been widely and successfully utilized in water treatment plants (Dentel and Kingery, 1989; Dentel, 1991) and other fields, such as sludge dewatering (Dentel, 1993), and their use is increasing. The current meter measures the surface charges of suspended particles based on the streaming current principle. Data from the current meter can be used to continuously monitor the extent of particle destabilization and adjust coagulant dosing to provide optimal destabilization thereby minimizing overdosing or under-dosing of chemicals. This ability may be important if LICD is implemented in the field. Storm water has been shown to be highly variable (Caltrans, 2001a; Heyvaert, unpublished data). A streaming current meter may be useful for identifying optimal dose and help prevent coagulant overdosing.

In this study, coagulant was incrementally added to 650 mL of continuously mixed synthetic storm water and surface charge was measured using a streaming current detector (SCD) when an equilibrium condition was reached. Output for the SCD was in mV. From these measurements, curves were developed showing dose vs streaming current voltage (SCV) for each coagulant.

2.2.2 Jar Test Procedures

Data from the charge titration studies provided a dosing range for implementing jar studies in which turbidity and phosphorus removal, as well as changes in other water quality constituents, could be evaluated.

Jar tests were conducted according to standard jar test procedures, using a six paddle stirrer with square mixing jars (PB950**,** Phipps and Bird**,** Richmond, Virginia). The following procedure was used for the jar studies:

1) Take initial measurements.
2) Transfer a 1-L aliquot to the square mixing jar while continuously mixing the batch.
3) With a burette add the predetermined coagulant dose.

4) Rapid mix for a specified time and intensity, and then follow that with slow mixing for a specified time and intensity.
5) After mixing is complete, allow quiescent settling for a desired time.
6) Sample from square mixing jar using jar sampling valve at predetermined settling times.

Rapid and slow mixing times and duration used were consistent with industry practices (Gnagy, 1994; Hudson and Wagner, 1981; Sims, personal communications). For this project, the performance of coagulants was initially assessed under different mixing regimes before the following specifications were selected: a rapid mix of 180 rpm was conducted for 2 minutes followed by a slow mix at 30 rpm for 4 minutes. Turbidity was initially sampled at 5, 10, 15, 30 and 60 minutes though, as the project progressed, the 60 minute sample point was discontinued as steady state conditions were achieved by 30 minutes. Water samples were taken at 30 minutes and then later at 60 minutes for water quality analyses. Water quality analyses were limited to unfiltered total phosphorus (UTP) and dissolved phosphorus (FTP – filtered total phosphorus) using methods developed by the TRG and based upon EPA methods.

2.2.3 Laboratory Study Experimental Design

In the original Research Plan for this study, a series of screening and validation charge titration studies and jar tests were envisioned. Under that approach, jar studies and charge titration studies were considered somewhat separate. Additionally, for both jar studies and charge titration studies, a series of screening or exploratory tests followed by validation tests were planned. Exploratory tests were simpler and had a narrower range of data than validation tests. The experimental plan was modified as required and evolved over time for the following reasons:

- Charge titration and jar studies were found to be two integrated components in a laboratory assessment approach used for evaluating and testing coagulants;
- Nearly all tests were replicated as the project progressed to meet more rigorous statistical requirements;
- Covariant effects were required to be considered; and
- Resources needed to be focused better to address the primary area of concern, phosphorus and fine particle removal.

The experimental approach for this study evolved as follows:

- Initial charge titration and jar studies to narrow coagulants from around 25 to around 10 using a SCV of 0 mV for jar studies. Jar studies were replicated (N=3). Turbidity was measured during the jar studies as a measure of pollutant and phosphorus (P) removal, and as an indicator of settling characteristics (Chapter 4);
- Reduced number of coagulants from around 10 coagulants to 4 coagulants based on assessment of the robustness of coagulant performance against different dosing levels in integrated charge titration/jar tests (Chapter 5). Both turbidity and P were determined during the jar studies, and treated waters were assessed in terms of soluble iron and aluminum.
- Tested the performance of 4 coagulants as measured by turbidity and P removal against variations in mixing regime, water quality and temperature to simulate field application

conditions (Chapter 6). Measured nitrogen, alkalinity and total iron and aluminum on a subset to assess the effects of coagulants on these water quality constituents.

A combination of synthetic and real storm water was used for these tests. Synthetic storm water was used initially to expedite the progress of the study. Real storm water collected at Lake Tahoe during storm events was later used as it became available.

2.2.4 Synthetic Storm Water

Synthetic storm water samples consisting of highway sweepings combined with Lake Tahoe water were initially used for the laboratory studies. Storm waters were developed to target two different turbidity ranges that were representative of the range of turbidities found in Tahoe Basin storm water, 50 and 500 NTU. The advantages of using a synthetically derived storm water include 1) having greater consistency of water samples, thus allowing a more systematic investigation of parameters that impact coagulation results; 2) not being dependent on the occurrence of major storm events happening within the project period; and 3) being able to start coagulation tests immediately and proceed at a steady pace thus improving quality control and assurance.

Storm waters were synthesized using sweepings from two geographic locations at Lake Tahoe (north and south side). A target of four to five cubic feet of highway sweepings were collected from both north Lake Tahoe (Nevada side) and South Lake Tahoe (California side) and brought back to the UC Davis Laboratories for particle size separation and analysis. Sweepings were initially sieved at 850 microns, with particles above that size discarded from the sediment collected. The remaining particles were separated by size according to the sieve analysis shown in Table 2-1. The sieved sizes of soil were stored in separate sealed containers at 4°C.

Synthetic storm water was produced by re-combining a pre-determined mass of each size range with Lake Tahoe water. The sweepings were ground because without grinding particles settled out rapidly and somewhat inconsistently, making the creation of consistent storm water very difficult. These recipes were based upon the particle distribution of the original collected sweepings. Table 2-2 shows a sample recipe for creating storm water at a target turbidity of 500 NTU using highway sweepings from South Lake Tahoe.

During laboratory studies, the synthetic storm waters were kept mixed using a Lightnin® mixer in order to keep the storm water sample homogeneous. This method was also used when testing real storm waters.

A complete chemical analysis of different synthetic and natural storm waters was conducted using the Division of Agricultural and Natural Resources (DANR) Laboratory at U.C. Davis and the U.C. Davis Tahoe Research Group Laboratory early in the study to assess the validity of this approach. Table 2-3 shows replicated data for three different synthetic storm waters as well as data for three real storm waters. The chemistry of both types of storm water is very similar and thus the approach of using synthetic storm water seemed justified for the stated reasons. Recorded turbidity values during these studies for storm water designed for a turbidity of 500 NTU were close to the targeted value, ranging from 490 to 560 NTU, and pH was around 8.

Table 2-1. Sieve Sizing

ASTM Standard No.	Size microns
20	850[1]
40	425
60	250
100	150
200	75
300	45
675	20

Notes

1. Discarded

Table 2-2 Sieve Analysis on Sweepings from Site 1 and Amounts used to Prepare Synthetic Storm Water of Target Turbidity 500 NTU

ASTM Standard No	Size (μm)	Soil Analysis (% retained)	Amount Added (g)
40	425	34.53	41.43
60	250	26.61	31.94
100	150	21.66	25.99
200	75	9.59	11.51
300	45	3.98	4.77
	<45	3.63	4.35
Total		100	120

Table 2-3 Chemical Analyses of Synthetic Storm Waters

Preparation and Identification of Stormwater						
Stormwater Code[1]	Rep	Type	Target Turb (NTU)	Prep or Collection Date	Source	Actual Turb (NTU)
S500N - 120902	1	Synthetic	500	12.09.02	North Tahoe sweepings	532
S500N - 120902	2	Synthetic	500	12.09.02	North Tahoe sweepings	532
S050N - 120902	1	Synthetic	50	12.09.02	North Tahoe sweepings	50
S050S - 120902	1	Synthetic	50	12.09.02	South Tahoe Sweepings	47.5
S500S - 120902	1	Synthetic	500	12.09.02	South Tahoe Sweepings	500
S500S - 120902	2	Synthetic	500	12.09.02	South Tahoe Sweepings	500
RCOON - 122702	1	Real	NA	12.27.02	Coon Street Basin	
RFOX - 122702	1	Real	NA	12.27.02	Fox Street Basin	
RFOX - 122702	2	Real	NA	12.27.02	Fox Street Basin	

Nitrogen, Chlorides, Hardness, Alkalinity and Solids												
Stormwater Code	Rep	Nitrogen (SOP 850 & 847)				Chloride (SOP 830)	Soluble Metals & Hardness (SOP 835 & 875))			Alkalinity (SOP 820)	Solids (SOP 870)	
		TKN ppm	FTKN ppm	NH4-N ppm	NO3-N ppm	Cl meq/L	Ca meq/L	Mg meq/L	Hardness grains/gal	Alkalinity meq/L	TDS ppm	TSS ppm
S500N - 120902	1	1.6	<0.1	<0.05	517.1	0.4	0.6	0.2	42.4	1.1	79	530
S500N - 120902	2	1.6	<0.1	<0.05	537.1	0.4	0.6	0.2	41.5	1.1	70	NES
S050N - 120902	1	0.4	<0.1	<0.05	462.4	0.1	0.5	0.2	35.8	0.9	40	32
S050S - 120902	1	0.5	<0.1	<0.05	503.1	0.1	0.5	0.2	35.4	0.9	35	22
S500S - 120902	1	1.1	<0.1	<0.05	590.0	0.1	0.5	0.2	36.6	1.0	49	792
S500S - 120902	2	0.7	<0.1	<0.05	641.8	0.1	0.5	0.2	35.2	1.1	35	20
RCOON - 122702	1	1.9	<0.1	0.16	519.3	0.7	0.4	0.3	33.8	0.7	65	140
RFOX - 122702	1	2.6	<0.1	<0.05	552.1	1.3	0.5	0.2	31.7	0.5	102	404
RFOX - 122702	2									0.6	99	NES

Total Metals												
Stormwater Code	Rep	Total Metals (SOP 590)										
		Ca ppm	Mg ppm	Zn ppm	Fe ppm	Cu ppm	Al ppm	As ppm	Cd ppm	Cr ppm	Pb ppm	Ni ppm
S500N - 120902	1	28	8	0.5	26.3	0.3	8.8	<0.1	<0.1	0.2	<0.1	0.1
S500N - 120902	2	31	8	0.5	26.4	0.4	8.9	<0.1	<0.1	0.2	<0.1	0.1
S050N - 120902	1	11	3	0.1	2.6	<0.1	1.0	<0.1	<0.1	<0.1	<0.1	<0.1
S050S - 120902	1	9	3	<0.1	2.5	<0.1	0.5	<0.1	<0.1	<0.1	<0.1	<0.1
S500S - 120902	1	16	8	0.2	31.1	0.2	6.5	<0.1	<0.1	0.1	<0.1	0.1
S500S - 120902	2	28	8	0.5	24.0	0.3	8.3	<0.1	<0.1	0.2	<0.1	0.1
RCOON - 122702	1	9	3	0.1	1.7	<0.1	<0.5	<0.1	<0.1	<0.1	<0.1	<0.1
RFOX - 122702	1	10	2	0.1	3.5	<0.1	1.3	<0.1	<0.1	<0.1	<0.1	<0.1
RFOX - 122702	2											

Total Filtered Metals												
Stormwater Code	Rep	Filtered Total Metals (SOP 590)										
		Ca ppm	Mg ppm	Zn ppm	Fe ppm	Cu ppm	Al ppm	As ppm	Cd ppm	Cr ppm	Pb ppm	Ni ppm
S500N - 120902	1	11	2	0.1	2.3	<0.1	<0.5	<0.1	<0.1	<0.1	<0.1	<0.1
S500N - 120902	2	9	2	<0.1	<0.1	<0.1	<0.5	<0.1	<0.1	<0.1	<0.1	<0.1
S050N - 120902	1	9	3	<0.1	0.1	<0.1	<0.5	<0.1	<0.1	<0.1	<0.1	<0.1
S050S - 120902	1	9	2	<0.1	0.6	<0.1	<0.5	<0.1	<0.1	<0.1	<0.1	<0.1
S500S - 120902	1	10	3	<0.1	0.3	<0.1	<0.5	<0.1	<0.1	<0.1	<0.1	<0.1
S500S - 120902	2	12	2	0.1	<0.1	<0.1	<0.5	<0.1	<0.1	<0.1	<0.1	<0.1
RCOON - 122702	1	8	3	<0.1	0.2	<0.1	<0.5	<0.1	<0.1	<0.1	<0.1	<0.1
RFOX - 122702	1	9	2	<0.1	0.5	<0.1	<0.5	<0.1	<0.1	<0.1	<0.1	<0.1
RFOX - 122702	2											

Notes

1. SnnnS - mmddyy: First S or R = synthetic or real stormwater; nnn = target turbidity or location:; Second S or N = south or north Tahoe; mmddyy = date

2.3 Settling Column Studies

Settling column studies were conducted with two primary goals:

- Validate laboratory studies at a scale more representative of basins; and
- Characterize settling characteristics of treated storm water.

Table 2-4 shows the specifications for the settling column experiments. These specifications were determined experimentally for each variable. The mixing regime, for example, was defined through a progressive series of experiments assessing flocculate formation and turbidity removal under different mixing regimes (rapid mixing speed, rapid mix duration, slow mixing speed, and slow mixing duration).

Three coagulants were selected based on the laboratory results. A real storm water that had been utilized during the latter period of jar test studies was used for this study to improve continuity between the jar test studies and the settling studies.

Table 2-4 Settling Column Specifications

Mixing Tank Operational Specifications		
Blended Volume for each batch	17.5	gallons
Rapid Mix Speed	161	rpm
Rapid Mix Duration	1	min
Slow Mix Speed	36	rpm
Slow Mix Duration	8	min
Impeller Dia	11.2	inches
Settling Column Specifications		
Columns per batch	3	
Diameter	6.031	in
Height	3	ft
Sampling locations (at depth)	0.5	ft
	1.5	ft
	2.5	ft
Coagulant Dosing Levels		
Coagulant	Dose	
	mg-Me/L	mg-coag/L
Sumachlor 50	2.2	18.1
PAX-XL9	4.3	76.8
JC-1720	1.4	23.1

As shown in Figures 2-1 and 2-2, the settling columns developed for this study were 4 feet long and had sampling points located every 6 inches. For this study, water was operated at 3-feet and samples were collected 0.5, 1.5 and 2.5 feet from the bottom. The number of sampling locations and their sampling frequency were constrained by both the need to provide data that could be analyzed statistically, and the need to not alter the data through collection of too many water samples.

Figure 2-1 Settling Column

(Rack of six columns employed such that two batches operated in replicates of three could be operated simultaneously)

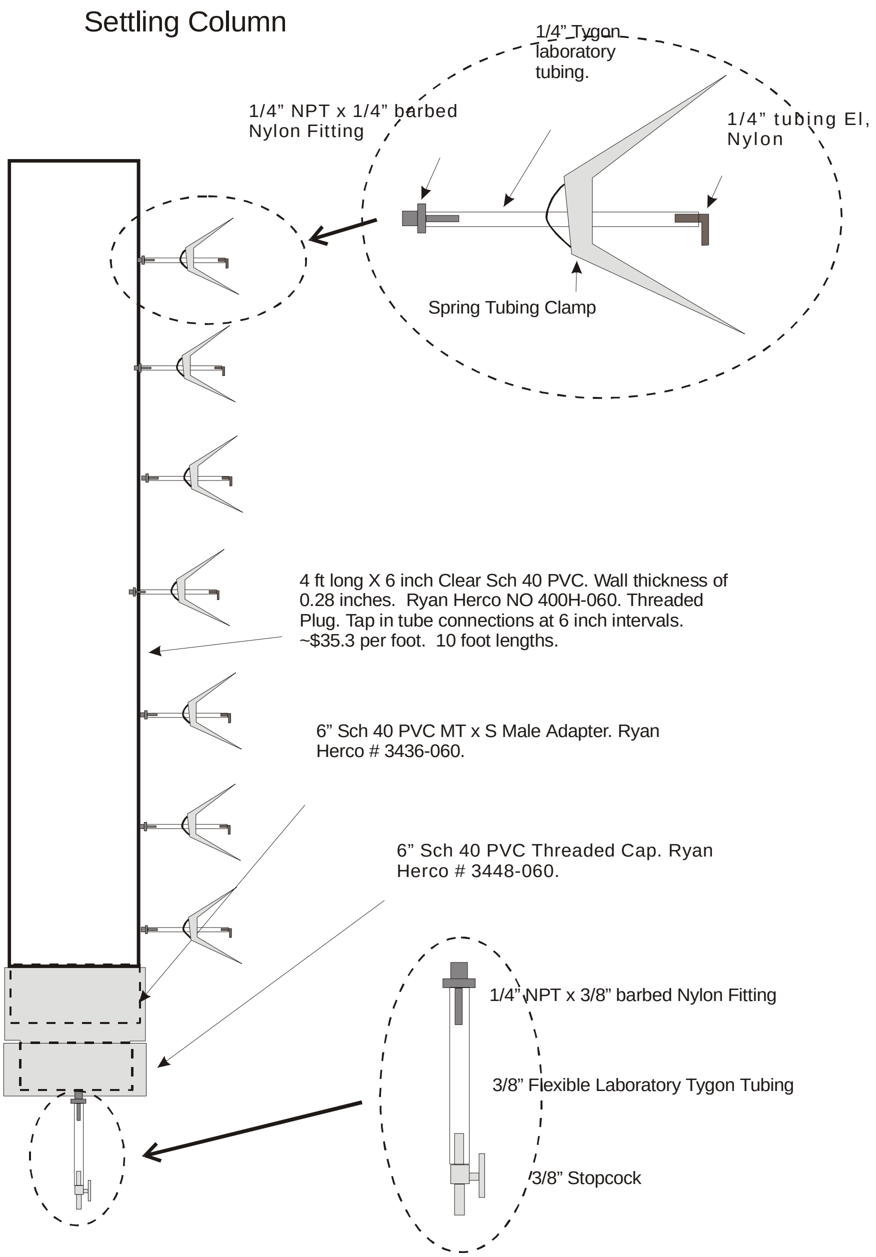
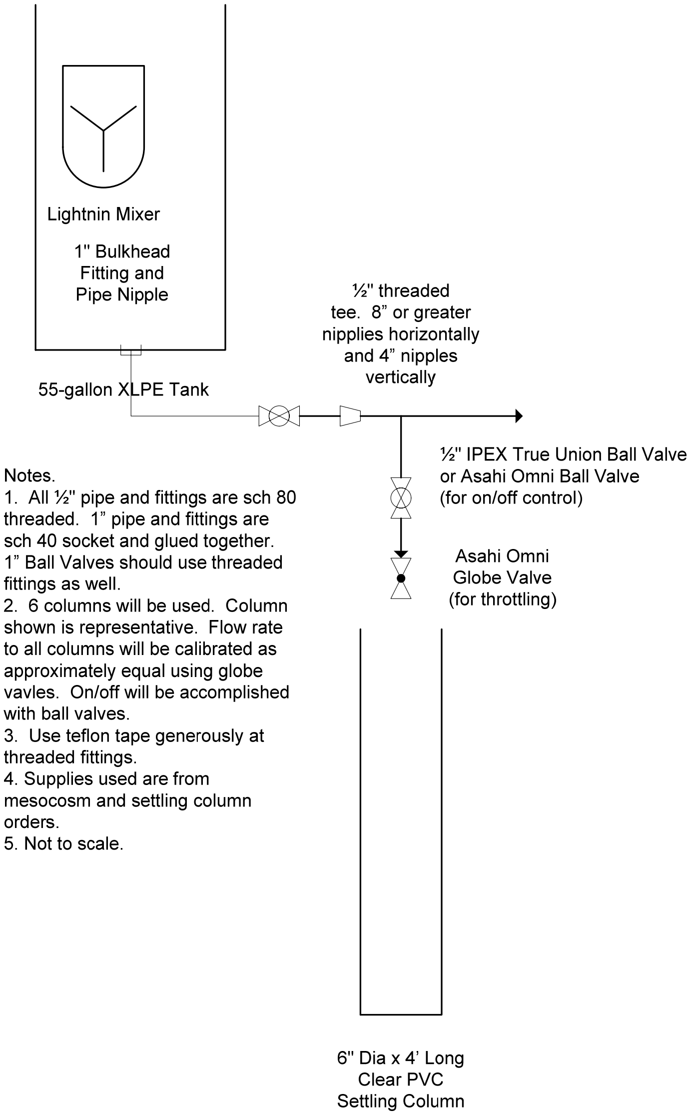


Figure 2-2 Schematic Showing Operation of Settling Columns



Notes.

1. All ½" pipe and fittings are sch 80 threaded. 1" pipe and fittings are sch 40 socket and glued together. 1" Ball Valves should use threaded fittings as well.
2. 6 columns will be used. Column shown is representative. Flow rate to all columns will be calibrated as approximately equal using globe vavles. On/off will be accomplished with ball valves.
3. Use teflon tape generously at threaded fittings.
4. Supplies used are from mesocosm and settling column orders.
5. Not to scale.

2.4 Data Analyses and Management

Samples were analyzed by the University of California Davis (UCD) Tahoe Research Group (TRG), UCD Soil Science Laboratory, UCD Division of Agriculture and Natural Resources (DANR) laboratory and a private lab, STL Sacramento. Each is discussed below.

2.4.1 Laboratory Studies

Samples for laboratory studies were analyzed by the TRG and DANR

Tahoe Research Group (TRG)

Phosphorus analyses were conducted by the Tahoe Research Group using methods developed for their laboratory and based upon standard EPA and Standard Method protocols. Phosphorus analyses conducted were for unfiltered total phosphorus (UTP) and filtered total phosphorus (FTP).

DANR Analysis

DANR conducted analyses of metals (total and total dissolved, soluble and filtered soluble), hardness, alkalinity, chloride, unfiltered and filtered TKN, nitrate, ammonia and total suspended and dissolved solids on real and synthetic storm waters as shown in Table 2-3. DANR also conducted aluminum, iron, alkalinity and nitrogen analyses on a subset of samples from the laboratory studies discussed in Chapters 4 and 5. Information on methods used is available on their website (http://danranlab.ucdavis.edu/).

2.4.2 Settling Studies

Settling study data was analyzed for phosphorus by the UC Davis Soils Laboratory in the Department of Land, Air and Water Resources. All other analyses were carried out by STL Sacramento.

UC Davis Soils Laboratory

Phosphorus analyses were conducted using similar methods as used by the Tahoe Research Group and followed standard EPA and Standard Method protocols. The UC Davis Soils Laboratory conducted these analyses to help expedite the project and worked closely with the TRG to ensure consistency in methods.

STL Sacramento

Total and dissolved aluminum and iron, TSS, TKN and filtered TKN, and alkalinity analyses were completed by STL Sacramento.

2.4.3 Database

All laboratory and settling column data was stored in an Access Database developed for this project. QA/QC was conducted according to the QAPP. An electronic version of this data is included with this report.

Table 2-5. Complete Chemical Analyses of Storm Water

Conventional	**Analytical Code**	
pH	pH	pH units
Total Suspended Solids (TSS)	TSS	mg L^{-1}
Total Dissolved solids (TDS)	TDS	mg L^{-1}
Hardness as $CaCO_3$	Hardness	mg L^{-1}
Dissolved Organic Carbon (DOC)	DOC	mg L^{-1}
Total Organic Carbon (TOC)	TOC	mg L^{-1}
Turbidity	Turbidity	NTUs
Chloride	Chloride	mg L^{-1}
Oil & Grease	O&G	mg L^{-1}
Nutrients		
Nitrate Nitrogen	NO3	mg L^{-1}
(Unfiltered) Total Kjeldahl Nitrogen (TKN)	UTKN	mg L^{-1}
Filtered Total Kjeldahl Nitrogen (TKN)	FTKN	mg L^{-1}
Total Phosphorus	UTP	µg L^{-1}
Total dissolved phosphorus	FTP	µg L^{-1}
Dissolved ortho-phosphate	FOP	µg L^{-1}
Total Metals		
Total Aluminum	UAL	µg L^{-1}
Total Iron	UFE	µg L^{-1}
Dissolved Metals		
Dissolved Aluminum	FAL	µg L^{-1}
Dissolved Iron	FFE	µg L^{-1}
Particle Size		
Particle Size Analyses	PSD	

Notes

1. Only for real storm water. Not to be analyzed for synthetic storm water.

2.5 Statistical Methods

Standard linear regression and Analyses of Variance (ANOVA) analyses were performed on the experimental data (Devore, 1991; Statsoft, 2001). These methods were used to show trends and to determine statistical differences between different treatments.

ANOVA analyses require replicated treatments to determine statistical differences between treatments. Treatments are defined as any combination of independent variables that may or may not affect the dependent variable. In this study, the dependent variables are the different metrics describing the effectiveness of coagulation and the independent variables are factors such as temperature, mixing regimes, coagulant dose and coagulant choice that were expected to affect the dependent variable and thus the outcome of coagulation. For ANOVA analyses in which treatments were found to differ significantly ($p<0.05$), a post-hoc analyses was conducted using the Tukey method. This method is very conservative in defining which independent treatments caused significantly different results for a given treatment. Statistical differences identified by the Tukey method are considered real.

2.6 Ranking Coagulants

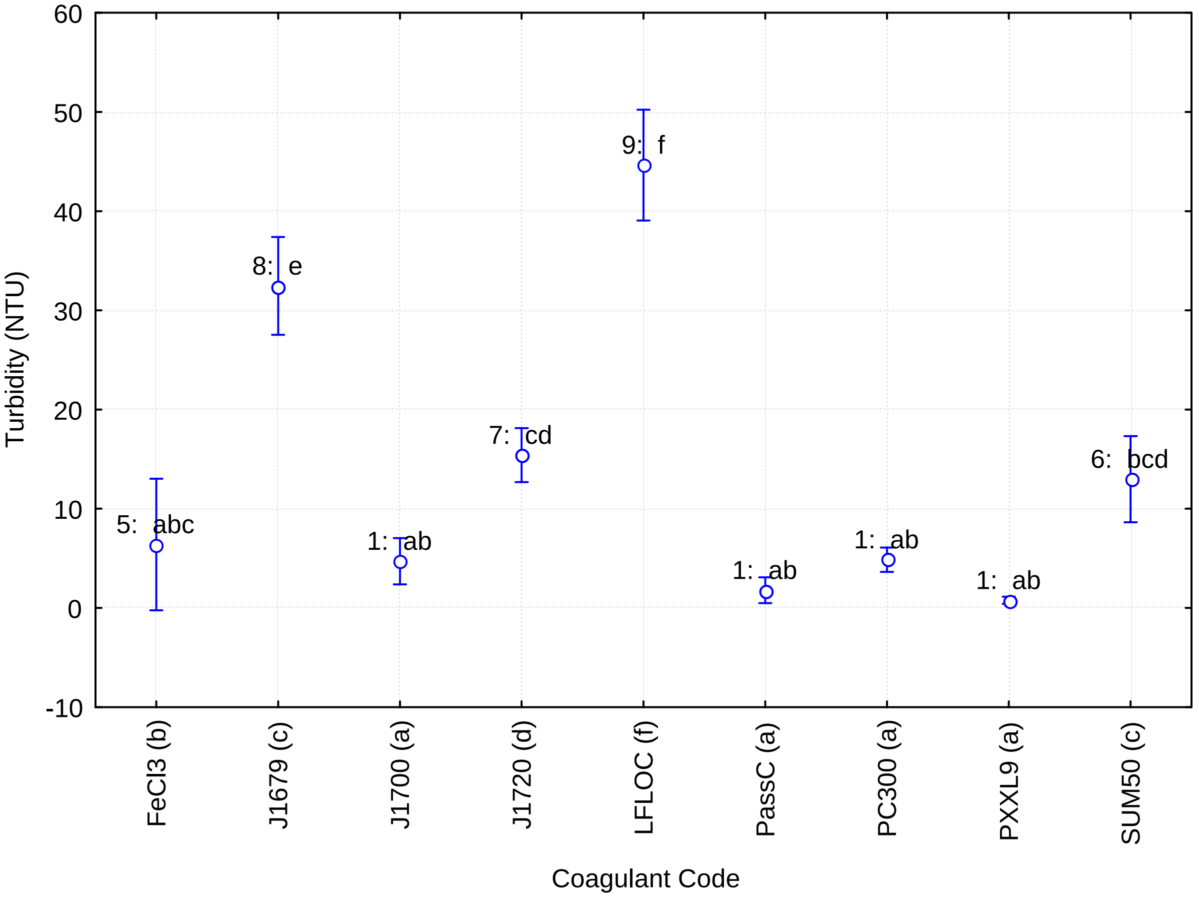
Coagulants were ranked based upon a statistical analysis of the experimental results. As an example, the methodology used for ranking coagulants for turbidity reduction is explained below.

Figure 2-3 shows an example in which turbidity achieved for different coagulants for an optimal dosing range of –300 to 0 mV is defined by the streaming current detector values. An “a” is assigned initially to the coagulant achieving the lowest value (PAX-XL9 in this case) and all coagulants that are not significantly different from this coagulant are identified by the same letter. A new letter (“b”) is assigned to the next lowest value that is statistically different from the first (“a”) and again all coagulants not statistically different are also assigned the same letter. This process is repeated until statistical differences have been identified.

In this example, PAX-XL9, Pass-C, PC300 and J1700 do not differ significantly from the same group of coagulants. However, FECl3 is assigned a “b” since it does not differ significantly from those four coagulants and with SUM50. SUM50 is assigned a “c” because it differs significantly from the four highest performing coagulants, but is similar to FeCl3 and JC1720. Letters are assigned to patterns of significance until all coagulants have been considered. For this example, the worst performing coagulant (LFLOC) is assigned a letter “f” and differs significantly from all the rest.

Thus, the letter groups define coagulants that perform similarly as defined by statistical significance. These groups are then ranked from the best performing group to the worst. In the example above, the coagulants given a rank of “1” are J1700, PAX-XL9, Pass-C and PC300. The next performing group consists of FeCL3 only. LFLOC alone makes up the worst performing group. This statistically ranking method was used throughout to differentiate coagulant performance.

Figure 2-3. Example for Ranking Coagulants -- Turbidity Achieved under Steady State Conditions for an Optimal Dosing Range of SCV (-300 to 0 mV).



2.7 Cost estimates

Cost estimates were provided from manufacturers for different volumes: 55 gallon, 275 gallon and bulk. These costs were provided for only the four top-ranked coagulants.

II. LITERATURE AND LABORATORY SCREENING OF COAGULANTS FOR PHOSPHORUS AND FINE PARTICLE REMOVAL

3 Literature and Industry Review of Coagulants

3.1 Review of Coagulants

The survey of initial coagulants was based upon a scientific literature review and discussions with industry representatives. Scientific literature review details, which include a review of Caltrans reports and other gray literature, can be found in the Research Plan (Bachand *et al.,* 2003). The survey considered aluminum and iron salts such as ferric chloride, ferric sulfate and alum, polyaluminum hydroxyl chlorides (PACls), polyferric sulfate and nitrogen-based organic cationic polymers such as Poly-DADMACs (polydiallydimehtyl ammonium chlorides) and Epi/DMA (epichlorohydrin dimehtylamine). This survey focuses broadly on PACls since these coagulants have received much investment in development and application and thus represent the cutting edge in coagulant technology.

A PACl is a pre-polymerised aluminum chloride. PACls are produced by titrating AlC_{l3} solutions with base. The most simple and easily manufactured PACl is straight aluminum chlorohydrates (ACHs). ACH has a basicity of approximately 80%. Basicity is defined as the molar ration of OH^- to aluminum. Basicity is thought to affect the aluminum speciation and alkalinity consumption during dosing (Muser, 2002). Lower basicity PACls are thought to more effectively remove phosphorus and higher basicity PACls are thought to better remove turbidity (Muser, 2002; Jennings 2002). As basicity increases up to about 70%, the Al_{13} polymer concentration increases relative to other aluminum polymers and monomers. At basicities > 70%, colloidal precipitate begins to form, decreasing Al_{13} polymer concentration.

More sophisticated PACls have been derived through more advanced chemistry manipulations and proprietary titration methods. These manipulations seek to optimize Al_{13} polymers as well as sulfate addition to improve precipitation and settling or silica addition to improve aggregation and settling.

Finally, coagulant companies focusing on blending have found a niche. These companies have begun with products of other manufactures and further altered the chemistry as well as added organic (nitrogen-based) polymers to improve flocculent aggregation and settling rates. Industrial representatives claim that organic polymers create larger, stronger and faster settling flocculates because of their large molecular weight, but tend to be less effective than inorganic polymers at removing fine particles. Organic polymers are often blended with PACls so that the complementary removal mechanisms of both polymer types can create a polymer blend which may provide better overall performance.

For ferric salts, inorganic polymer research is not as advanced. However, polyferric sulfate (PFS) is now being manufactured in the United States and is commercially available. PFS was selected for testing because its polymeric structure was expected to provide superior performance compared to iron salts.

Chitosan, a biopolymer derived from chitin, was not initially considered. Although some studies have shown that chitosan has had success for turbidity removal from storm water (MacPherson et al., 2002 and 2004), it was not commonly used in the United States at the initiation of this study and thus was not considered readily available. Chitosan was later selected because of interest in it in the Tahoe Basin. Anionic polyacrylamides (PAMs) were not considered because they are primarily flocculent aids and not coagulants; thus they were not considered relevant to these coagulant tests and this decision is supported by preliminary findings by Caltrans (Caltrans, 2003).

3.2 Coagulant Survey and Selection

Several leading coagulant manufacturers were interviewed to help identify potential coagulants for storm water treatment. These manufacturers were General Chemical, Kemiron, Summit Research Labs, Eaglebrook, JenChem and Westchlor. From these interviews, an initial list of over 30 inorganic aluminum- and iron-based coagulants was created. This list was further narrowed to approximately 25 coagulants, representing a full spectrum of coagulant chemistry (e.g. iron and aluminum based coagulants, a range of pH, a range of basicity, different percent metal concentrations, silica added, and sulfinated versus non-sulfinated). Table 2-1 lists the 25 coagulants and their relevant chemistry. Coagulants with redundant or similar chemistry were assumed to have similar performance, so some of the initial listed coagulants were eliminated based upon further review. The main criteria for retaining coagulants at this stage for initial screening through testing were:

- Not redundant chemistry
- Availability (West Coast suppliers and manufacturers favored over East Coast suppliers)
- Represent a full spectrum of coagulant chemistry:
- Range of basicity from low to very high;
- Varying metal content and pH;
- Sulfinated and non-sulfinated blends;
- Iron and aluminum based coagulants; and
- Inorganic PACls and inorganic/organic blends.

Under this approach, we hoped to test a wide variety of coagulant chemistries based upon available specifications. In some cases, proprietary coagulants thus represented a generic coagulant. For instance, four coagulants represent aluminum chlorohydrates (ACHs), the first PACl developed. In other cases, proprietary coagulants were assumed to represent coagulants with similar chemistry. Thus, this study does not intend to endorse specific products but to identify effective chemistries and identify differences and similarities in performance resulting from those chemistries.

Table 3-1. Coagulants Selected for Laboratory Screening

Classification	Commercial Coagulant Name	Metal Based	Vendor	Average			
				Basicity %	Al %	pH	SG[1]
Iron Coagulants							
Iron Salt							
	FeCl3	Fe	Kemiron	---	NA	<1	1.36
	FeSO4	Fe	Kemiron	---	NA	<1	1.62
Polymerized iron coagulants							
	PFS	Fe	Kemiron	---	NA	2	1.57
Aluminum Coagulants							
Aluminum Salt							
	Alum	Al	General Chemical	---	4.35	3.5	1.33
Aluminum Chlorohydrates (ACH - first generation PACl)							
	PAX-XL19®	Al	Kemiron	80	12.4	4.2	1.34
	HyperIon 1090®	Al	General Chemical	83	12.4	4.1	1.34
	JC 1600®	Al	JenChem	83	12.3	4.3	1.35
	Sumalchlor 50®	Al	Summit	83.5	12.4	4.2	1.34
Poly-aluminum chlorides (PAC) with low or medium % basicity							
	Sumaclear 910B®	Al	Summit	30	6.35	1.2	1.27
	PAX -11®	Al	Kemiron	40	10	2.4	1.2
	PAX-18®	Al	Kemiron	42	9	0.9	1.37
	PAC 300®	Al	Summit	47.5	5.8	2.55	1.2
	PAX XL8®	Al	Kemiron	55	5.4	2.7	1.23
	JC 1700®	Al	JenChem	70	6.6	4.3	1.31
	Sumaclear 700®	Al	Summit	70	10.2	1.6	1.33
Poly-aluminum chlorides (PAC) with high % basicity							
	HyperIon 1050®	Al	General Chemical	78	4.35	3	1.11
	HyperIon 4090®	Al	General Chemical	78	12.3	2	1.37
	JC 1800®	Al	JenChem	80	11.15	4.3	1.32
	Hyperion 1030®	Al	General Chemical	80	6.35	4	1.18
Poly-aluminum chlorides (PAC) modified with silica or sulfate							
	Pass®-C	Al	Eaglebrook	53.3	5.2	2.5	1.24
	PAX-XL9®	Al	Kemiron	67	5.6	2.8	1.26
Poly-aluminum chlorides (PAC) blended with organic polymers							
	JC 1720®	Al	JenChem	70	5.95	4.3	1.29
	JC 1750®	Al	JenChem	70	5.95	4.3	1.27
	JC 1670®	Al	JenChem	79	6.3	4.25	1.29
	JC 1679®	Al	JenChem	79	8.05	4.25	1.24

1. Specific gravity.

4 Initial Laboratory Coagulant Screening

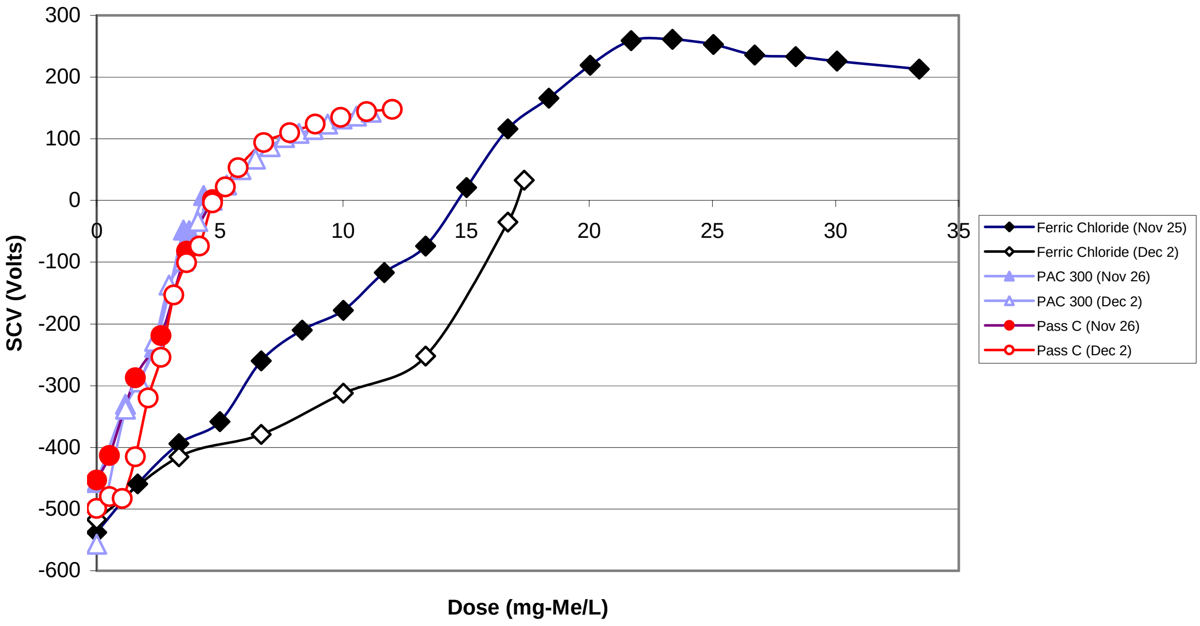
The goal of laboratory screening of coagulants was to narrow the list of coagulants down from the twenty-five selected by literature review to a manageable number of eight for further testing performance and robustness. Coagulants were initially screened based on turbidities achieved during charge titration studies. Charge titration was used to identify the dose at which charge neutralization was assumed to have occurred (e.g. SCV = 0 mV). Once this condition was achieved, particles were allowed to settle and turbidity was measured after 1 hour of settling. Streaming current values achieved during these studies were repeatable as shown in Figure 4-1. Near optimal performance was expected at or near the 0 mV dosing level; this expectation was supported by earlier findings during this study (Bachand *et al.*, 2003b).

The criteria for initial laboratory screening were:

- Effective turbidity removal;
- Maintain diverse coagulant chemistry as defined by chemical groups (e.g. iron-based salts, PACl, PACl blended with organic polymers, and straight ACHs);
- Low dosing levels.

For application in storm water basins and wetlands, where formed sediments will accumulate, the dosing level is expected to be important because it affects the quantity of flocculate formed and related maintenance to manage or remove the flocculate.

Figure 4-1 Repeatability of Streaming Current Values for Pass-C, PAC 300 and Ferric Chloride using Two Different Synthetic Storm Waters



4.1 Charge Titration Experiments

Charge titration experiments using synthetic storm water were used for exploratory screening of the coagulants; the results of these pre-screening experiments are presented in Table 4-1. Charge titration tests were used to select those coagulants that showed the best potential for particle destabilization and subsequent settling in the synthetic storm water at feasible coagulant dosages. In Table 4-1, coagulants are categorized by their group (e.g. iron coagulants, aluminum coagulants, inorganic/organic blends) and by their chemistry as defined by percent aluminum (e.g. low, medium, high), percent basicity (e.g. low, mid, mid to high, high), sulfinated or not, presence of silicate, and pH.

At this stage of the study, the emphasis was on retaining coagulants to reflect the diversity in coagulant chemistries as well as on trying to minimize the dosing levels needed in achieving charge neutralization. Further, a turbidity cutoff of 10 NTU was chosen for screening coagulants. Coagulants not achieving turbidity reduction to 10 NTU were rejected. Table 4-1 presents the justifications for accepting or rejecting coagulants using the above criteria. These justifications were:

- Group 1 – Iron chloride was selected because it was the best performing iron coagulant.
- Group 2 – PAX-XL9, Pass-C, JENCHEM 1700, HyperIon 4090, HyperIon 1030 and Sumaclear 910B were selected because they were the top six performing PACls providing the best final turbidity (< 8 NTU) of the PACls group at relatively low dosing

levels of less than 15 mg-metal L^{-1}. These coagulants provided a turbidity removal of 98% or better.

- Group 3 – PAC 300 and PAX-XL8 have very similar chemistry and performed similarly to each other and to those coagulants in Group 2. Because of their similar chemistry and performance, only one coagulant was retained. PAC 300 was selected.
- Group 4 – Sumaclear 700 was rejected because it required very high dosing levels compared to other PACls.
- Group 5 – The four aluminum chlorohydrate solutions achieved turbidity values of around 10 NTU and have nearly identical chemistry. Sumachlor 50 was selected because of the four it required the lowest dose to neutralize charge.
- Group 6 – All were rejected because they did not achieve good turbidity reduction (achieved > 10 NTU) and required relatively high dosing levels. PAX-11 was unable to achieve charge neutralization.
- Group 7 – These coagulants are derivatives of JENCHEM 1700 and JC 1600 (an ACH) but include the blending of an organic polymer. JENCHEM 1720 was selected because it was the top JENCHEM 1700 derivative, achieving a lower turbidity at a lower dose than JC 1750. JC 1679 was selected because it was the top JC 1600 derivative. These coagulants are selected to continue testing the effect of organic/inorganic polymer blends.

All coagulants slightly depressed pH though generally the effect was only slight. For the PACls, final pH concentrations ranged from 6.6 to 8.0, for an initial pH of around 8. Iron products depressed pH slightly more, with final pH values of between 6.0 and 6.3. pH was not considered critical at this time in selecting or rejecting coagulants.

Using the above approach, 11 coagulants were selected from the initial list of 25 coagulants. Table 4-1 shows the 11 selected coagulants (shaded) and summarizes the justification for the grouping and selection.

4.2 Jar Studies

The number of coagulants was further reduced through jar test experiments. Table 4-2 lists the 8 coagulants selected for further testing based upon the results of these jar studies. For the coagulants selected for further testing, an iron salt, an ACH, two inorganic/organic polymer blends and four PACls were retained. One of the PACls retained (Pass-C) is being extensively tested by Caltrans, and was therefore selected as a standard of comparison. Table 4-3 shows the chemistry of these coagulants.

4.3 Summary

From an initial review of available coagulants using industry surveys, industry literature and the scientific literature, over 25 coagulants were identified for screening with laboratory methods. The initial coagulant list represented a range of available coagulant chemistries:

- Iron and aluminum based salts and inorganic polymers (e.g. PACl, ACH, PFS)
- PACls with and without organic polymers additives
- Wide range of basicities

- PACls with and without sulfur or silica

The number of coagulants was initially narrowed to 11 based on charge titration studies, and further narrowed to 8 coagulants using jar studies. Screening criteria included the performance of coagulants at removing turbidity, a desire to maintain a chemically diverse group of coagulants, and a desire to maintain low dosing levels. The selection was intended to test the more effective coagulant chemistries as represented by these products.

Table 4-1 Charge Titration Results and Justification for Selection of 11 Coagulants for Further Testing

Group	Coagulant	Metal	Type^{2}	Basicity^{1}	%Al^{3}	Sulfinated^{4}	pH	Silica	Dose MG-Me/L	Turb at final SCV value^{7}	Final SCV	Final pH^{5,8}	Justification (Y= Yes, N= No)	
Step 1 - Inorganic coagulants Tested														
	Iron Coagulants													
1	$FeCl_3$	Fe	Iron salt	NA	NA		<1		26.4	5.5	0	6.3	Y	$FeCl_3$ was best Fe coagulant and achieved low turbidity. All Fe coagulants required very high doses (>25 mg-Me/L).
	PFS	Fe	PFS	NA	NA	Yes	2.00		34.2	7.9	0	6.0	N	
	$FeSO_4$	Fe	Iron salt	NA	NA	Yes	<1		32.6	11.8	0	6.2	N	
	Aluminum Coagulants													
2	PAX-XL9	Al	PACl	MH	L	Yes	2.80		11.4	2.3	0	6.8	Y	Top six aluminum coagulants providing best final turbidity (<8 NTU) at relatively low doses (<15 mg-Me/L).
	Pass-C	Al	PAHCS	M	L	Yes	2.50	Yes	13.4	4.2	0	6.6	Y	
	JC 1700	Al	PACl	MH	M	Yes	4.30		9.3	4.8	3	7.0	Y	
	HyperIon 4090	Al	PACl	H	H		2.00		8.8	5.0	0	7.4	Y	
	Hyperion 1030	Al	PACl	H	M		?		4.5	7.4	6	7.9	Y	
	Sumaclear 910B	Al	PACl	L	M		1.20		7.0	7.8	0	6.7	Y	
3	PAX XL8	Al	PACl	M	L	Yes	2.70		12.3	7.9	-2	6.9	N	Have similar chemistry and performed similarly. PAC 300 selected because of slightly lower dosing requirements.
	PAC 300	Al	PACl	M	L		2.55		10.9	8.8	0	7.0	Y	
4	Sumaclear 700	Al	PACl	MH	H		?		21.4	8.8	2	6.7	N	Rejected because of very high dosing requirements for a PACl (>15 mg-Me/L).
5	JC 1600	Al	ACH	H	H		4.30		4.1	9.0	4	7.7	N	Have similar chemistry and performed similarly. Sumachlor 50 selected because it had lowest dosing requirements.
	PAX-XL19	Al	ACH	H	H		4.20		4.1	9.9	8	7.7	N	
	HyperIon 1090	Al	ACH	H	H		4.10		3.6	10.3	0	7.9	N	
	Sumachlor 50	Al	ACH	H	H		4.20		2.3	10.3	0	7.9	Y	
6	PAX-18	Al	PACl	M	M	Yes	0.90		11.4	11.6	0	7.9	N	Not selected because coagulants achieved poor final turbidity (> 10 NTU). PAX 11 could not achieve charge neutralization. Most coagulants required high dosing levels.
	JC 1800	Al	PACl	H	H	Yes	4.30		4.0	13.6	0	7.7	N	
	PAX 11^{6}	Al	PACl	L	H	Yes	2.40		16.1	14.3	-30	6.9	N	
	Alum	Al	Al salt		L	Yes	3.50		12.9	19.9	0	6.9	N	
	HyperIon 1050	Al	PACl	H	L		3.00		5.1	23.0	0	7.9	N	
Step 2 - Inorganic/Organic Blends Tested (Derivatives of JC1600 and equivalents, and JC 1700)														
7	JC 1720	Al	PAHCS	MH	L	Yes	4.30		1.2	3.2	20	7.9	Y	Top JC1700 Derivative.
	JC 1679	Al	PACl	H	M		4.25		0.5	6.5	12	8.0	Y	Top JC1600 Derivative.
	JC 1670	Al	PACl	H	M		4.25		0.9	7.3	23	7.9	N	
	JC 1750	Al	PAHCS	MH	L	Yes	4.30		1.5	9.2	0	7.9	N	

Notes

1. L (Low basicity) up to 40, M (mid basicity) = from over 40 up to 55, MH (mid to high basicity) = from over 55 up to 70, High (high basicity) = from over 70 up to 85.
2. Codes for chemicals: ACH=aluminum chlorohydrate, PACl = Polyaluminum (hydroxy)chloride, PFS=polyferric sulfate, PAHCS=poly aluminum hydroxychlorosulfate. ACH and PAHCS coagulants are subsets of PACl coagulants as PACl is a broader definition.
3. NA = not applicable; L (Low) = 4 - 6% Al; M (Medium) = 6 - 9% Al; H (High) = 9 - 13% Al.
4. Yes means sulfinated but concentration unknown at this time.
5. Represents final pH of water. Initial water pH = 8 +/- 0.05.
6. Unable to reach zero value on Streaming Current Detector
7. Turbidity measured after 1 hour settling time after the completing of the charge titration studies. Shaded values represent final turbidity < or = to 10 NTU.
8. Measurements at completion of charge titration dosing.

Table 4-2 Jar Test Screening of Coagulants

Classification	Commercial Coagulant Name	Metal Based	Dose mgME/L		Turbidity at 30 minutes[1]			Selection Note	Selected[7]
			Means	Rank	Means	SD	Rank		
Iron Coagulants									
Iron Salt									
	FeCl3	Fe	12.6	11	0.50	0.22	4	2	X
Aluminum Coagulants									
Aluminum Chlorohydrates (ACH - first generation PACl)									
	Sumalchlor 50®	Al	3.8	3	2.36	0.52	8	2,3	X
Poly-aluminum chlorides (PAC) with low or medium % basicity									
	Sumaclear 910B®	Al	5.2	4	1.39	0.43	7	5	
	PAC 300®	Al	5.8	6	0.62	0.24	5		X
	JC 1700®	Al	7.7	9	0.37	0.08	3	4	X
Poly-aluminum chlorides (PAC) with high % basicity									
	HyperIon 4090®	Al	6.3	7	1.10	0.05	6	5	
	Hyperion 1030®	Al	5.5	5	6.05	1.62	11	5	
Poly-aluminum chlorides (PAC) modified with silica or sulfate									
	Pass®-C	Al	9.0	10	0.34	0.10	2	4,6	X
	PAX-XL9®	Al	7.5	8	0.26	0.05	1	4	X
Poly-aluminum chlorides (PAC) blended with organic polymers									
	JC 1720®	Al	1.6	2	2.60	2.09	9	3	X
	JC 1679®	Al	1.3	1	4.57	1.19	10	3	X

1. Control turbidity between 65 and 90 NTU depending upon day. Same synthetic stormwater used throughout.
2. Only coagulant in group.
3. Top three lowest doses
4. Top three in turbidity removal.
5. Worse three performers of PACs. Not unique representative of any group (I.e., iron based, ACH, inorg/org blend)

6. Used in small-scale tests by Caltrans (Caltrans 2003).
7. X indicates coagulant selected for further testing.

Table 4-3 Selected Coagulant Chemistry

Coagulant	Metal	Vendor	Type[2]	%Bas.[1]	%Al[3]	Sulfinated[4]	pH	Org poly	Silica Added
$FeCl_3$	Fe	Kemiron	Iron salt	NA	NA		<1		
PAX-XL9	Al	Kemiron	PACl	MH	L	Yes	2.80		
Pass-C	Al	Eaglebrook	PAHCS	M	L	Yes	2.50		Yes
JC 1700	Al	JenChem	PACl	MH	M	Yes	4.30		
PAC 300	Al	Summit	PACl	M	L		2.55		
Sumachlor 50	Al	Summit	ACH	H	H		4.20		
JC 1720	Al	JenChem	PAHCS	MH	L	Yes	4.30	Yes	
JC 1679		JenChem	PACl	H	M		4.25	Yes	

Notes

1. L (Low basicity) up to 40, M (mid basicity) = from over 40 up to 55, MH (mid to high basicity) = from over 55 up to 70, High (high
2. Codes for chemicals: ACH=aluminum chlorohydrate, PACl = Polyaluminum (hydroxy)chloride, PFS=polyferric sulfate, PAHCS=poly
3. NA = not applicable; L (Low) = 4 - 6% Al; M (Medium) = 6 - 9% Al; H (High) = 9 - 13% Al.
4. Yes means sulfinated but concentration unknown at this time.

5 Sensitivity of Coagulant Performance to Dosing Levels

This chapter focuses on tests of the robustness of coagulant performance under different dosing levels. For a coagulant to be successfully used for treating storm water, robust performance for varying dosing levels is required as storm water flows and quality vary greatly, and accurately predicting and achieving appropriate dosing levels is a challenge in the extreme environmental conditions common to Lake Tahoe. Nine coagulants are ranked for robustness to different dosing levels. Eight of these coagulants were identified in Chapter 4, and one additional coagulant, Liquid Floc (a chitosan product), was added because it is a naturally occurring biopolymer that has shown some promise in field applications (MacPherson *et al*., 2002 and 2004) and because there was interest in this coagulant in the Tahoe Basin.

5.1 Ranking Criteria

Table 5-1 shows the model used for assessing coagulants for robustness against different dosing levels. In this model, turbidity reduction at 5 minutes and turbidity reduction and dissolved and total phosphorus removal at 30 minutes are measures of performance. Both an optimal dosing range, as determined using charge titration studies, and a more general dosing range were used to describe two different operational conditions: controlled and variable. Additionally, turbidity removal at 5 minutes, changes in pH, and dosing levels were used as indicators for environmental effects, maintenance requirements and operational costs.

Table 5-1. Criteria Model for Ranking Coagulants

Parameter[1, 2, 3,4]	Ranking Criteria				
	Performance		Other Issues		
	Controlled/Typical Performance[8]	Robustness to Dosing Variability	Settling Rate & Capital Costs Considerations[10]	pH/Alkalanity Considerations[9]	Maintenance & Environmental Considerations[4]
All SCD dosing levels[5]					
Turbidity at 30 minutes		▨			
Turbidity at 5 minutes		▨	▨		
pH[7]				▨	
Dose (mg-Me/L)[4]					▨
UTP at 30 minutes		▨			
FTP at 30 minutes		▨			
For SCD dosing levels < or = 0 mV[6]					
Turbidity at 30 minutes	▨				
Turbidity at 5 minutes	▨		▨		
Dose (mg-Me/L)					▨
UTP at 30 minutes	▨				
FTP at 30 minutes	▨				

[1] T/To = Turbidity standardized against control turbidity (no dosing) at same sampling time (e.g. 0, 5, 10, 30 minutes)

[2] UTP = Unfiltered total phosphorus. Equivalent to total phosphorus

[3] FTP = Filtered total phosphorus. Equivalent to dissolved phosphorus.

[4] Dose affects environmental considerations such as metal and floc accumulation as well as logistical, equipment and other O&M considerations.

[5] All SCV dosing levels represent dosing under both over- and under-dosed conditions. Thus it is a measure of robustness with regard to dose.

[6] SCV < or = to 0 mV represents more optimal dosing conditions

[7] Charge titration results

[8] Represent performance if dosing levels are controlled or regulated

[9] Changes in pH below 0.5 Units are considered acceptable.

[10] Settling rate is used as an indicator for the potential of flocculate resuspension and may also indicate that smaller (less expensive, more logistically feasible) basins can be constructed.

5.2 Selection of Streaming Current Values and Jar Studies

This assessment was conducted through integrated charge titration and jar test studies. Charge titration studies were used to determine the dosing level for the coagulants and jar studies were used to assess performance at those dosing levels. Synthetic storm water made with South Lake Tahoe sweepings with a target turbidity of 500 NTU was used in these experiments.

Replicated charge titration tests (N=3) were conducted for each coagulant using synthetic storm water and temperature and pH measurements were taken at the end of each test. Dosing levels in mg/L were determined from the resulting charge titration curves. Figure 5-1 shows example charge titration curves for JenChem 1700, a PACl produced by JenChem. In general, good replication was achieved for a given coagulant and storm water in the charge titration studies.

This is demonstrated in Figure 5-1 by not only the similar curve shapes but also the similar dosing values achieved at critical SCV values (such as 0 mV).

Dosing levels corresponding to streaming current values (SCVs) of –300, -200, -100, 0, 75 and 150 mV were selected from the results of the charge titration tests. These SCVs were chosen to ensure a good range of dosing levels that would show performance under both over- and underdosing (Table 5-2). At these SCVs, coagulants were typically underdosed below the zero-dosing level by about 50% and overdosed by two times or more. These dosing ranges represent over- and underdosing and offer a wide dosing range for all coagulants.

SCVs were selected as the targets for dosing for several reasons:

1. The experimental results suggest streaming current detector (SCD) technology, if found to be accurate and reliable in field applications for storm water treatment, may aid chemical dosing (Bachand *et al.*, 2003).
2. Use of SCV as indicators for dosing would ensure similar charge characteristics of the dosed water regardless of coagulants used.

Jar studies were conducted for these defined dosing levels at ambient room temperature (~15 – 17 °C). Turbidity was measured at 0, 5, 10 and 30 minutes, and unfiltered total phosphorus (UTP) and filtered or dissolved total phosphorus (FTP) were sampled for at 30 minutes.

Table 5-2 Initial Synthetic Storm Water Quality

Stormwater Code	Turbidity			UTP			FTP			pH		
	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N
S500S-031703	496	21	5	977	355	4	35	14	4	7.52	0.05	4
S500S-032903	499	34	6	806	390	6	23	6	6	7.54	0.17	6

Figure 5-1 Sample Charge Titration Results for JenChem 1700

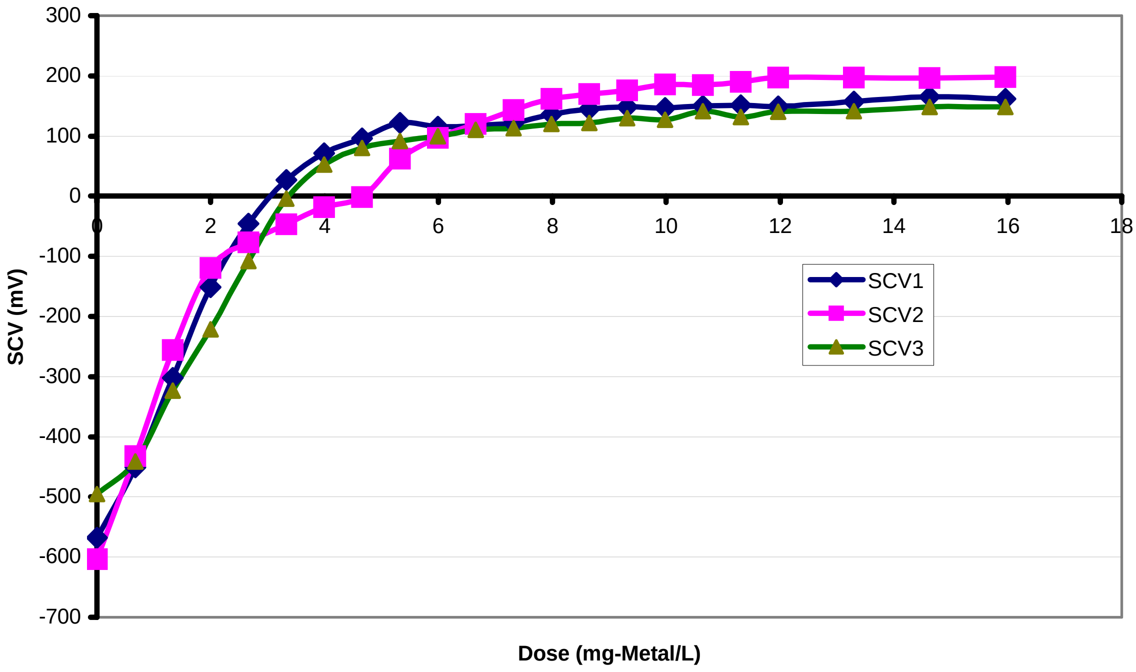


Table 5-3. Dosing Levels for SCVs from –300 to +150 mV for Nine Coagulants

Coag. Type	Chitosan		Iron-based		Aluminum-based													
Coag. Name	Liquid Floc (chitosan)		Ferric Chloride		Pac 300		Pass C		Pax XL9		JenChem 1700		JenChem 1720		Sumachlor 50		JenChem 1679	
Basicity	NA		NA		47.5		53.3		67		70		70		83.5		79	
Silica Added	No		No		No		Yes		No		No		No		No		No	
Sulfinated					No		Yes		Yes		Yes		Yes		No		No	
Organic Polymer	No		No		No		No		No		No		Yes		No		Yes	
	Dose																	
SCV (mV)	mg/L[2]	%[1]	mg_{Me}/	%[1]	mg_{Me}/	%[1]	mg_{Me}/	%[1]	mg_{Me}/	%[1]	mg_{Me}/	%[1]	mg_{Me}/	%[1]	mg_{Me}/	%[1]	mg_{Me}/	%[1]
-300	0.69	0.26	5.6	0.38	1.53	0.36	1.61	0.21	2.12	0.36	1.19	0.34	0.26	0.41	0.47	0.43	0.27	0.57
-200	1.29	0.49	8.11	0.55	2.3	0.54	2.97	0.39	3.1	0.53	1.82	0.52	0.38	0.59	0.67	0.61	0.33	0.70
-100	1.87	0.72	12	0.81	3.17	0.74	4.9	0.64	4.23	0.72	2.54	0.73	0.5	0.78	0.87	0.79	0.4	0.85
0	2.61	1.00	14.8	1.00	4.27	1.00	7.64	1.00	5.86	1.00	3.5	1.00	0.64	1.00	1.1	1.00	0.47	1.00
75	NA	NA	17.4	1.18	5.57	1.30	11	1.44	8.3	1.42	4.58	1.31	0.78	1.22	1.33	1.21	0.53	1.13
150	NA	NA	31.7	2.14	8.84	2.07	17.6	2.30	12.6	2.16	12.1	3.46	1.29	2.02	2.1	1.91	0.62	1.32

[1] Percent of zero-dose (Dose at which SCV = 0 mV).

[2] Liquid Floc is a chitosan alternative and does not contain aluminum or iron. Liquid Floc did not achieve a SCV of -50 mV regardless of dose used.

5.3 Performance Results

The nine coagulants were ranked based on turbidity and phosphorus removal at the different SCVs. Each coagulant was then ranked using the model shown in Table 5-1. Ranking was performed for the complete dosing range as well as for a more narrow optimal dosing range.

5.3.1 Defining an Optimal Dosing Range

Table 5-3 lists the dosing levels for SCVs from -300 mV to +150mV for the nine coagulants. This data was used to define a more "optimal" dosing range that showed minimal sensitivity of performance to dosing levels. Table 5-4 shows mean turbidity and phosphorus values for all nine coagulants for different SCVs. Turbidity and total phosphorus values were significantly higher ($p<0.05$) at an SCV of 150 mV than for lower SCV values. These trends are more pronounced when considering all coagulants (Figure 5-2a) instead of PACls alone (Figure 5-2b).

As shown in Figure 5-2, the variance in the results is much greater at SCVs of 75 and 150 mV than for SCVs between -300 and 0 mV, especially for turbidity and unfiltered total phosphorus (UTP) which are parameters influenced by the particulate fraction. Much of this variance is associated specifically with ferric chloride, and not Liquid Floc or the seven PACls. Figure 5-2a shows that total phosphorus and turbidity values at 75 mV do not differ significantly from corresponding values at lower SCVs. This is primarily due to the increased variance in the data at the 75 mV level, suggesting that overdosing may be occurring at SCV values lower than 75 mV. Figure 5-2b illustrates this in the much smaller variance at these higher SCVs for the PACls, but for this water over-dosing still appears to begin at SCVs between 75 and 150 mV.

There is clearly a trend towards less effective phosphorus and turbidity reduction as indicated by higher means and greater variance, especially for ferric chloride which appears to be more sensitive to overdosing than the PACls. Based on these results and statistical analysis, overdosing was assumed to occur at SCVs greater than 0 mV, and the optimal dosing range was defined as the dosing range corresponding to SCV values between –300 and 0 mV.

Table 5-4. Mean Turbidity and Phosphorus Levels Achieved 30 Minutes After Chemical Dosing.

Shaded cells represent statistically significant differences.

SCV	Turbidity			UTP			FTP		
	Mean	SD	Sig[1]	Mean	SD	Sig[1]	Mean	SD	Sig[1]
mV	NTU	NTU		ppb	ppb		ppb	ppb	
-300	12	14	a	30	17	a	15	9	a
-200	12	13	a	27	18	a	11	5	a
-100	12	16	a	31	19	a	12	6	a
0	14	15	a	32	18	a	8	4	a
75	39	65	a	54	72	a	11	12	a
150	89	88	b	107	91	b	12	15	a

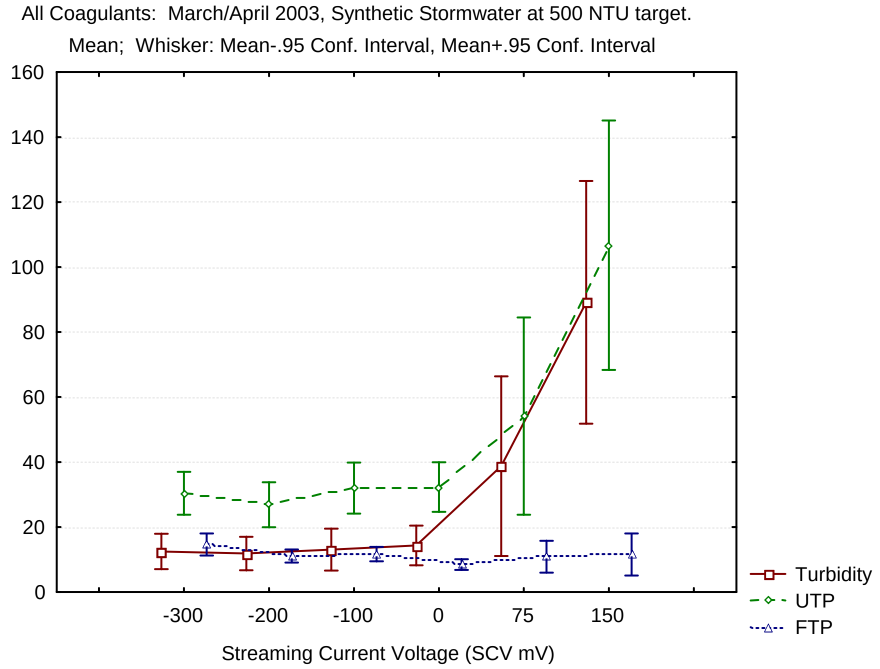
Notes

1. Sig = statistical significance. Values with the same letter are not statistically different ($p<0.05$)

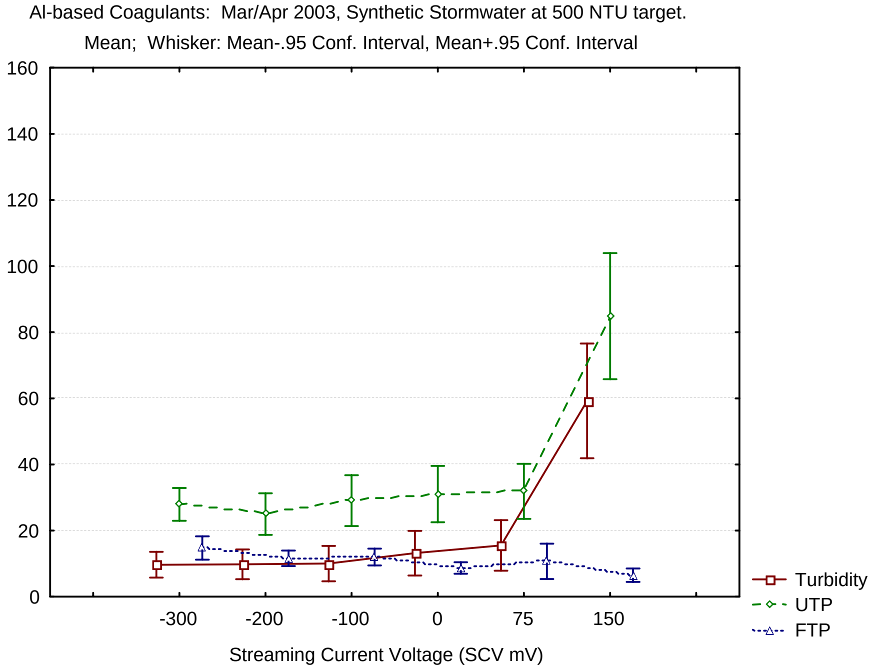
Figure 5-2 Turbidity and Phosphorus Concentrations at Different Streaming Current Values for a Synthetic Storm Water with an Initial Target Turbidity of 500 NTU

(Initial turbidity averaged 495 to 499 NTU (depending upon the batch prepared). For the two synthetic storm water batches used, after 30 minutes settling turbidity averaged 250 to 290 NTU. See Table 5-2 for water quality of synthetic storm water used.)

a. All Coagulants



b. Aluminum Based Coagulants



5.3.2 Coagulant Performance and Ranking

Table 5-4 shows the performance of the different coagulants at both the full and optimal dosing ranges. Metrics measured from the jar tests are indicators of the performance and logistical, economic and environmental criteria as described in Table 5-1. These metrics were as follows:

- Turbidity at 5 and 30 minutes of settling;
- Unfiltered and filtered total phosphorus at 30 minutes; and
- Coagulant dose in mg-metal per liter.

These metrics were analyzed statistically to determine means, standard deviations and standard errors, and ANOVA analysis was performed to determine statistical variance. The statistical analysis was conducted for both the full and optimal dosing range.

Table 5-5 shows the turbidity and phosphorus means and corresponding standard deviations and ranking for the nine coagulants for both full (Table 5-5a) and optimal (Table 5-5b) dosing ranges. Ranking was based on the procedures discussed in Section 2.6 Coagulants that achieved lower concentrations or values for turbidity and phosphorus were given a higher ranking, but for pH higher values were considered better because they indicated minimal affect on background alkalinity and pH.

5.3.3 Performance and Dosing Characteristics for Full and Optimal Dosing Levels

At the full dosing range, ferric chloride and Liquid Floc, the chitosan product, are generally poorer performers with regard to steady state (30 minute settling time in a jar test) turbidity and total phosphorus removal when compared to the PACls. This is partly due to both less effective conversion of dissolved phosphorus to particulate phosphorus and formed flocculates which do not settle as well. This relationship is less clear after only 5 minutes of settling, as the flocculates formed by the PACl settle at very different rates. For instance, turbidity after only 5 minutes of settling is less than 10 NTU for PAX-XL9 but near 80 NTU for PAC-300.

Ferric chloride required the highest mean metal dose. This is not surprising, as the molar weight of iron is almost twice that of aluminum and thus for the same number of moles of coagulant, twice the mass is needed. The mean dosing level required for PACls varies by over one order of magnitude between coagulants (Table 5-5a). This great variation in mean dose is due in part to whether an organic polymer is blended with the PACl.

Inorganic/organic blends consistently require much lower dosing levels for this tested water. They also tend to minimally affect pH, requiring very little alkalinity to neutralize particles and promote coagulation and flocculation. (SumaChlor 50, the straight ACH, also required very low dosing levels.) JenChem 1679, however, was one of the worst PACls at turbidity removal at 5 minutes, showing that the formed flocculate did not settle as well as flocculates formed without an organic polymer blended into the PACl. These blended coagulants have a lower percent aluminum, so the inability to achieve low concentrations may be due to both the size of the flocculate and its weight per volume relationship. After 30 minutes and at more steady state conditions, JenChem 1679 had very poor total phosphorus removal when compared to the other PACls and though turbidity removal did not differ statistically from the other PACls, the mean value was higher than all the other PACls. JenChem 1720 performed at a higher level than

JenChem 1679, with average total phosphorus and turbidity removal. Thus, the inorganic/organic blends may perform less well than traditional PACls, though a careful development of the blend may allow for equivalent turbidity and phosphorus removal at much lower doses. Notably, all coagulants reduced phosphorus below the surface water phosphorus threshold of 100 ppb to around 34 ppb, with 90% as particulate phosphorus. Only PAX-XL9 met the turbidity standard. The highest ranked coagulants for turbidity removal were PAX-XL9, PC300 and Pass-C.

At more optimal dosing ranges for this tested water (i.e. SCV = –300 to 0 mV), the overall performance improved. Average turbidity achieved after 30 minutes of settling ranged from about 1 ppb to 45 ppb. Four of the seven PACls met the turbidity standard, with PAX-XL9 once again performing the best. Ferric chloride also met the standard, but Liquid Flocculate was the worst performer, achieving a turbidity value of 45 NTU. JenChem 1679 was the worst PACl for turbidity and total phosphorus removal at steady state conditions, and amongst the worst for filtered phosphorus removal and flocculate settling.

At the more optimal dosing rates, all the coagulants met the phosphorus standard. Again PAX-XL9 was in the best performing group. That group achieved a total phosphorus concentration at or below 21 ppb with a very narrow standard deviation (<6 ppb).

5.3.4 Changes in Performance when Considering Optimal vs Full Dosing Range

A comparison of coagulant performance under optimal (controlled) and full dosing environments (Table 5-5a vs 5-5b) indicates that more optimal dosing improves performance of both the iron and aluminum based coagulants. The greatest improvements were clearly in ferric chloride where all measures of performance seemed to greatly improve under more optimal dosing. Thus, ferric chloride is not a very robust coagulant with regard to variations in dose and this lack of robustness is a very important issue when considering a coagulant for use in storm water treatment.

Improvements in aluminum-based coagulants were less dramatic. Some coagulants such as PAX-XL9, Sumachlor 50 (an ACH) and JenChem 1720 had very similar mean performance in both dosing ranges. Others like PAC-300 and JenChem 1700 showed more dramatic improvements. Overall, mean turbidity and total phosphorus removal for the coagulants showed an improvement of about 25%, mean dissolved phosphorus removal improved by nearly 50%, and turbidity standards were more easily achieved (Table 5-6). Thus, PACls are more robust than ferric chloride as a class, though that robustness varies with coagulant and parameter. These findings cannot be extrapolated to alum with a great deal of confidence. However, based upon the lack of robustness of the iron salt ferric chloride, it is expected that aluminum-salt will also lack robustness.

For Liquid Floc, a SCV greater than 0 mV could not be achieved regardless of dosing level, so values in both tables (Tables 5-5 and 5-6) are from exactly the same SCVs.

5.3.5 Standard of Comparison

Pass-C was selected as the standard of comparison because it has been the most widely tested by Caltrans in their small-scale and laboratory studies. Pass-C is among the more effective coagulants tested in this study, consistently ranking very high in steady state turbidity and phosphorus removal as well as settling rate (Table 5-5). Pass-C requires the highest dose though and apparently consumes the most alkalinity of all the PACls.

5.4 Coagulant Selection Criteria

Table 5-7 shows the coagulants ranked in terms of the performance indicators given in Table 5-1. PAX-XL9 and Pass-C are the top two performing coagulants under a full and more optimal dosing range. PAX-XL9 and JenChem 1720 provide the most rapid settling flocculates for the conditions tested here. JenChem 1720 is expected to have amongst the least maintenance and environmental considerations for flocculate management, and likely to minimally affect water pH. When all these criteria are equally weighted, the highest ranked coagulants are PAX-XL9, JenChem 1720, Sumachlor 50 and JenChem 1700. Ferric chloride and Liquid Floc are considered amongst the least favorably ranked coagulants. Neither performs well for turbidity or phosphorus removal for this storm water, and both are expected to have high maintenance costs due to flocculate production. Also, both Ferric chloride and Liquid Floc produce poor settling flocculate and thus capital costs may be higher as a function of the basin size needed for flocculate removal by settling.

5.5 Coagulants Selected For Further Testing

Based upon the above analysis, JenChem 1720, PAX-XL9, Sumachlor 50 and Pass-C were selected for further testing. Table 5-8 summarizes the justifications for the selections. In the final selection, a diversity of coagulants is maintained:

- High performing PACl (PAX-XL9)
- Straight ACH (Sumachlor 50)
- Inorganic/organic PACl blend (JenChem 1720)
- Standard-of-Comparison (Pass-C)

The selection process only considered the performance of coagulants for treating synthetic storm waters that were created from the same sweepings for the same target turbidity (Table 5-2). Selection of the most effective coagulants or highest ranked coagulants for treating a range of storm waters was not possible. However, the coagulants selected represent the more promising blends and represent distinctively different products in a context useful to current data and results generated from Caltrans small-scale and laboratory studies.

5.6 Summary

This chapter described the process used to select coagulants that had robust performance for different dosing levels while also having other characteristics that make them desirable from an economic or environmental perspective. A generalized model was developed based on criteria that considered performance, cost and environmental measures. The model used (and weighted) different measurement of performance as indicators for these broader criteria.

In general, all the coagulants were very effective at meeting surface water standards for both phosphorus and turbidity. More optimal dosing ranges as determined by the streaming current detector reduced the variance for phosphorus and turbidity levels achieved. For the more effective coagulants, the variance was relatively small for the full dosing ranges tested, showing their robustness with regard to dosing levels. Though inorganic/organic blends were generally less effective, they required lower dosing levels and had little affect on water pH, indicating lower potential environmental and maintenance costs.

Many coagulants showed good robustness for performance against different dosing levels. Iron and chitosan based coagulants were the least robust and had relatively poor performance when compared against the PACls. When a more controlled dosing protocol was used, mean turbidity and total phosphorus removal averaged an improvement of about 25%. For the final four coagulants tested for this study (Pass C, PAX-XL9, SumaChlor 50, Jenchem 1720), optimal dosing improved turbidity removal by about 30%, except for Pass C for which the improvement was around 80%, and improved total phosphorus removal by around 15 to 30%, except for PAX-XL9 for which the improvement was over 50%. Thus more optimal dosing should lead to more efficient coagulant utilization and better performance, even for the more robust coagulants.

Four coagulants were chosen for further study based upon their performance:

- JenChem 1720
- Pass-C
- PAX-XL9
- SumaChlor 50.

Pass-C has been tested extensively by Caltrans and is essentially a standard of comparison. These coagulants have differing coagulation chemistries and represent different approaches to.storm water treatment. SumaChlor 50 is a essentially a straight ACH and thus equivalent products can be found amongst all manufacturers. JenChem 1720 is a complex product in which organic polymers are blended with inorganic polymers. PAX-XL9 and Pass-C are two PACls. Pass-C has had silica added to improve performance. These coagulants represented coagulant chemistries that were considered more effective. These proprietary products do not necessarily represent the most effective coagulants and this report is not intended to endorse these coagulants.

Table 5-5. Coagulant Performance and Ranking

a. Full Dosing Range (-300 to 150 mV)

Coag. Code[1]	Jar Studies																									Charge Tritration					
	5 Minutes					30 Minutes																									
	Turbidity (NTU)					Turbidity (NTU)					UTP (ppb)					FTP (ppb)					Dose (mg-Me/L)[1]					pH					SCV (mV)[3]
	N	Mean	SD	Sig[1]	Rank	N	Mean	SD	Sig[1]	Rank	N	Mean	SD	Sig[1]	Rank	N	Mean	SD	Sig[1]	Rank	N	Mean	SD	Sig[1]	Rank	N	Mean	SD	Sig[1]	Rank	Mean
FeCl3	18	**124**	155	cde	**9**	18	**88**	123	b	**9**	18	**93**	131	bc	**9**	17	**14**	18	abcd	**3**	18	**14.9**	8.7	f	**6**	2	**3.4**	0.1	a	**9**	145
J1679	18	**82**	28	bcde	**6**	19	**39**	13	ba	**1**	19	**55**	16	abc	**5**	19	**15**	6	bcd	**7**	19	**0.4**	0.1	abc	**1**	3	**7.7**	0.06	def	**1**	56
J1700	18	**58**	53	abcde	**4**	18	**19**	34	ba	**1**	18	**32**	30	ab	**1**	18	**10**	4	abcd	**3**	18	**4.3**	3.8	abcde	**3**	3	**6.9**	0.1	bcde	**5**	212
J1720	18	**37**	22	abcd	**2**	18	**23**	12	ba	**1**	18	**46**	12	abc	**5**	18	**17**	12	bcd	**7**	18	**0.6**	0.3	abc	**1**	3	**7.2**	0.0	bcdef	**2**	149
LFLOC	12	**72**	19	abcde	**4**	12	**45**	9	ba	**1**	12	**60**	6	abc	**5**	11	**17**	6	bcd	**7**	12	**1.6**	0.7	abcd	**2**	1	**7.5**	0.0	bcdef	**2**	190
PassC	18	**41**	47	abcd	**2**	18	**10**	24	ba	**1**	18	**26**	31	ab	**1**	18	**7**	4	abc	**2**	18	**7.6**	5.6	cde	**5**	3	**6.7**	0.3	bcd	**8**	14
PC300	18	**81**	58	bcde	**6**	18	**24**	44	ba	**1**	18	**33**	43	ab	**1**	18	**9**	3	abcd	**3**	18	**4.3**	2.5	abcde	**3**	3	**7.0**	0.4	bcde	**5**	102
PXXL9	18	**8**	6	abc	**1**	18	**1**	1	ba	**1**	18	**40**	44	abc	**5**	18	**6**	5	ab	**1**	18	**6.0**	3.7	bcde	**4**	3	**7.0**	0.3	bcde	**5**	167
SUM50	18	**77**	32	bcde	**6**	18	**19**	12	ba	**1**	18	**35**	15	ab	**1**	18	**12**	5	abcd	**3**	18	**1.1**	0.5	abc	**1**	3	**7.4**	0.1	cde	**2**	133
Initial	11	**405**	17			11	**270**	38			10	**339**	95			9	**28**	7			11					28	**7.7**	0.1			

Notes

1. LFLOC dose is based upon chitosan and not metal. For ferric chloride, dose normalized to iron. For PACl, dose normalized to aluminum.
2. Sig = statistical significance. Values with the same letter are not statistically different ($p<0.05$) usng post-hoc analyses.
3. Corresponding average SCV for charge titration result (last dose on charge titration test).

b. Optimal Dosing Range (-300 to 0 mV) - Controlled Operation

Coag. Code[1]	Jar Studies																								
	5 Minutes					30 Minutes																			
	Turbidity (NTU)					Turbidity (NTU)					UTP (ppb)					FTP (ppb)					Dose (mg-Me/L)[1]				
	N	Mean	SD	Sig[1]	Rank	N	Mean	SD	Sig[1]	Rank	N	Mean	SD	Sig[1]	Rank	N	Mean	SD	Sig[1]	Rank	N	Mean	SD	Sig[1]	Rank
FeCl3	12	**23**	23	abcde	**2**	12	**6**	10	abc	**5**	12	**22**	20	a	**6**	11	**6**	2	abc	**1**	12	**10.12**	3.68		**9**
J1679	12	**67**	14	efgh	**8**	13	**32**	8	e	**8**	13	**54**	9	d	**8**	13	**17**	6	cde	**7**	13	**0.38**	0.08	abcd	**1**
J1700	12	**39**	35	bcdefg	**5**	12	**5**	4	ab	**1**	12	**21**	6	ab	**1**	12	**11**	3	abcde	**4**	12	**2.26**	0.90	bde	**5**
J1720	12	**26**	9	abcdef	**3**	12	**15**	4	cd	**7**	12	**40**	8	c	**7**	12	**16**	6	cde	**7**	12	**0.45**	0.15	abcd	**1**
LFLOC	12	**72**	19	fgh	**9**	12	**45**	9	f	**9**	12	**60**	6	d	**8**	11	**17**	6	cde	**7**	12	**1.62**	0.74	abcde	**4**
PassC	12	**28**	39	abcdef	**4**	12	**2**	2	ab	**1**	12	**18**	14	ab	**1**	12	**8**	4	abc	**1**	12	**4.28**	2.37	ef	**7**
PC300	12	**56**	33	cdefgh	**6**	12	**5**	2	ab	**1**	12	**18**	5	ab	**1**	12	**10**	3	abcd	**4**	12	**2.82**	1.07	def	**6**
PXXL9	12	**7**	6	abcd	**1**	12	**1**	1	ab	**1**	12	**18**	5	ab	**1**	12	**6**	5	abc	**1**	12	**3.83**	1.45	ef	**7**
SUM50	12	**66**	26	efgh	**7**	12	**13**	7	bcd	**6**	12	**27**	5	ab	**1**	12	**14**	5	bcde	**6**	12	**0.78**	0.24	abcd	**1**
Initial	11	**405**	17			11	**270**	38			10	**339**	95			9	**28**	7			11				

Notes

1. LFLOC dose is based upon chitosan and not metal. For ferric chloride, dose normalized to iron. For PACl, dose normalized to aluminum.
2. Sig = statistical significance. Values with the same letter are not statistically different ($p<0.05$) usng post-hoc analyses.

Table 5-6 Improvement in Mean Performance of All Coagulants as a Group for Optimal Dosing Ranges

Parameter	Unit	Value		% Improvement
		Full Range	More Optimal Range	
Turbidity at 5 minutes settling	NTU	55	41	24%
Turbidity at 30 minutes settling	NTU	19	10	46%
UTP	ppb	38	28	27%
FTP	ppb	11	11	1%

Table 5-7 Ranking Coagulants against the Criteria Model (Table 5-1)

Coag. Codes	Performance								Other Considerations												Overall Rating[5]	
	Controlled/Typical Performance				Robustness to dosing				Settling Rates & Capital Costs				pH/Alkalinity Consideration				Maintenance & Environmental					
	All[1]	Optimum[2]	Points[3]	Rank	All[1]	Opt[2]	Points[3]	Rank	All[1]	Opt[2]	Points[3]	Rank	All[1]	Opt[2]	Points[3]	Rank	All[1]	Opt[2]	Points[3]	Rank	Ave[6]	Rank
FeCl3	NA	14	14	5	30	NA	30	9	9	2	11	5	9	NA	9	9	6	9	15	9	7.4	9
J1679	NA	31	31	8	19	NA	19	8	6	8	14	9	1	NA	1	1	1	1	2	1	5.4	7
J1700	NA	11	11	3	9	NA	9	3	4	5	9	4	5	NA	5	5	3	5	8	5	4	3
J1720	NA	24	24	7	15	NA	15	6	2	3	5	2	2	NA	2	2	1	1	2	1	3.6	2
LFLOC	NA	33	33	9	17	NA	17	7	4	9	13	7	2	NA	2	2	2	4	6	4	5.8	8
PassC	NA	7	7	2	6	NA	6	1	2	4	6	3	8	NA	8	8	5	7	12	8	4.4	5
PC300	NA	12	12	4	11	NA	11	4	6	6	12	6	5	NA	5	5	3	6	9	6	5	6
PXXL9	NA	4	4	1	8	NA	8	2	1	1	2	1	5	NA	5	5	4	7	11	7	3.2	1
SUM50	NA	20	20	6	11	NA	11	4	6	7	13	7	2	NA	2	2	1	1	2	1	4	3

Notes

1. For dosing levels with SCV between -300 and 150 mV representing under- to over-dosing.
2. For dosing levels with SCV between -300 and 0 mV representing more controlled dosing conditions
3. Total of all ranking points for category.
4. Ranking based upon total points.
5. Overall considers different categories equally.
6. Average of all ranking values for each category.

Table 5-8. Summary of Justifications for Coagulants Selected for Further Testing

Coagulant	Justifications
PXXL9	Highest performing coagulant for turbidity and phosphorus removal. Very robust turbidity removal and dissolved phosphorus removal.
PASSC	Standard of Comparison Amongst the highest performing coagulants
SUM50	Amongst the highest performing coagulants at the full dosing range suggesting robust performance. Amongst the coagulants requiring the lowest dose thus providing environmental and cost benefits. Straight aluminum chlorohydrate and thus non-proprietary. Small affect on pH
J1720	Small affect on pH. Among the coagulants requiring the lowest dose thus providing environmental and cost benefits. Allows further testing of organic/inorganic blends under more variable conditions.

6 Environmental Robustness of Coagulant to Variations in Water Quality, Temperature and Mixing

The application of this technology for storm water systems necessitates an understanding of the robustness of different coagulants to variations in environmental conditions. These variations may be in mixing conditions, temperature, and water quality due to temporal and spatial variations in storm water runoff. Chemical dosing requires a certain degree of rapid mix, as defined by energy and time, and slow mix. Also, mixing may vary throughout the year if passive mixing systems such as static mixers, weir structures and baffles are used just because of temporal variations in flow to a site. This chapter investigates the importance of these variables to the performance of the four selected coagulants as measured by removal of phosphorus and turbidity.

6.1 Overview of Approach

A similar approach was used as used previously in this study. Jar studies were conducted on three different storm waters under varying conditions for a given slow mix (as defined by time), dose (as determined with the streaming current detector), rapid mix (as defined by speed), and coagulant. These studies consisted of two experiments; Table 6-1 shows the experimental design for these experiments. Both synthetic and real storm waters were used as shown in Table 6-2. Jar test dosing levels were determined using charge titration tests.

For the first experiment, dosing levels equivalent to SCVs of 0 and –200 mV were selected for each coagulant for the synthetic storm water (S050S). This experiment, conducted for two water temperatures (5 and 15 °C) and two slow mixing conditions (0 and 4 minutes), tested the effects of different dosing levels within a range considered near optimal, temperature and slow mixing conditions (Table 6-1). Turbidity was used as an indicator of performance.

The second experiment focused on the effects of different rapid mixing conditions (30, 90 and 180 rpms) and different water qualities on coagulant performance. For this experiment, two natural and one synthetic storm waters were used (Table 6-2). There were some differences in the methods for the different storm waters. This experiment was replicated for the real storm waters (N=3) but not for the synthetic storm water, and phosphorus measurements were taken for the real storm waters but not the synthetic storm water. The real storm water was considered a more accurate predictor of performance.

Jar tests and charge titration tests were conducted as discussed in Chapter 2 (Methods). The results from these experiments were analyzed using a factorial ANOVA approach (Statsoft, 2001) to assess the effects of these different environmental factors on coagulant performance. Where statiscal effects were shown ($p<0.05$), Tukey post-hoc analyses were used to identify these environmental effects and the coagulants affected.

Table 6-1 Experimental Design.

	Independent Variables						Measurements			
	Coagulant	Stormwater[2]	SCV	Temp.	Slow Mix Time	Rapid Mix Speed	5 min	30 min		
							Turbidity	Turbidity	UTP	FTP
	Code	Code	mV	deg C	min	rpm	NTU	NTU	ppb	ppb
	Experiment 1									
#	*4*	*1*	*2*	*2*	*2*	*1*	*X*	*X*		
Treatment	J1720	S050S	-200	5	0	180				
	SUM50		0	15	4					
	PASSC									
	PXXL9									
	Experiment 2									
#	*5*	*3*	*1*	*1*	*1*	*3*	*X*	*X*	*X*	*X*
Treatment	NOTRT	S050N[1]	0	15	4	30				
	J1720	RFOX1				90				
	SUM50	RMIX1				180				
	PASSC									
	PXXL9									

Notes

1. Treatments were not replicated for this water. Phosphorus was not measured for this water.
2. SXXXX defiines synthetic water. Rxxxx defines real stormwater

Table 6-2 Water Quality Characteristics of Tested Storm Waters

Stormwater Code	Turbidity (NTU)			UTP (ppb)			FTP (ppb)			pH		
	Average	SD	N	Average	SD	N	Average	SD	N	Average	SD	N
RFOXB-072903	102.1	2.4	9	285.7	28.8	3	11.4	1.8	3			
RMIX1-080503	110.4	11.6	15	207.6	117.1	7	21.4	11.2	7	7.6	0.2	7
S050N-061303	44.8	6.9	13			0			0	7.5	0.2	13

6.2 Variation in Coagulant Performance to Environmental Factors

The two experiments conducted to test environmental effects on coagulant performance (with regard to turbidity and P removal) were analyzed using ANOVA analyses. For both experiments, chemical dosing greatly reduced both turbidity and phosphorus concentrations. For the first experiment which used a synthetic storm water with a target turbidity of 50 NTU, initial settling was on average twice as fast when chemical dosing was used and final turbidity was on average about 25% of the final turbidity achieved when no chemical dosing was used (Table 6-3).

Table 6-3. Effects of Slow Mixing, Dose and Temperature for Selected Coagulants

(Dosing levels were determined using a Streaming Current Detector and corresponded to SCV of -200 mV and 0 mV).

	Treatment Codes^2	N	5 min settling (settling rate indicator)			30 min settling (steady state)		
			Turbidity			Turbidity		
			Mean	SD	% Rem^1	Mean	SD	% Rem^1
Total Untreated		9	35.9	4.4	26%	20.1	5.5	58%
Total Treated		88	16.2	5.9	67%	5.3	5.0	89%
Coagulant Effects								
	J1720	22	18.9	4.6	61%	9.9	2.6	80%
	PASSC	22	13.6	2.7	72%	1.0	0.7	98%
	PXXL9	22	11.7	3.4	76%	1.0	0.7	98%
	SUM50	22	20.5	7.0	58%	9.4	3.9	81%
Temperature Effects								
	5	48	17.5	6.8	64%	6.3	5.5	87%
	15	40	14.6	4.1	70%	4.1	4.0	91%
Dosing Level Effects (SCV-based)								
	-200	44	15.2	5.4	69%	4.9	4.5	90%
	0	44	17.1	6.2	65%	5.8	5.4	88%
Slow Mix Effects								
	0	48	18.7	5.8	61%	6.3	5.4	87%
	4	40	13.1	4.3	73%	4.1	4.1	91%

Notes

1. % removal below pre-mix untreated values.

For the second experiment which used a combination of real and synthetic storm waters, coagulation increased settling greatly and final turbidity was an order of magnitude less then levels achieved without chemical dosing (Table 6-4). Total P in the treated storm waters averaged less then 20% of total P in the untreated storm waters (Table 6-5) and dissolved P was reduced by over half.

Table 6-4 Effects of Rapid Mix Intensity and Source Water on Turbidity

	Treatment Codes[2]	N	5 Minutes Settling (Settling Rate Indicator)		30 Minutes Settling (Steady State Conditions)	
			Turbidity (NTU)		Turbidity (NTU)	
			Mean	SD	Mean	SD
Total Untreated			55.8	32.9	31.3	28.5
Total Treated		84	16.6	8.5	1.4	1.4
Coagulant Effects						
	J1720	21	14.4	7.1	2.1	1.8
	PASSC	21	14.8	6.3	0.6	0.4
	PXXL9	21	15.2	7.2	0.5	0.3
	SUM50	21	22.1	10.7	2.3	1.2
Source Water Effects						
	RFOXB-072903	36	20.4	7.7	1.3	1.2
	RMIX1-080503	36	17.1	6.2	1.6	1.6
	S050N-061303	12	4.0	3.1	0.8	0.6
Rapid Mix Effects						
	30	28	15.4	6.9	1.6	1.5
	90	28	15.0	7.5	0.9	0.8
	180	28	19.6	10.1	1.5	1.6

Table 6-5. Effects of Rapid Mix Intensity and Source Water on Phosphorus

	Treatment Codes	N	Total Phosphorus		Filtered Total Phosphorus	
			Mean	Std.Dev.	Mean	Std.Dev.
Total Untreated		15	66.5	47.0	14.3	5.5
Total Treated		71	13.1	6.1	6.1	2.2
Coagulant Effects						
	J1720	18	14.5	4.6	7.0	2.3
	PASSC	18	9.5	5.4	5.0	1.5
	PXXL9	18	17.6	6.4	5.7	2.3
	SUM50	17	11.0	4.7	6.6	2.4
Source Water Effects						
	RFOXB-072903	35	11.6	5.5	5.0	1.8
	RMIX1-080503	36	14.6	6.4	7.1	2.1
Rapid Mix Effects						
	30	24	14.4	7.1	6.2	2.2
	90	24	12.1	6.3	5.8	1.9
	180	23	12.9	4.6	6.3	2.7

6.2.1 Effects of Changes in Dosing Levels on Turbidity Removal and Settling Rates

The effects of different dosing levels selected from an optimal dosing range were studied in Experiment 1 using a synthetic storm water with low initial turbidity level (Table 6-1). This synthetic storm water was chosen because waters with low turbidity are more difficult to treat since flocculation is hindered when particle counts are low.

Variation in dosing levels significantly affected settling rates (as indicated by turbidity removal at 5 minutes) and steady state turbidity removal (as indicated by turbidity measurements at 30 minutes) for two of the four coagulants: Sumachlor 50 and JenChem 1720. Initial settling (as indicated by turbidity at 5 minutes) was affected by dosing level for Sumachlor 50 only (Figure 6-1). Initial settling rates for Pass-C and PAX-XL9 were clearly not affected by the different dosing levels. After 30 minutes of settling in the jars, turbidity levels dropped considerably for all coagulants (Figure 6-2). Sumachlor 50 continued to be affected by the dosing level, and Jenchem 1720 was affected to a lesser extent than was evident initially (Figure 6-1). All coagulants achieved turbidities below the turbidity standard for Lake Tahoe surface water discharge of 20 NTU.

These results are similar to those discussed in Section 5. Both Pass-C and PAX-XL9 appear very robust with regard to dosing levels and seem to maintain good performance over a broad dosing range.

Figure 6-1. Dosing Effects on Initial Settling

(Shown are mean values and 95% confidence interval.)

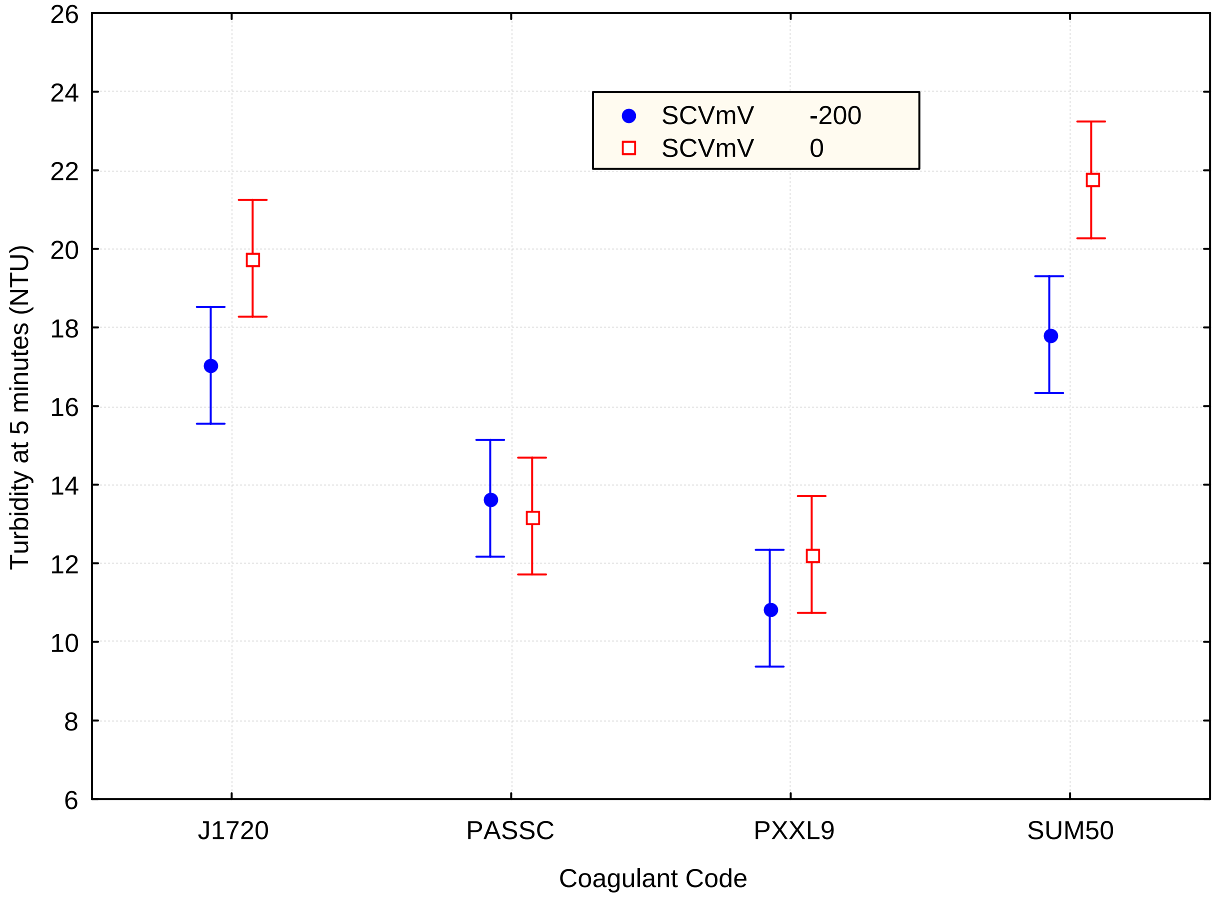
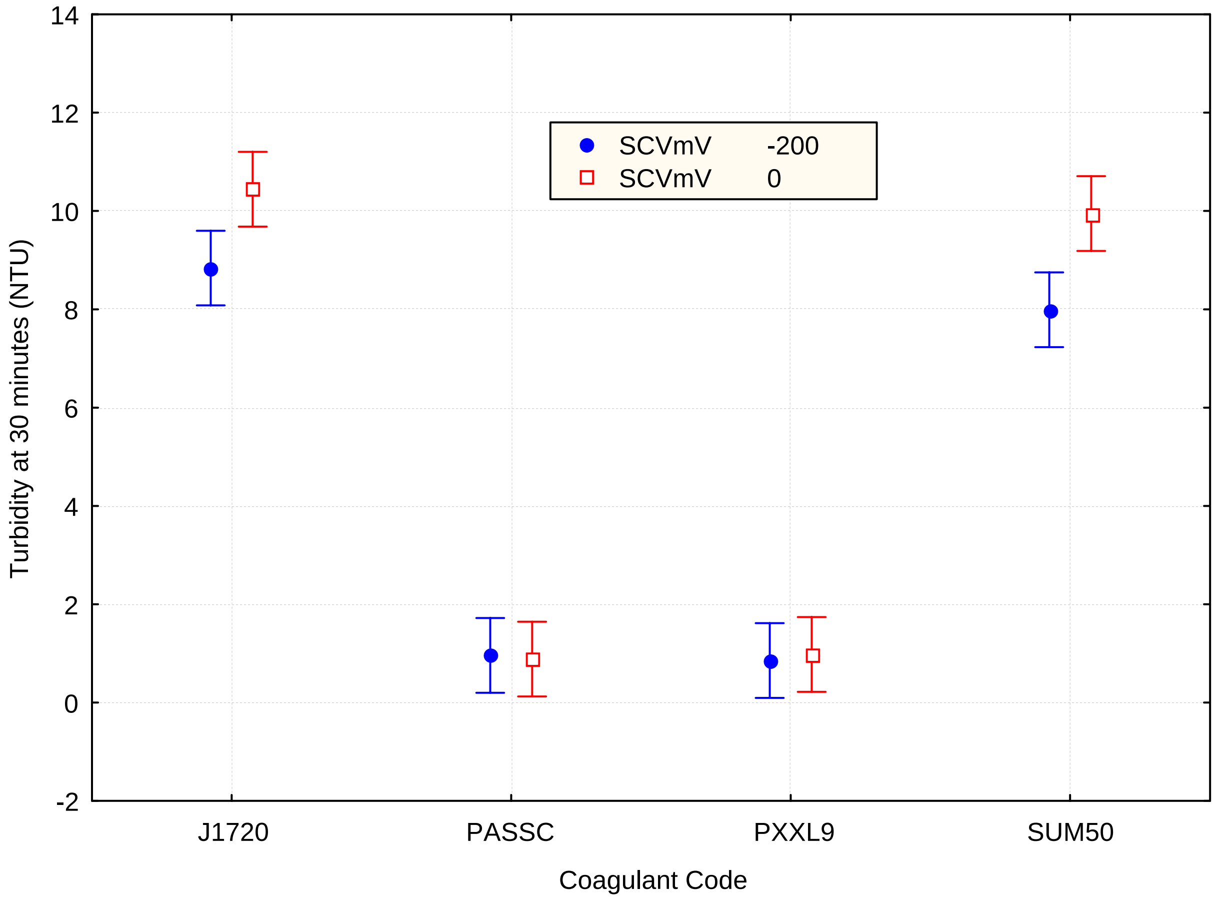


Figure 6-2. Dosing Effects on Final Settling
(Shown are mean values and 95% confidence interval.)



6.2.2 Temperature

Temperature effects were studied in Experiment 1 (Table 6-1). Temperature significantly affected both settling rates (as indicated by turbidity at 5 minutes) and steady state performance (as indicated by turbidity at 30 minutes) of two of the four coagulants. Temperature affected initial setting rates of Sumachlor 50 and had negligible effects on Pass-C and PAX-XL9 (Figure 6-3). Turbidity continued to decrease markedly for all coagulants. At 30 minutes of settling in the jars, both Pass-C and PAX-XL9 achieved turbidity values less than 2 NTU and their final turbidities were not affected by temperature (Figure 6-4). Both Sumachlor 50 and JenChem 1720 final turbidities were affected by water temperature. Both coagulants achieved turbidity values from three to six times higher then those values achieved by Pass-C or PAX-XL9.

These results are similar to those for variation in dosing levels (Figures 6-1, 6-2). Neither Pass-C nor PAX-XL9 seemed much affected by different initial water temperatures. Both JenChem 1720 and SumaChlor 50 were affected at some point in the settling process.

Figure 6-3. Temperature Effects on Initial Settling
(Turbidity after 5 minutes of settling is used as an indicator of initial settling. Shown are mean values and 95% confidence interval.)

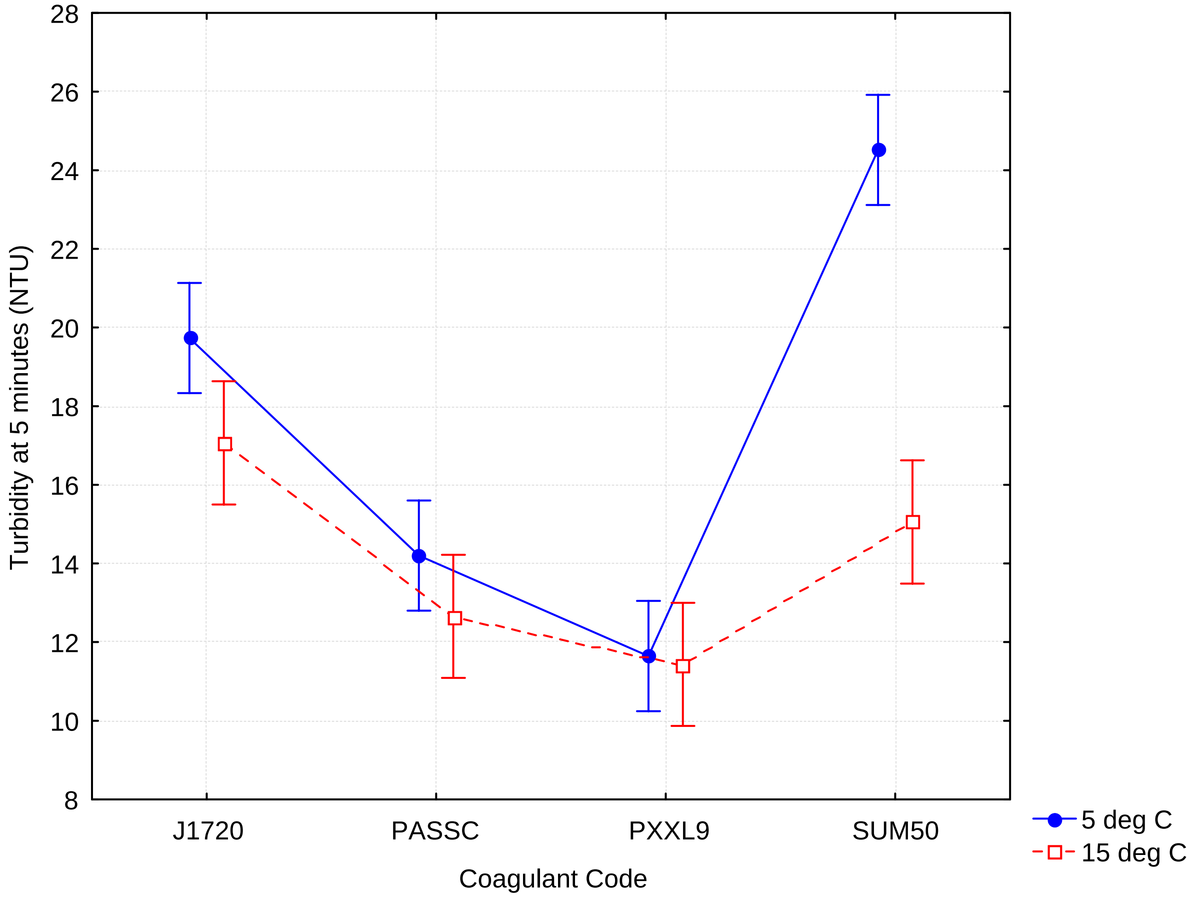
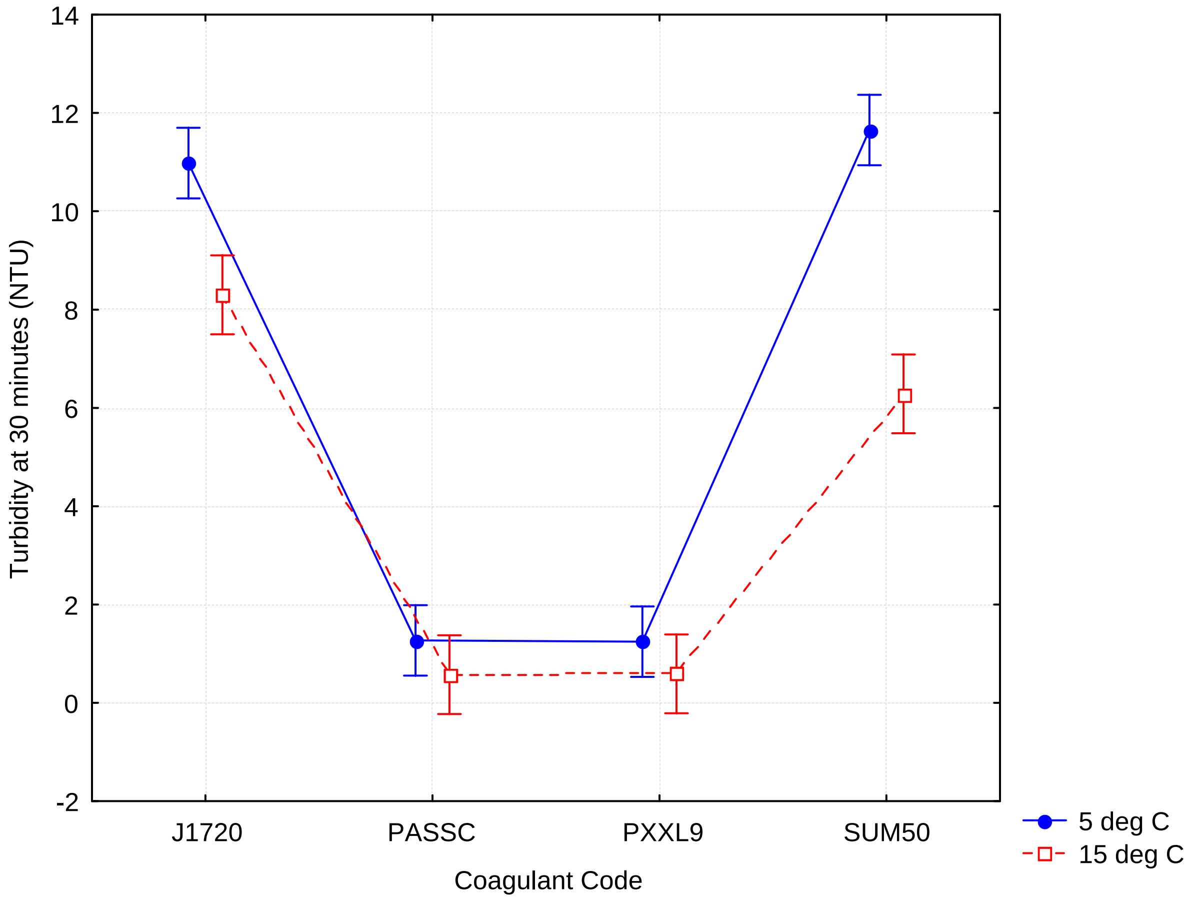


Figure 6-4. Temperature Effects on Final Settling
(Turbidity is measured at 30 minutes as an indicator of final results. Shown are mean values and 95% confidence interval.)



6.2.3 Mixing Regimes

Mixing for coagulants is typically characterized as a rapid mix regime for promoting molecular collisions and precipitation and a slow mix regime for promoting flocculate aggregation.

Rapid Mixing

Rapid mixing is an important consideration as it defines the logistics and infrastructure required for deploying chemical dosing systems for treating storm water. The less critical the rapid mix conditions the more easily this technology can be deployed. Rapid mixing was tested in Experiment 2 using three storm waters, one synthetic and two real storm waters.

Rapid mixing did not affect initial settling rates for any of the coagulants as shown for turbidity measurements at 5 minutes (Figure 6-5). Steady state turbidity levels were affected by rapid mixing for two of the four coagulants (Figure 6-6). Both JenChem 1720 and SumaChlor 50 had the lowest steady state turbidity for rapid mixing rate of 90 rpm; these results were statistically different for those coagulants then levels achieved at a rapid mixing rate of 180 rpm. In all cases, turbidity levels achieved were about an order of magnitude below the 20 NTU surface water discharge standard for the Tahoe Basin. Rapid mixing did not significantly affect dissolved P removal for the coagulants (Figure 6-7) but did significantly affect total P removal for one of the four coagulants (PAX-XL9; Figure 6-8).

A number of conclusions can be made from this analysis for the stormwaters tested:

- For all cases (e.g. dissolved P, total P and turbidity removal; initial settling), a rapid mixing rate of 90 rpm either gave the best performance or a performance that was not statistically different from another treatment.
- The results suggest that with some PACls both excess and inadequate turbulent energy can compromise performance.
- Absolute differences in performance metrics were relatively small for different rapid mix conditions. For instance, more optimal rapid mixing affected SumaChlor 50's final turbidity levels the most, with a final mean turbidity of about 1.6 NTU for a rapid mix condition of 90 rpm, as opposed to a value of about 2.9 for a rapid mix condition of 180 rpm. The ability to meet surface water turbidity and P discharge standards for the Tahoe Basin were not affected by different rapid mixing regimes.

Figure 6-5. Effects of Rapid Mixing on Initial Settling
(Shown are mean values and 95% confidence interval.)

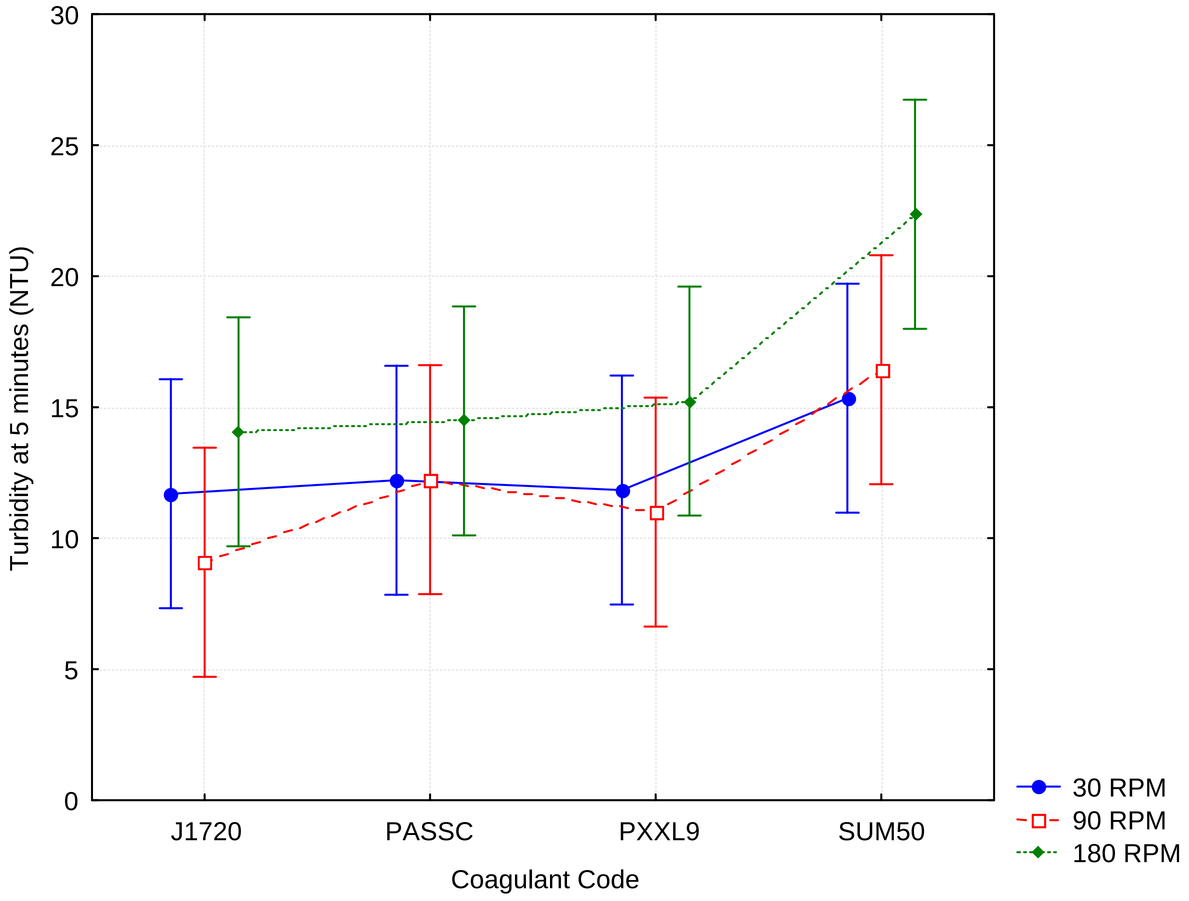


Figure 6-6. Effects of Rapid Mixing on Final Settling
(Shown are mean values and 95% confidence interval.)

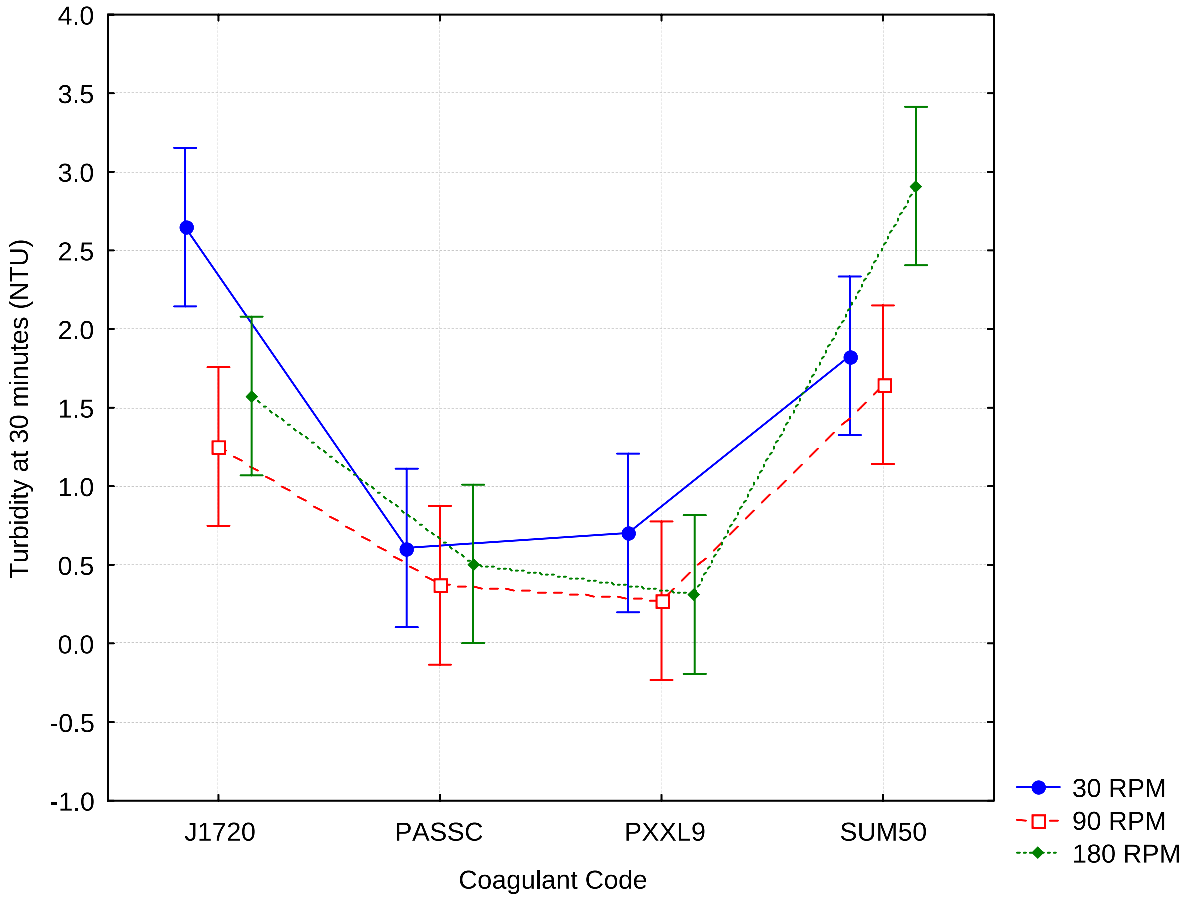


Figure 6-7. Rapid Mixing Effects on Dissolved P in Storm Water
(Shown are mean values and 95% confidence interval.)

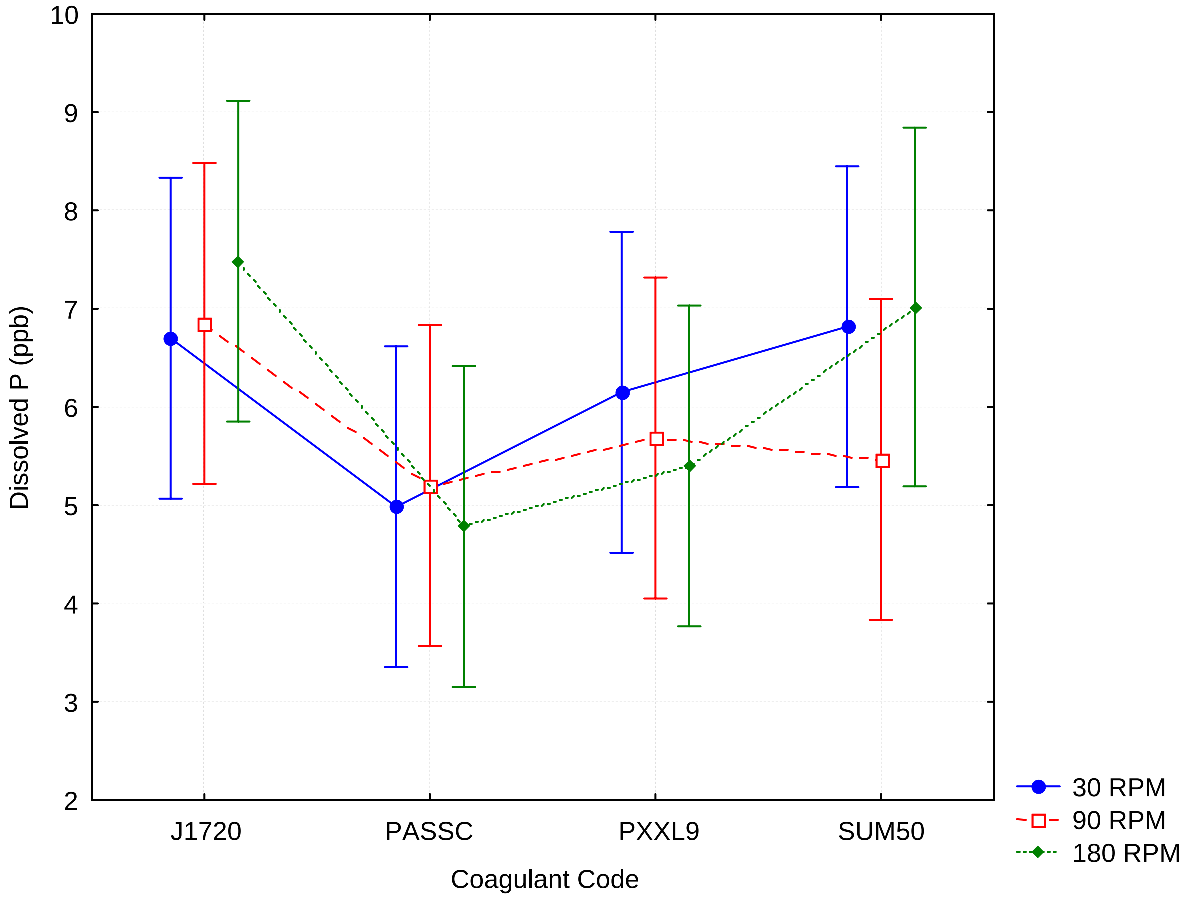
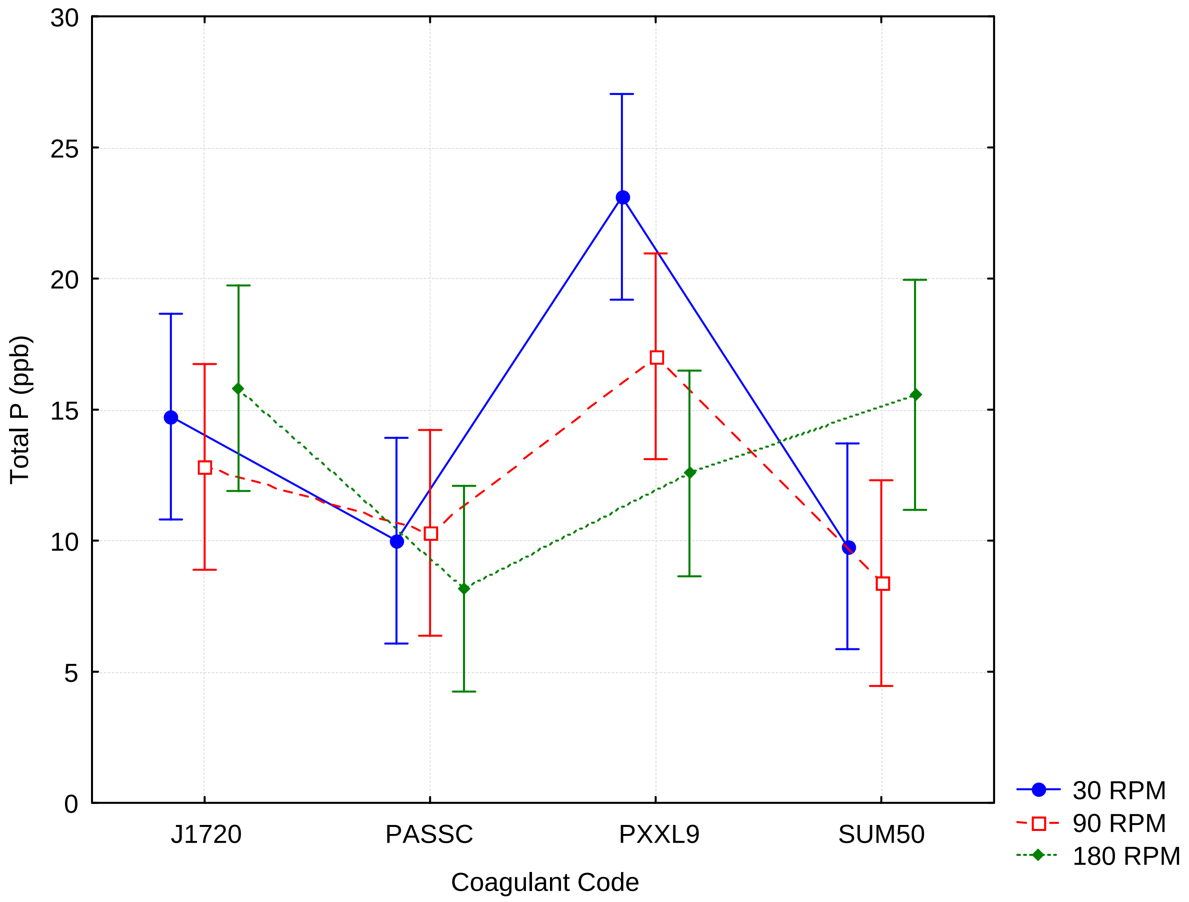


Figure 6-8. Effects of Rapid Mixing of Total P in Storm Water
(Shown are mean values and 95% confidence interval.)



Slow Mixing

The effects of slow mixing were investigated in Experiment 1 (Table 6-1). Slow mixing is another logistical consideration. Implementing slow mixing conditions in a storm water system may require baffling or structures to augment existing mixing.

For all coagulants, slow mixing significantly or nearly significantly affected initial settling (Figure 6-9). Thus, slow mixing seemed to improve initial flocculate aggregation. At steady state conditions (Figure 6-10), certain coagulants were significantly effected ($p<0.05$) whereas others were not. Specifically, for PAX-XL9 and Pass-C, the final turbidity was not significantly affected by slow mixing. However, both JenChem 1720 and SumaChlor 50 had improved steady state turbidity removal from slow mixing. Final turbidity values were about 30 to 50% lower when slow mixing was utilized for these two less effective coagulants. Thus, slow mixing may not be required for longer-term steady state conditions though it does improve initial settling and can improve final turbidity values for the less effective coagulants. In systems where wind or temperature induced mixing makes quiescent conditions difficult to achieve, some slow mixing may therefore improve performance.

Figure 6-9. Effects of Slow Mixing on Initial Settling
(Shown are mean values and 95% confidence interval.)

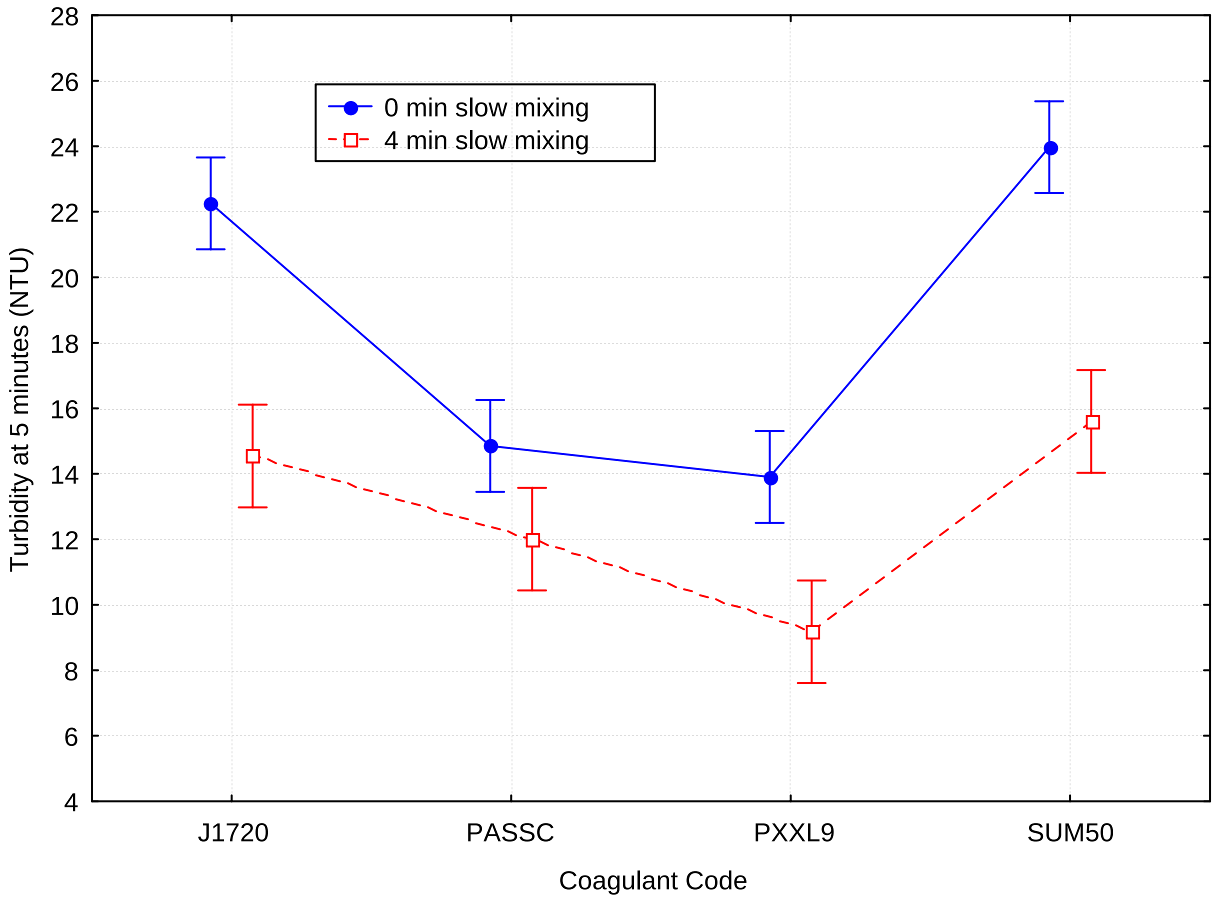
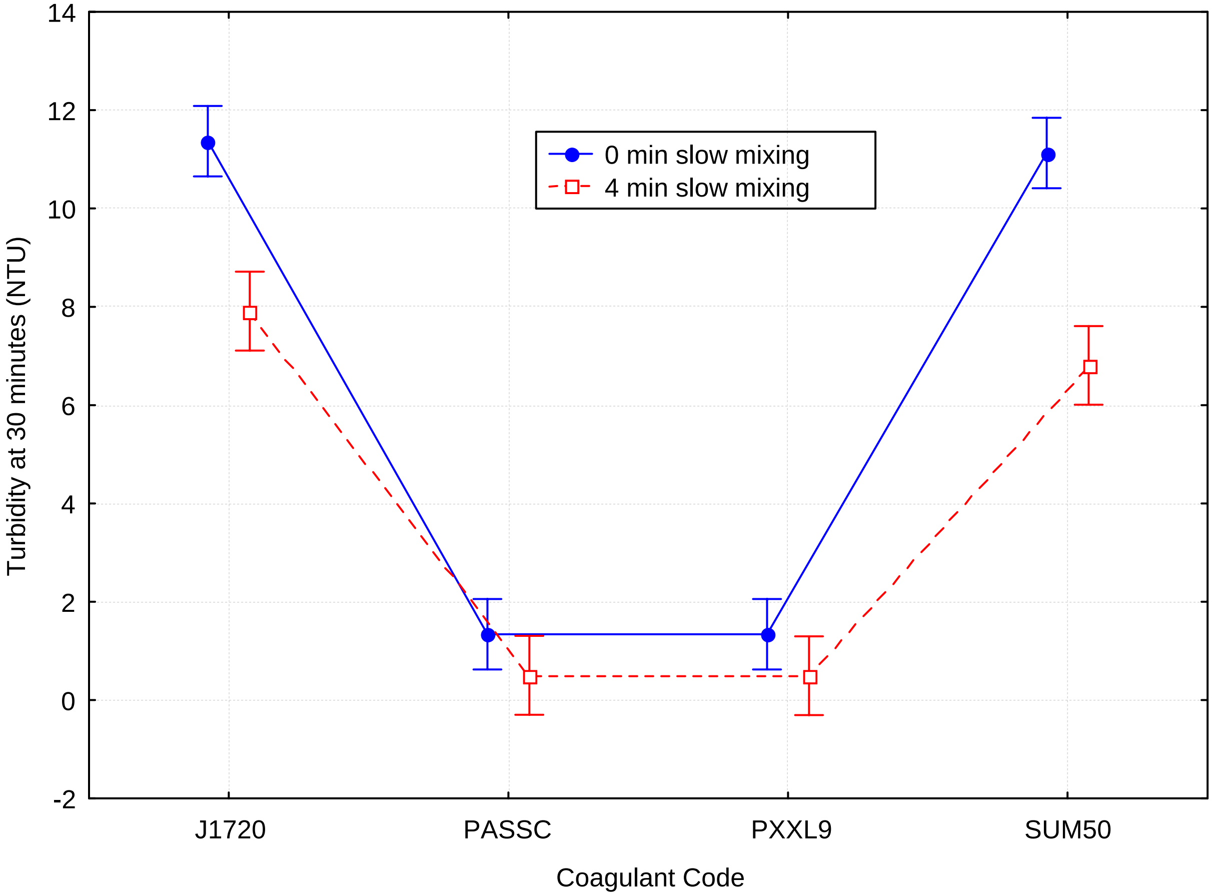


Figure 6-10. Effects of Slow Mixing on Final Turbidity
(Shown are mean values and 95% confidence interval.)



6.3 Water Quality

Table 6.2 shows the different water quality characteristics for the storm waters used to test the effects of water quality on coagulant performance. Two of these storm waters were real storm waters collected at Tahoe and one was synthetic storm water. (See Chapter 2 for discussion on synthetic storm waters). These storm waters varied in turbidity, total phosphorus and filtered phosphorus.

Table 6-4 shows that despite differing initial flocculate settling characteristics of these storm waters (turbidities at 5 minutes), similar final turbidity values were achieved for the coagulants. Total and filtered mean phosphorus concentrations differed significantly ($p<0.05$) for different storm waters (Table 6-5).

A post-hoc analysis was conducted on the data from Experiment 1 (Table 6-1) to better understand the effects of the different storm waters on coagulant effectiveness. For the most part, initial settling was better for all coagulants for the synthetic storm water then for the real storm waters (Figure 6-11). This result suggests that the real storm waters are more complex and therefore coagulant performance may not be as good. Average turbidity at five minutes was always below 7 NTU for the synthetic storm water and generally three to four times higher for the real storm waters.

Steady state turbidity values were similar for all the storm waters tested in Experiment 1, synthetic or real, for all the coagulants except JenChem 1720. For JenChem 1720, results differed significantly (Figure 6-12). When comparing the different coagulants based on their effectiveness in treating different storm waters, the turbidity levels differed significantly. For instance, for the storm water from Fox Basin, SumaChlor 50 turbidity values achieved after 30 minutes of settling were about two to four times higher than and differed significantly from turbidity achieved by other coagulants. The Pass-C and PAX-XL9 results for the storm waters tested were nearly identical and were on average the lowest (Figure 6-12).

For the two real storm waters, total achievable P did not differ significantly for any coagulant. All coagulants, except SumaChlor 50, achieved statistically similar dissolved P concentrations as well for the two real storm waters.

Several conclusions can be drawn from this analysis. First, use of synthetic storm waters may lead to overestimation of coagulant performance. Real storm waters are more complex and other constituents in the water likely complete with dissolved P to interact with the coagulants. Second, of the four coagulants tested, Pass-C and PAX-XL9 were the least affected by storm water quality with regard to turbidity removal. All of the coagulants achieved turbidity levels well below the surface water quality discharge limit of 20 NTU. Finally, both dissolved and total P removal was not affected significantly by the type of storm water tested for all the coagulants. This P analyses only looked at the real storm waters tested and not the synthetic storm waters. For these two storm waters, all the coagulants performed robustly.

Figure 6-11. Effects of Stormwater on Initial Settling

(Shown are mean values and 95% confidence interval.)

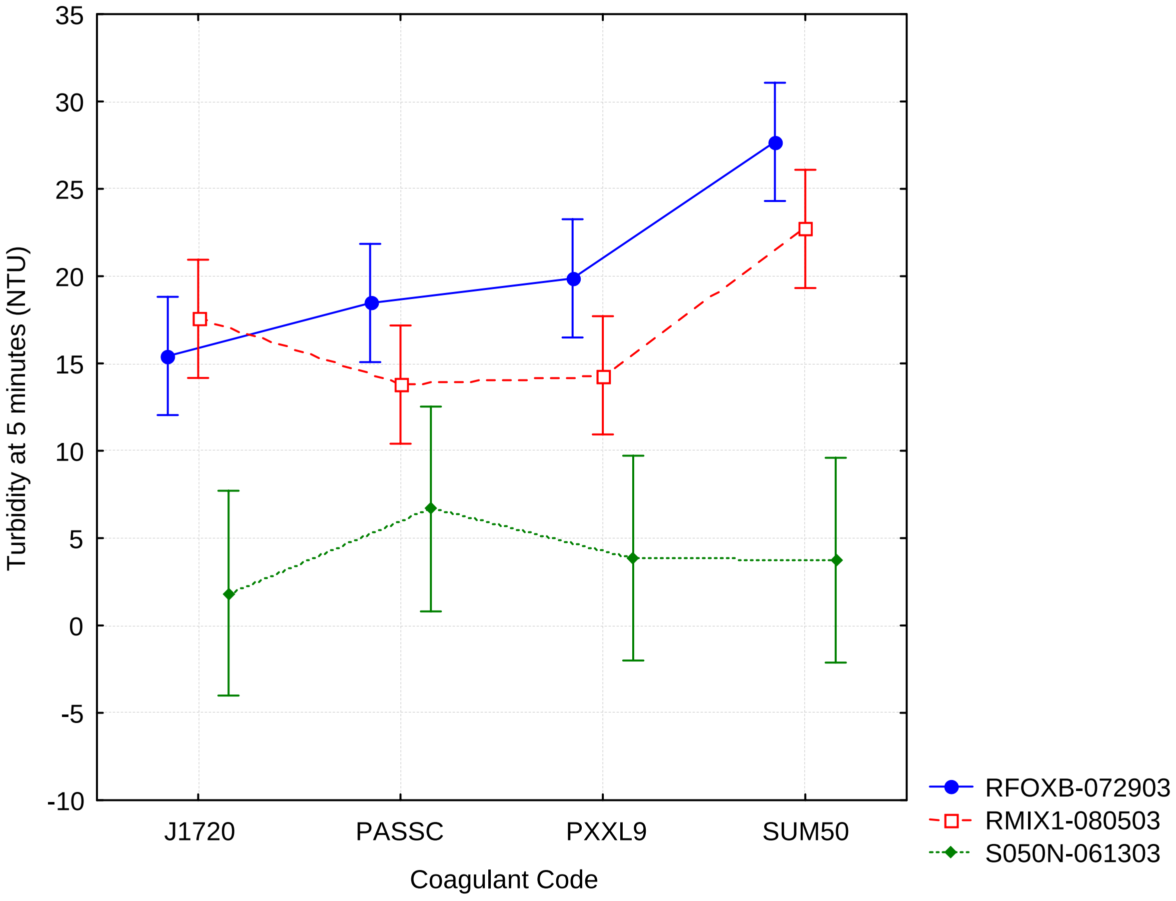


Figure 6-12. Source Water Effects on Final Settling

(Shown are mean values and 95% confidence interval.)

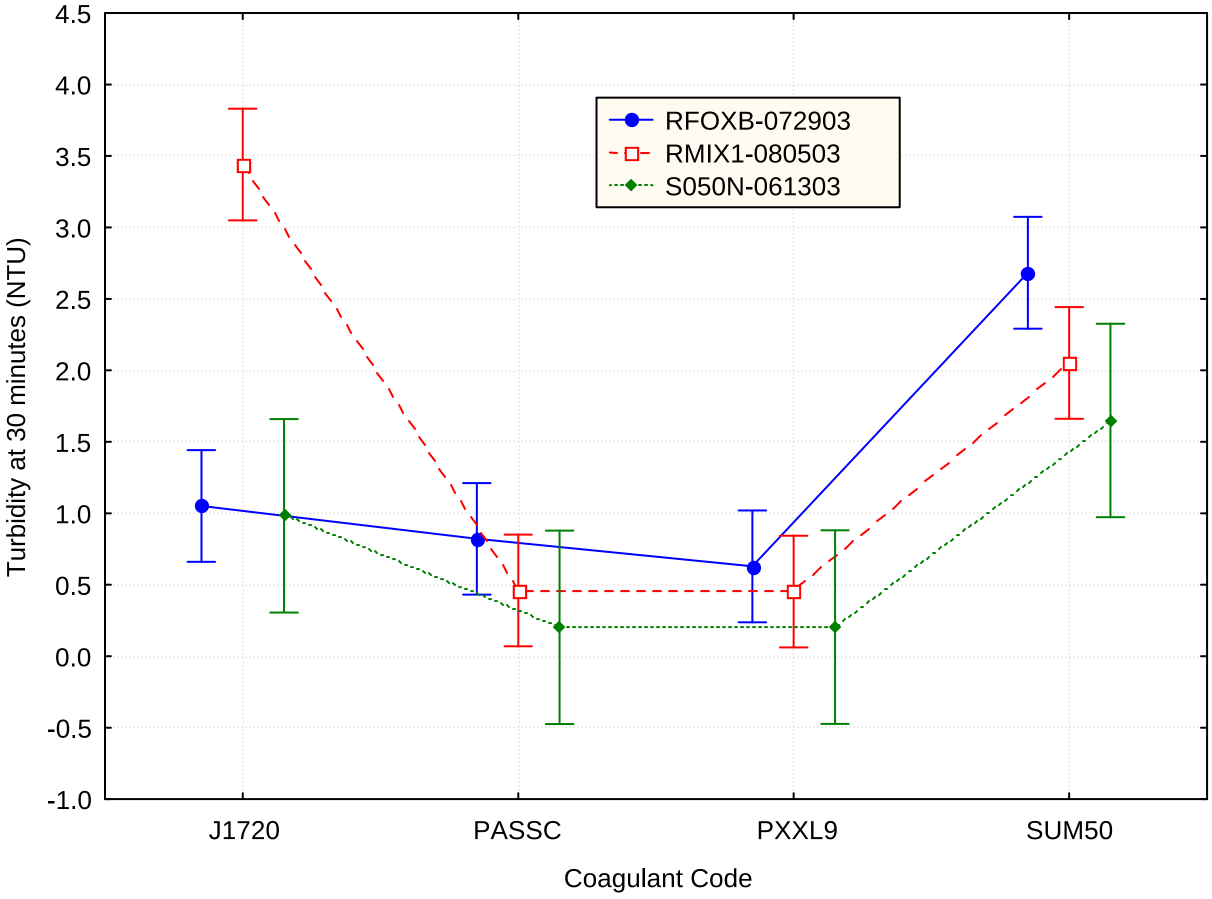


Figure 6-13. Storm Water Effects on Removal of Total P
(Shown are mean values and 95% confidence interval.)

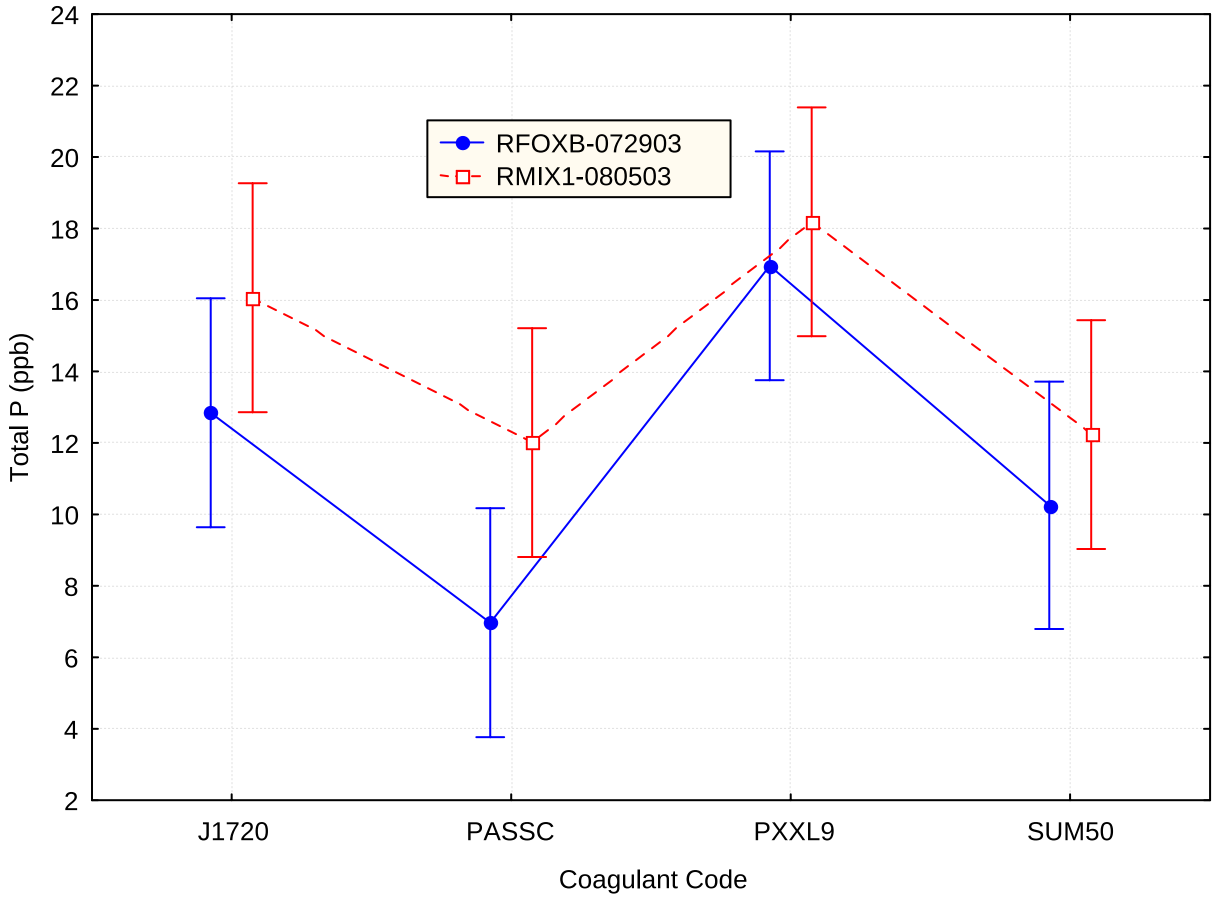
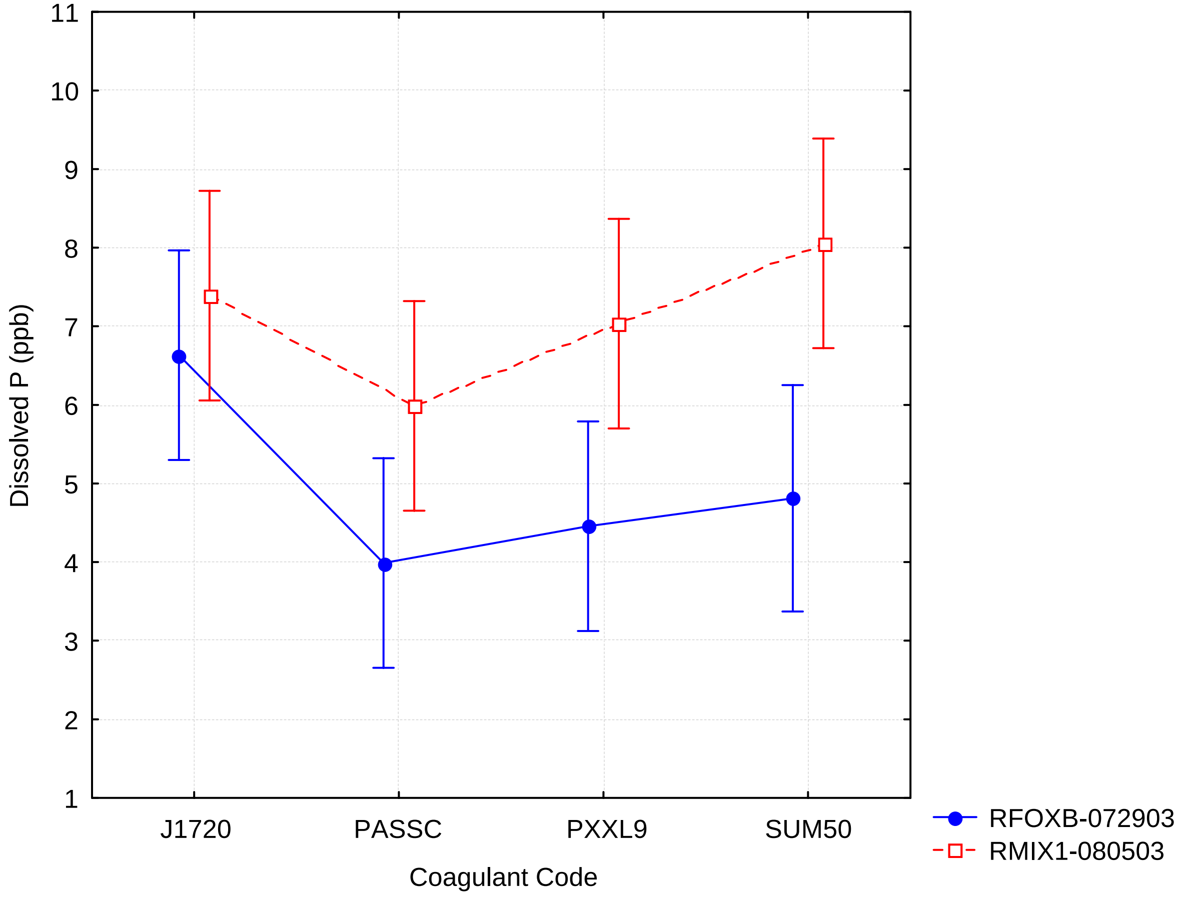


Figure 6-14. Effects of Storm Water on Final Dissolved P
(Shown are mean values and 95% confidence interval.)



6.4 Summary

This chapter has focused on identifying which environmental factors affected the performance of selected coagulants. The factors considered were slow mixing, rapid mixing, temperature, storm water source, and dosing range. Table 6-6 summarizes the effects of the different environmental factors on coagulant performance in terms of phosphorus and turbidity removal.

Experiments to test sensitivity to environmental factors showed that change in temperature, rapid mixing speed, slow mixing duration, or dose can result in significantly different turbidity removals ($p<0.05$) for JenChem1720 and SumaChlor 50. Source water quality and coagulant type can also lead to significantly different phosphorus removals ($p<0.05$) for these coagulants. Thus, modifications in dosing rate, mixing time and intensity, and environmental conditions can lead to optimal performance for JenChem1720 and SumaChlor 50.

Generally, PAX-XL9 and Pass-C were the only coagulants for which the performance metrics did not differ significantly. Thus, both these coagulants were very robust with regard to changes in the different environmental factors.

Table 6-6. Summary of Factors that Statistically Affected Coagulant Performance. Statistical effects are based upon $p < 0.05$ (95% confidence interval).

	Temperature	Slow Mixing	Rapid Mixing	Water Quality	Optimal Dosing Range
Variables Measured[1]	T5, T30	T5, T30	T5, T30, DP, TP	T5, T30, DP, TP	T5, T30
J1720	T30	T5, T30	T30	T5, T30	T30
PXXL9		T5	TP		
PASSC				T5	
SUM50	T5, T30	T5, T30	T30	T5, DP	T5, T30

Notes

1. T5 = 5 min turbidity as indicator for settling rates; T30 = 30 min turbidity as indicator for particulate removal; DP = Dissolved P at 30 minutes; TP = Total P at 30 minutes

These results have important implications:

- Coagulant selection is an important consideration when trying to overcome temperature, mixing and water quality (storm water source) effects on phosphorus and turbidity removal. There is a subset of coagulants that are likely to help minimize the performance variance resulting from these factors. This report is not intended to endorse specific products. The coagulants selected for this report represent a class of coagulant chemistries effective for treating the stormwater tested. For other stormwaters and other environments, other coagulants may be more effective. Moreover, for the stormwaters tested here, coagulants with similar chemistries would be assumed to perform similarly.

- An optimal dosing range, which can be defined by streaming current meters, should help improve P and turbidity removal. Some coagulants are more sensitive to dosing and thus for those coagulants the optimal dosing range will be narrower.

- The mixing regime can be modified to improve performance, though the importance of mixing depends upon the coagulant selected. More effective coagulants do not appear to be greatly affected by different rapid or slow mixing specifications. For the less effective coagulants, it appears that relatively fast or slow rapid mixing can affect performance, and some slow mixing appears to greatly improve performance with regard to turbidity or P removal compared to that for no slow mixing. Of these two mixing steps, slow mixing seems more important and implementing slow mixing in field applications may be useful.

7 Laboratory Performance Summary for Selected Coagulants

Laboratory studies utilizing both charge titration studies and jar testing were used to comprehensively screen available coagulants:

- Proprietary and non-proprietary products
- Alum, aluminum chlorohydrates and poly aluminum chlorides (PACls; inorganic aluminum-based polymers)
- Ferric sulfate, ferric chloride and poly ferric sulfate (inorganic iron-based polymers)
- Organic polymers
- Inorganic/organic polymer blends
- Chitosan-based coagulants

Four coagulants were used throughout these laboratory studies in a series of experiments that began with initial screening and finished with testing coagulant robustness to varying doses and environmental and operational variation:

- JenChem 1720
- Pass-C
- Kemiron PAX-XL9
- SumaChlor 50

These coagulants do not necessarily represent the best coagulants but they do represent coagulants that provide relatively robust performance with regard to turbidity and phosphorus removal, and are diverse with regard to chemistry (Table 7-1). For other stormwaters, other coagulants may be found to be more effective. And coagulants with similar chemistries are assumed to perform similarly.

Table 7-1. Chemical Specification for Selected Coagulants

Name	Code	Vendor	NSF Designation	Average						Max NSF dose	Polymer type
				Basicity	% Metal	% Sulfate	% Silica	pH	SG		
Pass-C	PASSC	Eaglebrook	Polyaluminum chloride	53.3	5.2	present but % unknown	present but % unknown	2.5	1.24	250	inorganic
PAX-XL9	PXXL9	Kemiron	Polyaluminum chloride	67	5.6	1.7		2.8	1.26	266	inorganic
JC 1720	J1720	JenChem	Polyaluminum chloride	70	5.95	present but % unknown		4.3	1.29	200	inorganic/organic blend
Sumachlor 50	SUM50	Summit	Aluminum chlorohydrate	83.5	12.4			4.2	1.34	250	inorganic

Table 7-2 presents a number of statistical measures of performance. Means and standard deviations have been used in the statistical analyses conducted previously, and medians, percentiles, and minimum and maximums provide an understanding of the typical range without any assumptions regarding distribution.

All the selected coagulants differed statistically from each other throughout the laboratory studies ($p<0.05$) with regard to filtered total phosphorus removal, turbidity removal and dose. Pass-C was the most effective coagulant of these four for total P removal and JenChem 1720 was the worst. All coagulants provided good filtered total phosphorus removal, though PAX-XL9 and Pass-C were slightly better. All four coagulants consistently met the phosphorus surface water standard throughout this study and though the storm water did vary throughout this study, the quartile ranges for both total and filtered total phosphorus are relatively narrow, suggesting that very similar phosphorus concentrations are achieved for a variety of storm water qualities.

Both PAX-XL9 and Pass-C provided near complete turbidity removal and almost always met the turbidity standard. JenChem 1720 and SumaChlor 50 performed similarly to each other and were much less likely to meet the standard then the other two coagulants.

PAX-XL9 and Pass-C required much higher dosing levels then either the JenChem 1720 or the Sumachlor 50. On average, dosing levels were about five times higher when standardized against aluminum mass and nearly ten times higher in terms of coagulant mass for PAX-XL9 and Pass-C. The relatively lower dosing levels of both Sumachlor 50 and JenChem 1720 may suggests that they would be more difficult to overdose with regard to aluminum dosing because less aluminum is generally required. Also, these much lower dosing levels suggest there is much less flocculate produced and that systems utilizing these types of low-dose coagulants would have fewer environmental considerations and lower maintenance costs.

Table 7-2. Laboratory Performance Summary of Selected Coagulants

Total Phosphorus (ppb)									
	Means	**N**	**Std.Dev.**	**Median**	**Q25**	**Q75**	**Minimum**	**Maximum**	**p-value**
PASSC	17.8	42.0	21.4	11.5	7.2	19.8	4.2	134.7	
PXXL9	27.5	42.0	30.8	19.3	14.0	24.4	9.7	154.3	
J1720	29.2	41.0	17.4	24.6	14.2	42.2	7.2	69.0	
SUM50	23.1	35.0	16.5	19.8	9.2	29.5	5.9	71.4	
All Grps	*24.4*	*160.0*	*22.8*	*18.6*	*11.2*	*27.3*	*4.2*	*154.3*	0.09908
Filtered Total Phosphorus (ppb)									
	Means	**N**	**Std.Dev.**	**Median**	**Q25**	**Q75**	**Minimum**	**Maximum**	**p-value**
PASSC	6.3	42.0	4.1	5.6	4.1	8.3	-0.5	23.3	
PXXL9	5.8	42.0	3.5	5.1	3.6	7.1	0.3	21.2	
J1720	11.1	42.0	9.4	8.2	5.8	13.3	3.1	58.6	
SUM50	9.3	36.0	4.8	7.6	5.7	12.8	3.4	22.2	
All Grps	*8.1*	*162.0*	*6.3*	*6.3*	*4.7*	*9.7*	*-0.5*	*154.3*	0.00013
Turbidity (NTU)									
	Means	**N**	**Std.Dev.**	**Median**	**Q25**	**Q75**	**Minimum**	**Maximum**	**p-value**
PASSC	3.3	69.0	12.5	0.7	0.4	1.7	0.2	79.7	
PXXL9	0.9	69.0	0.9	0.7	0.3	1.1	0.1	4.7	
J1720	10.2	69.0	10.4	7.5	2.4	13.2	0.4	49.5	
SUM50	9.6	63.0	9.7	6.1	2.5	13.5	1.0	52.9	
All Grps	*5.9*	*270.0*	*10.2*	*1.7*	*0.7*	*7.3*	*-0.5*	*154.3*	0.00000
Dose Mg-Me/L									
	Means	**N**	**Std.Dev.**	**Median**	**Q25**	**Q75**	**Minimum**	**Maximum**	**p-value**
PASSC	6.2	69.0	3.5	6.4	3.0	7.6	1.6	17.6	
PXXL9	5.3	69.0	2.4	5.5	3.1	5.9	2.1	12.6	
J1720	1.0	69.0	0.8	0.5	0.4	1.6	0.3	2.4	
SUM50	1.9	63.0	1.6	1.1	0.7	3.8	0.5	4.8	
All Grps	*3.6*	*270.0*	*3.2*	*2.8*	*1.1*	*5.6*	*-0.5*	*154.3*	0.00000
Dose Mg-Coag/L									
	Means	**N**	**Std.Dev.**	**Median**	**Q25**	**Q75**	**Minimum**	**Maximum**	**p-value**
PASSC	119.6	69.0	67.0	123.1	57.0	146.9	31.0	338.5	
PXXL9	93.9	69.0	43.2	98.7	55.4	104.6	37.8	225.5	
J1720	16.6	69.0	12.7	8.4	6.4	26.8	4.4	40.9	
SUM50	15.3	63.0	12.6	8.4	5.4	30.3	3.8	38.3	
All Grps	*62.4*	*270.0*	*61.9*	*40.9*	*8.4*	*100.5*	*-0.5*	*338.5*	0.00000

Figures 7-1 through 7-4 show achievable turbidity and phosphorus levels for these coagulants for a variety of storm waters, indicating overall coagulant performance. The figures show the median values and the non-outlier minimum and maximum values. Outliers are defined as those values that exceed the 75th percentile value by 1.5 times the difference between the 75th and 25th percentile. JenChem 1720 and Sumachlor 50 had relatively higher variance in the turbidity and phosphorus levels achieved for the different storm water tested compared to Pass-C and PAX-XL9 which both achieved more consistent median values for turbidity and phosphorus regardless of the storm water tested. These data demonstrate the relative robustness of Pass-C and PAX-XL9 in achieving similar phosphorus and turbidity results for storm waters with different chemistries.

Though different coagulants achieved different steady state turbidity and phosphorus levels, only with regard to turbidity removal did any one coagulant (PAX-XL9) have an exceptionally low variance in comparison to the other coagulants (Table 7-2, Figure 7-4).

Figure 7-1 Achievable Phosphorus and Turbidity Levels during Laboratory Studies for JenChem 1720.

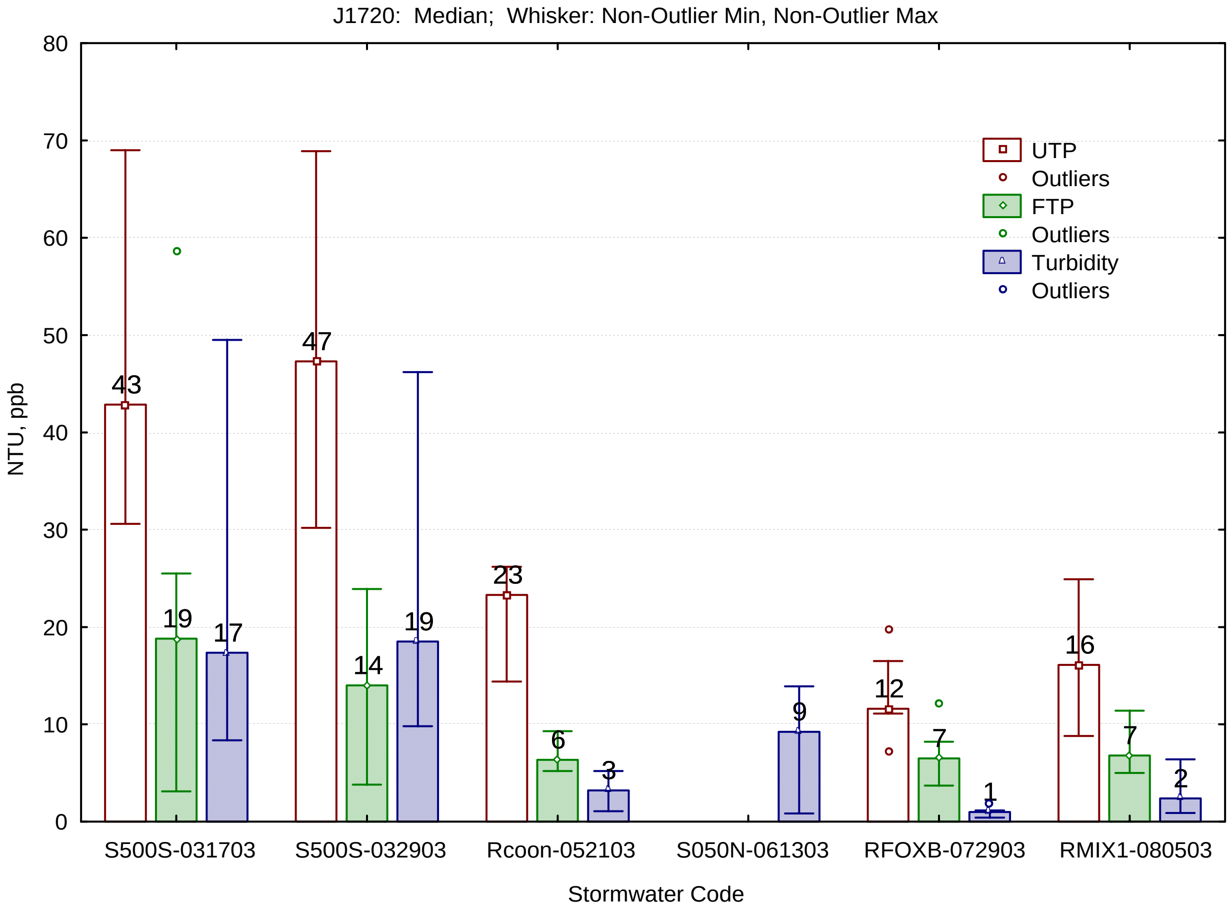


Figure 7-2 Achievable Phosphorus and Turbidity Levels during Laboratory Studies for SumaChlor 50.

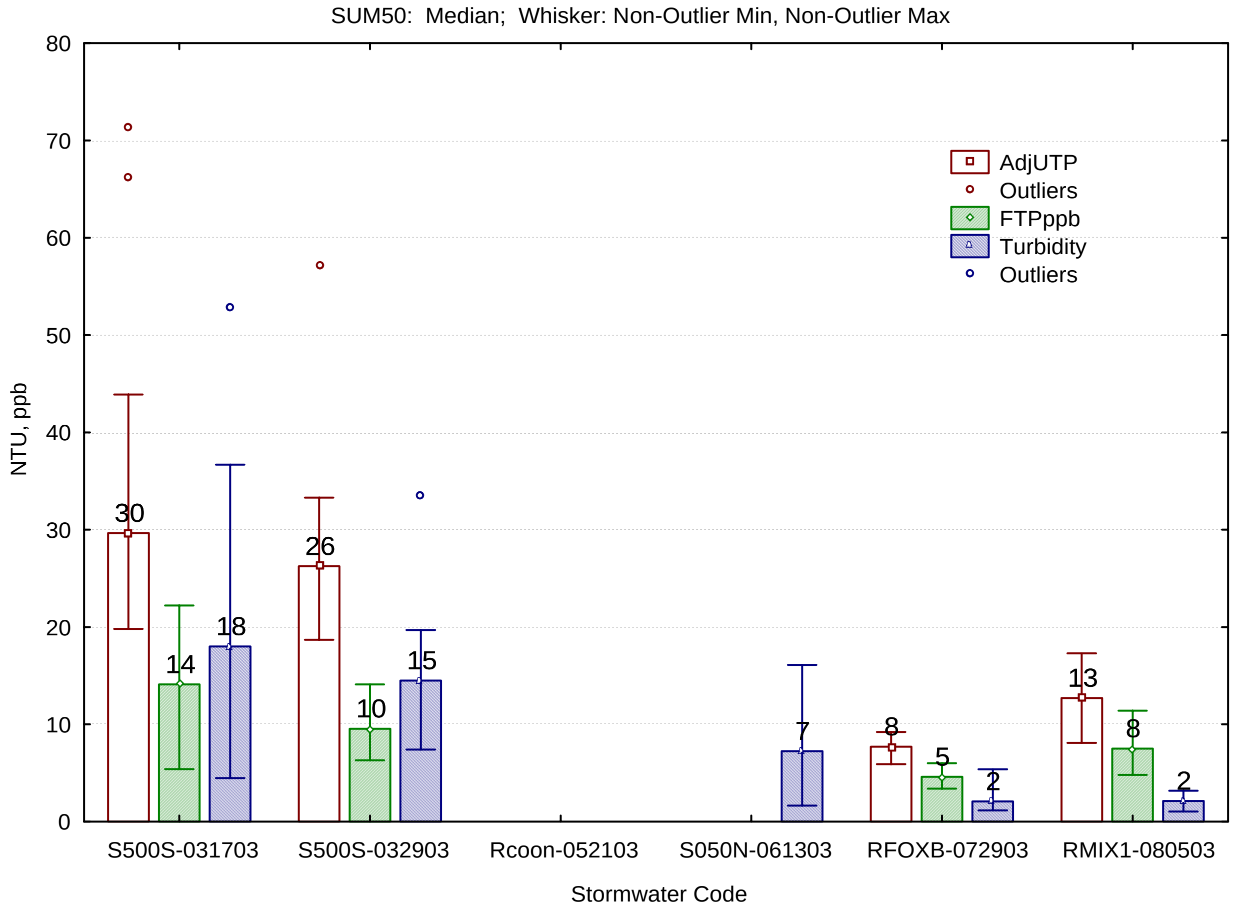


Figure 7-3 Achievable Phosphorus and Turbidity Levels during Laboratory Studies for Pass C.

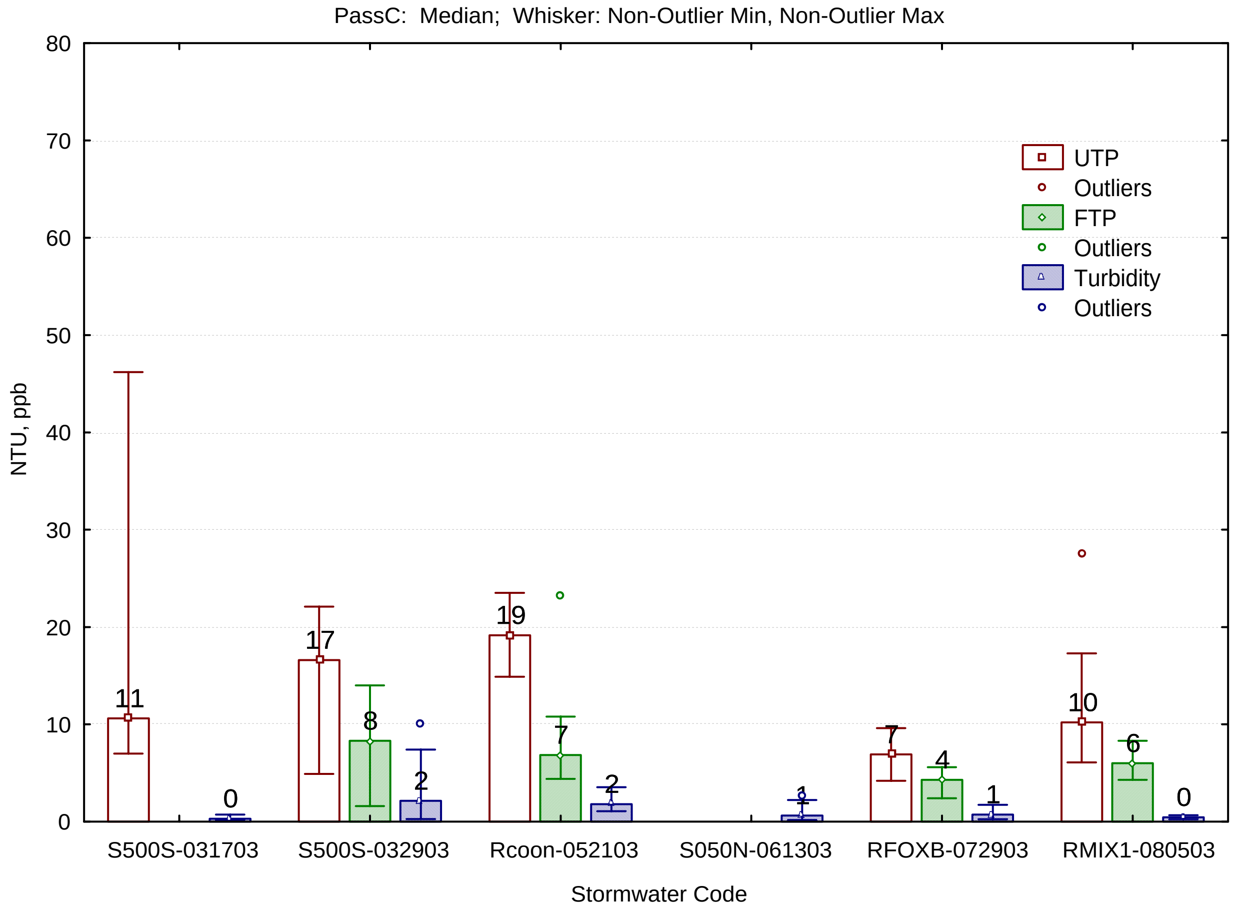
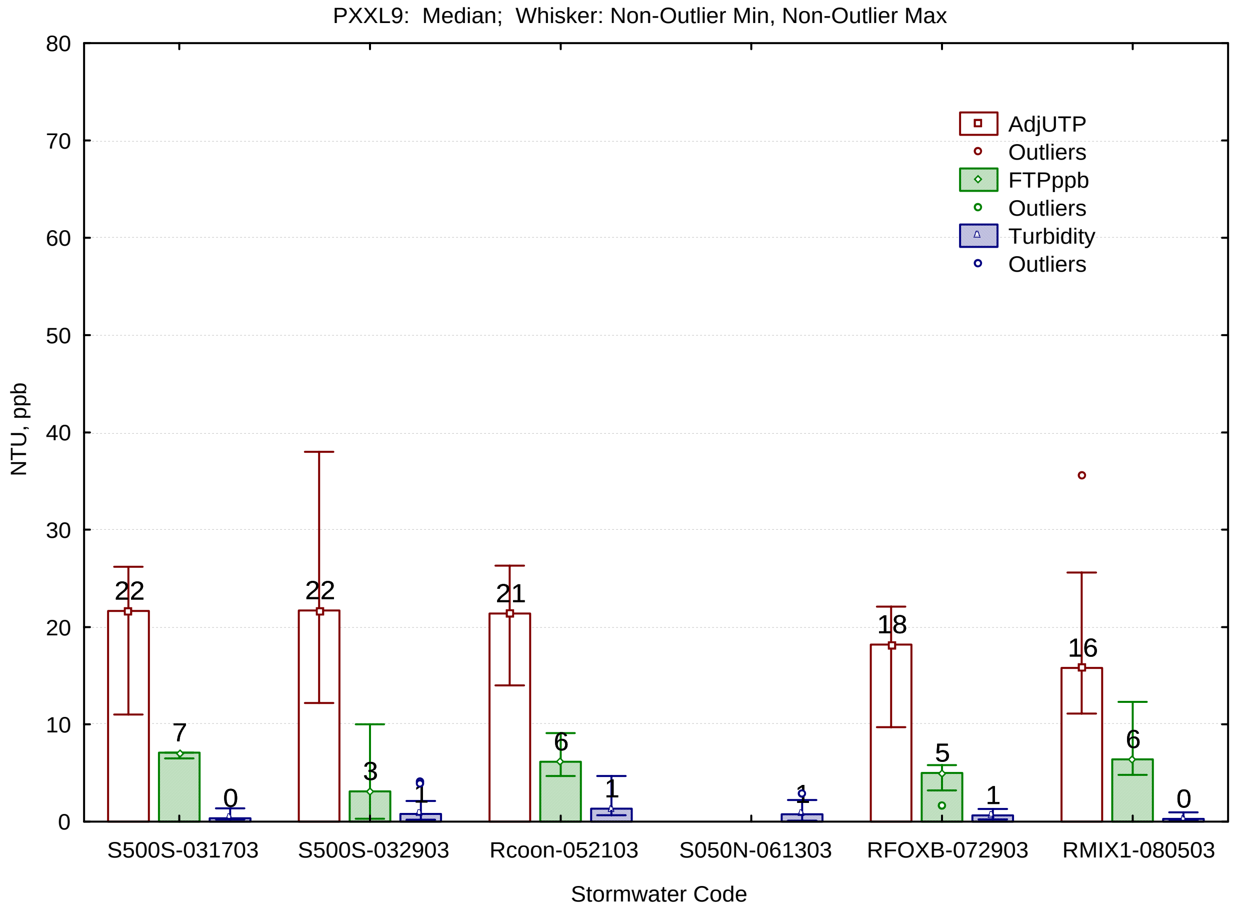


Figure 7-4 Achievable Phosphorus and Turbidity Levels during Laboratory Studies for PAX-XL9.



III. COAGULANT WATER QUALITY EFFECTS

8 Water Quality Changes Due to Chemical Dosing

Changes in water quality due to chemical dosing were studied in two experiments. One experiment focused on changes in soluble iron and aluminum and the second experiment focused on a broader analytical suite.

8.1 Changes in Soluble Iron and Aluminum in Synthetic Storm Waters

For this experiment, two synthetic storm waters were used (Table 8-1). These storm waters had a target turbidity of 500 NTU. Total P was near 1000 ppm and filtered total P was in the 20 – 40 ppb range.

Soluble iron and aluminum are determined by ICP analysis and do not require digestion (See DANR for information on analyses). These analyses were conducted for filtered and unfiltered samples. Under ICP analyses, one micron particles are thought to be completely digested in the analyses as well as the outside one micron of suspended particles that are larger than one micron. Filtered ICP analyses provides a measure of dissolved constituents, as well as colloids and small particulates passing through the filter. The unfiltered ICP analyses include those same constituents, plus some contribution from larger suspended material in which the outer one micron or so has been digested by the ICP itself (Green, 2005). For the filtered soluble analysis conducted for this study, water samples were passed through a 0.45 micron filter, while for an unfiltered soluble analysis samples were not passed through a filter.

Filtered soluble samples represent more biologically available and reactive forms. If an aquatic system is however limited by a given constituent and there greater biological demand for the constituent then is available in its filtered soluble form, then it is possible that some of the additional constituent measured using unfiltered samples might also be biologically available..

Table 8-1 Initial Storm Water Quality

Stormwater Code	Turbidity			UTP			FTP			pH		
	Average	SD	N	Average	SD	N	Average	SD	N	Average	SD	N
Rcoon-052103	47.9	5.4	2	105.6	3.3	2	9.0	1.7	2			0
S500S-031703	495.8	21.1	5	976.5	355.4	4	34.8	14.4	4	7.5	0.0	4
S500S-032903	499.2	33.8	6	806.0	389.8	6	23.1	6.0	6	7.5	0.2	6

Table 8-2 shows the changes in soluble iron and aluminum due to chemical dosing. The synthetic storm waters had an initial mean concentration of unfiltered soluble iron of 2 ppm and filtered soluble iron of less than the detection limit of 0.10 ppm (Table 8-2). These storm waters also had an initial mean concentration of unfiltered soluble aluminum of around 2.4 ppm and filtered soluble aluminum of around 0.15 ppm.

Changes in soluble iron and aluminum were measured in the synthetic storm waters for both aluminum and iron based coagulants. Ferric chloride was selected as the iron coagulant. When dosed with ferric chloride, unfiltered soluble iron was on average over 400% of the initial concentration and filtered soluble iron was on average over an order of magnitude greater than the initial concentration (Table 8-2). Unfiltered soluble aluminum decreased for ferric chloride dosing and filtered soluble aluminum was unchanged.

Several PACls were selected as the aluminum coagulants. When dosed with these PACls, unfiltered soluble iron was reduced from 2 ppm to less than 0.3 ppm and filtered soluble iron remained at or near initial levels, whilst filtered and unfiltered soluble aluminum either remained at about the initial levels or decreased by up to about 75% for some coagulants.

Thus, dosing with ferric chloride, the iron coagulant, increased soluble iron and decreased soluble aluminum levels. Dosing with aluminum coagulants decreased soluble iron levels and either maintained or decreased soluble aluminum levels (Table 8-2).

Figures 8-1 and 8-2 graphically summarize the trends in Table 8-2. Both iron and aluminum coagulants generally did not increase filtered or unfiltered soluble iron and aluminum in the storm water except under high dosing conditions. In the case of iron, for instance, dosing increased filtered soluble iron only at the very highest dosing level and total soluble iron increased at a dosing level of around 15 mg-Fe/L (Figure 8-1). This corresponded to a streaming current voltage of 0 mV. For aluminum, dosing,showed no increase in filtered soluble aluminum at any dosing level, but did show an increase in total soluble aluminum at a dosing level of around 10 mg-Al/L (Figure 8-2). These dosing levels represent relatively high concentrations of aluminum for this storm water, corresponding to a SCV of around 150 mV (Figure 8-3). As Figure 8-3 shows, for this storm water total aluminum stays low and settles out within 30 minutes at dosing levels corresponding to a SCV of 75 mV or lower, but there is a significant increase in total soluble aluminum at higher concentrations. Filtered soluble aluminum stays low and constant at all dosing levels.

These results are consistent for the individual coagulants used. Figure 8-4 shows for the aluminum based coagulants, a SCV greater then 0 mV generally led to increases in soluble aluminum in the stormwater. Up to a SCV of 0 mV, dissolved aluminum concentrations were below background levels and were generally flat. This trend is not evident with the organic/inorganic blends (JenChem 1679 or 1720) or SumaChlor 50, which was effective at very low doses. However, when unfiltered soluble aluminum is graphed against mass dosing levels as shown in Figure 8-5, it is apparent that all the coagulants show an increase in soluble aluminum when the dosing exceeds the zero charge point and that this increase is related to the dosing level used.

These data suggest that as the dosing concentration increases, more and more relatively reactive or soluble flocculate remains in the water. These levels can be below, at or near background levels as was the case for this storm water. However, total soluble concentrations of the dosed metal (aluminum or iron) at an overdosing condition increase due to either poorer settling characteristics or because of the formation of more soluble flocculates and colloids. Overdosing clearly created a water quality problem pertaining to the dosed metal for this storm water, and this problem is likely to be common for other dosed waters.

Table 8-2 Soluble Iron and Aluminum after Dosing and 30 Minutes of Settling

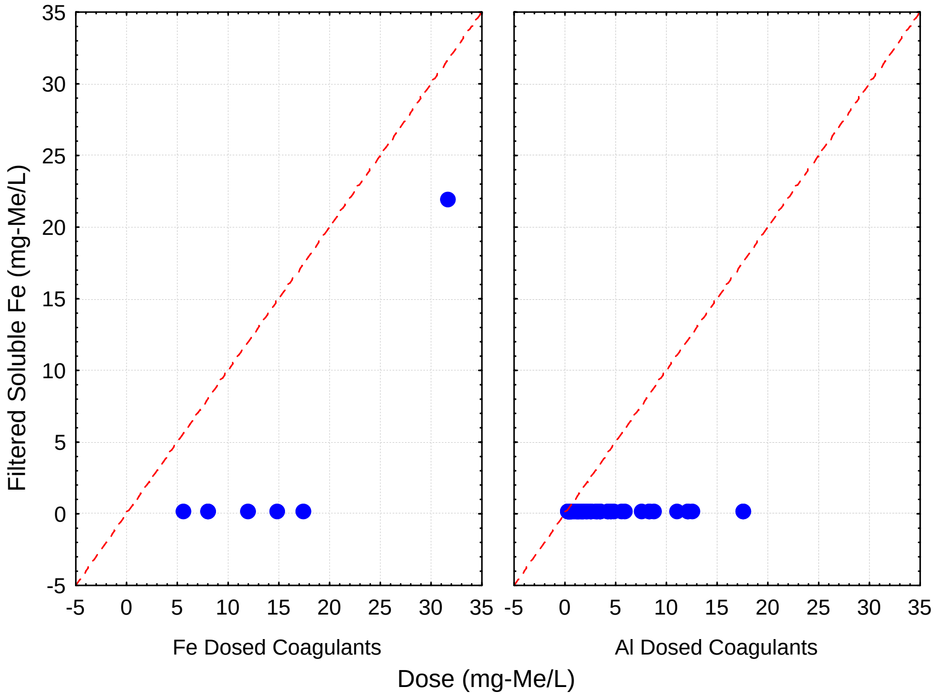
Coagulant Code	Dose mg-Me/L			Unfiltered Soluble Fe					Filtered Soluble Fe					Unfiltered Soluble Al					Filtered Soluble Al				
	Mean	SD	N	Mean	SD	N	%D[1]	%B[2]	Mean	SD	N	%D[1]	%B[2]	Mean	SD	N	%D[1]	%B[2]	Mean	SD	N	%D[1]	%B[2]
Control																							
NOTRT	0.0	0.0	12	2.00	0.00	2	NA	NA	0.10	0.00	2	NA	NA	2.40	0.00	2			0.15	0.07	2		
Fe-based Coagulants																							
FECl3	14.6	8.6	19	8.39	11.73	7	58%	419%	3.21	8.24	7	22%	3214%	0.80	1.12	7	NA	33%	0.17	0.15	7	NA	114%
Al-based Coagulants																							
J1679	0.4	0.1	20	0.26	0.08	7	NA	13%	0.10	0.00	7	NA	100%	0.50	0.20	7	114%	21%	0.10	0.00	7	23%	67%
J1700	4.2	3.6	20	0.16	0.17	13	NA	8%	0.10	0.00	13	NA	100%	1.89	3.64	13	45%	79%	0.11	0.03	13	3%	72%
J1720	0.6	0.3	19	0.16	0.05	7	NA	8%	0.10	0.00	7	NA	100%	0.57	0.23	7	89%	24%	0.27	0.19	7	42%	181%
PASSC	7.6	5.9	21	0.10	0.00	9	NA	5%	0.10	0.00	7	NA	100%	1.97	3.10	9	26%	82%	0.17	0.13	7	2%	114%
PC300	4.2	2.4	19	0.24	0.38	7	NA	12%	0.10	0.00	7	NA	100%	2.41	3.08	7	57%	101%	0.14	0.11	7	3%	95%
PXXL9	6.2	3.6	19	0.10	0.00	7	NA	5%	0.10	0.00	7	NA	100%	1.29	1.89	7	21%	54%	0.13	0.08	7	2%	86%
SUM50	1.1	0.5	20	0.15	0.11	8	NA	8%	0.13	0.05	8	NA	125%	0.53	0.53	8	49%	22%	0.28	0.32	8	26%	183%
Chitosan-based Coagulants																							
LFLOC	1.7	0.7	14	0.38	0.05	4	NA	NA	0.10	0.00	4	NA	NA	0.53	0.10	4			0.15	0.10	4		
All Grps	4.3	5.7	183	1.04	4.23	71			0.42	2.62	69			1.30	2.27	71			0.17	0.15	69		

Notes

1. % of dosed metal
2. % of background as defined by "NOTRT". Filtered or Unfiltered as appropriate.

Figure 8-1. Total and Filtered Soluble Iron in Solution after Coagulant Dosing

a. Filtered Soluble Iron



b. Total Soluble Iron.

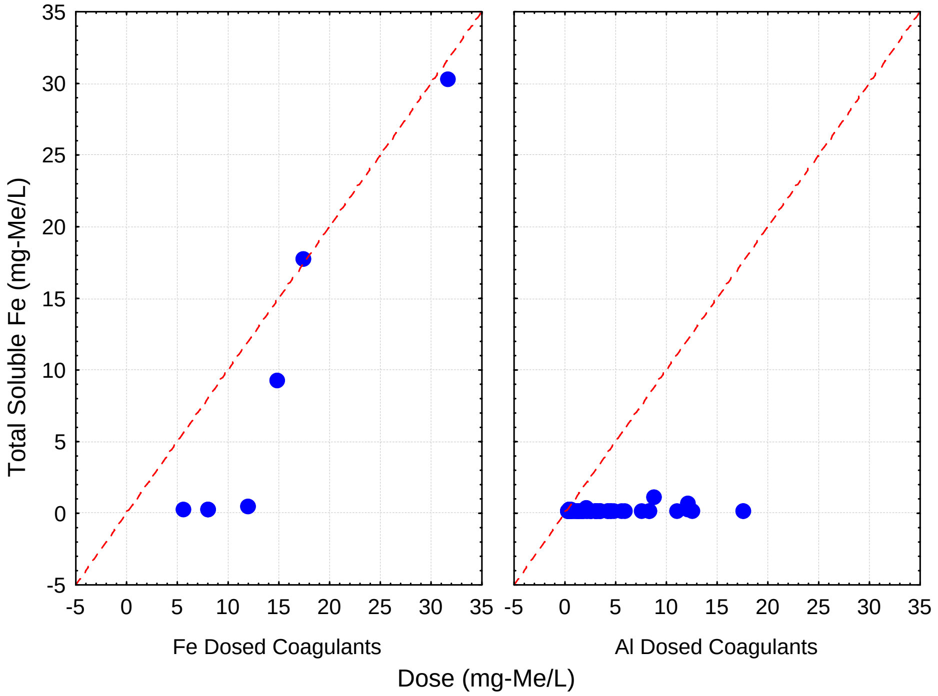
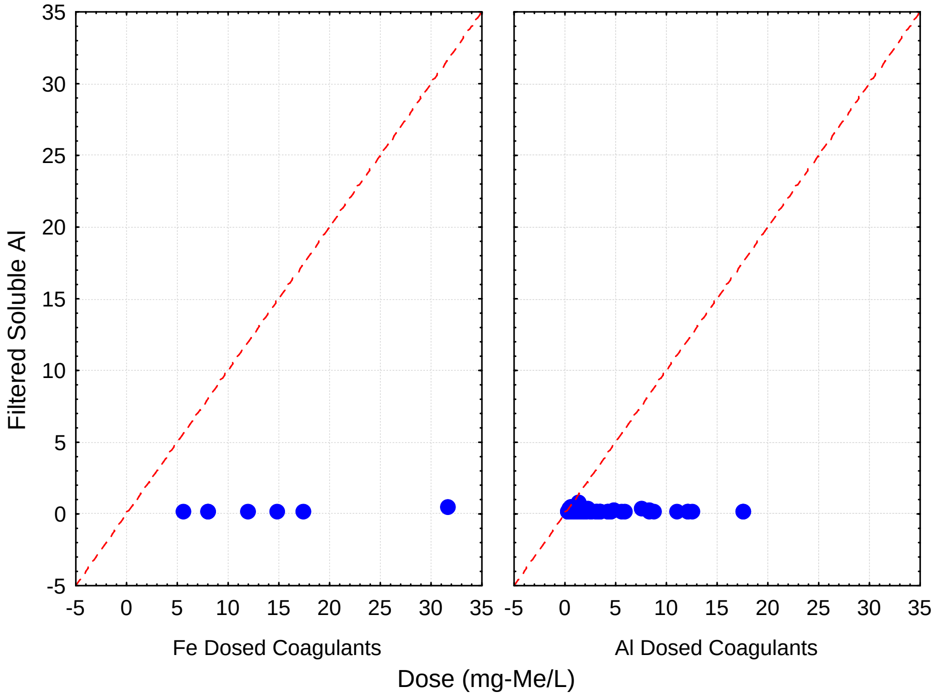


Figure 8-2 Total and Filtered Soluble Aluminum in Solution after Coagulant Dosing

a. Filtered Soluble Aluminum



b. Total Soluble Aluminum

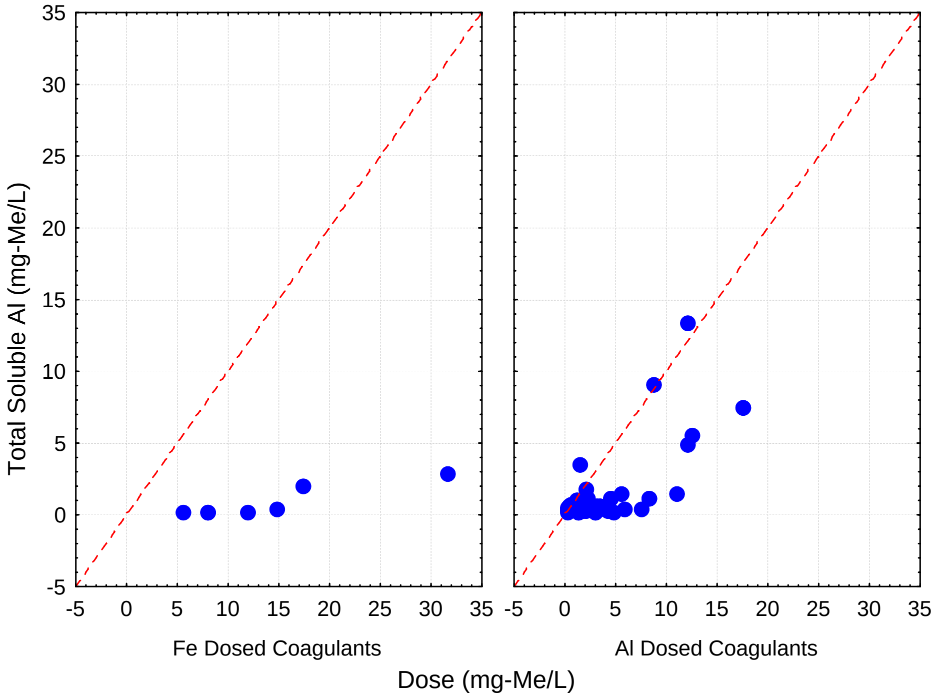


Figure 8-3 Increasing Soluble Metal Under Overdosing Conditions.

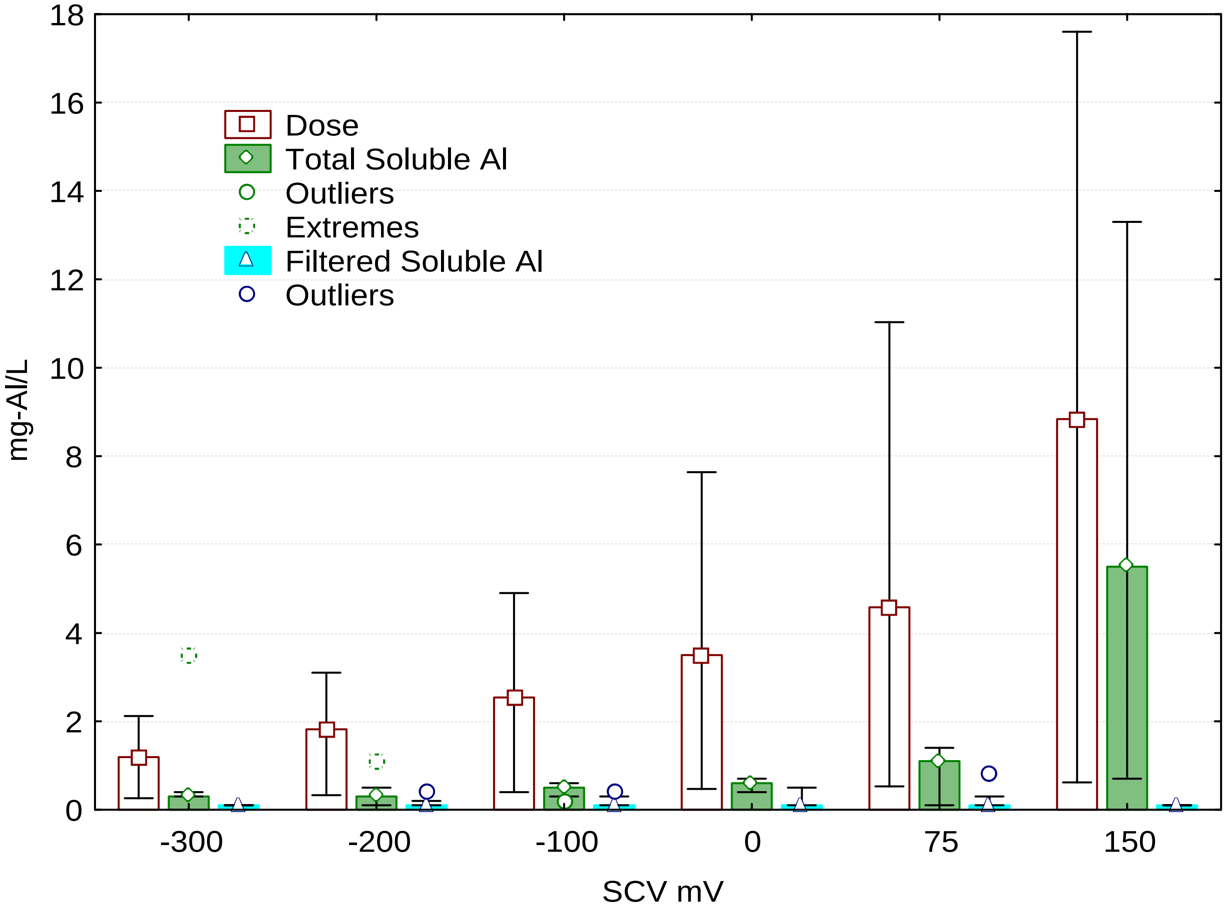


Figure 8-4 Unfiltered Soluble Aluminum Increases for Different Dosing Levels Corresponding to Streaming Current Values.

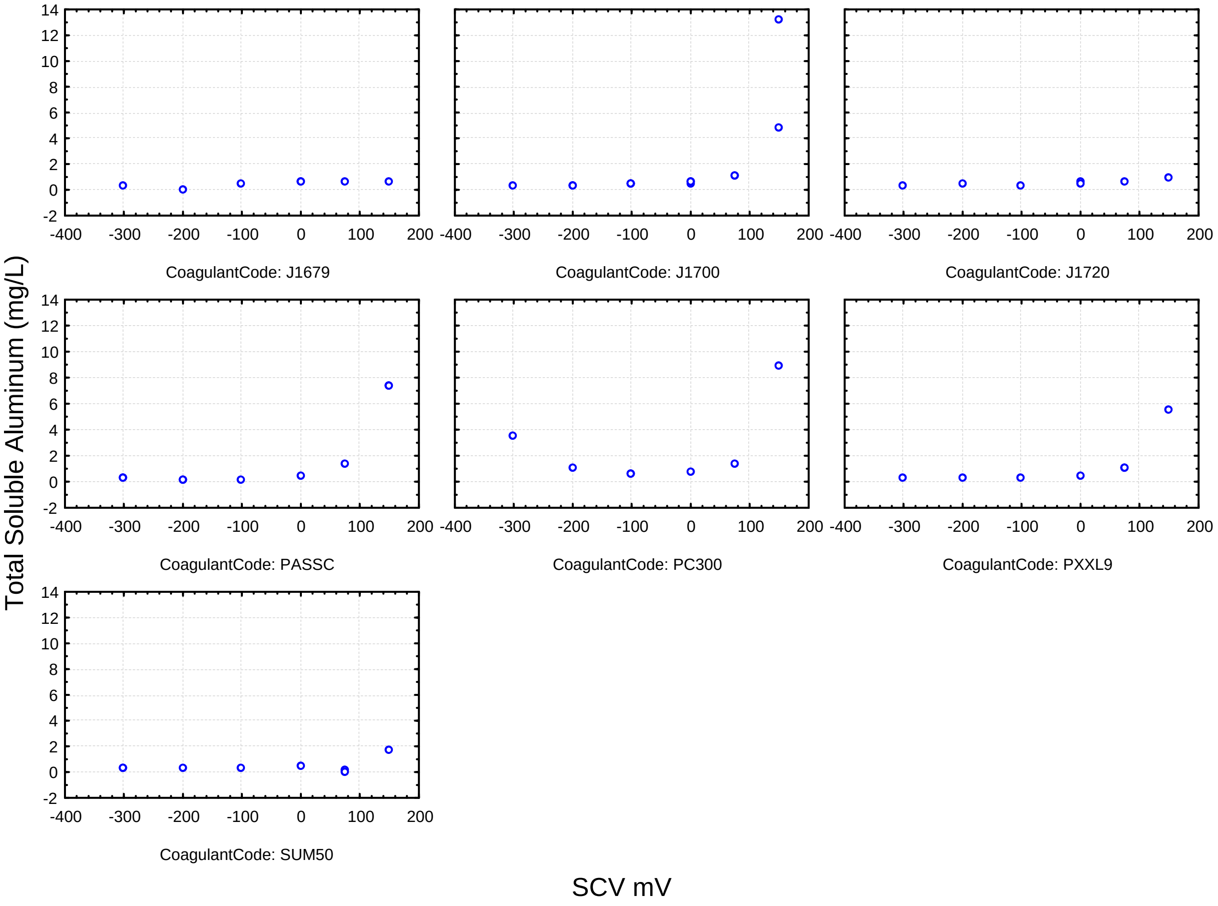
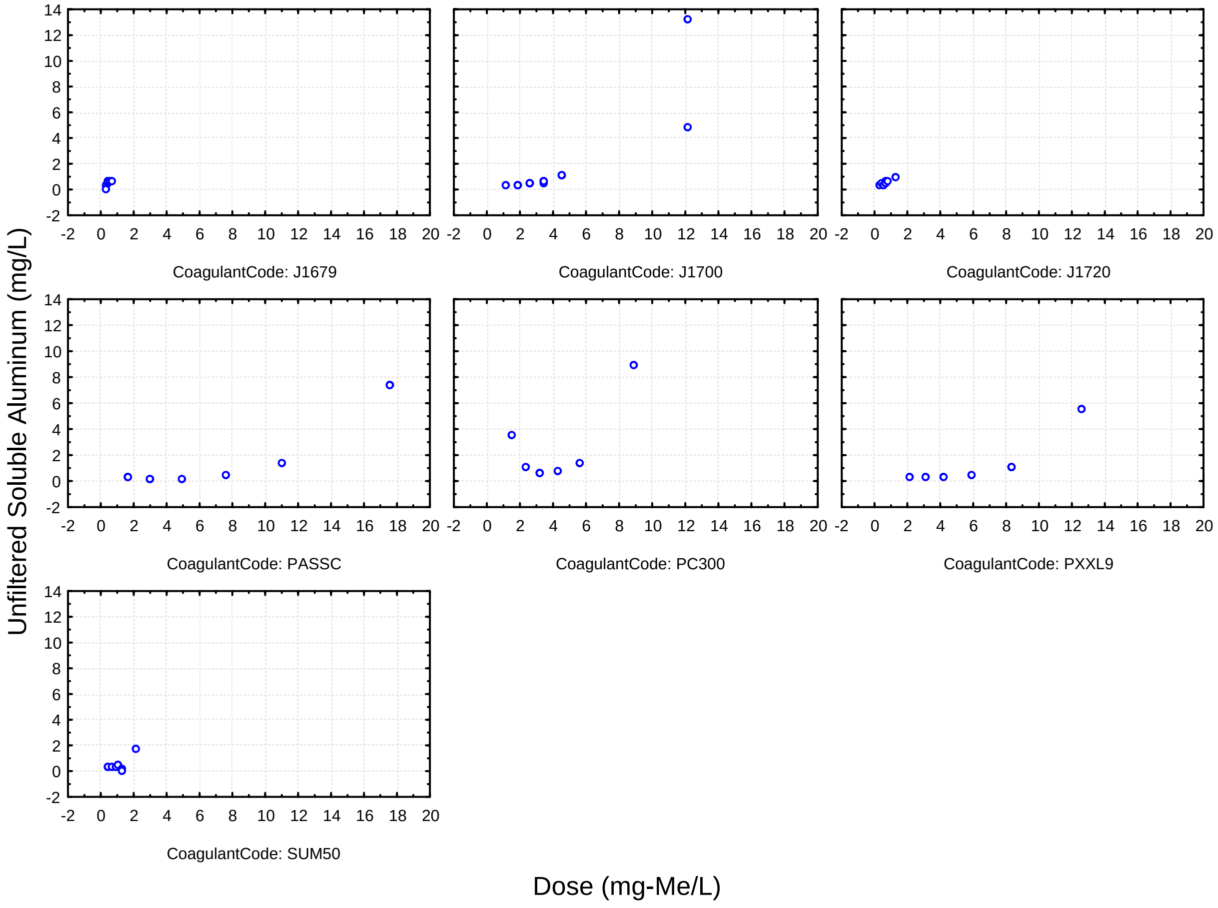


Figure 8-5. Unfiltered Soluble Aluminum increases for Different Chemical Dosing Levels



8.2 Water Quality Changes to a Real Storm Water after Chemical Dosing

Storm water from the Coon St Basin in Kings Beach was collected in May 2003 and dosed at a SCV of 0, -100 and –200 mV during standard jar tests within about one week of collection. These experiments were not replicated at the different dosing levels because of limited water volume. However, based upon the results of this study, this was assumed to be an optimal dosing range.

Table 8-3 summarizes changes in turbidity, phosphorus, TKN, alkalinity and soluble iron and aluminum under chemical dosing. Before treatment and settling, the Coon St water had total phosphorus concentrations of approximately 100 ppb and turbidity of about 50 NTU (Table 8-1). After no chemical dosing but 30 minutes of settling (NOTRT), phosphorus concentrations in these waters had decreased by about 50% to around 47 ppb and turbidity had dropped by 80% to about 13 NTU. With chemical dosing, total phosphorus levels decreased by another 50% to around 20 ppb for all coagulants and turbidity further decreased by nearly an order of magnitude to around 2 to 3 NTU. Performance differed statistically for different coagulants, though in many cases the differences were negligible in terms of meeting surface water standards at Lake Tahoe. These improvements in water quality are consistent with findings in the earlier chapters.

Table 8-3 also shows measurements for other constituents. TKN decreased under chemical dosing for all coagulants, but TKN values did not differ significantly between the different chemical treatments ($p<0.05$). Filtered TKN was unchanged by chemical dosing. None of the coagulants consumed much alkalinity or had noticeable effects on total or filtered total soluble iron or aluminum at the more optimal dosing ranges. This is consistent with the findings in Section 8.1, where changes in constituent concentrations occurred under over-dosing conditions.

8.3 Summary

Overdosing can lead to increased concentrations of the dosed metal in the water column in a “soluble” form. Solubility is defined by the ICP analyses and the soluble form can either be a dissolved or colloidal form of the metal.

Under optimal dosing conditions, increases in concentrations of the dosed metal either did not occur or were relatively small for the storm waters tested. This was true for both the real and synthetic storm waters tested. In some cases, the soluble metal concentrations may actually be below background due to the removal of the metal during the coagulation process. Thus, controlling dosing to near optimal levels is expected to minimize increases of the soluble metal.

Coagulant dosing effects on TKN and alkalinity were tested with real storm water. For the storm water tested, alkalinity and filtered TKN were also unaffected by chemical dosing. Total TKN was not affected by the chemical treatment used though the data was insufficient to determine if it differed significantly from the non-treated storm water.

Table 8-3 Changes in Water Quality under Chemical Dosing of the Coon Street Storm Water.

(P-values represent if there was a significant difference in the constituent for the different treatments shown. A p-value less then 0.05 shows a significant difference. P-values do not include raw water as a treatment.)

Coagulant Code[3]	Dose (mg- Me/L)			Turbidity (NTU)			Total P (ppb)			Filtered Total P (ppb)		
	p=0.00001			p=0.00000			p=0.00000			p=0.30964		
	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*
Raw	NA	NA	*NA*	47.90	5.37	*2*	105.60	3.25	*2*	9.00	1.70	*2*
NOTRT	0.0	0.0	*2*	12.51	5.64	*2*	46.65	2.33	*2*	7.75	1.63	*2*
J1720	1.5	0.4	*7*	3.29	1.44	*7*	22.45	4.57	*6*	7.27	1.90	*7*
PASSC	3.6	1.3	*9*	2.00	0.96	*9*	19.69	2.73	*9*	10.80	7.45	*9*
PXXL9	4.4	1.1	*7*	1.75	1.46	*7*	19.74	4.92	*7*	6.46	1.63	*7*
All Grps	2.9	1.7	*25*	3.13	3.33	*25*	22.64	8.35	*24*	8.35	4.88	*25*

Coagulant Code	Dose (mg- Me/L)			TKN (ppm)			Filtered TKN (ppm)			Alkalinity (meq/L)			Filtered Alk (meq/L)		
	p=0.00001			p=0.42121			p=0.30959			p=0.01178			p=0.14447		
	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*
Raw	NA	NA	*NA*	2.50	0.00	*1*	0.45	0.21	*2*	0.50	0.00	*1*	0.55	0.07	*2*
NOTRT	0.0	0.0	*2*	NMA	NA	*NA*	0.20	0.14	*2*	NMA	NA	*NA*	0.50	0.00	*2*
J1720	1.5	0.4	*7*	0.27	0.15	*7*	0.40	0.22	*7*	0.50	0.00	*6*	0.47	0.05	*7*
PASSC	3.6	1.3	*9*	0.44	0.29	*9*	0.41	0.28	*9*	0.40	0.08	*7*	0.43	0.07	*8*
PXXL9	4.4	1.1	*7*	0.31	0.33	*7*	0.24	0.08	*7*	0.42	0.04	*6*	0.40	0.08	*7*
All Grps	2.9	1.7	*25*	0.35	0.27	*23*	0.34	0.22	*25*	0.44	0.07	*19*	0.44	0.07	*24*

Coagulant Code	Dose (mg- Me/L)			Total Soluble Fe (ppm)			Filtered Sol Fe (ppm)			Total Soluble Al (ppm)			Filtered Sol Al (ppm)		
	p=0.00001			p undefined			p undefined			p undefined			p undefined		
	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*
Raw	NA	NA	*NA*	0.10	0.00	*1*	0.10	0.00	*2*	0.10	0.00	*1*	0.10	0.00	*2*
NOTRT	0.0	0.0	*2*	NMA	NA	*NA*	0.10	0.00	*2*	NMA	NA	*NA*	0.10	0.00	*2*
J1720	1.5	0.4	*7*	0.10	0.00	*7*	0.10	0.00	*7*	0.10	0.00	*7*	0.10	0.00	*7*
PASSC	3.6	1.3	*9*	0.10	0.00	*9*	0.10	0.00	*9*	0.10	0.00	*9*	0.10	0.00	*9*
PXXL9	4.4	1.1	*7*	0.10	0.00	*7*	0.10	0.00	*7*	0.10	0.00	*7*	0.10	0.00	*7*
All Grps	2.9	1.7	*25*	0.10	0.00	*23*	0.10	0.00	*25*	0.10	0.00	*23*	0.10	0.00	*25*

Notes

1. NA = Not applicable; NMA = Not Measured/Analyzed
2. P-value from ANOVA analysis does not include Raw water as a treatment.
3. Raw is initial water. NOTRT is for settling but no chemical dosing

IV. SETTLING COLUMN MESOCOSM STUDIES

9 Settling Column Experiments

Settling columns were run to confirm the results of the jar studies. Chapter 2 discusses the design of the columns and the methods used. This chapter discusses the experimental design and results for this study.

9.1 Experimental Design

Table 9-1 shows the experimental design for the settling column study. The primary goal of this study was to confirm that dosed Tahoe Basin storm waters would have improved settling and associated turbidity and phosphorus removal than non-dosed waters. The same storm water used for conducting many of the laboratory studies discussed in Chapter 6 (RMIX-080503) was used to maintain continuity. Initial dosing ranges were based upon streaming current values but because the settling column studies were done after the completion of the laboratory studies and the storm water had been stored during that period, final dosing levels were determined with jar studies. The goal was to validate the performance results that were achieved at the jar scale at a larger-scale which utilized different mixing equipment and was more representative of the settling conditions found in the field. These columns were designed to simulate marsh or basin settling conditions and therefore were operated at an initial 3-foot water depth.

Three coagulants were tested: Sumachlor 50, PAX-XL9 and JenChem 1720. Pass-C was not tested as throughout the earlier laboratory studies, both Pass C and PAX-XL9 performed similarly. This selection of coagulants allowed testing of an aluminum chlorohydrate, a top-ranked PACl, and an inorganic/organic polymer blend.

For each coagulant, storm water was mixed in the mixing tank using mixing criteria determined from jar tests. This is explained in greater detail in Chapter 3. After mixing, treated storm water was transferred to the settling columns. Three replicate columns were operated for each treatment. These columns were then sampled at three depths over a 72-hour period, as shown in Table 9-1, for turbidity and phosphorus removal, TKN, iron, aluminum, and total suspended solids. Sampling periods were very closely spaced initially because settling was expected to be relatively rapid during this period. After the first 6 hours, samples were collected less frequently (daily) to assess longer-term trends.

Storm water used for these experiments was collected during Spring/Summer 2003, and was used for studies described in Chapter 6. This storm water was stored such that it could be used for these settling studies, which were conducted during March/April 2004. During the storage time, some changes were expected to occur in water quality. Ortho-P would be expected to be converted to dissolved phosphorus and some dissolved phosphorus would be expected to be converted to total phosphorus. Other nutrients may also have been utilized depending upon the biotic activity in the storm water. Dosing levels determined for these settling column studies from the jar tests were not much different from those that had been determined using streaming current detectors when the storm water was tested earlier in the laboratory studies. Dosing levels for JenChem 1720, PAX-XL9 and SumaChlor 50 corresponded to streaming current values of about -30, -65 and -130 mV respectively, based upon the streaming current curves developed during the laboratory studies. Thus, though the storm water no doubt changed over time, the consumption of coagulant needed to treat the storm water was similar.

Table 9-1. Experimental Design for Settling Column Study.

Water Quality^{3}	Coagulant^{1,2}	Sampling locations (ft from bottom)	Elapsed Time after dosing	Water Sampling (volumes in parentheses where appropriate. ^{4,5}			
				Turbidity	temperature	UTP, FTP^{5}	UFE, FFE, UAL, FAL, pH, Alk, FTKN, UTK, TSS
			Pre-dose	**X**	**X**	**100 (from tank)**	
			Post-dose	**X**	**X**	**100 (from tank)**	
RMIX Water	Day 1 - Sum50	2.5	**0.25^{6}**	**X**			
	Day 2 - PXXL9	1.5	0.5	**X**			
	Day 5- NoTrt	0.5	1	**X**		100	
	Day 6- J1720		2	**X**			
			4	**X**		100	
			6	**X**			
			24	**X**		100	
			48	**X**			
			72	**X**		250	500 (1 or 2 places)

Notes

1. Coagulants dosing levels were determined using jar tests.
2. Includes controls (no coagulant, no dose)
3. Water quality will be defined by turbidity and type of stormwater (I.e. natural, synthetic). Selected water will be one that has been previously used in jar test studies (CTMP Task 3.4.2).
4. Turbidity will be measured at each sampling time. Other parameters being samples will be UTP, FTP, UFE, FFE, UAL, FAL, pH, alkalinity, FTKN, UTK, TSS and PSD will be determined less frequently.
5. Samples taken from all sampling locations unless otherwise specified
6. First sample event begins approximately 10-15 minutes after adding dosed water to columns.

9.2 Turbidity and Phosphorus Removal and Settling Characteristics

Table 9-2 shows the turbidity and phosphorus levels achieved in the settling columns for non-dosed and dosed conditions. These values are average values for all sample depths over the course of the 72-hour study for each coagulant. For the non-dosed or control column, about half the turbidity was removed over the first six hours and 75% during the first 24 hours. After 24 hours, the turbidity decreases very slowly and is over three times the turbidity standard after 72 hours. Total unfiltered phosphorus in the control column decreased from an average initial concentration of 316 ppb to 46 ppb at 24 hours. Only 1/3 of the remaining total phosphorus is removed during the next two days, indicating that the remaining particulate phosphorus is associated mostly with poorly settling fine particles. Very little dissolved phosphorus was found in this storm water.

For the treated (dosed) columns, initial turbidity and dissolved phosphorus were lower than that in the control column at time zero, the initiation of the settling column studies. The coagulants converted dissolved phosphorus to total phosphorus in the mixing tank and turbidity reduction started during the slow mixing stage. Thus, time zero was used as an indicator of initial flocculate size and settleability. Although differences in flocculate size were observed for the various coagulants, initial turbidity was lower than that in the control for all the treated columns.

For PAX-XL9 and JENCHEM 1720, the flocculate settled very rapidly and the turbidity water quality standard of 20 NTU was achieved within 1 hour. SumaChlor 50 flocculate settled less well and just met the turbidity standard after about 6 hours of settling. After 24 hours settling, all the coagulants produced treated storm water which easily met the turbidity discharge standard.

Variation in total phosphorus in the treated storm waters was very similar to that for turbidity, with a few exceptions. Initial total P concentrations were relatively high, indicating that phosphorus may have been associated with more poorly settling, smaller flocculates. Total phosphorus concentrations were at steady state at about 4 hours for PAX-XL9 and JENCHEM 1720, and at about 6 hours for SumaChlor 50. After only 1 hour of settling, all the treated storm waters easily met the phosphorus surface water quality standard of 100 ppb. After 4 hours, phosphorus concentrations in the treated storm waters were more than an order of magnitude lower than in the control.

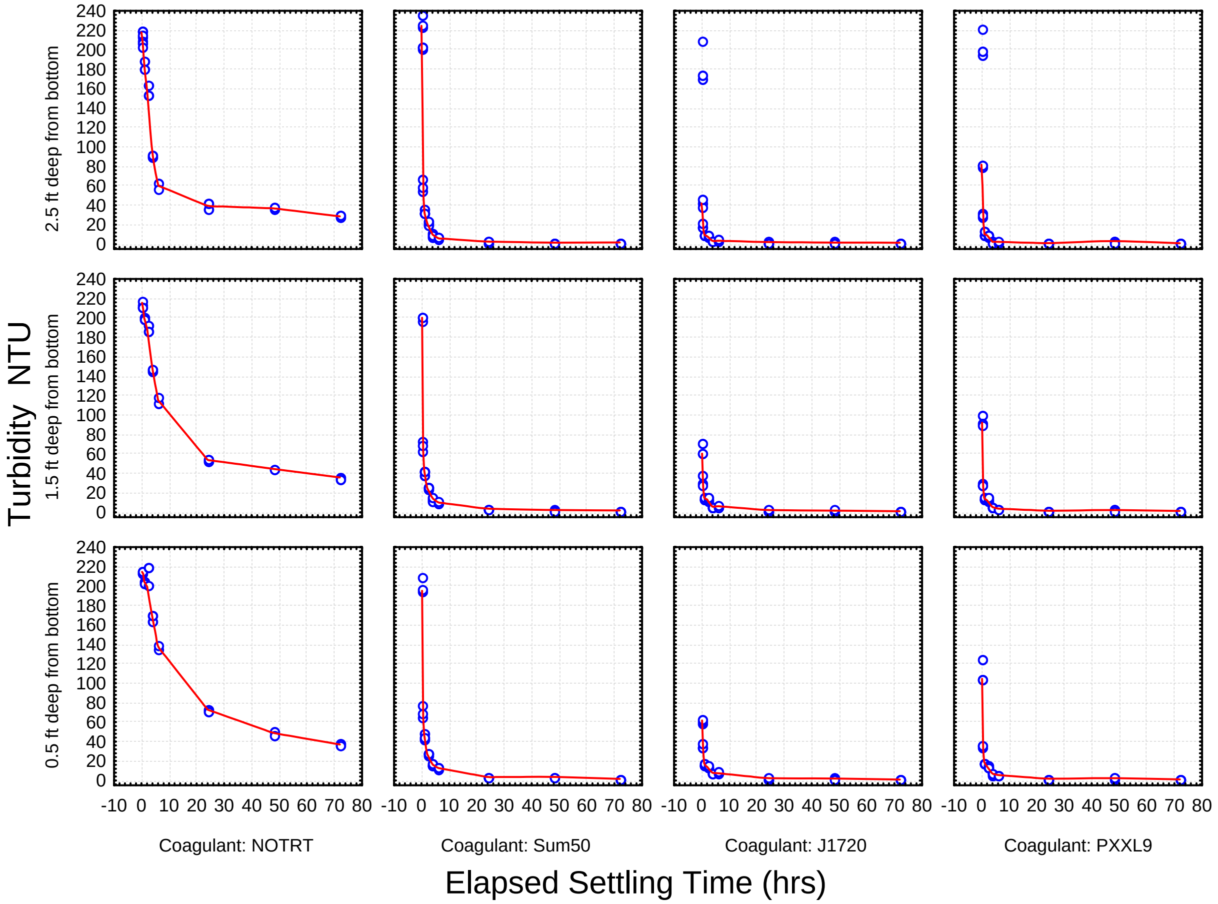
Table 9-2 Turbidity and Phosphorus Levels During Settling Column Test

	Elapsed Time (hrs)	No Treatment			Treatment								
					PXXL9			J1720			SUM50		
Turbidity (NTU)		Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N
	0	213	4	15	84	60	21	63	54	21	147	72	21
	1	196	10	6	14	3	9	14	3	9	40	5	9
	2	186	24	6	12	3	9	12	3	9	25	3	9
	4	135	35	6	5	2	9	5	2	9	13	3	9
	6	104	36	6	4	1	9	6	2	9	10	3	9
	24	55	15	6	1	0	9	2	0	9	3	1	9
	48	43	6	6	3	1	9	2	0	9	2	1	9
	72	34	4	6	1	0	9	1	0	9	2	0	9
	All Grps	136	74	57	25	45	84	20	36	84	47	69	84
Total P (ppm)		Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N
	0	0.316	0.000	1	0.347	0.001	2	0.266	0.091	2	0.331	0.013	2
	1	0.265	0.022	6	0.021	0.004	9	0.013	0.003	9	0.042	0.006	9
	2												
	4	0.158	0.050	6	0.011	0.003	9	0.008	0.000	9	0.018	0.007	9
	6												
	24	0.046	0.027	6	0.008	0.001	9	0.006	0.001	9	0.009	0.001	9
	48												
	72	0.030	0.003	6	0.013	0.012	9	0.006	0.001	9	0.009	0.006	9
	All Grps	0.133	0.106	25	0.031	0.076	38	0.022	0.060	38	0.036	0.072	38
Filtered Total P (ppm)		Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N
	0	0.010	0.000	1	0.005	0.000	2	0.009	0.001	2	0.008	0.004	2
	1	0.009	0.002	6	0.005	0.005	9	0.004	0.008	9	0.007	0.005	9
	2												
	4	0.008	0.001	6	0.004	0.003	9	0.003	0.003	9	0.005	0.000	9
	6												
	24	0.008	0.001	6	0.003	0.002	9	0.005	0.007	9	0.002	0.000	9
	48												
	72	0.007	0.003	6	0.008	0.013	9	0.003	0.002	9	0.005	0.004	9
	All Grps	0.008	0.002	25	0.005	0.007	38	0.004	0.005	38	0.005	0.004	38

Figures 9-1 and 9-2 show turbidity at different depths for the three coagulants. Figure 9-1 shows that turbidity reduction is rapid at all water depths for the treated waters. There appears to be very little variation in turbidity through the water column for the treated storm waters for the times recorded.

For the no treatment column, the upper sample location has a more rapid decrease in turbidity then found in the deeper sample locations (Figure 9-1). Turbidity values measured at deeper sample locations not only reflect the settling of particles from that depth but also the accumulation of smaller particles from depths above. Thus, turbidity decreases more slowly with depth in the non-treated columns. And because very fine particles do not settle well at all, the lower limit for turbidity for this storm water when not treated is about 30 to 35 NTU. This lower limit is about an order of magnitude higher than the limit for the treated storm waters. An ANOVA analysis (Table 9-3) showed that turbidity reductions differed significantly ($p<0.05$) for both different types of coagulant and the elapsed times when compared to the control.

Figure 9-1 Turbidity Variation for Different Dosing Treatments



For this tested storm water, total phosphorus is nearly completely removed to below the surface water discharge limit (100 ppb) within about four hours at all depths (Figure 9-2). In the control columns, the surface water discharge limit is reached two to ten hours after settling has begun depending upon the depth the sample is collected.

Figure 9-2 Phosphorus Variations for Different Dosing Treatments

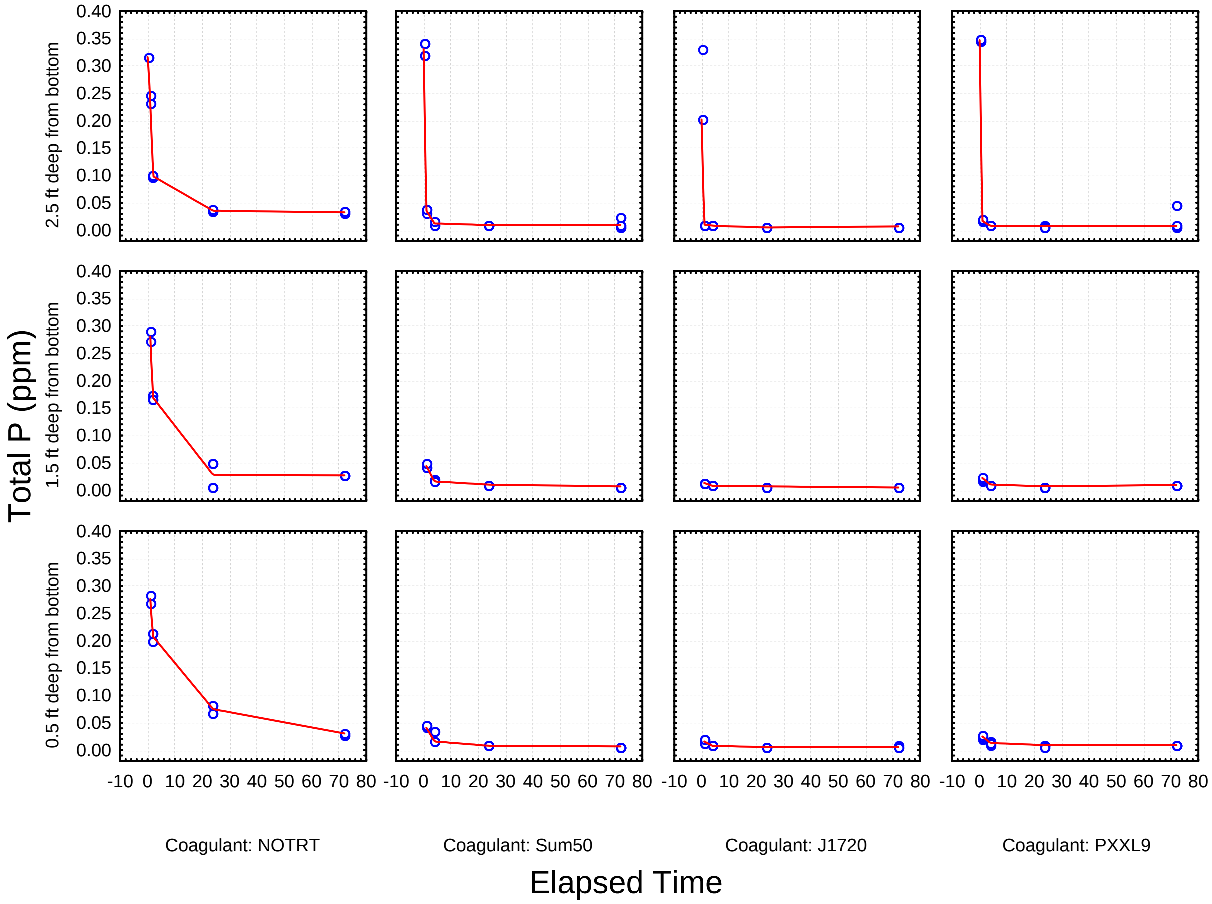
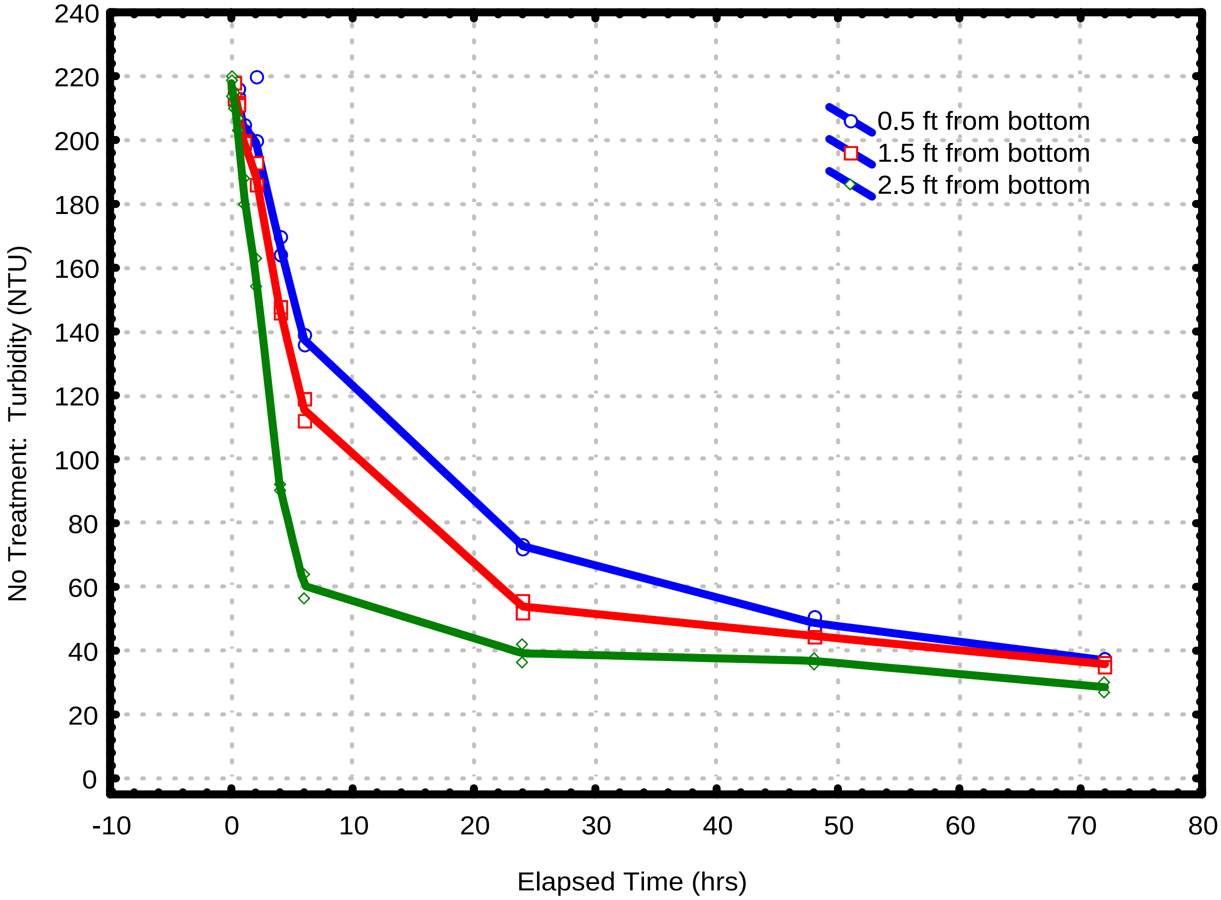


Table 9-3 ANOVA Analysis

Treatment	p-value
Coagulant	0.00000
Elapsed Time	0.00000
Sampling Depth	0.77150

Figure 9-3 shows turbidity at different depths for the control column. In the control column, turbidity stratifies with depth but this stratification decreases over time. Settling of this storm water did not provide sufficient treatment to meet the surface water quality standard for turbidity of 20 NTU within 72 hours. As with turbidity, phosphorus concentrations initially stratify with depth (Figure 9-4), but this stratification is no longer evident at 72 hours.

Figure 9-3 Turbidity at Different Sampling Depths for Control (No Treatment)



Figures 9-5 and 9-6 show turbidity and phosphorus concentrations achieved with coagulant dosing. Turbidity concentrations stratify only slightly with depth because of much faster flocculate settling. Surface water discharge limits for turbidity were achieved within four hours at all depths. Phosphorus surface water limits were achieved within one half hour after dosing. A steady state equilibrium condition is achieved between 6 hours and 24 hours after dosing. An ANOVA analysis of the treated storm waters shows that turbidity values achieved at one half hour elapsed time and beyond do not differ significantly ($p<0.05$). Thus, steady state conditions are achieved relatively rapidly for dosed waters when compared to non-dosed waters.

Figure 9-4 Total P at Different Sampling Depths for Control (No Treatment)

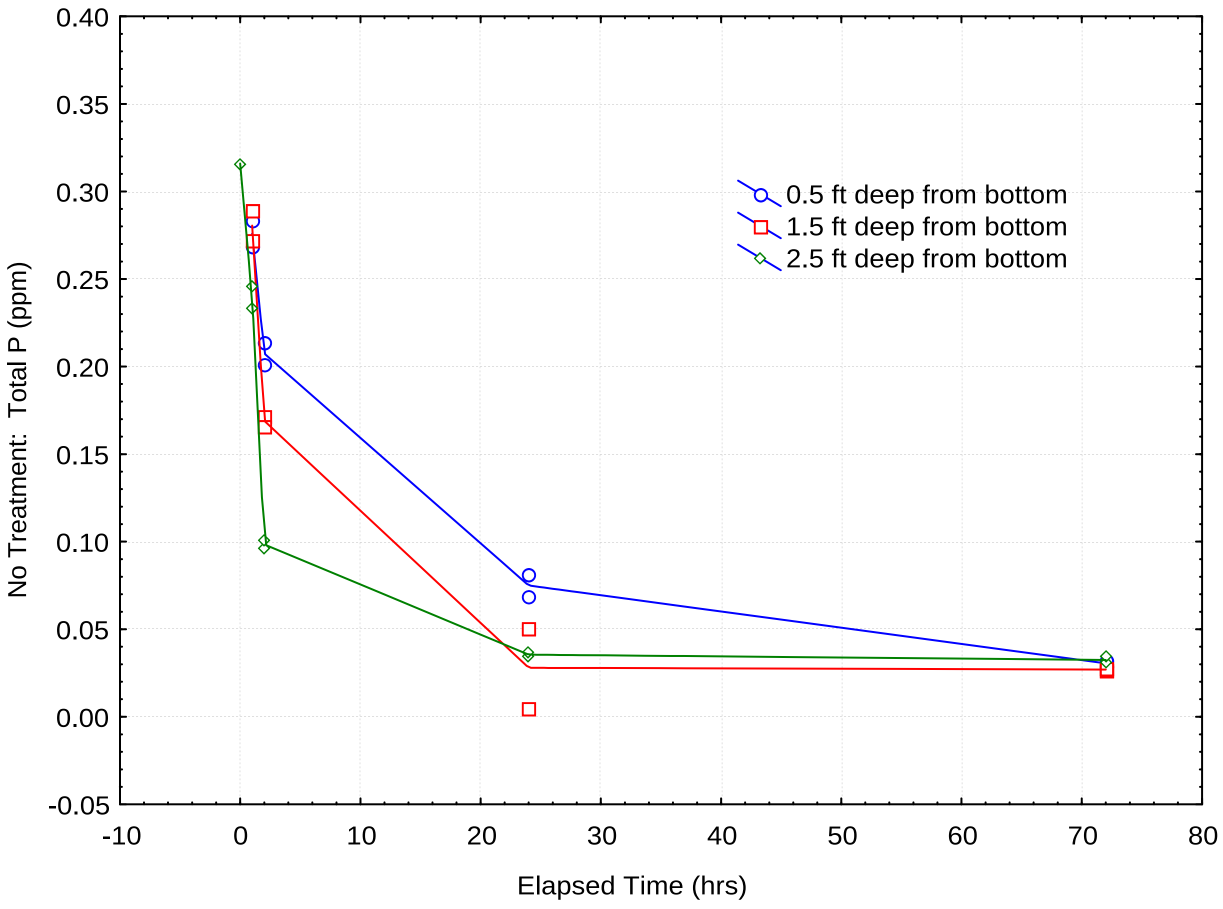


Figure 9-5 Turbidity at Different Depths for a PAX-XL9 Treated Storm Water

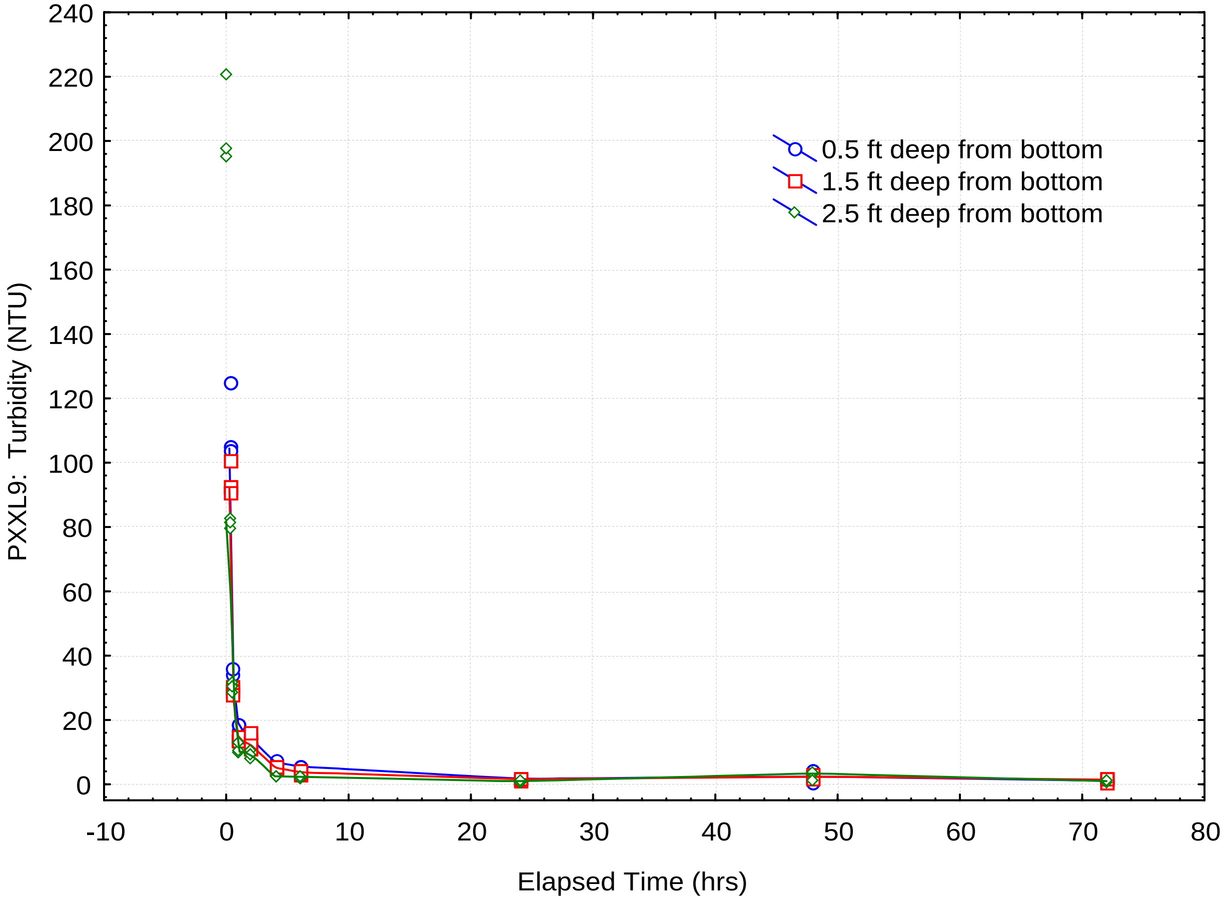
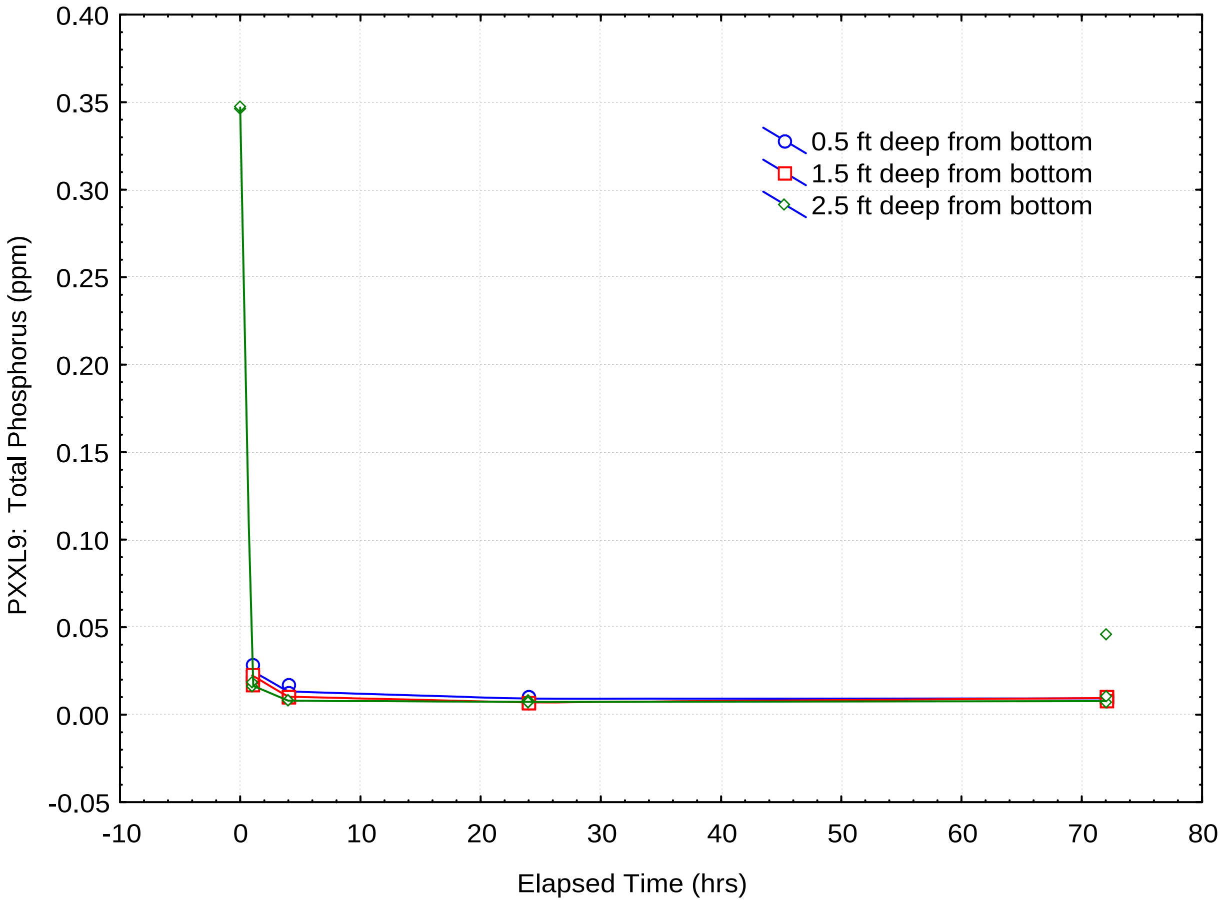


Figure 9-6. Total P at Different Depths for a PAX-XL9 Treated Storm Water



9.3 Coagulant Effects on Other Water Quality Constituents

Tables 9-4 and 9-5 summarize the effects of coagulant type and sampling depth, respectively, on a number of other water quality parameters, including total and filtered aluminum and iron. The objectives of these measurements were to validate the laboratory findings at a larger scale and to assess any trends. These analyses are for a smaller subset of data collected at an elapsed time of 72 hours (SD = 0 indicates measurements were at or below the detection limit; NOTRT indicates no treatment or no coagulant dosing before settling).

Both Tables 9-4 and 9-5 provide descriptive statistical results (e.g., mean, standard deviation) as well as univariate ANOVA analyses for the effects of coagulant type and sampling depth for each water quality parameter. The resulting p-values show whether the parameter differs significantly for the given independent variable (e.g. coagulants, depth). P-values shown in red indicate a significant effect ($p<0.05$). For both tables, p-values are given for including and excluding the NOTRT to clearly show if the coagulants affected the water quality constituents when compared not only with the control but also between themselves.

9.3.1 Turbidity and Phosphorus

Turbidity and total P removal differ significantly between coagulants but not between sampling depths. Turbidity levels and total phosphorus concentrations achieved with coagulant dosing were much lower than for no treatment, but dissolved phosphorus concentrations were less affected by chemical dosing.

9.3.2 Effects on Nitrogen

Chemical dosing lowered unfiltered TKN below that of non-dosed waters. Unfiltered TKN values averaged 0.7 mg/L for the untreated storm water. When data for the untreated water (NOTRT) was considered with data for the other chemical treatments, unfiltered TKN concentrations were found to differ significantly between treatments. However, when data for only chemically treated waters was considered, no statistical difference between treatments was found. Thus, chemical treatment significantly reduced TKN concentrations below those of the untreated storm water.

Filtered TKN was not significantly different between treated and untreated storm waters, though mean FTKN concentration was higher in the untreated water. Thus, chemical dosing also significantly decreased TKN concentrations; the decrease appears to be due to both improved settling and precipitation of dissolved species. These conclusions are consistent with the jar test findings.

9.3.3 Effects on Alkalinity

Chemical dosing resulted in a significant ($p<0.05$) decrease in alkalinity which varied with the type of coagulant used. PAX-XL9 most affected alkalinity. This is not surprising as PAX-XL9 required the highest dose, with a dosing level nearly twice that of JenChem 1720 and three times SumaChlor 50.

9.3.4 Effects on Metals

Chemical dosing significantly decreased ($p<0.05$) total iron and aluminum concentrations ($p=0.0034$ for total iron; $p = 0.000$ for total aluminum). The effects of chemical dosing on dissolved iron and aluminum are unclear as most of the readings were at the detection limit of 0.1 ppm. Values below that level were estimated by the analytical laboratory and included in this data analysis. Because most of the reported values for dissolved iron and aluminum were at or below the detection limit, no conclusion can be drawn from this data regarding reduction in metals.

Table 9-4. Coagulant Effects on Water Quality Constituents in Settling Columns

	N	Turbidity (NTU)		Total P (ppb)		Filtered P (ppb)		UTKN (ppm)		FTKN (ppm)	
Descriptive Results											
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
All Treatments	22	7.72	13.85	0.0112	0.0087	0.0044	0.0038	0.5141	0.1773	0.5064	0.1608
Independent Variable											
J1720	6	1.02	0.33	0.0055	0.0012	0.0020	0.0000	0.5033	0.1221	0.4500	0.1225
NOTRT	4	36.40	1.04	0.0288	0.0025	0.0060	0.0024	0.7175	0.1650	0.6850	0.2749
PXXL9	6	1.28	0.41	0.0093	0.0010	0.0040	0.0049	0.3883	0.2015	0.5000	0.0000
Sum50	6	1.74	0.25	0.0070	0.0000	0.0062	0.0045	0.5150	0.0892	0.4500	0.1225
Univariate Analysis											
p-value (with NOTRT)		0.0000		0.0000		0.2007		0.0114		0.0802	
(w/o NOTRT)		0.0052		0.0000		0.1883		0.2367		0.5953	

	N	Total Al (ppm)		Total Fe (ppm)		Filtered Al (ppm)		Filtered Fe (ppm)		Alk (mg CACO3/L)	
Descriptive Results											
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
All Treatments	22	0.2490	0.4704	0.1989	0.3342	0.0806	0.0318	0.0838	0.0284	32.5	3.0
Independent Variable											
J1720	6	0.0373	0.0208	0.1000	0.0000	0.0583	0.0456	0.1000	0.0000	33.9	0.3
NOTRT	4	1.1650	0.4222	0.7075	0.5952	0.0560	0.0170	0.0435	0.0118	35.5	1.2
PXXL9	6	0.0367	0.0109	0.1000	0.0000	0.1000	0.0000	0.1000	0.0000	28.0	0.6
Sum50	6	0.0622	0.0279	0.0577	0.0464	0.1000	0.0000	0.0782	0.0365	33.5	0.2
Univariate Analysis											
p-value (with NOTRT)		0.0000		0.0034		0.0101		0.0016		0.0000	
(w/o NOTRT)		0.0189		0.0254		0.0250		0.1669		0.0000	

Table 9-5. Stratification Effects on Water Quality Constituents in Settling Columns

(These results are from a subset of data collected at an elapsed time of 72 hours following the experimental design shown in Table 9-1. SD = 0 indicates measurements were at or below the detection limit. Thus, much of the filtered metal data is at the detection limit.)

	N	Turbidity (NTU)		Total P (ppb)		Filtered P (ppb)		UTKN (ppm)		FTKN (ppm)	
Descriptive Results											
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
All Treatments	22	7.72	13.85	0.0112	0.0087	0.0044	0.0038	0.5141	0.1773	0.5064	0.1608
Independent Variable											
IntDist 0.5 ft	11	7.72	14.48	0.0116	0.0095	0.0055	0.0048	0.4455	0.1440	0.4727	0.1849
IntDist 1.5 ft	11	7.72	13.90	0.0107	0.0082	0.0033	0.0021	0.5827	0.1869	0.5400	0.1327
Univariate Analysis											
p-value (with NOTRT)		1.0000		0.1092		0.1500		0.0258		0.2881	
(w/o NOTRT)		0.0981		0.4637		0.1668		0.0921		0.1643	

	N	Total Al (ppm)		Total Fe (ppm)		Filtered Al (ppm)		Filtered Fe (ppm)		Alk (mg CACO3/L)	
Descriptive Results											
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
All Treatments	22	0.2490	0.4704	0.1989	0.3342	0.0806	0.0318	0.0838	0.0284	32.5	3.0
Independent Variable											
0.5 ft	11	0.2265	0.4178	0.2147	0.3447	0.0850	0.0292	0.0851	0.0265	32.8	3.1
1.5 ft	11	0.2715	0.5376	0.1831	0.3393	0.0763	0.0350	0.0825	0.0314	32.2	3.0
Univariate Analysis											
p-value (with NOTRT)		0.5580		0.7708		0.4294		0.7647		0.0164	
(w/o NOTRT)		0.0022		0.4897		0.4609		0.6464		0.1347	

Table 9-6 Dosing Levels used During Settling Studies

Coagulant	SG	%Al	Dose	
			mg-Me/L	mg-coag/L
SumaChlor 50	1.3	12.4	2.2	18.1
PAX-XL9	1.3	5.6	4.3	76.8
JenChem 1720	1.3	6.0	1.4	23.1

9.4 Summary

Settling column experiments in general validated jar test findings. For the three coagulants tested, total phosphorus and turbidity were reduced effectively with virtually no stratification of particles in the water column after a period of only about an hour. Both turbidity and phosphorus surface water discharge standards were met for the storm water tested after only four hours. For the untreated storm water, stratification remained for up to 72 hours after the initiation of settling and the surface water standards for turbidity were not met within 72 hours.

Chemical treatment resulted in reductions in unfiltered TKN, total aluminum and total iron. Improved settling of flocculates clearly aided in the removal of these constituents. The data was inconclusive on the effect on dissolved aluminum and dissolved iron as most measurements were at or below the detection limit of 0.1 mg/L used in this study.

All coagulants affected alkalinity. This effect depended upon aluminum dosing level, with coagulants requiring a greater dosing level of aluminum leading to a greater decrease in alkalinity.

V. OTHER ISSUES

10 Economics

Table 10-1 shows the costs of different coagulants (provided by vendors during October 2003). JenChem 1720 is the most expensive coagulant, more than double the costs of PAX-XL9 and about 60% more than Pass-C. However, use of an inorganic/organic blend may reduce other costs. During the laboratory studies, JenChem 1720 was dosed at a level an order of magnitude less than Pass-C or PAX-XL9 (Table 7-2). In the settling studies, dosing levels for JenChem 1720 continued to be the lowest, with dosing levels one third that of PAX-XL9.

Table 10-1 Coagulant Costs

Vendor	Coagulant Code	Name	Price $/lb		
			55 Gallon Drums	275 Gallon Totes	4000 Gal or Bulk
Eaglebrook	Pass-C	Pass-C		0.28	0.198
Kemiron	PXXL9	PAX-XL9	0.251	0.196	0.155*
JenChem	J1720	JC 1720	0.730*	0.650*	0.320*
Summit	SUM50	Sumachlor 50	0.320*	0.340*	0.240*
Kemiron	PXL19++	PAX-XL19	0.363	0.308	0.241*

*Transport cost is included in price

++ACH alternative to SumaChlor 50

11 Conclusions and Recommendations

From this study, there are a number of conclusions:

1. Chemical dosing shows promise in helping meet current Tahoe Basin storm water discharge limits of turbidities less than 20 NTU and phosphorus less than 0.1 mg/L. All four coagulants in the final selection for full testing were effective at meeting the surface water discharge limits for total phosphorus and turbidity in the laboratory studies. When properly implemented, coagulant dosing shows promise to markedly improve storm water quality as measured by turbidity and phosphorus concentrations over non-dosed systems and these improvements are likely to be statistically significant ($p<0.05$).
2. Coagulant selection, and not mixing, temperature or dosing level, was found to be the most important variable determining phosphorus and turbidity removal. Selection of an effective coagulant can help overcome the effects of temperature, mixing, water quality and dosing on coagulant performance. The performance of the less effective coagulants in reducing phosphorus and turbidity was affected by changes in temperature, mixing regime, water quality and dosing.
3. PAX-XL9 and Pass-C were the most effective and most robust coagulants tested of the final four that were selected for the stormwaters tested. These coagulants are sulfinated, medium to medium-high basicity coagulants. The performance of these coagulants with regard to phosphorus and turbidity removal was minimally affected by changes in temperature, mixing regimes, storm water quality and dose. This report is not intended to endorse an individual product and coagulants with similar chemistry are assumed to perform similarly.
4. Though inorganic/organic blends (e.g JENCHEM 1720) were relatively less effective in removing phosphorus and reducing turbidity, they required lower dosing levels (sometimes an order of magnitude lower) than PACls and had little effect on water pH.
5. Many PACls had very good performance over a broad dosing range, and inorganic/organic polymer blends appear to be the most difficult to overdose. However, more optimal dosing was found to improve coagulant performance. Mean turbidity and total phosphorus removal averaged an improvement of 25 % during the intermediate tests (used to narrow the coagulants tested in this study from nine coagulants to four) when the performance of coagulants were tested for a full-dosing range as compared to an optimal dosing range. Thus more optimal dosing should lead to more efficient coagulant utilization and better performance, even for the more robust coagulants.
6. Overdosing was found to lead to increased soluble concentrations of dosed metal that does not occur under more optimal dosing conditions. Overdosing is defined in this report as dosing above a point of zero charge on a streaming current detector, which for practical purposes represents the point of charge neutralization. Inefficient metal utilization due to overdosing will likely lead to increased coagulant and maintenance costs, and may also lead to greater environmental issues. This is more important for coagulants that require higher dosing levels of aluminum to achieve charge neutralization. For instances, for the inorganic/organic blends, the increases in soluble aluminum were small because such low doses of aluminum were used. But for

coagulants such as PAX-XL9 and Pass C which required higher aluminum dosing levels to neutralize charge, soluble aluminum concentrations increased from around 0.25 mg/L to over 1 mg/L for a dosing increase of about 2 to 3 mg aluminum/L above the zero charge point dosing level.

7. The most robust coagulants (PAX-XL9 and Pass-C) were less affected by different rapid or slow mixing specifications. Slow mixing appears to more affect coagulant performance in terms of turbidity and phosphorus removal than rapid mixing.
8. Turbidity discharge limits were generally more difficult to meet than the total phosphorus discharge limits.
9. Streaming current meters were useful for predicting an optimal dosing range for different coagulants and different storm waters.
10. The PACl coagulants have minimal effect on alkalinity, pH and concentrations of nitrogen, iron and aluminum. Alkalinity is decreased and that decrease is dependent upon dosing level. Nitrogen concentrations, as well as concentrations of total iron and aluminum, also decrease. These reductions may be due to precipitation and improved settling.
11. Settling column experiments suggest that treated storm waters will have less stratification of fine particles in the water column and more rapid removal of turbidity than non-dosed storm waters. Thus, chemical dosing should either reduce the needed treatment footprint or increase the capacity of an existing footprint. Moreover, because chemical dosing aggregates and settles fine particles, outflow from a chemically treated system should have relatively fewer fine particles then outflow from a non-treated system.
12. For this study, the coagulants slightly affected alkalinity, pH and concentrations of nitrogen, iron and aluminum. Alkalinity is decreased and that decrease is dependent upon dosing level. Nitrogen concentrations, as well as concentrations of total iron and aluminum, also decreased. These reductions may be due to precipitation and improved settling.

12 References

Ann, Y. 1996. Phosphorus immobilization by chemical amendments in a constructed wetland (Florida). University of Florida Accension number: AAG9703504. DAI 57-09B, page 5557. 221 p.

Ashland Chemical: Drew Industrial – Coagulants. 2002. http://162.128.70.45/DI/DIcoag.html. Visited October 4, 2002.

Bachand, P.A.M., P. Vaithiyanathan and C.J. Richardson. 2000. Phase II Low Intensity Chemical Dosing (LICD): Development of Management Practices. Final Report submitted to Florida Department of Environmental Protection in fulfillment of Contract No. WM720. Report available at www.bachandassociates.com.

Bachand, P., J. Reuter, A. Heyvaert, R. Fujii and J. Darby. 2001. Chemical Treatment Methods Pilot (CTMP) for Treatment of Urban Runoff, Phase 1. Feasibility and Design. Proposal submitted to the City of South Lake Tahoe (City) in response to request for Proposal by the U.S. Forest Service

Bachand, P., J. Reuter, J. Darby, J. Trejo and A. Heyvaert. 2003a. Low Intensity Chemical Dosing (LICD) for Treatment of Urban Runoff, Experimental Plan for Bench-Scale Coagulant Tests. Submitted to Office of Water Programs, CSUS as Deliverable for Contract No. 43A0073, Task Order 13.

Bachand, P., J. Trejo and J. Darby. 2003b. Milestone Memorandum 3. Submitted to Office of Water Programs CSUS. February 12, 2003. Department of Civil and Environmental Engineering, UC Davis.

Bachand, P.A.M., S.M. Bachand, A. Heyvaert and OWP. 2005. Task 2. BMP treatment technologies, monitoring needs, and knowledge gaps: Status of the knowledge and relevance within the Tahoe Basin. By Bachand & Associates, UC Davis Tahoe Research Group and Office of Water Programs at CSUS. In: Stormwater Best Management Practices in the Tahoe Basin, Review of Current and New Technologies in Stormwater Management By M.L. Johnson, John Muir Institute of the Environment, Aquatic Ecosystem Analysis Laboratory, University of California, Davis. Prepared for El Dorado Department of Transportation, October 31, 2005.

Bachand, P., A. Heyvaert and J. Reuter. 2006. Chemical Treatment Methods Pilot (CTMP) for Treatment of for Urban Runoff – Phase I. Feasibility and Design, Draft Final Report. Submitted April 2006 in partial fulfillment of 2002-12 with the City of South Lake Tahoe.

Briley D.S. and D.R.U. Knappe. 2002. Optimizing Ferric Sulfate Coagulation of Algae with Streaming Current Measurements. Journal AWWA 94(2):80-90.

Caltrans. 2000. Guidance Manual: Storm water Monitoring Protocols (Second Edition). CTSW-RT-00-005. July.

Caltrans. 2001a. Tahoe Basin Storm water Monitoring Program, Monitoring Season 2000-2001.

Caltrans. 2001b. New Technologies for Storm water Treatment, Chemical Treatment to Improve Settling Reconnaissance Study. CTSW-RT-01-026. June 2001.

Caltrans. 2001C. Data Analysis Tool Excel Add-in Documentation. Jan 2001.

Caltrans. 2001D. Laboratory EDD Processing Tool. Caltrans StomrWater Management. Version 2.0.

Caltrans. 2002a. Draft - Lake Tahoe Storm Water Treatment Pilot Project Jar Test Results and Summary Report. March 2002.

Caltrans 2002b. Draft - Lake Tahoe Storm Water Treatment Pilot Project First Year Report. July 2002.

Dentel, S.K. and K.M. Kingery, Using streaming current detectors in water treatment. J. Am. Water Works Assoc., 1989. **91**: p. 85-94.

Dentel, S.K. 1991. Coagulant Control in Water Treatment. Critical Reviews in Environmental Control **21**(1): p. 41-135.

Dentel, S.K. and M.M. Abu-Orf. 1993. Application of the streaming current detectors in sludge conditioner selection and control. Wat. Sci. Tech. **28**(1): p. 169-179.

Dentel, S.K. 1995. Use of the streaming current detector in coagulation monitoring and control. J. Water SRT-Aqua.**44**(2): p. 70-79.

Devore, J.L. 1991. Probabiliy and Statistics for Engineering and the Sciences, 3rd Edition. Brooks/Cole Publishing Company, Pacific Grove, CA.

Gnagy, M. 1994. Review of Jar Testing, Procedures and Calculations. Presented by Jones and Henry Engineers, Inc. at the AWWA Ohio Section Conference, September 1994.

Green, P. 2005. Personal communications. September 2005. UC Berkeley. pggreen@ucdavis.edu.

Hall, K.J., T.P.D. Murphy, M. Mawhinney and K.I. Ashley. 1994. Iron treatment for eutrophication control in Black Lake, British Columbia. Lake and Reservoir Management 9(1): 114-117.

Harper, H.H. 1994. Alum treatment of storm water runoff - Orlando's Lake Dot and Lake Lucerne systems. Lake and Reservoir Management 9(2): 81.

Heyvaert. Unpublished data. Particle size distribution of storm water in the Tahoe Basin as measured by the Tahoe Research Group.

Hudson, H.E. and E.G. Wagner. 1981. Conduct and use of jar tests. Journal AWWA 73:218-223.

Jacoby, J.M., H.L. Gibbons, K.B. Stoops and D.D. Bouchard. 1994. Response of a shallow, polymictic lake to buffered alum treatment. Lake and Reservoir Management 10(2): 103-112.

James, W.F., J.W. Barko and W.D. Taylor. 1991. Effects of alum treatment on phosphorus dynamic in a north-temperate reservoir. Hydrolobiologia 215(3): 231-241.

Jennings, C. Personal Communications 2002 through 2004. JenChem. charles@jenchem.com.

Kadlec, R.H. and R.L. Knight. 1996. Treatment Wetlands. CRC Press, Florida.

Leckie, J.L. and W. Stumm. 1970. Phosphate precipitation. In E.F. Gloyna and WW Eckenfelder, Jr. (eds) Water quality improvement by physical and chemical processes. University of Texas Press. Austin, TX.

Lind, C. Director of Environmental Products & Services . General Chemical. clind@genchemcorp.com. Phone: (800) 631-8050. Personal communications. September and October 2002.

MacPherson, J., M. LeMaster, A. Jack and A. Kilander. 2002. Dredging and Water Quality, Tahoe Keys Marina Project Review, South Lake Tahoe, California. World Dredging Mining and Construction: 8 – 14. December.

MacPherson, J. 2004. Storm-Klear (Chitosan) Toxicity and Applications, Construction Stormwater Treatment. Presentation at the California EPA Conference on Advanced Treatment of Stormwater, Sacramento. October 21.

Muser, M. Sales Director, Summit Research Labs. Office phone: (410) 356-5312. Cell phone: (410) 952-1555. Personal communications. September and October 2002.

Narasiah, K.S., C. Morasse and J. Lemay. 1994. Phosphorus removal from aerated lagoons using alum, ferric chloride and lime. Water Pollution Research Journal of Canada 29(1): 1-18.

Offerman, B. Kemiron. Personal Communications, 2002 through 2004. bofferman@kemiron.com.

Peer Consultants, P.C./ Brown and Caldwell 1996. Desktop Evaluation of Alternative Technologies. Final Report. Contract C-E008 A3. August 1996.

Richardson, C.J. and C.B. Craft. 1993. Effective Phosphorus Retention in Wetlands: Fact or Fiction? In *Constructed Wetlands for Water Quality Improvement*, G.A. Moshiri, Ed. Lewis Publishers, Florida. 271-282.

Schueler, T.R. 2000. Comparative Pollutant Removal Capability of Storm water Treatment Practices. pp. 31 – 36 in T.R. Schueler and Heather K. Holland (eds) The Practice of Watershed Protection. The Center For Watershed Protection, Ellicott City, MD.

Sims, F. Quality Assurance Manager, Technical Services Department. Phone: 863-533-5990. fsims@kemiron.com. Personal Communications. September and October 2002.

Smeltzer, E. 1990. A successful alum/aluminate treatment of Lake Morey, Vermont. Lake and Reservoir Management 6(1): 9-19.

Statsoft. 2001. Statistica, V6.0.

Souza, S.J., F.S. Lubnow and R.L. Conner. 1994. An innovative use of alum to control blue-green algae blooms. Lake and Reservoir Management 9(2): 115.

Walker, W. W. 1989. Design and evaluation of eutrophication control measures for the St. Paul water supply. Lake and Reservoir Management 5: 71-83.

Welch, E.B. and G.D. Schrieve. 1994. Alum treatment effectiveness and longevity in shallow lakes. Hydrobiologia 275-276(0): 423-431.

Wong, T.H.F. and W.F. Geiger. 1997. Adaptation of wastewater surface flow wetland formulae for application in constructed storm water wetlands. Ecological Engineering 9:187-202.

Van Benschoten, J.E. and J.K. Edzwald. 1990. Chemical Aspects of Coagulation using Aluminum Salts – I. Hydrolytic Reactions of Alum and PolyAluminum Chloride.

Van Bernhardt, H. and H. Schell. 1993. Phosphorus elimination at the Wahnbach reservoir Seigburg, FRG. SAGE Presentation Report.

APPENDIX A

The attached electronic ACCESS database contains the following data:

- Jar test experiment data collected with field sensors and the related analytical data from the UC Davis Tahoe Research Group Lab and DANR
- Charge titration data
- Settling column data including sensor data, data from STL Sacramento and data from UCD Soils Lab
- Coagulant data
- Analyses of storm water used
- QAQC code definitions
- Data Qualifier Codes.

The database tables are documented in the associated .pdf file. And the tables are included in the EXCEL file as well. The ACCESS database contains full descriptions of all table fields.

I. Site Selection Matrix

An Excel file with all site selection information is included with the document. The following pages are a printout of that file.

			City of South Lake Tahoe			
		Criteria	**Stateline**		**Osgood (Ski Run)**	
			Scale[1]	Comments	Scale[1]	Comments
	General description					
		Design	NA	Three basins. Top basin is wetland. Second basin is dry. Third basin (lower) gets road runoff.	NA	Water from Heavenly Valley and urban development (330 ac). Very high flows with an opportunity for further treatment. Upstream area approximately 67% pervious.
		Rapid or slow infiltration? Do we know?		Impervious soils.		Unknown
		Groundwater high or low?		High water table keeping upper basin wet.		
Step 1	**Fatal Flaw**		1	None	1	None
	Score		**1**	**Continue Consideration**	**1**	**Continue Consideration**

		Criteria	**Glorene & 8th**		**Eloise**	
			Scale[1]	Comments	Scale[1]	Comments
	General description					
		Design	NA	Two separate systems (Caltrans, City) that combine at the bottom.	NA	
		Rapid or slow infiltration? Do we know?		Rapid (14 - 18 in per hr) in excavated areas. Sandy.		Rapid infiltration (~6 in/hr). Standing water only during rain events. Very dry 2 to 3 days after event.
		Groundwater high or low?				High water table
Step 1	**Fatal Flaw**		1	None	1	None
	Score		**1**	**Continue Consideration**	**1**	**Continue Consideration**

CTMP P1 Final: Site Rating

		Criteria	**West Sierra Track**		**Rocky Point**	
			Scale[1]	Comments	Scale[1]	Comments
	General description					
		Design	NA		NA	
		Rapid or slow infiltration? Do we know?		Unknown		Observed to have some exfiltration into pond during wet periods.
		Groundwater high or low?				
Step 1	**Fatal Flaw**		1	None	1	None
	Score		**1**	**Continue Consideration**	**1**	**Continue Consideration**

			El Dorado County			
		Criteria	**Christmas Valley 2 Industrial Area**		**DOT Yard in Christmas Valley**	
			Scale[1]	Comments	Scale[1]	Comments
	General description					
		Design	NA	Round - undersized	NA	Single basin with spillway after yard. Most of runoff from upper forested watershed co-mingles with parking lot and hits basin via culverted system. Runoff from the majority of the yard does not reach the basin but flows overland to the ditch.
		Rapid or slow infiltration? Do we know?		Unknown		Mod - slow
		Groundwater high or low?		Unknown		Unknown
Step 1	**Fatal Flaw**		1	Know potential pollutant loads from the Caltrans Yard studies…could apply them for treatment loads	2	Site is likely to have lots of O&G and provide stormwater unrepresentative of other areas in the Tahoe Basin.
	Score		**1**	**Continue Consideration**	**2**	**Continue Consideration**

CTMP P1 Final: Site Rating

		Criteria	**Cattlemans (Pioneer Trail III ECP)**		**Pioneer Trail Basins - Kokanee**	
			Scale[1]	Comments	Scale[1]	Comments
	General description					
		Design	NA	Large milti-stage basin with inlet riser and rock spillway w/headwall. Monitoring at the inlets (cattlemans court and the culvert under PT carrying subdivision runoff). Monitoring at the outlet (basin has only topped 3 times I believe)	NA	Large milti-stage basin with rock steppools cascading in, rock spillway w/headwall, final stage is a rock bowl that does fill in with local groundwater from the meadow.
		Rapid or slow infiltration? Do we know?		Mod - slow		Rapid - mod
		Groundwater high or low?		High		Low in main basin. High at final pool/rock bowl.
Step 1	**Fatal Flaw**		1	Not sure where you would put cells? Beginning of treatment train or end? Room on both ends, however is a Steve Goldman "pet" area. Steve may not want to see "unsightly" man made constructed things in this wildlife sanctuary and high profile meadow. However, I am just guessing and packaged right it might work. Also, would need to implement after Spring 2005 because the USGS/ElDoCo Cattlemans Basin Study field work ends then (would not want to interfere with the data). The stations are set up already (property of El Dorado County). However this would be a great site. Lots of data on background, runoff, Cold Creek, flows and water quality. Precipitation WQ/levels, and Groundwater WQ/levels. Microbial Activities (organic carbon ratios) in background and basin. Evapotranspiration rates estimated.	3	Location is parallel to Pioneer Trail between Golden Bear and Sierra House School. Steep sloped near basin but easy access for parking and equipment. Rock configuration not the best for technology. May not be room for monitoring cells here!!!! Fatal Flaw Fatal Flaw….
	Score		**1**	**Continue Consideration**	**3**	**Eliminate from Consideration**

		Criteria	**Cold Creek Basin (other side of Cold Creek, parallel**		**Apalachee Basin - Nottawa**	
			Scale[1]	Comments	Scale[1]	Comments
	General description					
		Design	NA	Small multi stage basin	NA	Treatment train system with offline clay lined detenton basin, drain system, and modified DC sand filter.
		Rapid or slow infiltration? Do we know?		Moderate		Slow filtration, variable drawdown rate using drain system and flow regulating valve. Max drawdown rate 72 hours
		Groundwater high or low?		High		High
Step 1	**Fatal Flaw**		3	may be too close to creek and groundwater for dosing.	1	Flow monitoring equipment here/data since 2000. WQ data 2001, 2002 and part of 2003. Precip station.
	Score		**3**	**Eliminate from Consideration**	**1**	**Continue Consideration**

		Criteria	**Apalachee 2 (to be built in 2005) (Apalachee 3 online**		**Black Bart - Subdivision after Cole Creek after STPID**	
			Scale^1	Comments	Scale^1	Comments
	General description					
		Design	NA	Design yet to be completed. Top of project area for Phase 2 is steep sloped, draining to a large meadow area between streets prior to being culverted to the upper truckee meadow.	NA	4 basins
		Rapid or slow infiltration? Do we know?		Higher typically. Rapid at lower elevations. SEZ/Wetlands are slow.		Unknown
		Groundwater high or low?		High in some areas		Unknown
Step 1	**Fatal Flaw**		1	all residential	2	Unknown much about this project.
	Score		**1**	**Continue Consideration**	**2**	**Continue Consideration**

		Criteria	**Hekpa - Near Apalachee 1 on Southern Side of**		**Silvertip**	
			Scale[1]	Comments		
	General description					
		Design	NA	2 large basins. Culvert inlet. Spillway and channel outlet.	NA	Large-med size (80 x 100)SF
		Rapid or slow infiltration? Do we know?		Unknown		Rapid (per soils report)
		Groundwater high or low?		Unknown		Low
Step 1	**Fatal Flaw**		2	Infiltration basin design. More likely to be oversized for flows.	3	Lawsuits had delayed project construction….
	Score		**2**	**Continue Consideration**	**3**	**Eliminate from Consideration**

					Placer County	
		Criteria	**Patlowe Bike Trail - Meyers Caltrans COOP**		**Fox**	
			Scale[1]	Comments	Scale[1]	Comments
	General description					
		Design	NA	Basins and bike trail on each side of HWY 50	NA	Single Basin
		Rapid or slow infiltration? Do we know?		Some low & some rapid areas.		Unknown
		Groundwater high or low?		Low		<10-15 feet bsg. Varies with season.
Step 1	**Fatal Flaw**		3	small area to work in within the right of way. (near agriclture station in Meyers)	1	
	Score		**3**	**Eliminate from Consideration**	**1**	**Continue Consideration**

		Criteria	**Coon**		**Bear Street**	
			Scale[1]	Comments	Scale[1]	Comments
	General description					
		Design	NA	Single Basin	1	Single basin
		Rapid or slow infiltration? Do we know?		Unknown		Unknown
		Groundwater high or low?		<10-15 feet bsg. Varies with season.		<10-15 feet bsg. Varies with season.
Step 1	**Fatal Flaw**		1		1	
	Score		**1**	**Continue Consideration**	**1**	**Continue Consideration**

CTMP P1 Final: Site Rating

		Criteria	Fox St II/Brockway Vista		Cutthroat	
			Scale[1]	Comments	Scale[1]	Comments
	General description					
		Design	1	Single Basin	NA	
		Rapid or slow infiltration? Do we know?		Unknown		Unknown.
		Groundwater high or low?		<10-15 feet bsg. Varies with season.		Unknown.
Step 1	**Fatal Flaw**		1		3	Will be the subject of a TRG infiltration and BMP efficiency monitoring project in 2005-2007. Basin will not be available for your study.
	Score		**1**	**Continue Consideration**	**3**	**Eliminate from Consideration**

		Criteria	**Beaver**		**Chipmunk**	
			Scale[1]	Comments	Scale[1]	Comments
	General description					
		Design	NA		NA	Single basin
		Rapid or slow infiltration? Do we know?		Unknown.		Unknown.
		Groundwater high or low?		Unknown.		<10-15 feet bsg. Varies with season.
Step 1	**Fatal Flaw**		3	Infiltration Basin. Very low capacity. Not recommended for study.	1	
	Score		**3**	**Eliminate from Consideration**	**1**	**Continue Consideration**

		Criteria	**Nile Upper Basin**		**Nile Lower Basin**	
			Scale[1]	Comments	Scale[1]	Comments
	General description					
		Design	NA		NA	
		Rapid or slow infiltration? Do we know?		Unknown.		Unknown.
		Groundwater high or low?		Unknown.		
Step 1	**Fatal Flaw**		3	Outside KB area. Not expected to need more advanced CEBMP approaches	3	Outside KB area. Not expected to need more advanced CEBMP approaches
	Score		**3**	**Eliminate from Consideration**	**3**	**Eliminate from Consideration**

CTMP P1 Final: Site Rating

		Criteria	**Barton Creek**	
			Scale[1]	Comments
	General description			
		Design	NA	
		Rapid or slow infiltration? Do we know?		Unknown.
		Groundwater high or low?		Unknown.
Step 1	**Fatal Flaw**		3	Water Quality is likely atypical of other stormwater in the basin
	Score		**3**	**Eliminate from Consideration**

CTMP P1 Final: Site Rating

		Criteria	Stateline		Osgood (Ski Run)	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria[4]**				
		Is there sufficient water during runoff events?	3	Dry much of the year.	1	Very high flows
		Is there available background data?	3	No data	3	No data
		High nutrient loading, land use[3]	1	commercial, corridor, hwy 50	1	Commercial land use; Ski run. Expect tht there is opportunity for further treatment.
		Online by 2005?	1	Online	1	Online
		Experimental design friendly; accommodate treatment cells? Mostly about size.	1	Middle basin unused. Lots of room	1	Plenty of room in basin and adjoinging basin
		Endangered species?	1	None	1	None
		Outflow destination (lake, meadow, downstream basin)?	1	No outflow	3	Lake.
		Current Design Inadequate in the context of upcoming TMDL?	3	Oversized. Very low flows relative to design.	1	Undersized
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	1	Easy to plumb. Enough fall.	1	Workable. Easy.
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	2	Works fine. Dirty water into site.	2	Takes lots of water. SEZ.
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	3	This system is low profile and underutilized.	1	System is considered one that could be improved
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	2	Needs to clean up cattails.	2	Needs maintenances. Identify needed maintenances. Expand basin.

CTMP P1 Final: Site Rating

		Criteria	Glorene & 8th		Eloise	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria[4]**				
		Is there sufficient water during runoff events?	2	SEZ. More like a stream then a basin.	3	Dries out because of high percolation rates
		Is there available background data?	1	Current data	2	Data available but not in hand. Data not current
		High nutrient loading, land use[3]	2	Minimum highway, minimum commercial, residential	1	Industrial, highway, commercial
		Online by 2005?	1	In construction	1	Online
		Experimental design friendly; accommodate treatment cells? Mostly about size.	2	Some room. Kind of small.	3	Small. Plumbing problems. Water backs up into the system as treats huge drainage area
		Endangered species?	1	None	1	None
		Outflow destination (lake, meadow, downstream basin)?	1	Discharge to meadow; doesn't make it to the lake.	1	To grassy swale.
		Current Design Inadequate in the context of upcoming TMDL?	3	In design	1	Undersized.
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	2	Possible but challenging.	3	Lots of problems. Backs up.
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	2	SEZ. Lots of area for treatment	1	Bad water. Too small.
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	2		1	System is considered one that could be improved
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	3	Just want it built and completed.	1	Would like to cover maintenance without spending City of SLT money.

CTMP P1 Final: Site Rating

		Criteria	West Sierra Track		Rocky Point	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria[4]**				
		Is there sufficient water during runoff events?	1	Sufficient water	1	Sufficient water
		Is there available background data?	3	No data	3	No data
		High nutrient loading, land use[3]	1	Highway, commercial, residential	2	Residential, Commercial, transportation
		Online by 2005?	1	Online	1	Online
		Experimental design friendly; accommodate treatment cells? Mostly about size.	2	Some room. Kind of small.	1	Big; plenty of flow
		Endangered species?	3	Upper Truckee Marsh; Yellow Cress Downstream.	3	Separate strain of Yellow Cress
		Outflow destination (lake, meadow, downstream basin)?	3	Discharge to Upper Truckee.	2	Stream to Lake
		Current Design Inadequate in the context of upcoming TMDL?	2	Not outstanding.	3	Assumed to treat everythiing. No data.
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	2	Workable	2	Comes in at basin bottom.
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	3	Goes directly to river. Not a problem site.	3	Yellow cress, new site. Do not believe any further treatment is required.
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	3		1	Lots of enthusiasm by USDA Forest Service
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	1	Would like to cover maintenance without spending City of SLT money.	3	Completed. Very little enthusiasm by City but high enthusiasm by USDA Forest Service

		Criteria	**Christmas Valley 2 Industrial Area**		**DOT Yard in Christmas Valley**	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria[4]**				
		Is there sufficient water during runoff events?	1	yes	1	Sufficient
		Is there available background data?	2	CTR toxics rule sampling (1 storm event per 3 years)	3	No data
		High nutrient loading, land use[3]	1	Industrial	1	Industrial, yard
		Online by 2005?	3	Onlilne by 2007	1	pre 1998
		Experimental design friendly; accommodate treatment cells? Mostly about size.	3	Lots are expensive so will put in right away (15 - 20 ft off the road). Narrow configuration may be difficult to work with.	1	Could probably manage six cells. Reconstruct basins
		Endangered species?	1	None	1	None
		Outflow destination (lake, meadow, downstream basin)?	2	Culverted to Upper Truckee	2	Culverted to Upper Truckee
		Current Design Inadequate in the context of upcoming TMDL?	3	In design	1	Inadequate: Doesn't perculate; lots of loads; Unlined.
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	1	In design	2	Inlet gets submerged
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	1	High. Would like to treat before it co-mingles with residential runoff.	1	High. Treat before discharge to the upper truckee via culvert. Lots of land between, but will comingle with caltrans flows and eventually hit the Truckee River
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	1	Yes	1	Yes
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	1	In design and would like to look at more effective methods	1	Great benefit to County. Also a benefit to the project because would know the potential treatment of the indutrial load prior to it reaching the residential portion of the project.

		Criteria	Cattlemans (Pioneer Trail III ECP)		Pioneer Trail Basins - Kokanee	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria**[4]				
		Is there sufficient water during runoff events?	1	Sufficient	a	sufficient
		Is there available background data?	1	Lots flow and nutrient data since 1999	3	No flow and no chemistry. Only design calcs (Mannings)
		High nutrient loading, land use[3]	2	Residential and a little bit of highway	2	Highway and residential (Montgomery Estates)
		Online by 2005?	1	1999	1	2000
		Experimental design friendly; accommodate treatment cells? Mostly about size.	1	Big round basin (60 x 100 ft basin)	1	Linear
		Endangered species?	1	None	1	None
		Outflow destination (lake, meadow, downstream basin)?	2	Infiltrates to Cold Creek and meadow adjacent to Cold Creek	1	Meadow
		Current Design Inadequate in the context of upcoming TMDL?	2	So close to creek it perculates out. Good for sediment but only fair for N.	3	not sure
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	1	No problems on monitoring so far and easy access for equipment	2	Series of stepped pools into basin. Two input sources.
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	2	Lahonton supported research. CTC installation	1.5	Probably
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	1.5	Probably	1.5	Probably
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	1	Lots of support by Lahontan. Lots of work done there already. CTC has funded through ElDoCo ~$600k, and USGS ~$460k through 2006.	2	Not as much interest as yard or other higher impact or more research oriented site

		Criteria	**Cold Creek Basin (other side of Cold Creek, parallel**		**Apalachee Basin - Nottawa**	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria[4]**				
		Is there sufficient water during runoff events?	1	sufficient	1	Sufficient
		Is there available background data?	3	No data	1	2001, 2002 and early 2003 nutrient and flow. Flow thru July 2004
		High nutrient loading, land use[3]	1	Highway	2	Residential, lots of sediment potential, lots of sanding in the area
		Online by 2005?	1	2000	1	2004/05
		Experimental design friendly; accommodate treatment cells? Mostly about size.	2	Third of the size of Cattleman's	1	Very large.
		Endangered species?	1	None	1	None
		Outflow destination (lake, meadow, downstream basin)?	2	Drains to groundwater or meadow adjacent to Cold Creek	1	Meadow to Upper Truckee
		Current Design Inadequate in the context of upcoming TMDL?	3	Slightly upstream of Cattlemans. (Basin location true, but discharge location is downstream +/- 200 feet)	2	Not treating dissolved. Works better for particulates
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	3	Rock lined channel coming in (sheet runoff). Series of step pools into basin and pipe.	1	Has big vault at end of cul-de-sac. 3 cells happening already (Vault, sediment basin, sand filter)
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	1.5	Probably	1	Yes
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	1.5	Probably	1	Yes
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	2	Not as much interest as yard or other higher impact or more research oriented site	3	Would like to test right now and see how it is working.

		Criteria	Apalachee 2 (to be built in 2005) (Apalachee 3 online		Black Bart - Subdivision after Cole Creek after STPID	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking Criteria[4]**					
		Is there sufficient water during runoff events?	1	Sufficient	1	sufficient
		Is there available background data?	3	No data	3	No data. Constructed in 1996
		High nutrient loading, land use[3]	2	Residential steep	2	residential, lots of use
		Online by 2005?	2	2005	1	1998
		Experimental design friendly; accommodate treatment cells? Mostly about size.	1	Flat. Couple of basins that would work	1	small medium and large
		Endangered species?	1	None	1	None
		Outflow destination (lake, meadow, downstream basin)?	1	Meadows	2	Not sure. Not directly to Lake.
		Current Design Inadequate in the context of upcoming TMDL?	3	In design	1	probably marginal treatment. Is an infiltration basin
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	1	Easy monitoring with existing channel.	1	2 culverts in spillway out. 2 spots in channel in chanel out
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	1	Yes	2	Constructed long time ago…not sure
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	1	Area on TRPA and CTC EIP Lists	2	Maybe
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	2	In design and EC is looking at innovative treatments	3	Not high profile

CTMP P1 Final: Site Rating

		Criteria	Hekpa - Near Apalachee 1 on Southern Side of		Silvertip	
			Scale[1]	Comments		
Step 2	**Qualitative Ranking**	**Criteria[4]**				
		Is there sufficient water during runoff events?	1	sufficient	1	sufficient. Possible additional flow from Caltrans in the future
		Is there available background data?	3	No data	2	Some since 97
		High nutrient loading, land use[3]	2	residential, steep	1	High traffic (HWY 89) some residential
		Online by 2005?	1	1999	1	2004
		Experimental design friendly; accommodate treatment cells? Mostly about size.	1	Plenty of room. As big as Cold Creek or perhaps a bit bigger	1	Lots of room
		Endangered species?	1	None	1	None
		Outflow destination (lake, meadow, downstream basin)?	1	Meadow	3	Lake / Beach
		Current Design Inadequate in the context of upcoming TMDL?	3	Good size. Infiltration basin design	2	Unknown
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	1	From culvert/outlet	1	Easy access steep gradients
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	2	Constructed long time ago…not sure. But think this site is worth checking into.	2	Small portion of EIP 713. County will do more work in the area in a future project. Treats mostly USFS & Caltrans runoff, very little is county
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	1	Area on TRPA and CTC EIP Lists	1.5	Probably
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	3	Not high profile		

CTMP P1 Final: Site Rating

		Criteria	Patlowe Bike Trail - Meyers Caltrans COOP		Fox	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria[4]**				
		Is there sufficient water during runoff events?	1	sufficient	1	Sufficient
		Is there available background data?	3	No data	1	Data from TRG
		High nutrient loading, land use[3]	1	High traffic, mixed transportation and commercial	2	Medium density residential
		Online by 2005?	1	pre 1998	1	Online
		Experimental design friendly; accommodate treatment cells? Mostly about size.	3	Very small. Skinny so would be difficult to do parallel treatment	1	Has been previously used by Placer County for treatment and as an experimental site.
		Endangered species?	1	None	1	None
		Outflow destination (lake, meadow, downstream basin)?	2	Probably culverted to upper truckee	3	Culverted to the Lake. No downstream treatment
		Current Design Inadequate in the context of upcoming TMDL?	1	Infiltration design. Not perculating well	3	Current design is assumed to be adequate.
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	3	Great place to monitor and easy access. Lots of traffic. Sheet flow in.	3	Difficult to measure since inflow is from beneath surface grade.
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	2	Visible. Unknown.	1	County would support pilot treatment study at any basin.
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	1.5	Probably	2	Unknown
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	1	High visibility. Bad runoff. Alternative treatment attractive	2	Pilot study results can be used, as applicable, in subsequent County designs.

CTMP P1 Final: Site Rating

		Criteria	Coon		Bear Street	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria**[4]				
		Is there sufficient water during runoff events?	1	Sufficient		
		Is there available background data?	1	Data from TRG	3	No data
		High nutrient loading, land use[3]	2	medium density residential	3	Residential and near top of watershed.
		Online by 2005?	1	Online	1	Online
		Experimental design friendly; accommodate treatment cells? Mostly about size.	1	Has been previously used by Placer County for treatment and as an experimental site.	3	Unknown what size you are looking for. Could be too small.
		Endangered species?	1	None	1	None
		Outflow destination (lake, meadow, downstream basin)?	3	Culverted to the Lake. No downstream treatment	1	Coon street basin
		Current Design Inadequate in the context of upcoming TMDL?	1	Short-circuiting likely. May not best utilize area for treatment.	3	Current design is assumed to be adequate.
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	3	Difficult to measure since inflow is from beneath surface grade.	2	Could measure influent flow with meter.
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	1	County would support pilot treatment study at any basin.	1	County would support pilot treatment study at any basin.
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	2	Unknown.	2	Unknown.
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	2	Pilot study results can be used, as applicable, in subsequent County designs.	2	Pilot study results can be used, as applicable, in subsequent County designs.

CTMP P1 Final: Site Rating

		Criteria	Fox St II/Brockway Vista		Cutthroat	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria[4]**				
		Is there sufficient water during runoff events?	1	Sufficient		
		Is there available background data?	3	No data		
		High nutrient loading, land use[3]	1	Highway and residential		
		Online by 2005?	1	Online		
		Experimental design friendly; accommodate treatment cells? Mostly about size.	1	yes		
		Endangered species?	1	None		
		Outflow destination (lake, meadow, downstream basin)?	3	Outflow is culverted to lake		
		Current Design Inadequate in the context of upcoming TMDL?	3	Current design is assumed to be adequate.		
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	3	Difficult to measure since inflow is from beneath surface grade.		
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	1	County would support pilot treatment study at any basin.		
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	2	Unknown.		
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	2	Pilot study results can be used, as applicable, in subsequent County designs.		

CTMP P1 Final: Site Rating

		Criteria	Beaver		Chipmunk	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria[4]**				
		Is there sufficient water during runoff events?				
		Is there available background data?			3	No data
		High nutrient loading, land use[3]			3	Residential
		Online by 2005?			1	Online
		Experimental design friendly; accommodate treatment cells? Mostly about size.			3	Small
		Endangered species?	1	None	1	None
		Outflow destination (lake, meadow, downstream basin)?	1	Fox Street Basin	3	Outflow is culverted to lake
		Current Design Inadequate in the context of upcoming TMDL?			3	Current design is assumed to be adequate.
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?			2	Unknown.
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	1	County would support pilot treatment study at any basin.	1	County would support pilot treatment study at any basin.
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?	2	Unknown.	2	Unknown
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?	2	Pilot study results can be used, as applicable, in subsequent County designs.	2	Pilot study results can be used, as applicable, in subsequent County designs.

		Criteria	Nile Upper Basin		Nile Lower Basin	
			Scale[1]	Comments	Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria[4]**				
		Is there sufficient water during runoff events?				
		Is there available background data?	3	No data	3	No data
		High nutrient loading, land use[3]	2	Residential and steep	2	Residential and steep
		Online by 2005?	2	Under construction	2	Under construction
		Experimental design friendly; accommodate treatment cells? Mostly about size.	3	Small	3	Small
		Endangered species?	1	None	1	None
		Outflow destination (lake, meadow, downstream basin)?				
		Current Design Inadequate in the context of upcoming TMDL?	3	Current design is assumed to be adequate.	3	Current design is assumed to be adequate.
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?	1	Large hydraulic gradient through system.	1	Large hydraulic gradient through system.
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?				
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?				
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?				

		Criteria	**Barton Creek**	
			Scale[1]	Comments
Step 2	**Qualitative Ranking**	**Criteria[4]**		
		Is there sufficient water during runoff events?		
		Is there available background data?	3	No data
		High nutrient loading, land use[3]	1	Maintenance yard runoff. Oil/water separator.
		Online by 2005?	1	Online
		Experimental design friendly; accommodate treatment cells? Mostly about size.	3	Small.
		Endangered species?	1	None
		Outflow destination (lake, meadow, downstream basin)?		
		Current Design Inadequate in the context of upcoming TMDL?	3	Current design is assumed to be adequate.
		Easy Flow Monitoring? Plumbing, available hydraulic gradient?		
		Enthusiasm - city or county. Is there some reason the city or county would support work here instead of some other basin?	1	County considers this a good location for implementation of projects
		Enthusiasm - outside agencies. Are outside agencies (FS, CTC, Lahonton) interested in doing work here?		
		Potential project benefits to City or County. Are their potential benefits here rather than elsewhere?		

CTMP P1 Final: Site Rating

		Criteria	Stateline		Osgood (Ski Run)	
			Scale[1]	Comments	Scale[1]	Comments
Step 3	**Summary Site Ranking**					
		General Summary	**22**		**18**	
		Visited		Yes		Yes
		Bottom Line Qualitative assessment		Not a great site for testing as it does not have lots of inflow.		This is a great site with lots of opportunities for everyone involved.
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				12 EIP projects in Master Plan for this watershed.
		Master Plan				Watershed analysis of erosion control and water quality projects
	General Site Information					
		Location				Osgood and Ski Run
		Lot area				
		Capacity (ac-ft)[2]				
		Estimated basin size (ac)				1.4 acres plus additional acreage available in adjacent basin.
		Miscellaneous				Can knock down center berm and redesign basin.
		Opportunities for Agency				Can provide Vac-truck access, improve forebay and utilize unused adjacent basin. City understands there are opportunities for improvement.
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis (Phase 2)**					
		Continue to Watershed Analysis		No		Yes
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of Existing Conditions to meet Regulatory and Funding Agency Needs.					
	3. For Kings Beach area based in part upon map by Harding showing risks to water quality: non source, minor/potential source, source & major source					

CTMP P1 Final: Site Rating

		Criteria	Glorene & 8th		Eloise	
			Scale[1]	Comments	Scale[1]	Comments
Step 3	**Summary Site Ranking**					
		General Summary	**22**		**19**	
		Visited		Yes		Yes
		Bottom Line Qualitative assessment		This might be a good site if it were not in such transition. Implementing here would be too great a burden on the City		This site has some opportunities in that it is undersized for the watershed. A downside is that it is often dry and so water supply could be a problem and longterm studies may not be feasible.
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location				Eloise and 5th
		Lot area				
		Capacity (ac-ft)[2]				
		Estimated basin size (ac)				0.5 - 1 acres
		Miscellaneous				
		Opportunities for Agency				Aesthetic and scenic improvements. Improve functionality. Help support maintenance costs.
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis		No		Yes
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

		Criteria	West Sierra Track		Rocky Point	
			Scale[1]	Comments	Scale[1]	Comments
Step 3	**Summary Site Ranking**					
		General Summary	**25**		**25**	
		Visited		No		Yes
		Bottom Line Qualitative assessment				This site remains a favorite of the Forest Service and offers lots of opportunities because of high flows. These benefits keep it under consideration.
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location				
		Lot area				
		Capacity (ac-ft)[2]				
		Estimated basin size (ac)				
		Miscellaneous				
		Opportunities for Agency				
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis		No		Yes
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

CTMP P1 Final: Site Rating

		Criteria	Christmas Valley 2 Industrial Area		DOT Yard in Christmas Valley	
			Scale[1]	Comments	Scale[1]	Comments
Step 3	**Summary Site Ranking**					
		General Summary	**20**		**16**	
		Visited				
		Bottom Line Qualitative assessment		Won't be online until 2007. May be difficult to implement a replicated study in available space.		Opportunities for improving inadequate design. Limited room available.
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location				
		Lot area				
		Capacity (ac-ft)[2]				
		Estimated basin size (ac)				
		Miscellaneous				
		Opportunities for Agency				
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis		No		
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

		Criteria	**Cattlemans (Pioneer Trail III ECP)**		**Pioneer Trail Basins - Kokanee**	
			Scale[1]	Comments	Scale[1]	Comments
Step 3	**Summary Site Ranking**					
		General Summary	**16.5**		**NA**	
		Visited				
		Bottom Line Qualitative assessment		Broad support and plenty of room. Lots of data and infrastructure.		
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location				
		Lot area				
		Capacity (ac-ft)[2]				
		Estimated basin size (ac)				
		Miscellaneous				
		Opportunities for Agency				
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis				No
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

CTMP P1 Final: Site Rating

		Criteria	**Cold Creek Basin (other side of Cold Creek, parallel**		**Apalachee Basin - Nottawa**	
			Scale[1]	Comments	Scale[1]	Comments
Step 3	**Summary Site Ranking**					
		General Summary	**22**		**16**	
		Visited				
		Bottom Line Qualitative assessment				Large, underperforming system.
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location				
		Lot area				
		Capacity (ac-ft)[2]				
		Estimated basin size (ac)				
		Miscellaneous				
		Opportunities for Agency				
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis		No		
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

		Criteria	Apalachee 2 (to be built in 2005) (Apalachee 3 online		Black Bart - Subdivision after Cole Creek after STPID	
			Scale^1	Comments	Scale^1	Comments
Step 3	**Summary Site Ranking**					
		General Summary	**19**		**20**	
		Visited				
		Bottom Line Qualitative assessment		Steep slopes may require good system for sediment removal.		
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location				
		Lot area				
		Capacity (ac-ft)^2				
		Estimated basin size (ac)				
		Miscellaneous				
		Opportunities for Agency				
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis				No
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

		Criteria	Hekpa - Near Apalachee 1 on Southern Side of		Silvertip	
			Scale[1]	Comments		
Step 3	**Summary Site Ranking**					
		General Summary		**20**		
		Visited				
		Bottom Line Qualitative assessment				
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location				
		Lot area				
		Capacity (ac-ft)[2]				
		Estimated basin size (ac)				
		Miscellaneous				
		Opportunities for Agency				
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis		No		No
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

CTMP P1 Final: Site Rating

		Criteria	Patlowe Bike Trail - Meyers Caltrans COOP		Fox	
			Scale[1]	Comments	Scale[1]	Comments
Step 3	**Summary Site Ranking**					
		General Summary	**20.5**		**21**	
		Visited				Prelimiinary visit
		Bottom Line Qualitative assessment				
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location				Fox St and Salmon Avenue
		Lot area				
		Capacity (ac-ft)[2]				0.35
		Estimated basin size (ac)				
		Miscellaneous				
		Opportunities for Agency				
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis		No		
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

		Criteria	Coon		Bear Street	
			Scale[1]	Comments	Scale[1]	Comments
Step 3	**Summary Site Ranking**					
		General Summary	**19**		**22**	
		Visited		Prelimiinary visit		Prelimiinary visit
		Bottom Line Qualitative assessment				Does not score as well overall as Coon and Fox Street Basins in which previous work has been conducted.
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location		Coon St and Trout Ave		Bear Street and Steelhead Avenue
		Lot area		0.56		
		Capacity (ac-ft)[2]		0.85		0.29
		Estimated basin size (ac)				
		Miscellaneous				
		Opportunities for Agency		Possible opportunities for retrofit for improved hydrology. Basin design promotes short-circuiting.		
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis				No
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

		Criteria	**Fox St II/Brockway Vista**		**Cutthroat**	
			Scale[1]	Comments	Scale[1]	Comments
Step 3	**Summary Site Ranking**					
		General Summary		**22**		**NA**
		Visited		Prelimiinary visit		Prelimiinary visit
		Bottom Line Qualitative assessment		Does not score as well overall as Coon and Fox Street Basins in which previous work has been conducted.		
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location		South side of SH28 (Brockway Vista)		Dolly Varden between Fox St and Chipmunk St
		Lot area				
		Capacity (ac-ft)[2]				
		Estimated basin size (ac)				
		Miscellaneous				
		Opportunities for Agency				
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis		No		No
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

CTMP P1 Final: Site Rating

		Criteria	Beaver		Chipmunk	
			Scale[1]	Comments	Scale[1]	Comments
Step 3	**Summary Site Ranking**					
		General Summary		**NA**		**24**
		Visited		Prelimiinary visit		Prelimiinary visit
		Bottom Line Qualitative assessment				
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location		Chipmunk St near Salmon Avenue		SR 28 and Chipmunk St
		Lot area		0.73		
		Capacity (ac-ft)[2]		0.03		0.27
		Estimated basin size (ac)				
		Miscellaneous				
		Opportunities for Agency				
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis		No		No
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

		Criteria	Nile Upper Basin		Nile Lower Basin	
			Scale[1]	Comments	Scale[1]	Comments
Step 3	**Summary Site Ranking**					
		General Summary		**NA**		**NA**
		Visited		Yes		Yes
		Bottom Line Qualitative assessment		This site is outside the KB area and is therefore not considered as optimum of site for a demonstration pilot study		This site is outside the KB area and is therefore not considered as optimum of site for a demonstration pilot study
Step 4	**General Watershed Information**					
		EIP projects in Master Plan				
		Master Plan				
	General Site Information					
		Location				
		Lot area				
		Capacity (ac-ft)[2]				
		Estimated basin size (ac)				
		Miscellaneous				
		Opportunities for Agency				
		Watershed Notes				
Step 5	**Assessment for Continuation to Watershed Analysis**					
		Continue to Watershed Analysis		No		No
	Notes:					
	1. 1 = good for pilot; 2 = OK; 3 = bad.					
	2. Harding ESE. 2002. Task 3 Final Report. Studies of					
	3. For Kings Beach area based in part upon map by Har					

CTMP P1 Final: Site Rating

		Criteria	**Barton Creek**	
			Scale[1]	Comments
Step 3	**Summary Site Ranking**			
		General Summary		**NA**
		Visited		Yes
		Bottom Line Qualitative assessment		This site has lots of O&G and is therefore not typical of other stormwater sources in the Tahoe Basin
Step 4	**General Watershed Information**			
		EIP projects in Master Plan		
		Master Plan		
	General Site Information			
		Location		
		Lot area		
		Capacity (ac-ft)[2]		
		Estimated basin size (ac)		
		Miscellaneous		
		Opportunities for Agency		
		Watershed Notes		
Step 5	**Assessment for Continuation to Watershed Analysis**			
		Continue to Watershed Analysis		NO
	Notes:			
	1. 1 = good for pilot; 2 = OK; 3 = bad.			
	2. Harding ESE. 2002. Task 3 Final Report. Studies of			
	3. For Kings Beach area based in part upon map by Har			

CTMP P1 Final: Watershed Rating

		City of South Lake Tahoe					
	Criteria	Stateline		Osgood (Ski Run)		Glorene & 8th	
		Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
General Watershed Information							
	Watershed Area						
	Subwatershed Number[2]						
	Contributing Area[2]						
	Impervious Area						
	% impervious area						
	Estimated water quality risk[3]						
	EIP projects in Master Plan				12 EIP projects in Master Plan for this watershed.		
	Master Plan				Watershed analysis of erosion control and water quality projects		
	Drainage Area		Small area		Large drainage area		
General Site Information							
	Location				Osgood and Ski Run		Glorene and 8th, SLT
	Lot area						
	Capacity (ac-ft)[2]						
	Estimated basin size (ac)				1.4 acres plus additional acreage available in adjacent basin.		0.5 acres
	Configuration description		Three basins. Top basin is wetland. Second basin is dry Third basin (lower) gets road runoff.		Water from Heavenly Valley and urban development (330 ac). Very high flows with an opportunity for further treatment. Upstream area approximately 67% pervious.		Two separate systems (Caltrans, City) that combine at the bottom.
	Infiltration rate		Impervious soils.				Rapid (14 - 18 in per hr) in excavated areas. Sandy.
	Groundwater		High water table keeping upper basin wet.				
	Water Quality				Have measured low and high turbidity		
	Miscellaneous				Can knock down center berm and redesign basin.		
	Opportunities for Agency		Aesthetics		Can provide Vac-truck access, improve forebay and utilize unused adjacent basin. City understands there are opportunities for improvement.		
	Watershed Notes						

CTMP P1 Final: Watershed Rating

Criteria	Eloise		West Sierra Track		Rocky Point	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
rshed Information						
Watershed Area						
Subwatershed Number[2]						
Contributing Area[2]						
Impervious Area						
% impervious area						
Estimated water quality risk[3]						
EIP projects in Master Plan						
Master Plan						
Drainage Area		Large drainage area				
Information						
Location		Eloise and 5th				
Lot area						
Capacity (ac-ft)[2]						
Estimated basin size (ac)		0.5 - 1 acres				
Configuration description						
Infiltration rate		Rapid infiltration (~6 in/hr). Standing water only during rain events. Very dry 2 to 3 days after event.				
Groundwater		High water table				
Water Quality						
Miscellaneous						
Opportunities for Agency		Aesthetic and scenic improvements. Improve functionality. Help support maintenance costs.				
Watershed Notes						

CTMP P1 Final: Watershed Rating

			El Dorado County			
Criteria	Christmas Valley 1 (Grass Lake		Christmas Valley 2 Industrial Area		DOT Yard in Christmas Valley	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
rshed Information						
Watershed Area						
Subwatershed Number[2]						
Contributing Area[2]						
Impervious Area						
% impervious area						
Estimated water quality risk[3]						
EIP projects in Master Plan						
Master Plan						
Drainage Area						
Information						
Location						
Lot area Capacity (ac-ft)[2]						
Estimated basin size (ac)						
Configuration description						
Infiltration rate						
Groundwater						
Water Quality						
Miscellaneous						
Opportunities for Agency						
Watershed Notes						

CTMP P1 Final: Watershed Rating

Criteria	Cattleman's		Pioneer Trail Basins - Kokohnee		Cole Creek Basin (other side of the river	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
rshed Information						
Watershed Area						
Subwatershed Number[2]						
Contributing Area[2]						
Impervious Area						
% impervious area						
Estimated water quality risk[3]						
EIP projects in Master Plan						
Master Plan						
Drainage Area						
Information						
Location						
Lot area Capacity (ac-ft)[2]						
Estimated basin size (ac)						
Configuration description						
Infiltration rate						
Groundwater						
Water Quality						
Miscellaneous						
Opportunities for Agency						
Watershed Notes						

CTMP P1 Final: Watershed Rating

Criteria	Apalachee Basin - Nottawa		Apalachee 2 (Apalachee 3)		Black Bart - Subdivision after Cole Creek	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
rshed Information						
Watershed Area						
Subwatershed Number[2]						
Contributing Area[2]						
Impervious Area						
% impervious area						
Estimated water quality risk[3]						
EIP projects in Master Plan						
Master Plan						
Drainage Area						
Information						
Location						
Lot area Capacity (ac-ft)[2]						
Estimated basin size (ac)						
Configuration description						
Infiltration rate						
Groundwater						
Water Quality						
Miscellaneous						
Opportunities for Agency						
Watershed Notes						

CTMP P1 Final: Watershed Rating

Criteria	Hekpa - Near Apalachee 1 on Southern Side		Montgomery Estates (Drainage above		Patlowe Bike Trail - Meyers Caltrans	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
rshed Information						
Watershed Area						
Subwatershed Number[2]						
Contributing Area[2]						
Impervious Area						
% impervious area						
Estimated water quality risk[3]						
EIP projects in Master Plan						
Master Plan						
Drainage Area						
Information						
Location						
Lot area Capacity (ac-ft)[2]						
Estimated basin size (ac)						
Configuration description						
Infiltration rate						
Groundwater						
Water Quality						
Miscellaneous						
Opportunities for Agency						
Watershed Notes						

CTMP P1 Final: Watershed Rating

	Placer County					
Criteria	Fox		Coon		Bear Street	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
rshed Information		stormwater basin		stormwater basin		
Watershed Area		133.3		20		44.5
Subwatershed Number[2]		10		12		8
Contributing Area[2]		108		20		45
Impervious Area		12.3		5.8		4.8
% impervious area		9%		29%		11%
Estimated water quality risk[3]		1.5		1.5		1
EIP projects in Master Plan						
Master Plan						
Drainage Area						
Information						
Location		Fox St and Salmon Avenue		Coon St and Trout Ave		Bear Street and Steelhead Avenue
Lot area				0.56		
Capacity (ac-ft)[2]		0.35		0.85		0.29
Estimated basin size (ac)						
Configuration description						
Infiltration rate						
Groundwater						
Water Quality						
Miscellaneous						
Opportunities for Agency				Possible opportunities for retrofit for improved hydrology. Basin design promotes short-circuiting.		
Watershed Notes						

CTMP P1 Final: Watershed Rating

Criteria	Fox St II/Brockway Vista		Deer Street Project		Cutthroat	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
rshed Information						
Watershed Area				74		289
Subwatershed Number[2]				5		9
Contributing Area[2]				8		40
Impervious Area				9.2		16
% impervious area				12%		6%
Estimated water quality risk[3]		1.5				1.25
EIP projects in Master Plan						
Master Plan						
Drainage Area						Large upstream drainage area.
Information						
Location		South side of SH28 (Brockway Vista)		Deer St and Loch Leven Ave (School); Deer Street and Steelhead Ave (Church)		Dolly Varden between Fox St and Chipmunk St
Lot area Capacity (ac-ft)[2]				0.09		
Estimated basin size (ac)						
Configuration description						Installed to capture runoff from Utility. Put into protect property. Very steep slopes
Infiltration rate						
Groundwater						
Water Quality						
Miscellaneous						
Opportunities for Agency						
Watershed Notes						

CTMP P1 Final: Watershed Rating

Criteria	Beaver		Chipmunk		Nile Upper Basin	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
rshed Information		infiltration basin				stormwater basin
Watershed Area		133		64.5		
Subwatershed Number[2]		10		11		
Contributing Area[2]		25		65		
Impervious Area		12.3		7.3		
% impervious area		9%		11%		
Estimated water quality risk[3]		1.5		0		
EIP projects in Master Plan						
Master Plan						
Drainage Area						
Information						
Location		Chipmunk St near Salmon Avenue		SR 28 and Chipmunk St		
Lot area		0.73				
Capacity (ac-ft)[2]		0.03		0.27		
Estimated basin size (ac)						
Configuration description						
Infiltration rate						
Groundwater						
Water Quality						
Miscellaneous						
Opportunities for Agency						
Watershed Notes						

CTMP P1 Final: Watershed Rating

Criteria	Nile Lower Basin		Barton Creek	
	Scale[1]	Comments	Scale[1]	Comments
rshed Information		stormwater basin		stormwater basin
Watershed Area				
Subwatershed Number[2]				
Contributing Area[2]				
Impervious Area				
% impervious area				
Estimated water quality risk[3]				
EIP projects in Master Plan				
Master Plan				
Drainage Area				
Information				
Location				
Lot area				
Capacity (ac-ft)[2]				
Estimated basin size (ac)				
Configuration description				
Infiltration rate				
Groundwater				
Water Quality				
Miscellaneous				
Opportunities for Agency				
Watershed Notes				

CTMP P1 Final: Watershed Rating

	Criteria	Stateline		Osgood (Ski Run)		Glorene & 8th	
		Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
Qualitative Ranking Criteria							
	Background data	3	No data	3	No data	1	Current data
	High nutrient loading, land use	1	commercial, corridor, hwy 50	1	Commercial land use; Ski run.	2	Minimum highway, minimum commercial, residential
	Online by 2005	1		1		1	
	Experimental design friendly; accommodate treatment cells	1	Middle basin unused. Lots of room	1	Plenty of room in basin and adjoinging basin	2	Some room. Kind of small.
	Endangered species	1	None	1	None	1	None
	Outflow destination	2		2	Lake.	1	Discharge to meadow; doesn't make it to the lake.
	Curent Design Inadequate	3	Oversized. Very low flows relative to design.	1	Undersized	3	In design
	Easy Flow Monitoring	1	Easy to plumb. Enough fall.	1.5	Workable. Easy.	2	Possible but challenging.
	Enthusiasm - agency	2	Works fine. Dirty water into site.	2	Takes lots of water. SEZ.	2	SEZ. Lots of area for treatment
	Potential benefits to City	2	Needs to clean up cattails.	2	Needs maintenances. Identify needed maintenances. Expand basin.	3	Just want it built and completed.
Summary Site Ranking							
	General Summary	17	Easy implementation	15.5	Undersized. Goes to Lake.	18	Easy to implement. Design is good. Discharge to meadow. Doesn't make it to lake.
	Bottom Line Qualitative assessment		Not a great site for testing as it does not have lots of inflow.		This is a great site with lots of opportunities for everyone involved.		This might be a good site if it were not in such transition. Implementing here would be too great a burden on the City
Notes:							
1. 1 = good for pilot; 2 = OK; 3 = bad.							
2. Harding ESE. 2002. Task 3 Final Report. Studies of Existing Conditions to meet Regulatory and Funding Agency Needs.							
3. Based upon map by Harding showing risks to water quality: 0 non source, 1 minor/potential source, 2 source, 3 major source							

CTMP P1 Final: Watershed Rating

Criteria	Eloise		West Sierra Track		Rocky Point	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
anking Criteria						
Background data	2	Data available but not in hand. Data not current	3	No data	3	No data
High nutrient loading, land use	1	Industrial, highway, commercial	1	Highway, commercial, residentia	2	Residential, Commercial, transportation
Online by 2005	1		1		1	
Experimental design friendly; accommodate treatment cells	3	Small. Plumbing problems. Water backs up into the system as treats huge drainage area	2	Some room. Kind of small.	1	Big; plenty of flow
Endangered species	1	None	3	Upper Truckee Marsh; Yellow Cress Downstream.	3	Separate strain of Yellow Cress
Outflow destination	1		3	Discharge to Upper Truckee.	2	
Curent Design Inadequate	1	Undersized.	2	Not outstanding.	3	Treats everything.
Easy Flow Monitoring	3	Lots of problems. Backs up.	2	Workable	2	Comes in at basin bottom.
Enthusiasm - agency	1	Bad water. Too small.	3	Goes directly to river. Not a problem site.	3	Yellow cress, new site. Why need of good design
Potential benefits to City	1	Would like to cover maintenanc without spending City of SLT money.	1	Would like to cover maintenanc without spending City of SLT money.	3	Completed. Very little enthusiasm by City but high enthusiasm by USDA Forest Service
e Ranking						
General Summary	15	Implementation is difficult.	21		23	
Bottom Line Qualitative assessment		This site has some opportunities in thatit is undersized for the watershed. A downside is that i is often dry and so water supply could be a problem and longtern studies may not be feasible.				This site remains a favorite of the Forest Service and offers lots of opportunities because of high flows.
r pilot; 2 = OK; 3 = bad						
SE. 2002. Task 3 Final						
n map by Harding show						

Criteria	Christmas Valley 1 (Grass Lake		Christmas Valley 2 Industrial Area		DOT Yard in Christmas Valley	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
anking Criteria						
Background data	2	Flow Data since 2003	2	CTR toxics rule sampling (1 storm event per 3 years)	3	No data
High nutrient loading, land use		Highway and residential (straight off Caltrans culverts) - El Dorado County responsible for residential treatment and conveyance	1	Industrial	1	Industrial, yard
Online by 2005			3	Onlilne by 2007	1	pre 1998
Experimental design friendly; accommodate treatment cells			2	Lots are expensive so will put in right away (15 - 20 ft off the road)	1	Could probably manage 6. Reconstruct basins
Endangered species			1	None	1	None
Outflow destination			2	Culverted to Upper Truckee	2	Culverted to Upper Truckee
Curent Design Inadequate			3	In design	1	Inadequate. Doesn't perk, lots of loads, unlined
Easy Flow Monitoring			1	In design	2	Inlet gets submerged
Enthusiasm - agency			3		1	Lahonton aware it's a difficult site
Potential benefits to City			1	In design and would like to look at mor effective methods	1	
e Ranking						
General Summary	2		19		14	
Bottom Line Qualitative assessment						
r pilot; 2 = OK; 3 = bad						
SE. 2002. Task 3 Final						
n map by Harding show						

Criteria	Cattleman's		Pioneer Trail Basins - Kokohnee		Cole Creek Basin (other side of the river	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
anking Criteria						
Background data	1	Lots flow and nutrient data since 1999	3	No flow and no chemistry. Only design calcs (Mannings)	3	No data
High nutrient loading, land use	2	Residential and a little bit of highway	1	Highway and residential (Montgomery Estates)	1	Highway and a little of residential
Online by 2005	1	1999	1	2000	1	2000
Experimental design friendly; accommodate treatment cells	1	Big round basin (60 x 100 ft basin)	3	Narrow	2	Third of the size of Cattleman's
Endangered species	1	None	1	None	1	None
Outflow destination	2	Infiltrates to Cole Creek	1	Meadow	2	Drains to groundwater or meadow
Curent Design Inadequate	2	So close to creek it perks out. Good for sediment but only fair for N.	3		3	Slightly upstream of Cattleman's
Easy Flow Monitoring	1	No problems on monitoring so far and easy access for equipment	2	Series of stepped pools into basin. Two input sources.	3	Rock lined channel coming in (sheet runoff).
Enthusiasm - agency	2	Lahonton supported research. CTC installation	3		3	
Potential benefits to City	1	Lots of support by Board. Lots of work done there	2	Not as much insenstive as yard or other higher impact or more research oriented site	2	Not as much insenstive as yard or other higher impact or more research oriented site
e Ranking						
General Summary	14		20	Too narrow	21	
Bottom Line Qualitative assessment						
r pilot; 2 = OK; 3 = bad						
SE. 2002. Task 3 Final						
n map by Harding show						

CTMP P1 Final: Watershed Rating

Criteria	Apalachee Basin - Nottawa		Apalachee 2 (Apalachee 3)		Black Bart - Subdivision after Cole Creek	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
anking Criteria						
Background data	1	2001, 2002 and early 2003 nutrient and flow. Flow thru July 2004	3	No data	3	No data. Constructed in 1996
High nutrient loading, land use	3	Residential, lots of sediment potential, lots of sanding in the area	3	Residential steep	2	residential, lots of use
Online by 2005	1	2004/05	2	2005	1	1998
Experimental design friendly; accommodate treatment cells	1	Very large.	1	Flat. Couple of basins that would work	2	Not sure
Endangered species	1	None	1	None	1	None
Outflow destination	1	Meadow to Upper Truckkee	1	Meadows	1	Not sure
Curent Design Inadequate	2	Not treating dissolved. Works better for particulates	3	In design		
Easy Flow Monitoring	1	Has big vault at end of cul-de-sac. 3 cells happening already (Vault, sediment basin, sand filter)	1			
Enthusiasm - agency	3		3		3	
Potential benefits to City	3	Would like to test right now and see how it is working.	2	In design and EC is looking at innovative treatments	3	Not high profile
e Ranking						
General Summary	17		20		16	
Bottom Line Qualitative assessment						
r pilot; 2 = OK; 3 = bad						
SE. 2002. Task 3 Final						
n map by Harding show						

CTMP P1 Final: Watershed Rating

Criteria	Hekpa - Near Apalachee 1 on Southern Side		Montgomery Estates (Drainage above		Patlowe Bike Trail - Meyers Caltrans	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
anking Criteria						
Background data	3	No data			3	No data
High nutrient loading, land use	3	residential, steep			1	High traffic, mixed transportation and commercia
Online by 2005	1	1999	1	pre 1998	1	pre 1998
Experimental design friendly; accommodate treatment cells	1	Plenty of room. As big as Cole Creek or perhaps a bit bigger			3	Very small. Skinny so would be difficult to do parallel treatment
Endangered species	1	None	1	None	1	None
Outflow destination	1	Meadow			2	Probably culverted to upper truckee
Curent Design Inadequate	3	Good size. Infiltration basin design			1	Infiltration design. Not perking well
Easy Flow Monitoring					3	Great place to monitor and easy access. Lots of traffic. Sheet flow in.
Enthusiasm - agency	3				2	Visible. Don't know.
Potential benefits to City	3	Not high profile			1	High visibility. Bad runoff. Alternative treatment attractive
e Ranking						
General Summary	19		2		18	
Bottom Line Qualitative assessment						
r pilot; 2 = OK; 3 = bad						
E. 2002. Task 3 Final						
n map by Harding show						

CTMP P1 Final: Watershed Rating

Criteria	Fox		Coon		Bear Street	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
anking Criteria						
Background data	1	Data from TRG	1	Data from TRG	3	No data
High nutrient loading, land use	1	medium density residential	1	medium density residential		
Online by 2005	1	Currently operational	1	Currently operational		
Experimental design friendly; accommodate treatment cells	1	Has been previously used by Place County for treatment and as an experimental site.	1	Has been previously used by Place County for treatment and as an experimental site.		
Endangered species	1	None	1	None	1	None
Outflow destination		Culverted to the Lake. No downstream treatment	3	Culverted to the Lake. No downstream treatment		
Curent Design Inadequate			1	Short-circuiting likely. May not best utilize area for treatment.		
Easy Flow Monitoring						
Enthusiasm - agency						
Potential benefits to City						
e Ranking						
General Summary						
Bottom Line Qualitative assessment						
r pilot; 2 = OK; 3 = bad						
E. 2002. Task 3 Final						
n map by Harding show						

CTMP P1 Final: Watershed Rating

Criteria	Fox St II/Brockway Vista		Deer Street Project		Cutthroat	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
anking Criteria						
Background data	3	No data	3	No data	3	No data
High nutrient loading, land use					1	Loading from steep upstream slopes.
Online by 2005					1	Currently under construction
Experimental design friendly; accommodate treatment cells					1	Adequate space for small treatment cells.
Endangered species	1	None	1	None	1	None
Outflow destination					1	Outflow to Coon street basin
Curent Design Inadequate					3	Current design is assumed to be adequate.
Easy Flow Monitoring					1	Large hydraulic gradient through system.
Enthusiasm - agency						
Potential benefits to City						
e Ranking						
General Summary						
Bottom Line Qualitative assessment						
r pilot; 2 = OK; 3 = bad						
SE. 2002. Task 3 Final						
n map by Harding show						

CTMP P1 Final: Watershed Rating

Criteria	Beaver		Chipmunk		Nile Upper Basin	
	Scale[1]	Comments	Scale[1]	Comments	Scale[1]	Comments
anking Criteria						
Background data					3	No data
High nutrient loading, land use		Mixed residential, commercial, highway		Residential	2	Residential and steep
Online by 2005		Planned			1	Under construction
Experimental design friendly; accommodate treatment cells					3	Small
Endangered species					1	None
Outflow destination		Fox Street Basin				
Curent Design Inadequate					3	Current design is assumed to be adequate.
Easy Flow Monitoring					1	Large hydraulic gradient through system.
Enthusiasm - agency						
Potential benefits to City						
e Ranking						
General Summary						
Bottom Line Qualitative assessment						
r pilot; 2 = OK; 3 = bad						
E. 2002. Task 3 Final						
n map by Harding show						

Criteria	Nile Lower Basin		Barton Creek	
	Scale[1]	Comments	Scale[1]	Comments
anking Criteria				
Background data	3	No data	3	No data
High nutrient loading, land use	2	Residential and steep	1	Maintenance yard runoff. Oil/water separator.
Online by 2005	1	Under construction	1	Online
Experimental design friendly; accommodate treatment cells	3	Small	3	Small.
Endangered species	1	None	1	None
Outflow destination				
Curent Design Inadequate	3	Current design is assumed to be adequate.	3	Current design is assumed to be adequate.
Easy Flow Monitoring	1	Large hydraulic gradient through system.		
Enthusiasm - agency				
Potential benefits to City				
e Ranking				
General Summary				
Bottom Line Qualitative assessment				
r pilot; 2 = OK; 3 = bad				
SE. 2002. Task 3 Final				
n map by Harding show				

CTMP P1 Final: Site Selection Criteria

	Historical Data	Implementation Logistics	Environmental Issues and Concerns	Experimental Design	Community Support
* Background Data for site such that there is a history of hydrologic and nutrient loading to the site.	X				
* High nutrient loading to the site as indicated by historical data or land use. For land use assessment there is sufficient watershed characterization to predict or estimat nutrient and hydrologic loads.	X				
* Site expected to be online by no later than Fall 2005.		X			
* Experimental design can be easily implemented at site through either integration into current design or through retrofit. Site will accommodate at least 3 treatment cells that will cover only a portion of the site.		X		X	
* No endangered species isssues. Minimial EIR issues.		X	X		X
* Outflow from experimental site will no discharge directly to lake.			X		X
* Current or planned basin design (w/o LICD or other more sophisticated modifications) has potential to be inadequate for future nutrient and hydrologic loads to the site.			X		
* Easy flow monitoring with no backflow at inflow and outflow.		X			
* Enthusiasm from interested local, state and federal agencies.		X	X		X
* Enthusiasm from the City of South Lake Tahoe with likely benefits to the City.		X	X		X

CTMP P1 Final Report: Sites Considered

Jurisdiction	Site Name	Location
City of South Lake Tahoe		
	Stateline	
	Osgood	
	Glorene and 8	Intersection of Glorene and 8th
	Eloise	
	West Sierra Track	
	RP	
El Dorado County		
	Christmas Valley 2 Industrial Area	
	DOT yard in Christmas Valley	
	Cattleman's	
	Pioneer Trail Basins (Kokohnee)	
	Cole Creek Basin	
	Apalachee Basin - Nottawa	
	Apalachee 2	
	Apalachee 3	
	Black Bart	
	Hekpa	
	Montgomery Estates	
	Patlowe Bike Trail	
Placer County		
	Fox Street	
	Coon Street	
	Griff Creek	
	Bear Street	
	Fox St II/Brockway Vista	
	Wetland outside Kings Beach	
	Deer Street Project	
	Cut-throat	
	Lower Nile Basin	
	Upper Nile Basin	
	Barton Creek	
Nevada Resource Conservation District		

CTMP P1 Final: Site Selection Summary

Site Name	Step 1 - Fatal Flaw Based on Water supply or quality, Design, Logistics or Availability	Step 2 & 3 - Qualitative Ranking Criteria and Assessment[1]	Step 4 - General Watershed Assessment
City of South Lake Tahoe			
Stateline		Ranking score, low inflow	
Osgood			
Glorene and 8th		Ranking score, availability	
Eloise			Water supply[5]
West Sierra Track		Ranking score	
Rocky Point		Ranking score[2]	
El Dorado County			
Christmas Valley 2 Industrial Area		Ranking score, availability	
DOT yard in Christmas Valley		Insufficient room	
Cattleman's			Env. Issues & Availability
Pioneer Trail Basins (Kokohnee)	Design & Logistics		
Cole Creek Basin	Design		
Apalachee Basin - Nottawa			Limited Opportunities
Apalachee 2		Design & Logistics - steep	
Black Bart		Ranking Score	
Hekpa		Ranking Score	
Silvertip	Availability - lawsuits		
Patlowe Bike Trail	Design & Logistics		
Placer County			
Fox St			Ranking Score, Limited Opp[4]
Coon Street			Ranking Score, Limited Opp[4]
Bear Street		Ranking Score	
Fox St II/Brockway Vista		Ranking Score	
Cut-throat	Availability		
Beaver	Water supply/quality		
Chipmunk		Ranking Score	
Lower Nile Basin	Water supply/quality		
Upper Nile Basin	Water supply/quality		
Barton Creek	Water supply/quality		
Nevada Resource Conservation District[3]			

[1] Ranking score means in ranking against criteria, site did not score in the top group.

[2] Forest Service interest in site but City saw complications (environmental, logistics)

[3] No highly rated opportunities for urban sites.

[4] Not considered as desirable as top sites in the City of South Lake Tahoe. Fewer opportunities in watershed.

[5] Often dry and may not support longterm studies.

J. Database

Excel files are included in the document for Settling Column and Toxicity Data

K. Cost worksheet

Below is a summary of the costs based in 2004 dollars to implement the experiments discussed in Appendix G.

	Task Description	2005				2006				2007				2008				2009				
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
Task 1	Project Administration				##	##	##	##	##	##	##	##	##	##	##	##	##	##				77,000
Task 2	CEQA/NEPA Documents				##	##																10,000
Task 3	Quality Assurance Project Plan				##	##																17,987
Task 4	TAC				##	##	##	##	##	##	##	##	##	##	##	##						25,450
Task 5	Final Design and Implementation				##	##	##	##														420,496
Task 6	Determine LICD effects								##	##	##	##	##	##	##	##						634,913
Task 7	Retardation Coefficients								##	##	##	##	##	##	##	##						97,223
Task 8	Flocculate Fate Studies						##	##	##	##	##	##	##	##	##	##	##	##				242,587
Task 9	Ecotoxicity								##	##	##	##	##	##	##	##						173,665
Task 10	Basin Extrapolation and Validation														##	##	##	##				51,585
Task 11	Outreach						##	##	##	##	##	##	##	##	##	##	##	##				30,819
Task 12	Draft and Final Reports																##	##				47,450
					126,738	126,738	135,529	135,529	143,630	143,630	143,630	143,630	143,630	143,630	156,526	156,526	64,905	64,905				1,829,175
					524,534				574,519				600,312				129,810					

Assuming a 3% annual increase, the estimated costs for this project would be $2 million dollars over a 3.5 year period.