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 Environmental Research Center (TERC); [3]U.C. Davis Civil and Environmental Engineering

in partial fulfillment of Contract No. 43A0073 of Task Order Number 13
between the State of California, Department of Transportation and University of California at Davis.

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

LIST OF ABBREVIATIONS AND ACRONYMS

Technical Terms

ACH	Aliminum Chlorohydrate
ANOVA	Analysis of Variance
Al	Aluminum
ASTM	American Society for Testing and Materials
DOC	Dissolved Organic Carbon
Epi/DMA	Epichlorohydrin dimethylamine polymers
FAL	Filtered Aluminum
Fe	Iron
FFE	Filtered Iron
FOP	Filtered Organic Phosphorous
FTKN	Filtered Total Kjeldahl Nitrogen
FTP	Filtered Total Phosphorous
ICP	Inductively Coupled Plasma Spectrometry
LICD	Low Intensity Chemical Dosing
mg/L	milligrams per liter (ppm)
N	Nitrogen
NOTRT	No Treatment
NTU	Nephlometric Turbidity Units
O&M	Operation & Maintenance
P	Phosphorus
PACl	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)
PSD	Particle Size Distribution
QAPP	Quality Assurance Project Plan
QA/QC	Quality Control/ Quality Assurance
SCD	Streaming Current Detector
SCV	Streaming Current Voltage
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen (ammonia plus organic nitrogen)
TP	Total Phosphorous
TSS	Total Suspended Solids
UAL	Unfiltered Aluminum
UFE	Unfiltered Iron
UTKN	Unfiltered Total Kjeldahl Nitrogen
UTP	Unfiltered Total Phosphorous
µg/L	micrograms per liter (ppb)

Organizations

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

ACKNOWLEDGEMENTS

This project was funded through a contract with Caltrans. Efforts of the Tahoe Environmental Research Center staff supported the studies in the project. Particularly, A. Heyvaert provided technical input and coordinated the implementation of this project with the Tahoe Environmental Research Center staff. T. Delaney supported this project by providing laboratory analyses, managing samples, and conducting field experiments. Coagulants used in this study were provided as samples by the different coagulant manufacturers identified in this report for the stated purpose of comparison testing. The Office of Water Programs (OWP) at California State University Sacramento helped secure funds for this project, provided technical input throughout this project and peer reviewed the final report. J. Johnston and D. Patel at OWP were particularly involved in this project. The U.S.D.A. Forest Service Lake Tahoe Basin Management Unit provided seed funds for the investigation of the feasibility of chemical dosing to treat storm water in the Tahoe Basin, for which the Caltrans funds were provided as a match.

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 $\mu g\ L^{-1}$.

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:

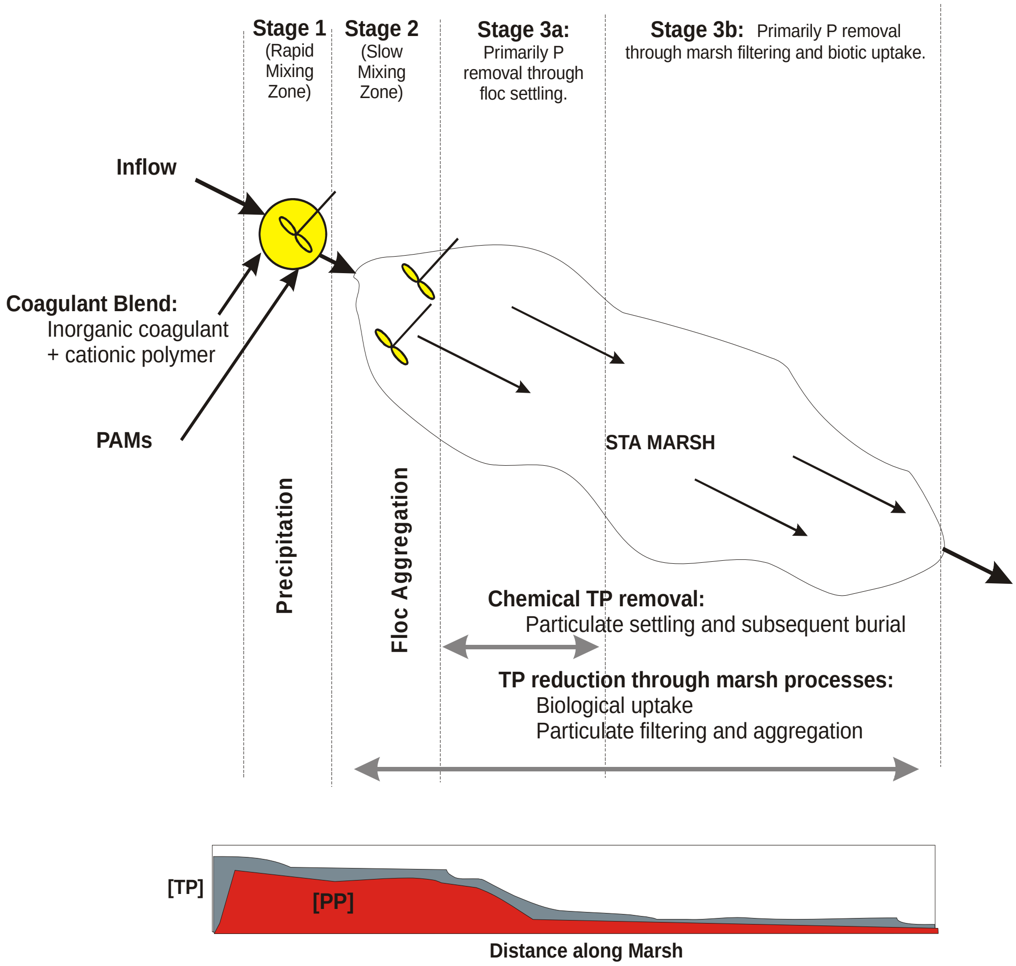
- Increased surface roughness leading to improved filtering, flow buffering and dispersion, and more quiescent waters;
- Biotic activity in the water column and sediments; and
- Wet and dry cycling.

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 TERC 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 Environmental Research Center 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)

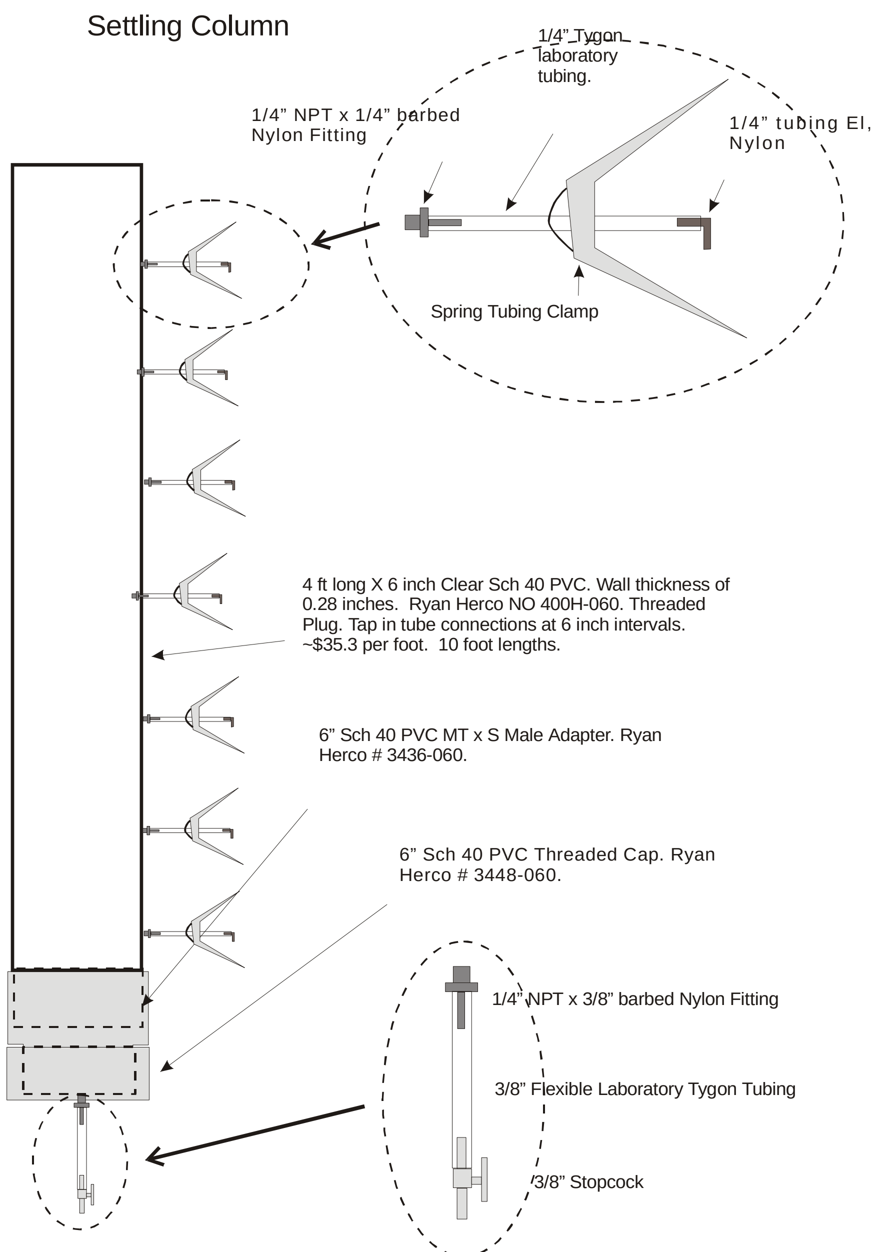
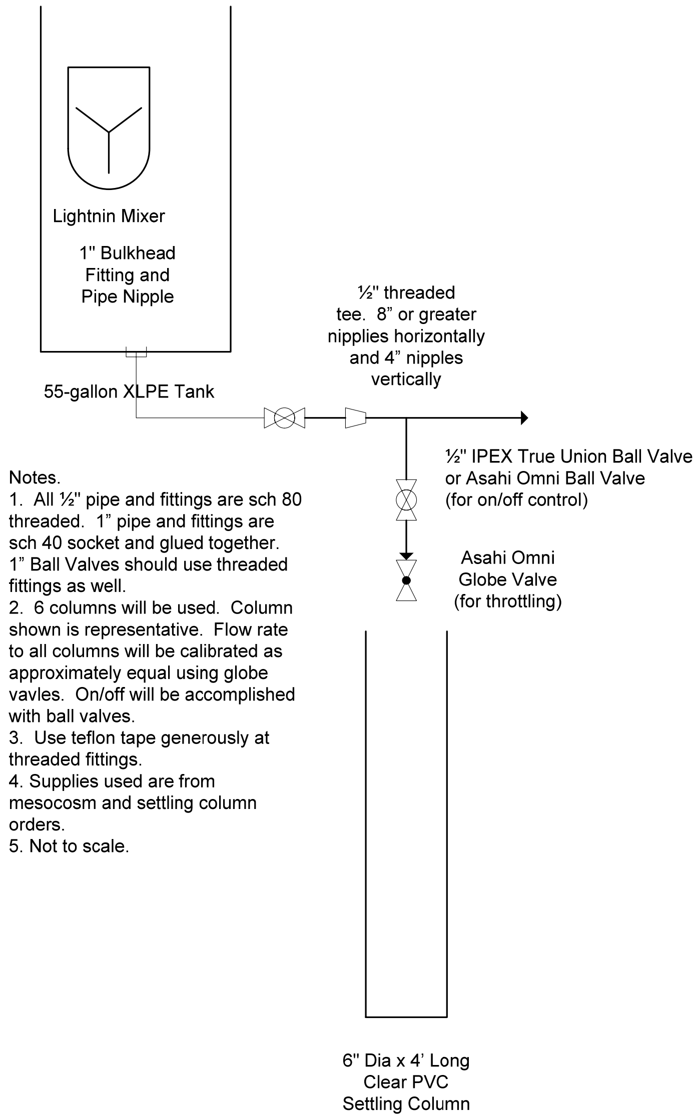


Figure 2-2 Schematic Showing Operation of Settling Columns



2.4 Data Analyses and Management

Samples were analyzed by the University of California Davis (UCD) Tahoe Environmental Research Center (TERC), 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 TERC and DANR

Tahoe Environmental Research Center (TERC)

Phosphorus analyses were conducted by the Tahoe Environmental Research Center 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 Environmental Research Center 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 TERC 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

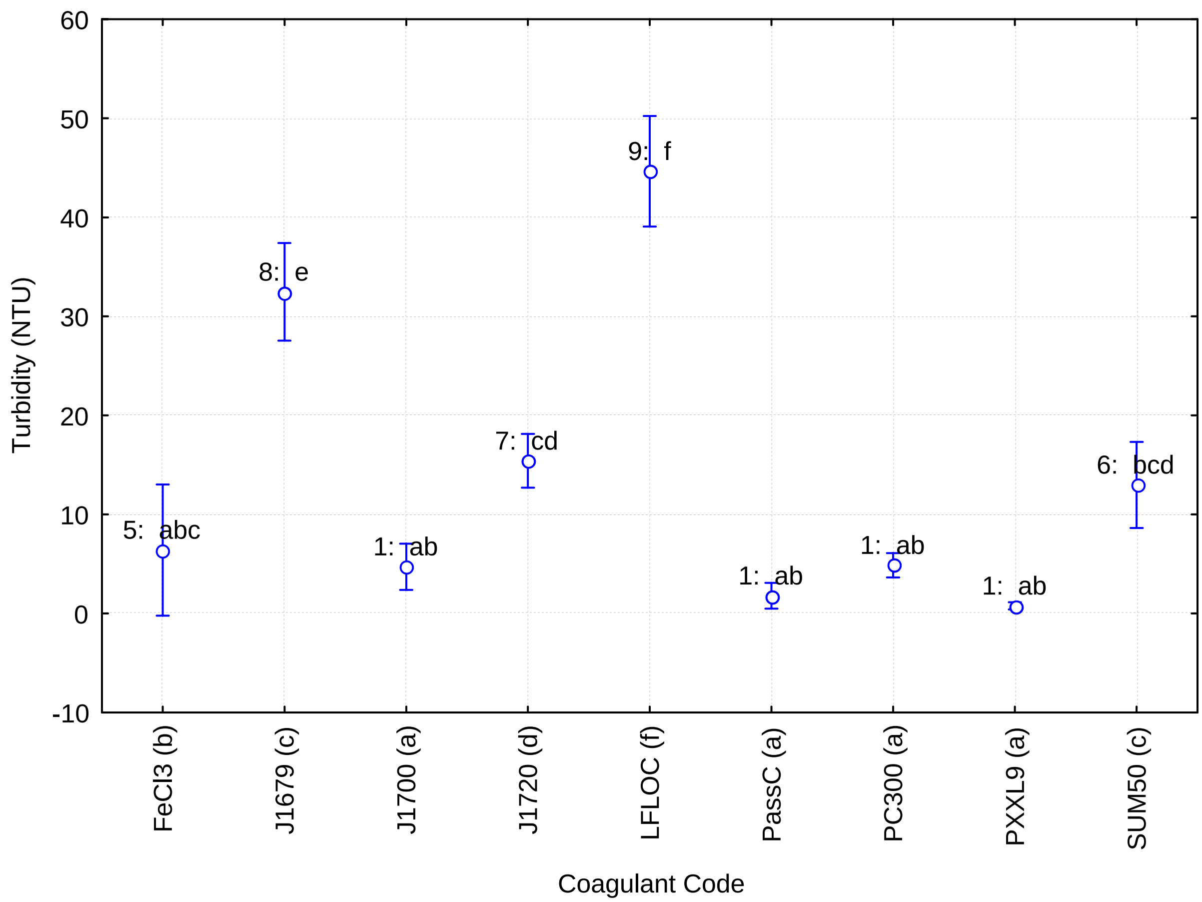
Coagulants were ranked based upon a statistical analysis of the experimental results. As an example, the methodology used for ranking coagulants for turbidity reduction is explained below.

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

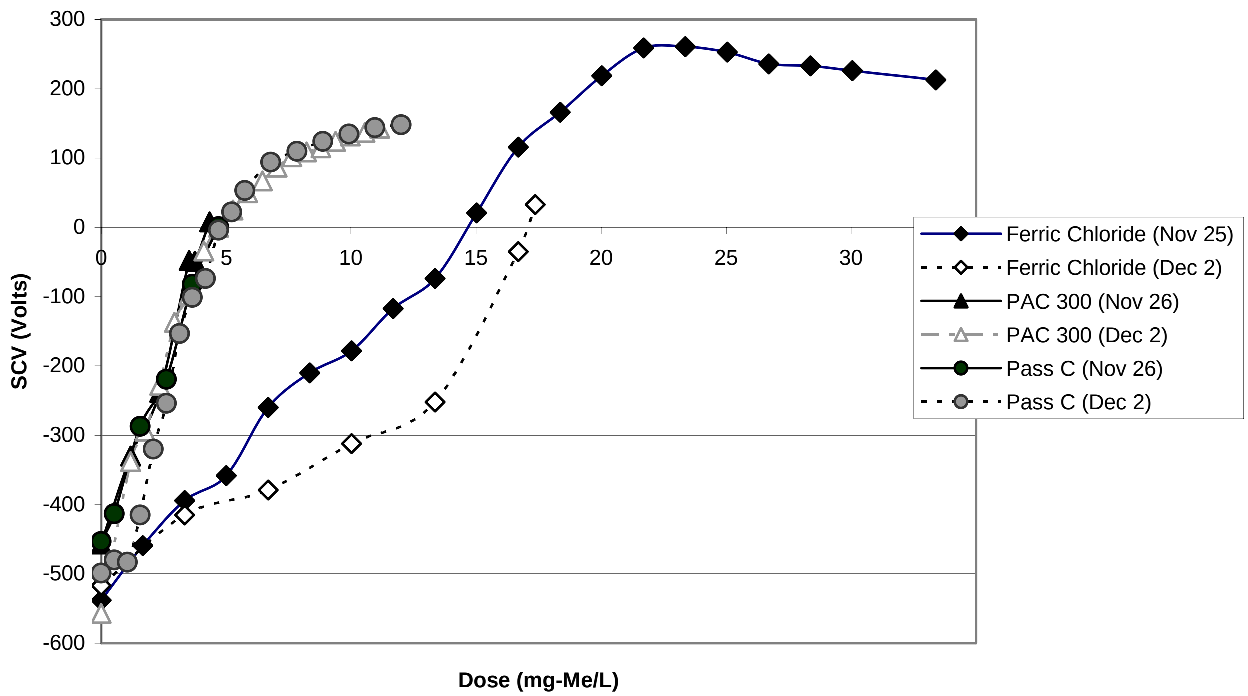
The goal of laboratory screening of coagulants was to narrow the list of coagulants down from the twenty-five selected by literature review to a manageable number of eight for further testing performance and robustness. Coagulants were initially screened based on turbidities achieved during charge titration 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	Coagulant Characterization							Dose	Turb at final	Final	Final	Justification (Y= Yes, N= No)	
		Metal	Type[2]	Basicity[1]	%Al[3]	Sulfinated[4]	pH	Silica	MG-Me/L	SCV value[7]	SCV	pH[5,8]		
Step 1 - Inorganic coagulants Tested														
	Iron Coagulants													
	$FeCl_3$	Fe	Iron salt	NA	NA		<1		26.4	5.5	0	6.3	Y	$FeCl_3$ was best Fe coagulant and achieved
1	PFS	Fe	PFS	NA	NA	Yes	2.00		34.2	7.9	0	6.0	N	low turbidity. All Fe coagulants required very
	$FeSO_4$	Fe	Iron salt	NA	NA	Yes	<1		32.6	11.8	0	6.2	N	high doses (>25 mg-Me/L).
	Aluminum Coagulants													
	PAX-XL9	Al	PACl	MH	L	Yes	2.80		11.4	2.3	0	6.8	Y	Top six aluminum coagulants providing best
	Pass-C	Al	PAHCS	M	L	Yes	2.50	Yes	13.4	4.2	0	6.6	Y	final turbidity (<8 NTU) at relatively low
	JC 1700	Al	PACl	MH	M	Yes	4.30		9.3	4.8	3	7.0	Y	doses (<15 mg-Me/L).
2	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	
	PAX XL8	Al	PACl	M	L	Yes	2.70		12.3	7.9	-2	6.9	N	Have similar chemistry and performed
3	PAC 300	Al	PACl	M	L		2.55		10.9	8.8	0	7.0	Y	similarly. PAC 300 selected because of
														slightly lower dosing requirements.
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).
	JC 1600	Al	ACH	H	H		4.30		4.1	9.0	4	7.7	N	Have similar chemistry and performed
5	PAX-XL19	Al	ACH	H	H		4.20		4.1	9.9	8	7.7	N	similarly. Sumachlor 50 selected because it
	HyperIon 1090	Al	ACH	H	H		4.10		3.6	10.3	0	7.9	N	had lowest dosing requirements.
	Sumachlor 50	Al	ACH	H	H		4.20		2.3	10.3	0	7.9	Y	
	PAX-18	Al	PACl	M	M	Yes	0.90		11.4	11.6	0	7.9	N	Not selected because coagulants achieved
	JC 1800	Al	PACl	H	H	Yes	4.30		4.0	13.6	0	7.7	N	poor final turbidity (> 10 NTU). PAX 11
6	PAX 11[6]	Al	PACl	L	H	Yes	2.40		16.1	14.3	-30	6.9	N	could not achieve charge neutralization.
	Alum	Al	Al salt		L	Yes	3.50		12.9	19.9	0	6.9	N	Most coagulants required high dosing levels.
	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)														
	JC 1720	Al	PAHCS	MH	L	Yes	4.30		1.2	3.2	20	7.9	Y	Top JC1700 Derivative.
7	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

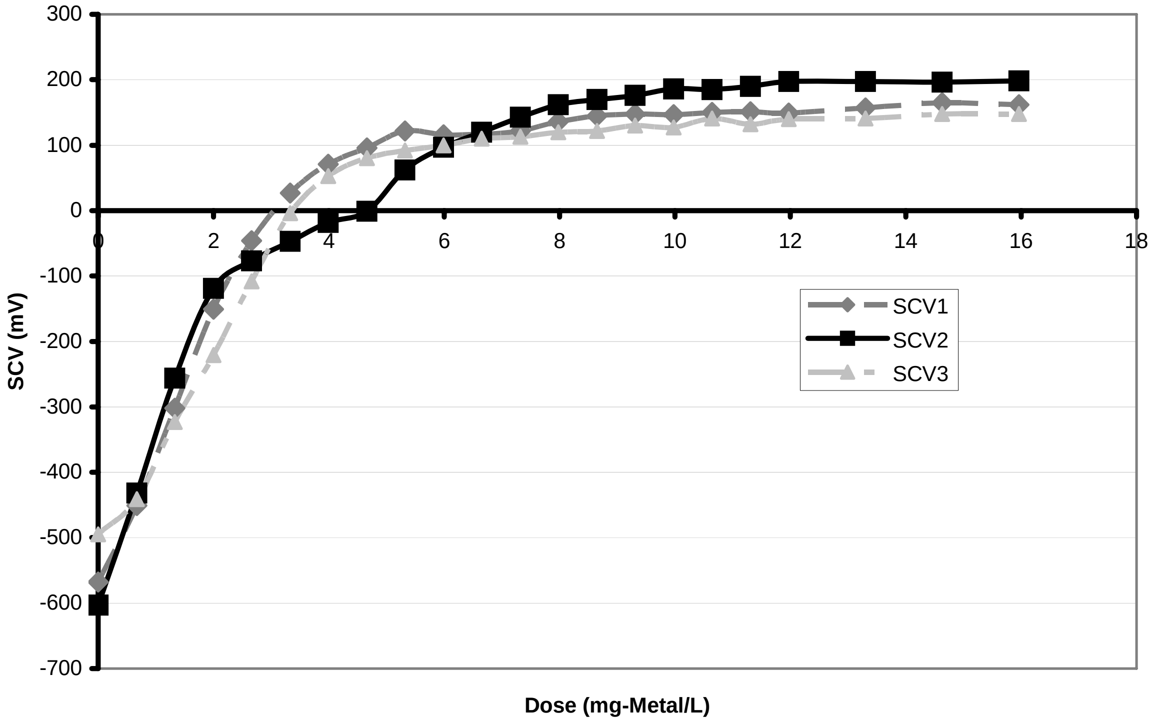


Table 5-3 Dosing Levels for SCVs from –300 to +150 mV for Nine Coagulants

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

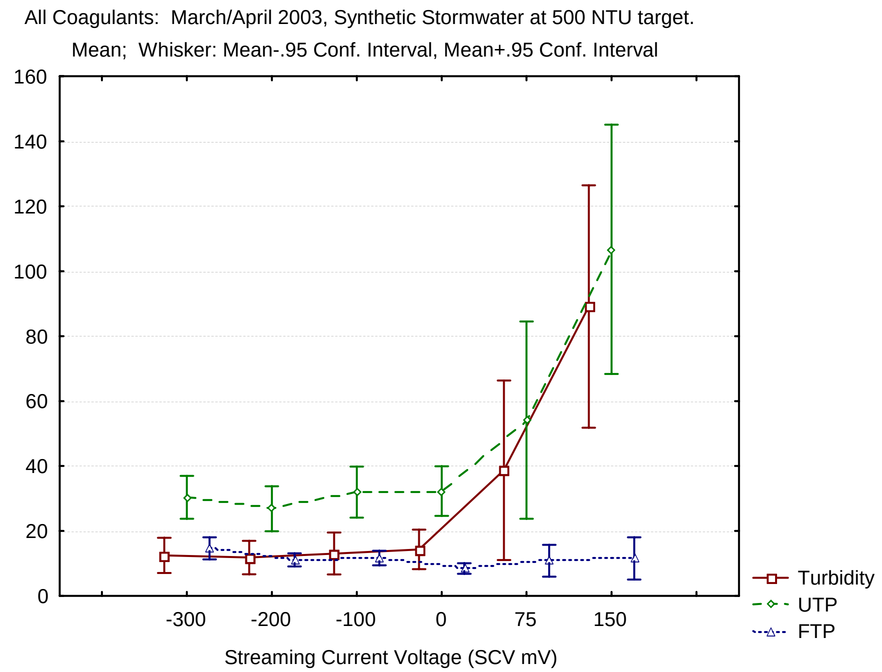
Notes

1. Sig = statistical significance. Values with the same letter are not statistically different ($p<0.05$)

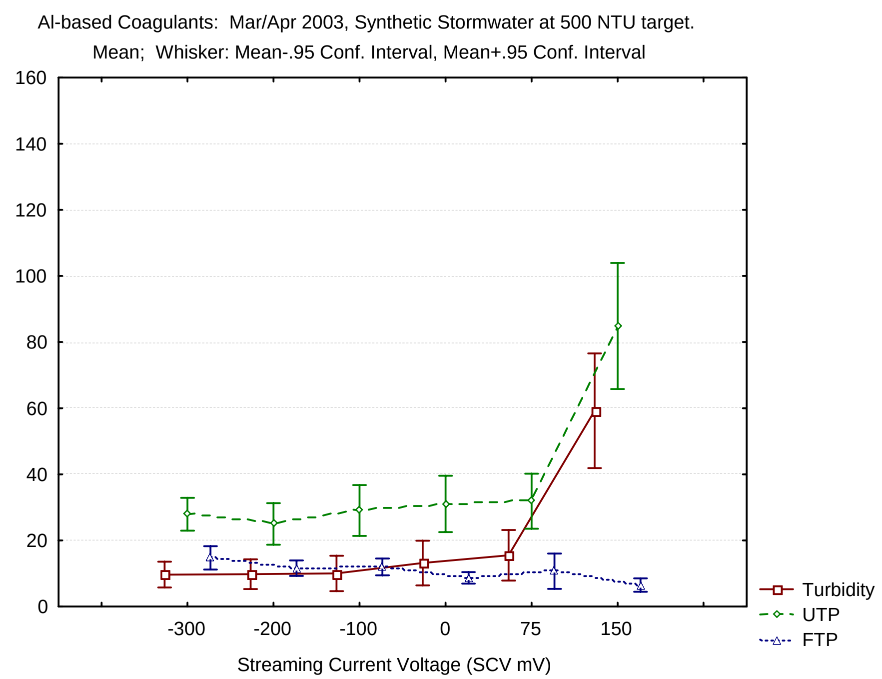
Figure 5-2 Turbidity and Phosphorus Concentrations at Different Streaming Current Values for a Synthetic Storm Water with an Initial Target Turbidity of 500 NTU

(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: Full Range	Value: More Optimal Range	% Improvement
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 Turbidity	30 min Turbidity	30 min UTP	30 min 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) Turbidity (NTU) Mean	SD	30 Minutes Settling (Steady State Conditions) Turbidity (NTU) 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 Mean	Std.Dev.	Filtered Total Phosphorus 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.)

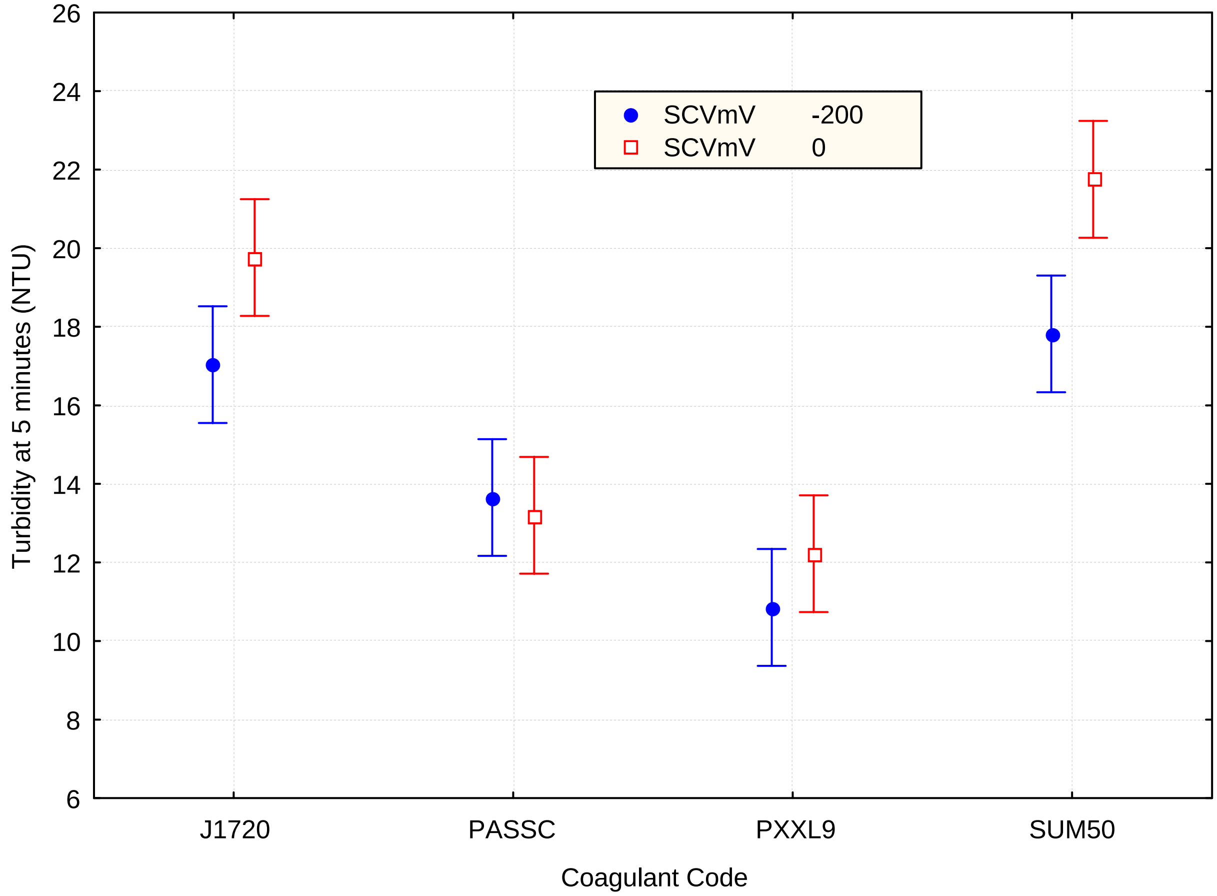
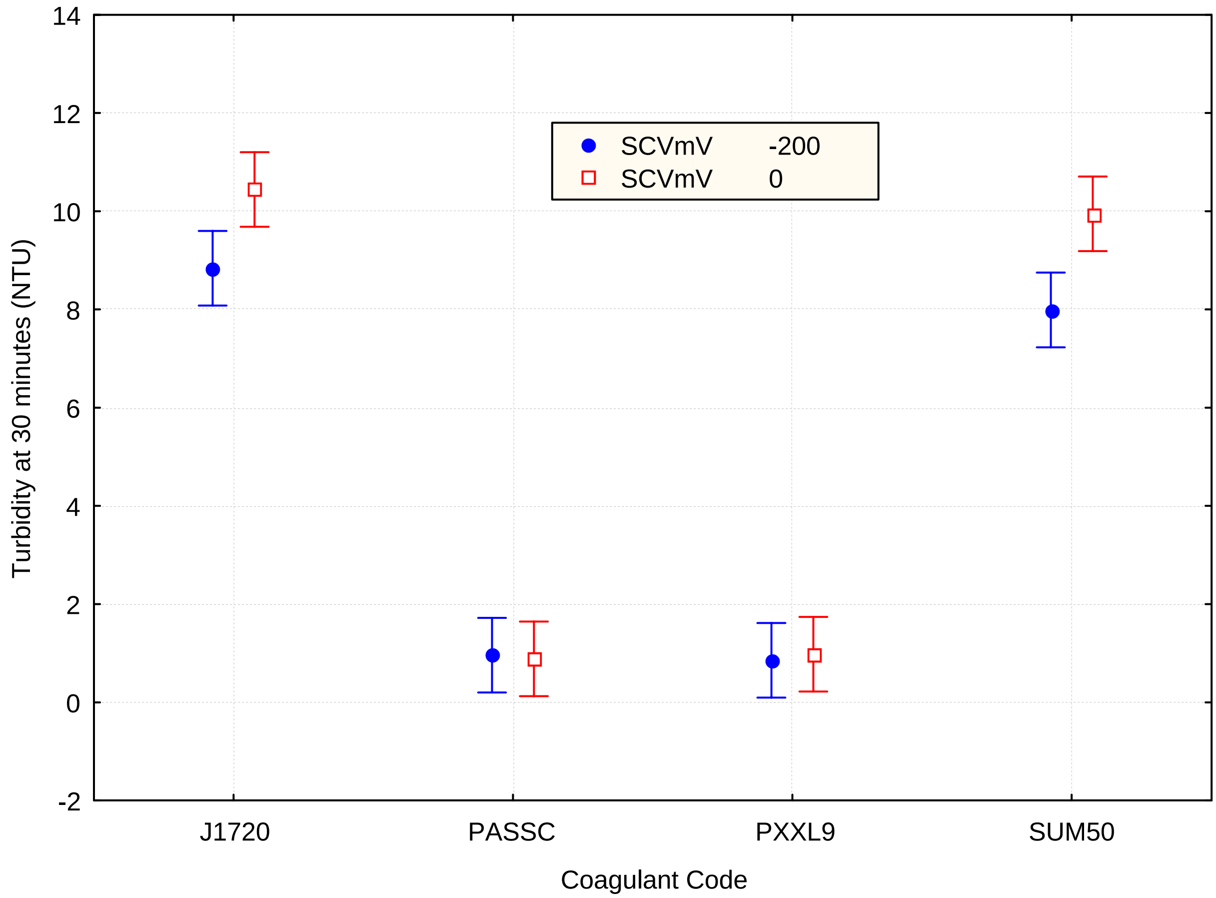


Figure 6-2 Dosing Effects on Final Settling
(Shown are mean values and 95% confidence interval.)



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.)

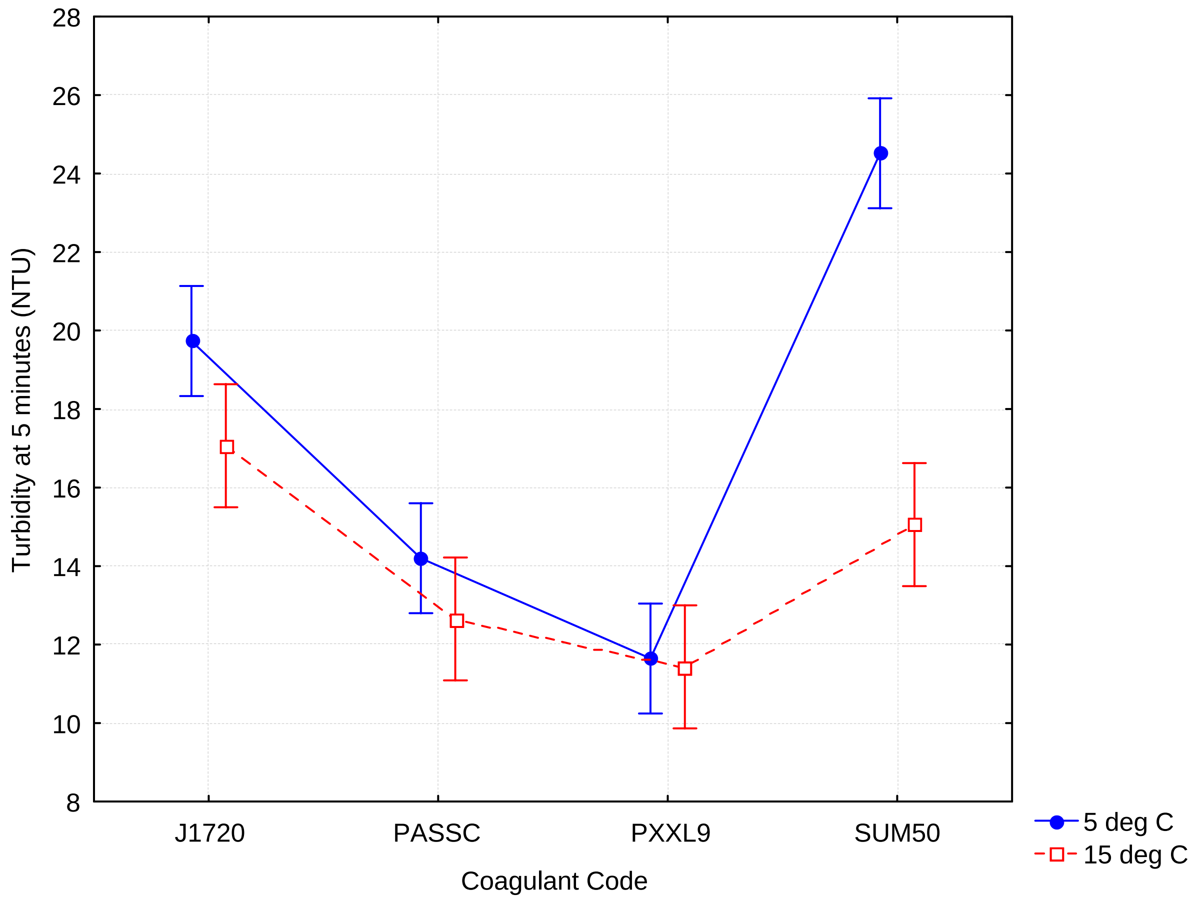
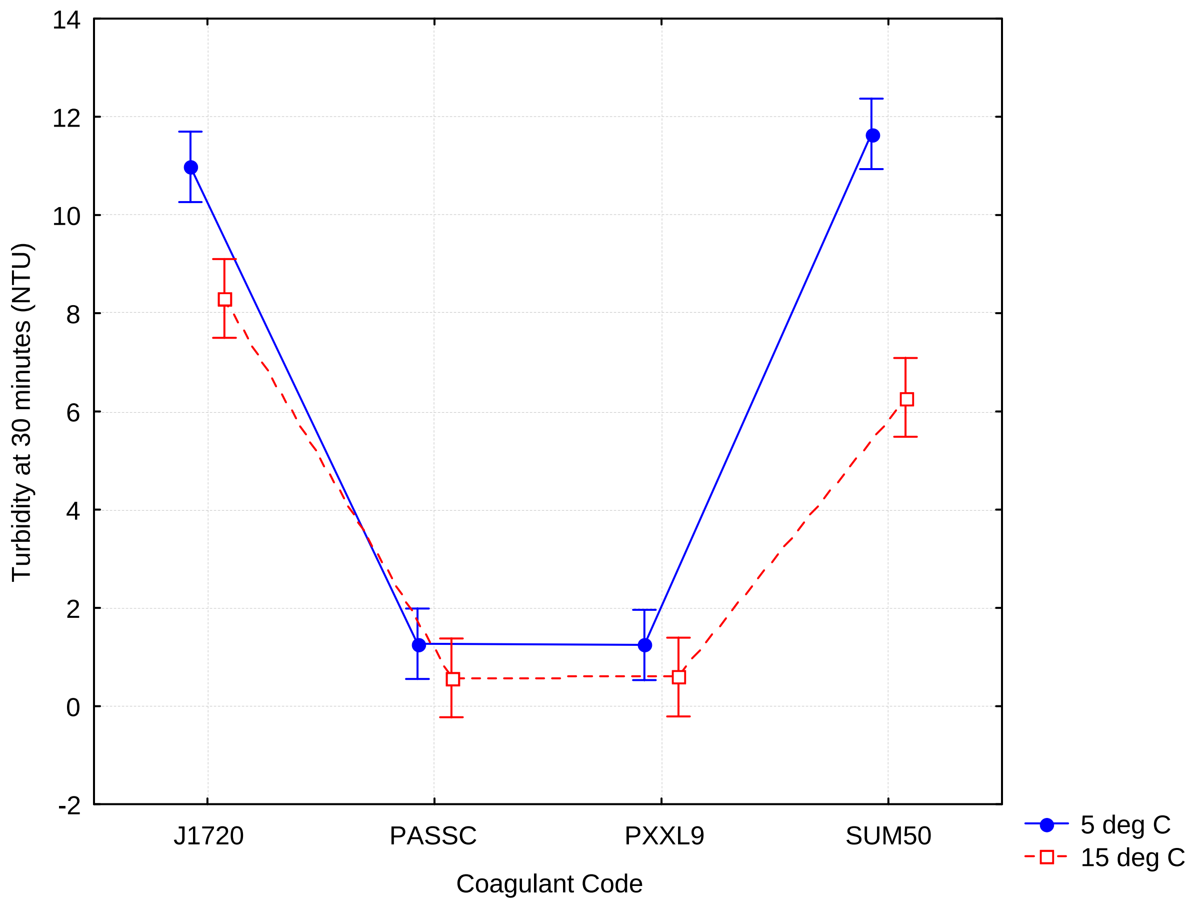


Figure 6-4 Temperature Effects on Final Settling
(Turbidity is measured at 30 minutes as an indicator of final results. Shown are mean values and 95% confidence interval.)



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.)

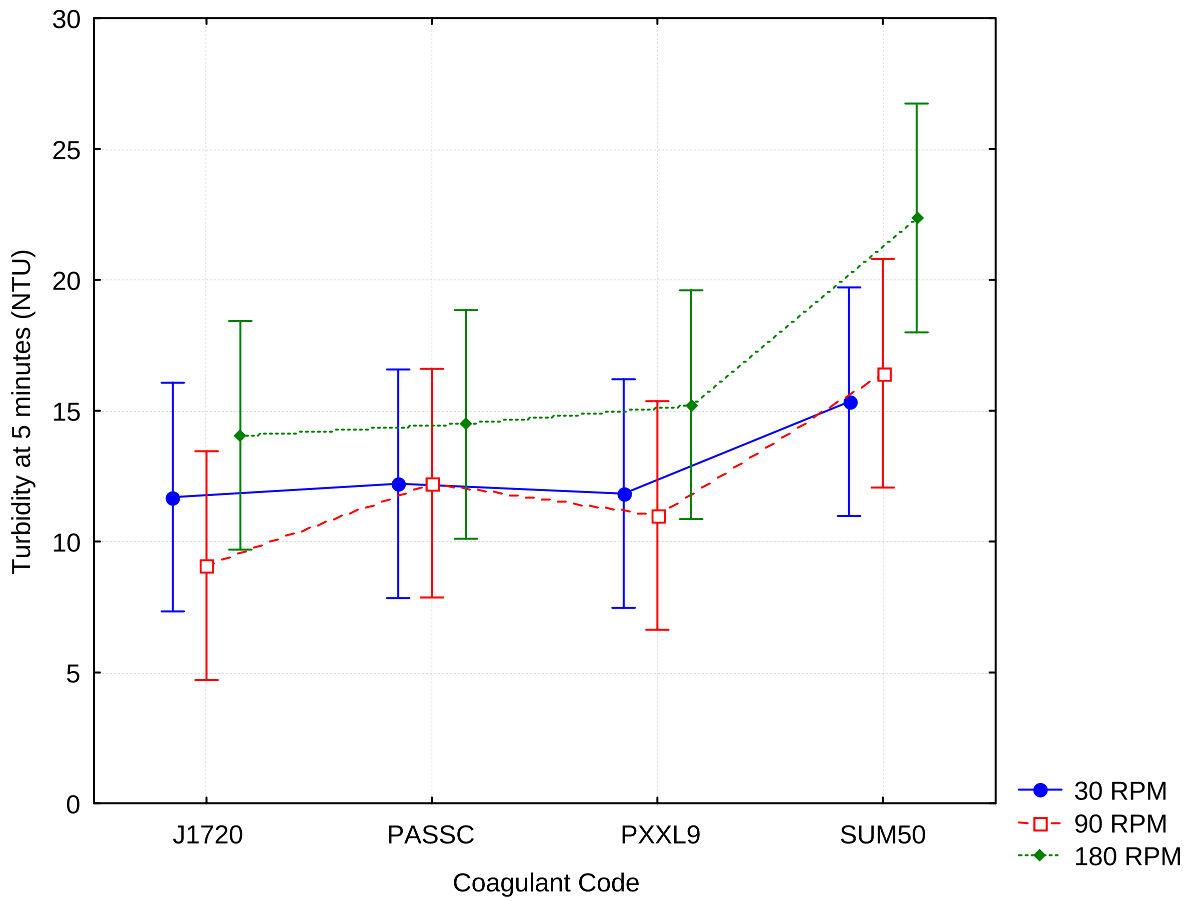


Figure 6-6 Effects of Rapid Mixing on Final Settling
(Shown are mean values and 95% confidence interval.)

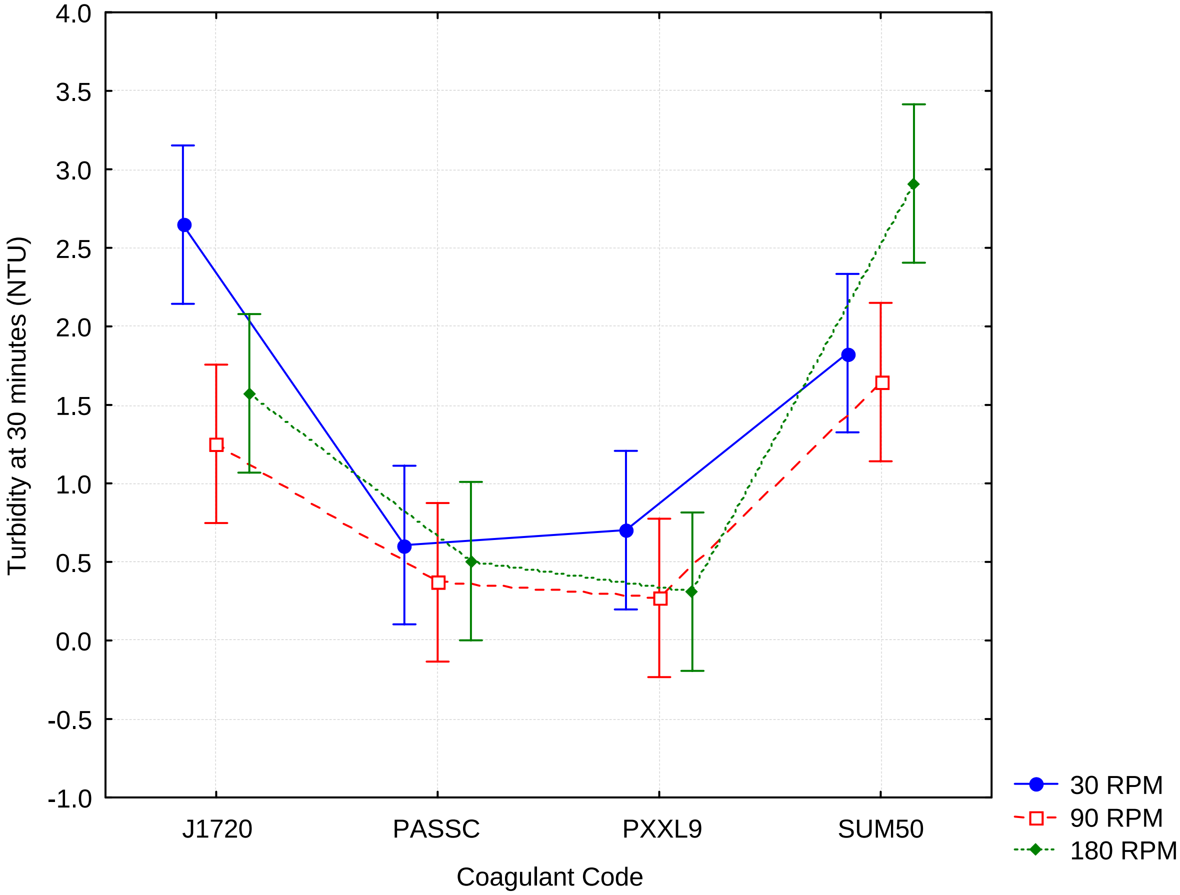


Figure 6-7 Rapid Mixing Effects on Dissolved P in Storm Water
(Shown are mean values and 95% confidence interval.)

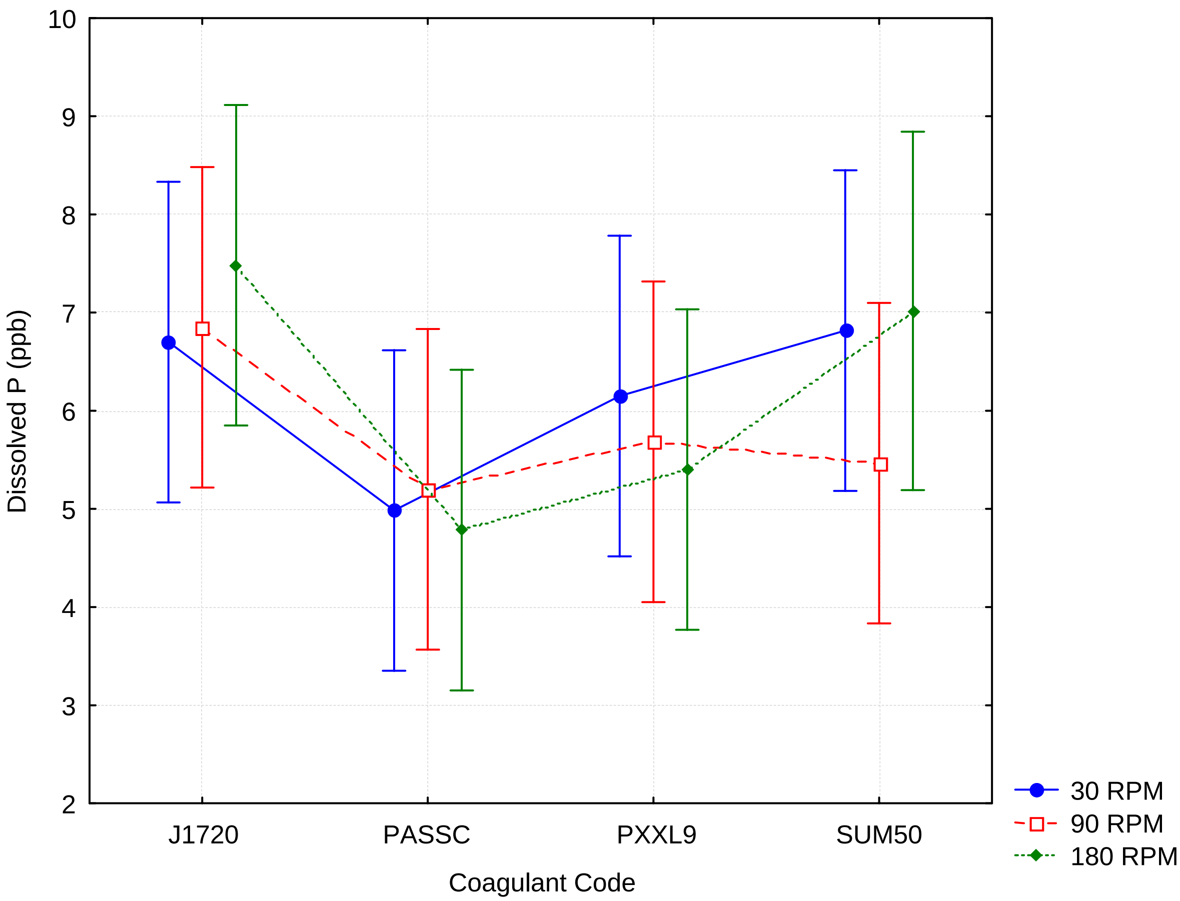
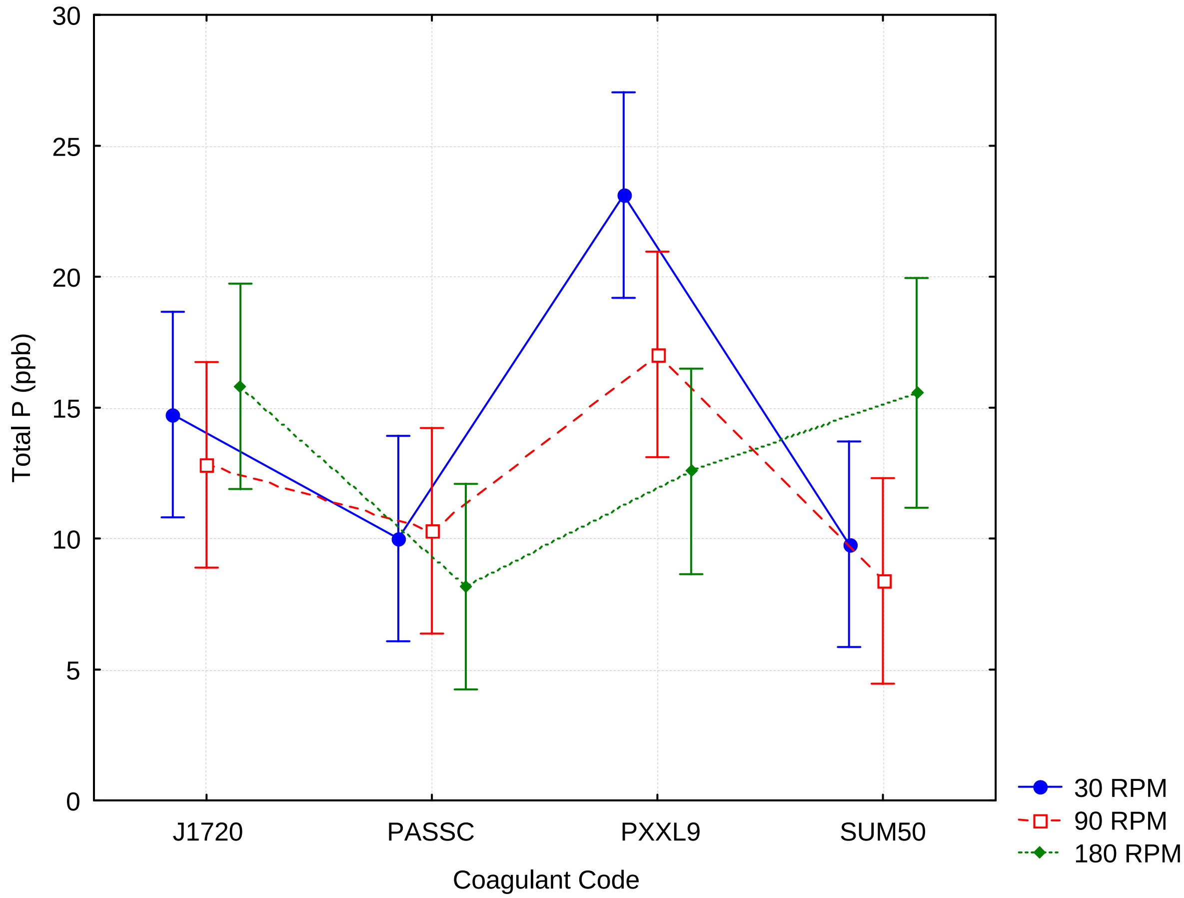


Figure 6-8 Effects of Rapid Mixing of Total P in Storm Water
(Shown are mean values and 95% confidence interval.)



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.)

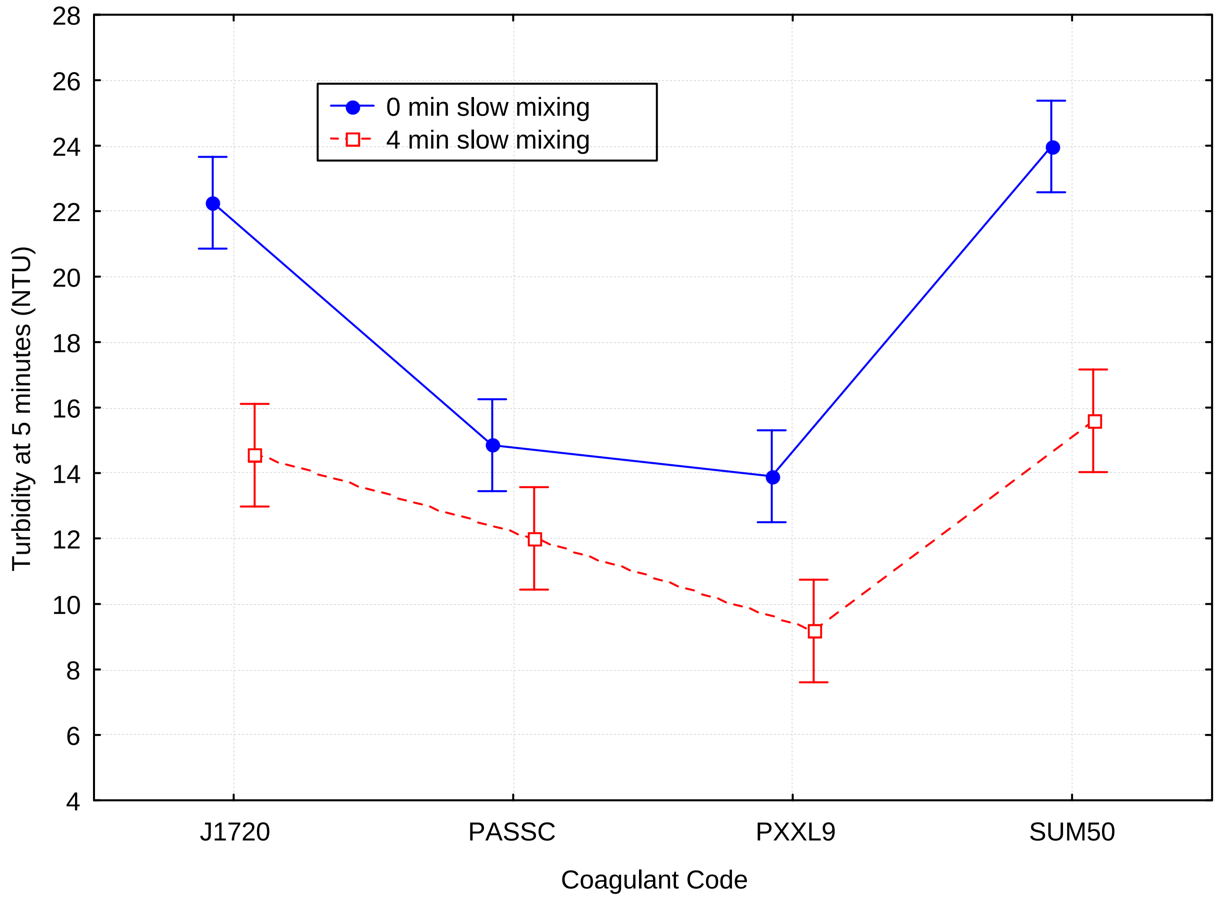
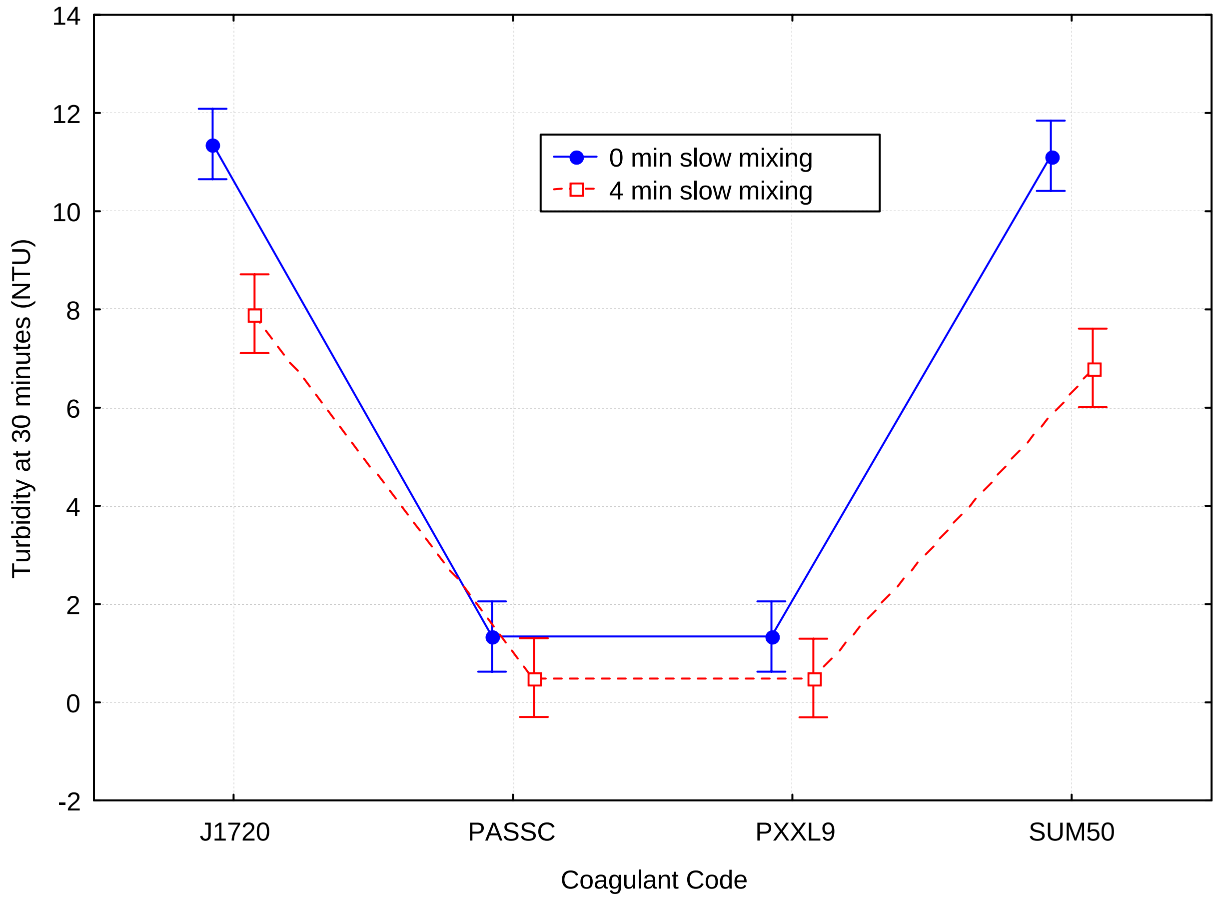


Figure 6-10 Effects of Slow Mixing on Final Turbidity
(Shown are mean values and 95% confidence interval.)



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.)

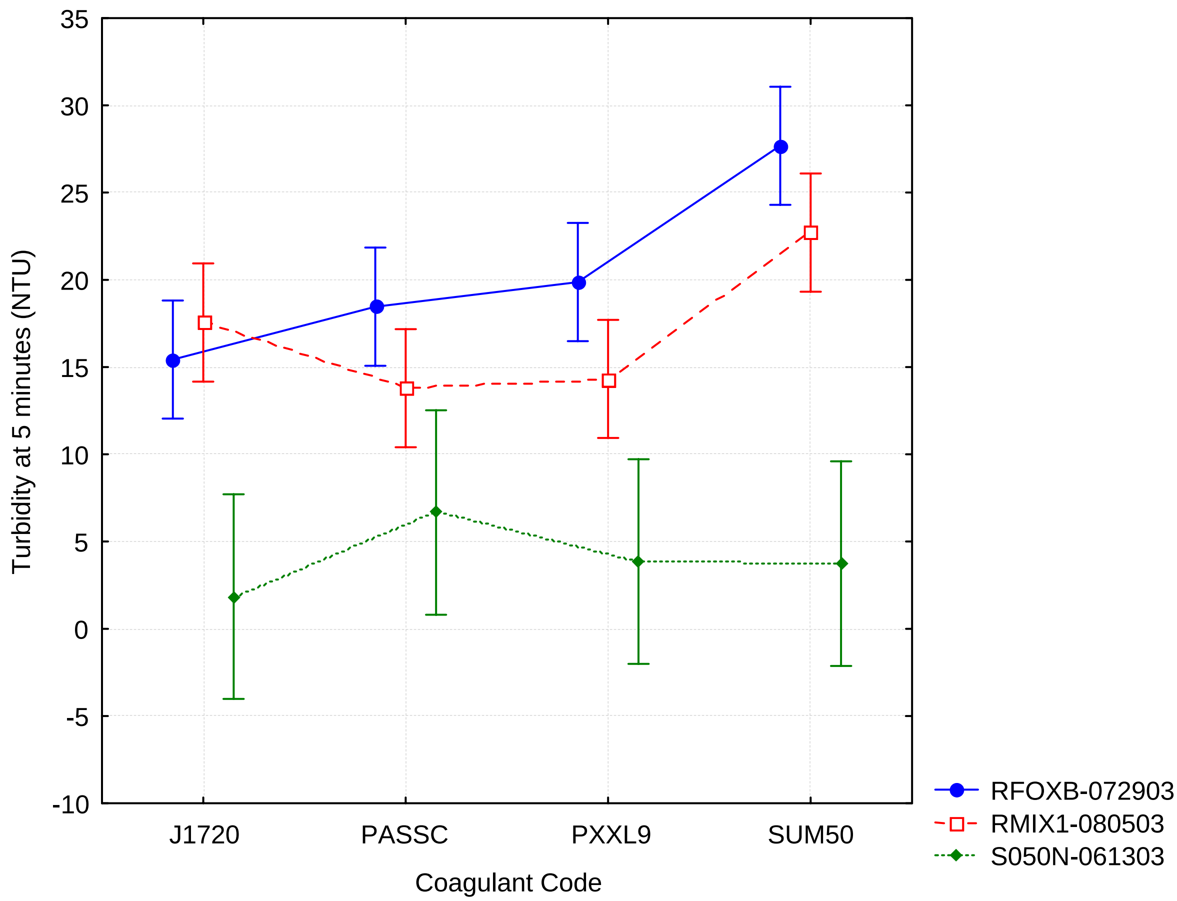


Figure 6-12 Source Water Effects on Final Settling
(Shown are mean values and 95% confidence interval.)

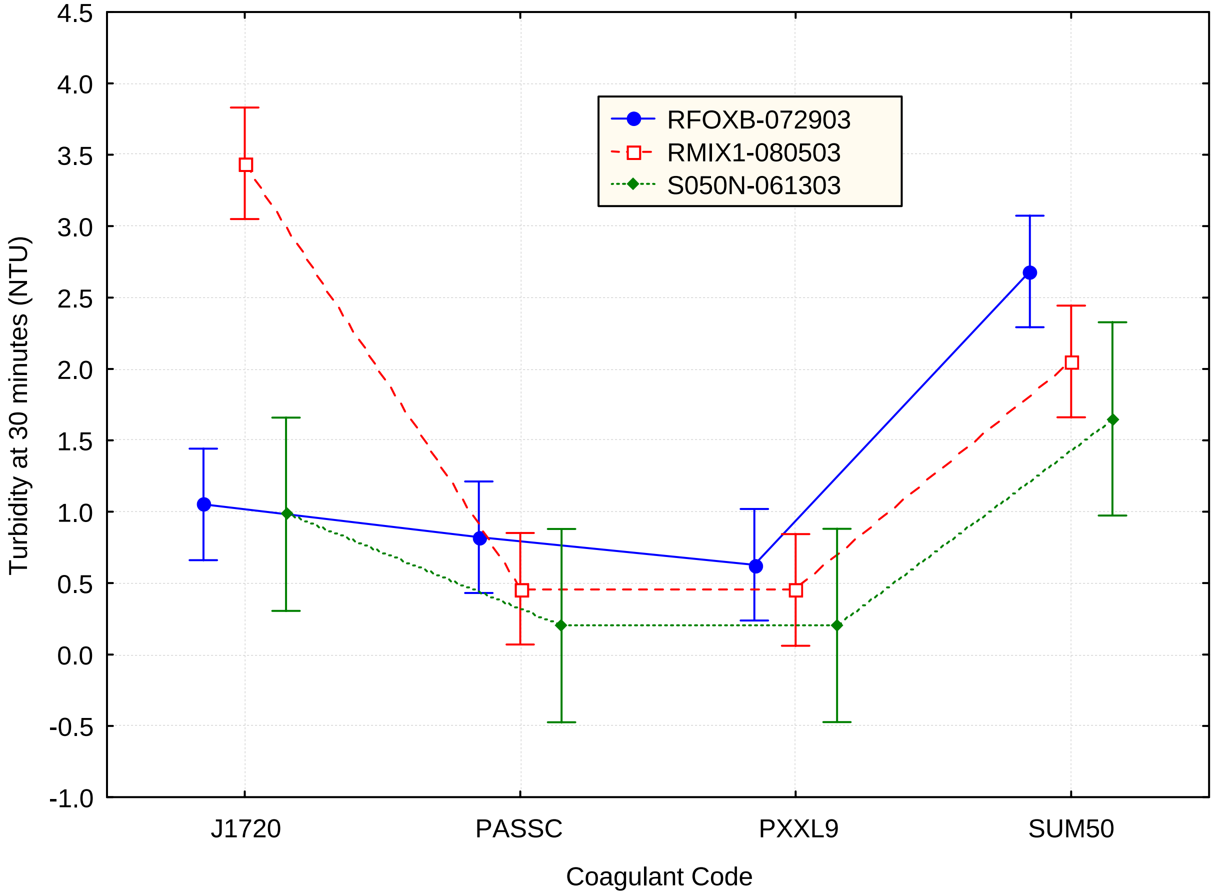


Figure 6-13 Storm Water Effects on Removal of Total P
(Shown are mean values and 95% confidence interval.)

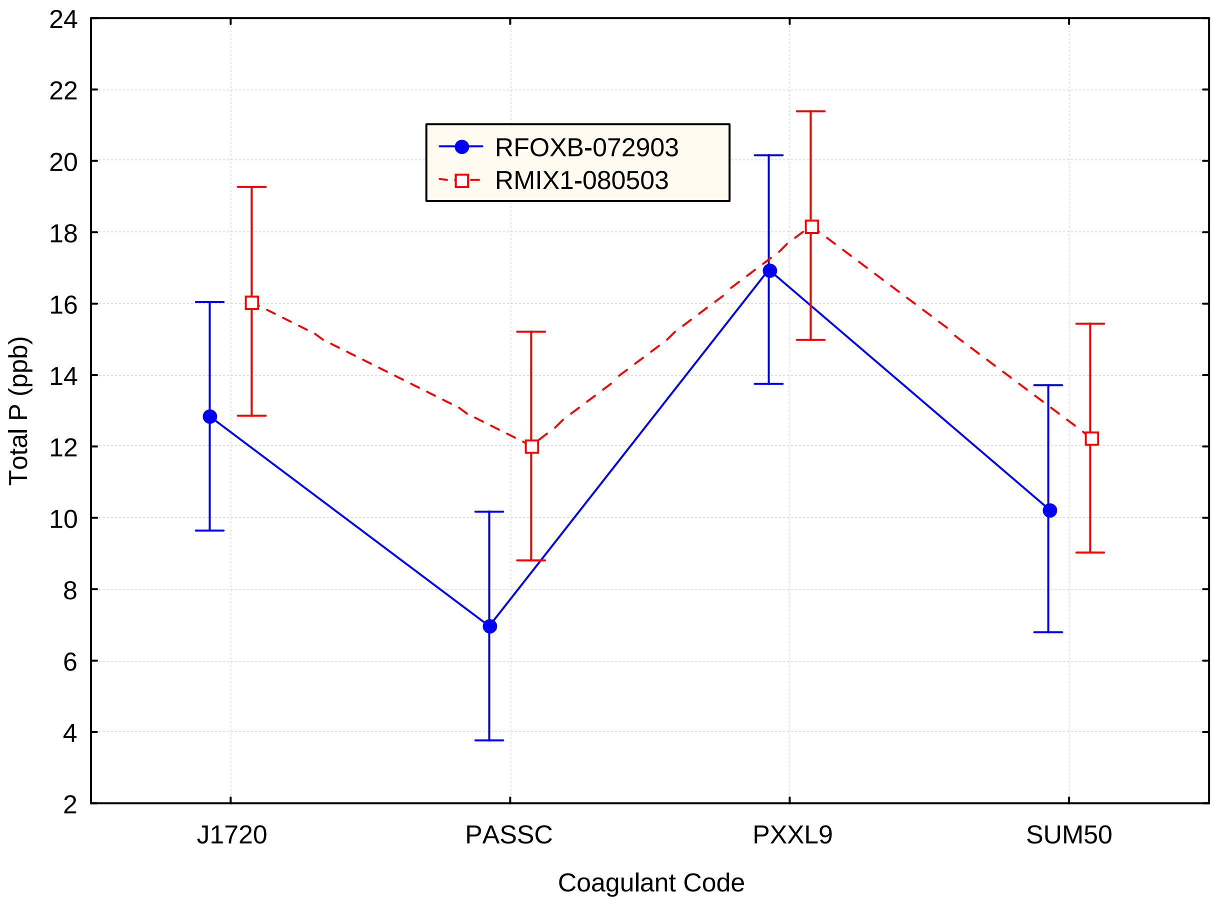
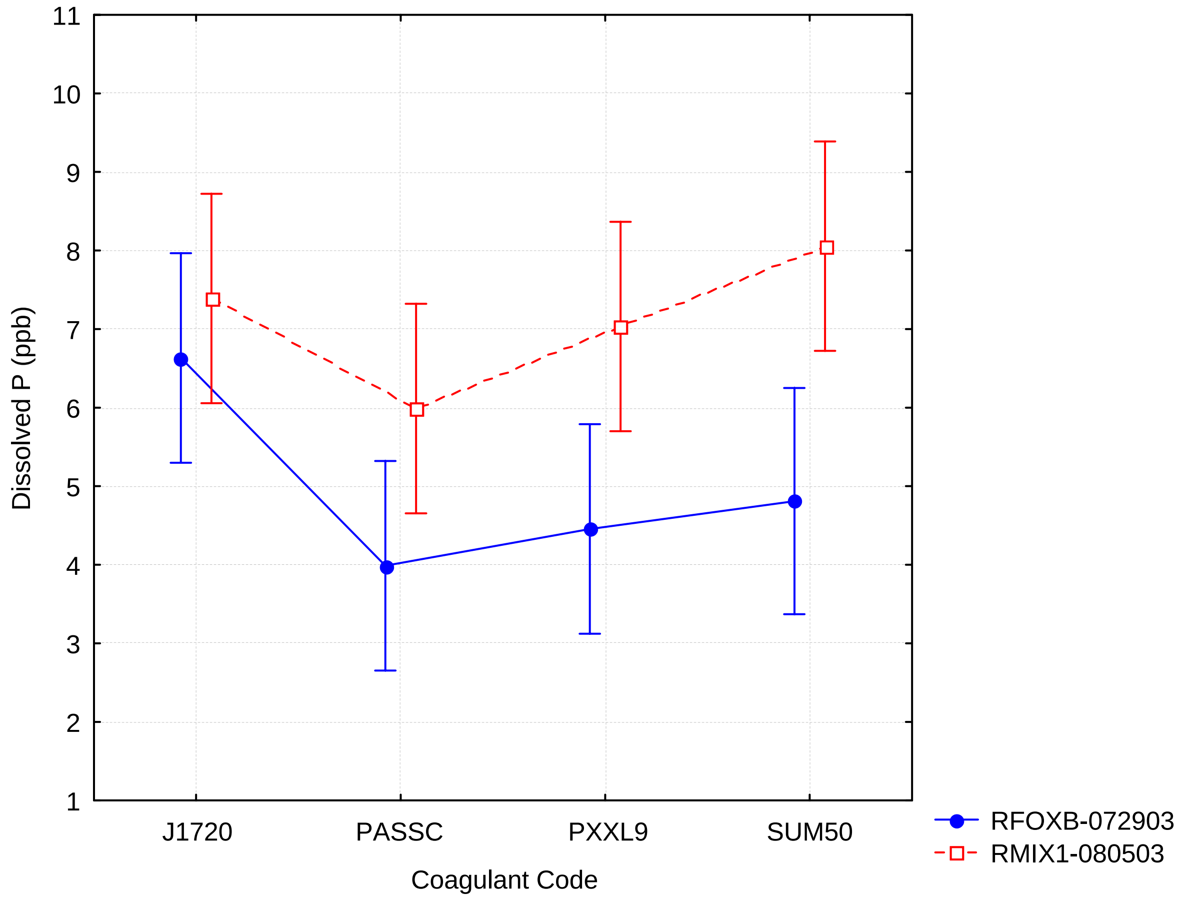


Figure 6-14 Effects of Storm Water on Final Dissolved P
(Shown are mean values and 95% confidence interval.)



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

	Means	N	Std.Dev.	Median	Q25	Q75	Minimum	Maximum	p-value
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.

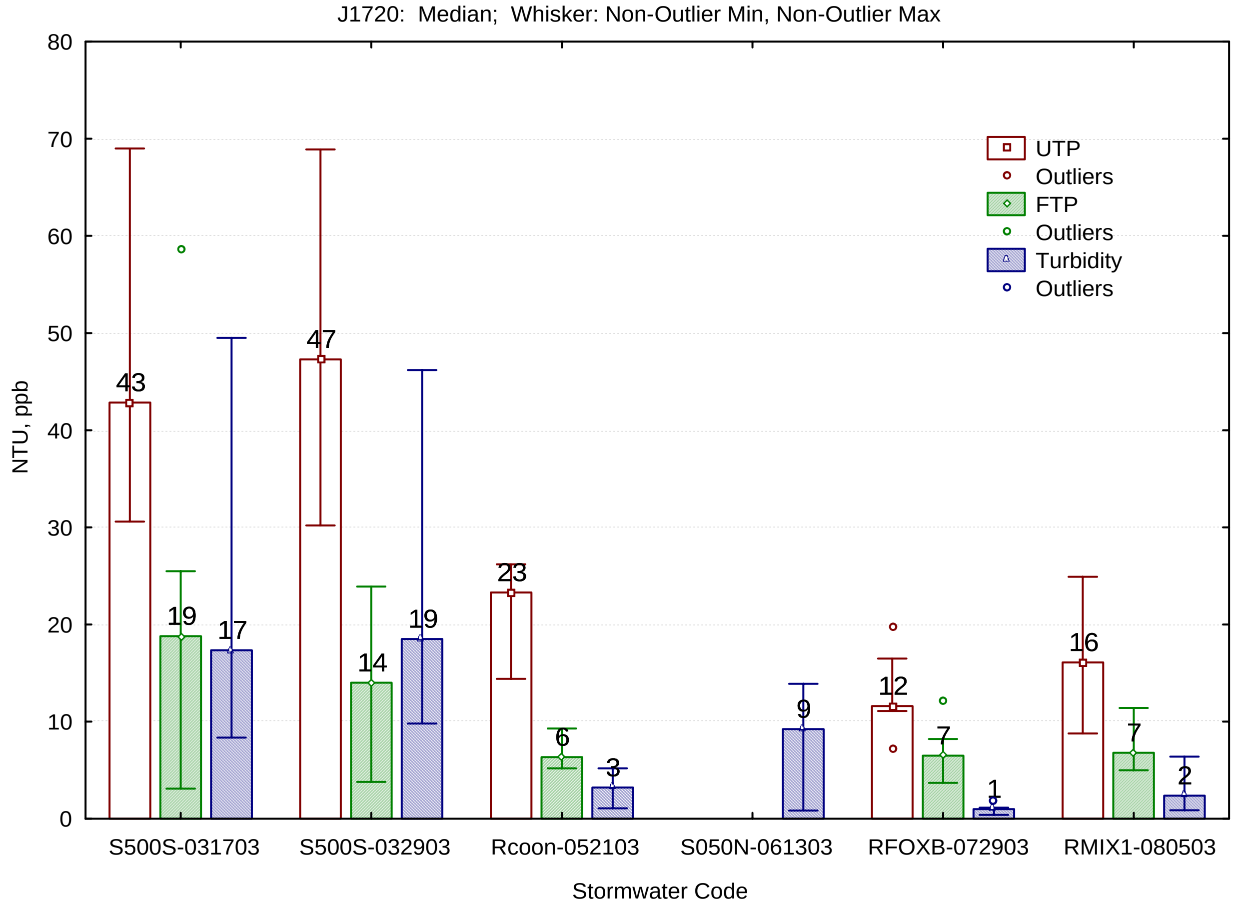


Figure 7-2 Achievable Phosphorus and Turbidity Levels during Laboratory Studies for SumaChlor 50.

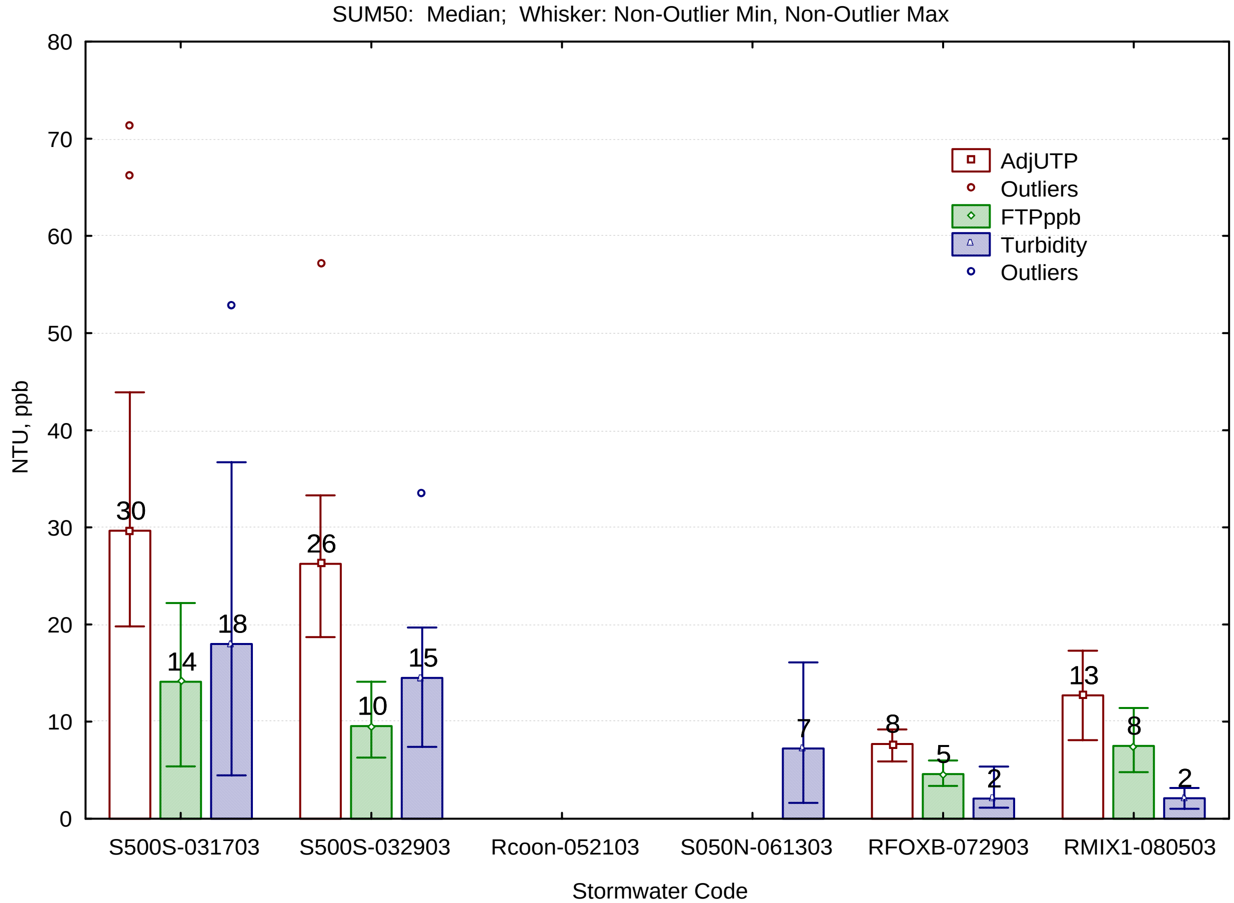


Figure 7-3 Achievable Phosphorus and Turbidity Levels during Laboratory Studies for Pass C.

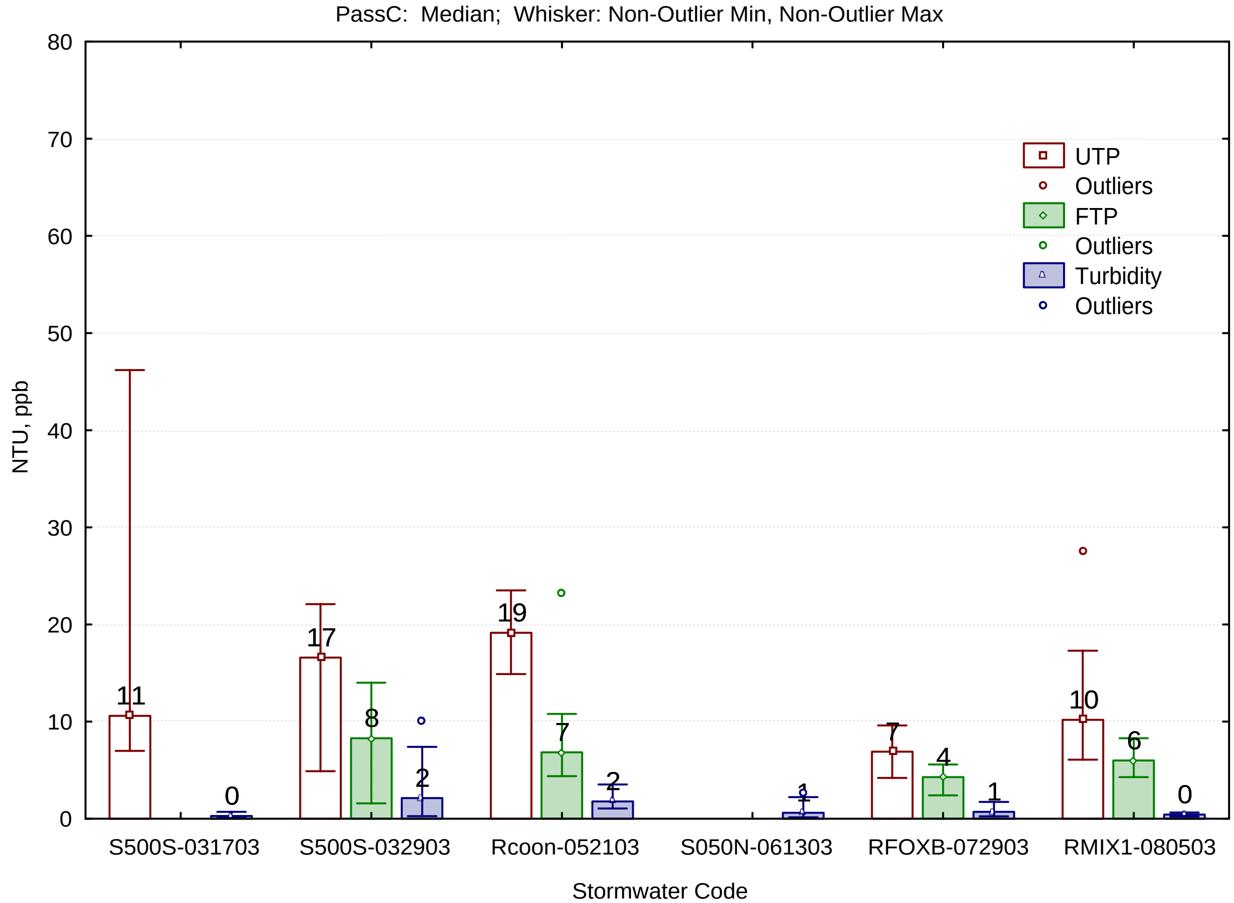
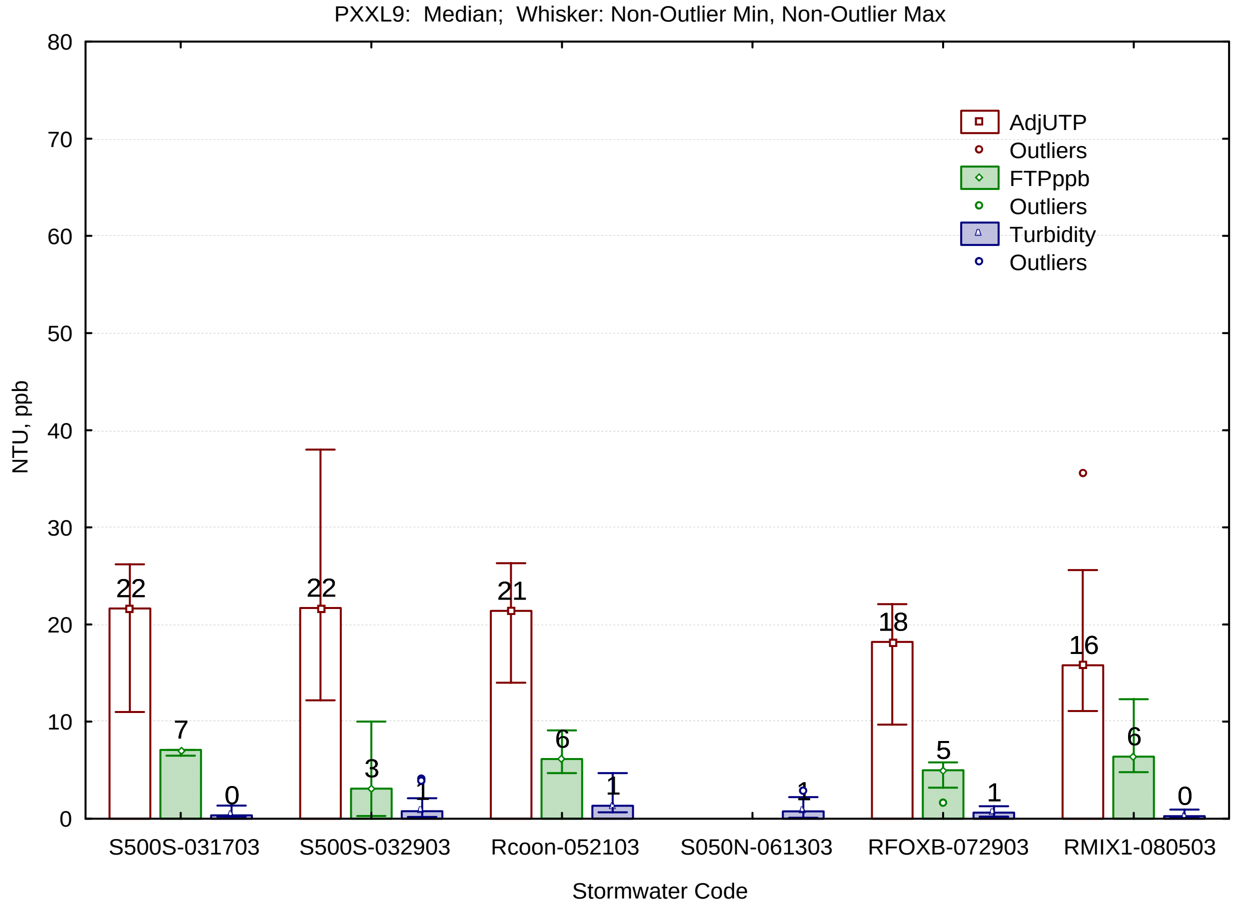


Figure 7-4 Achievable Phosphorus and Turbidity Levels during Laboratory Studies for PAX-XL9.



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.

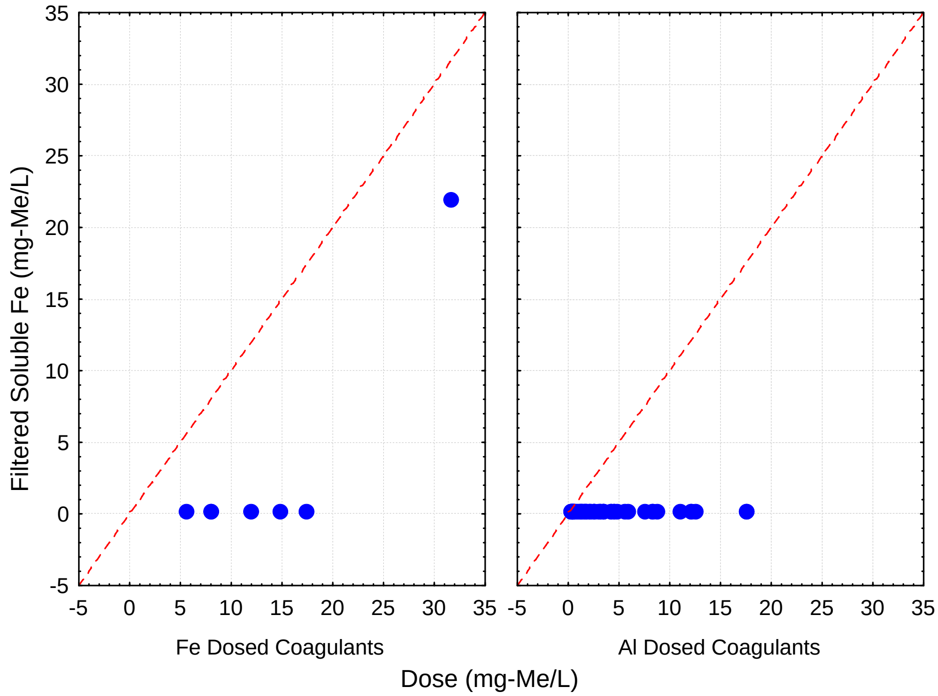
Table 8-2 Soluble Iron and Aluminum after Dosing and 30 Minutes of Settling

Coagulant	Dose mg-Me/L			Unfiltered Soluble Fe					Filtered Soluble Fe					Unfiltered Soluble Al					Filtered Soluble Al				
Code	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.

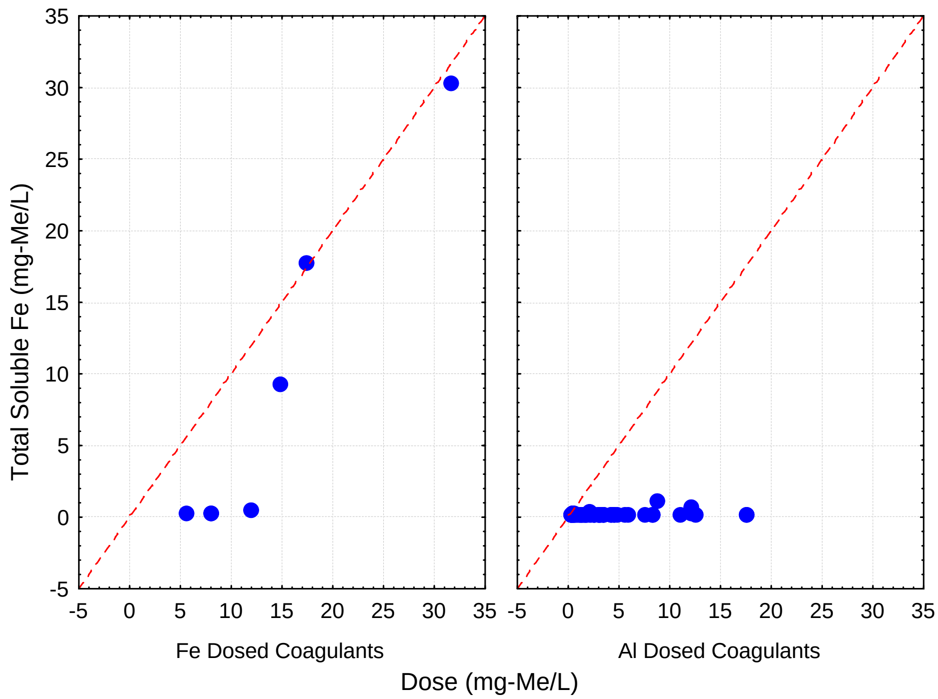
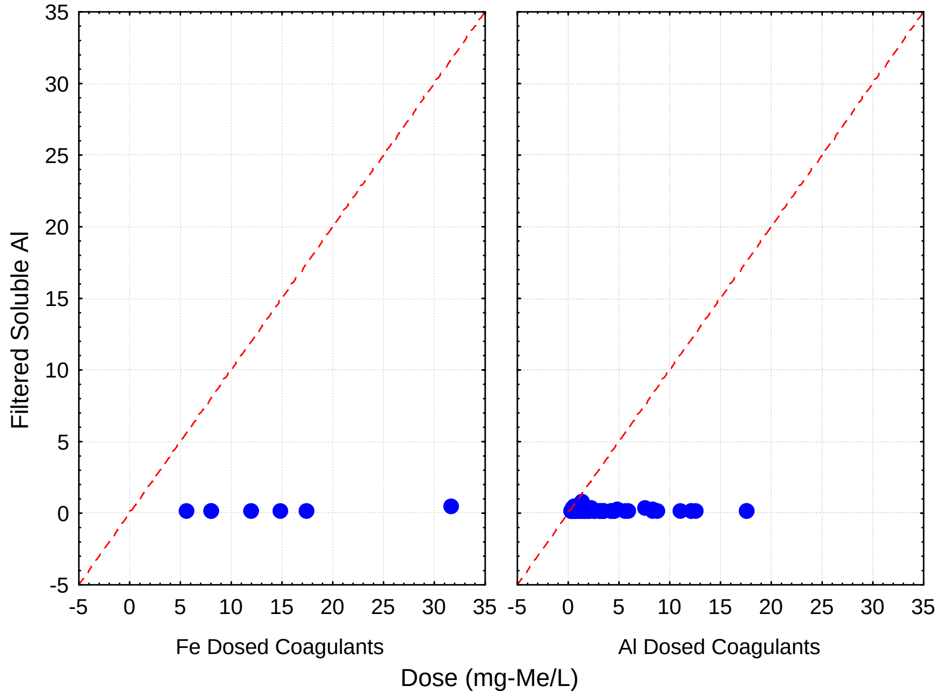


Figure 8-2 Total and Filtered Soluble Aluminum in Solution after Coagulant Dosing

a. Filtered Soluble Aluminum



b. Total Soluble Aluminum

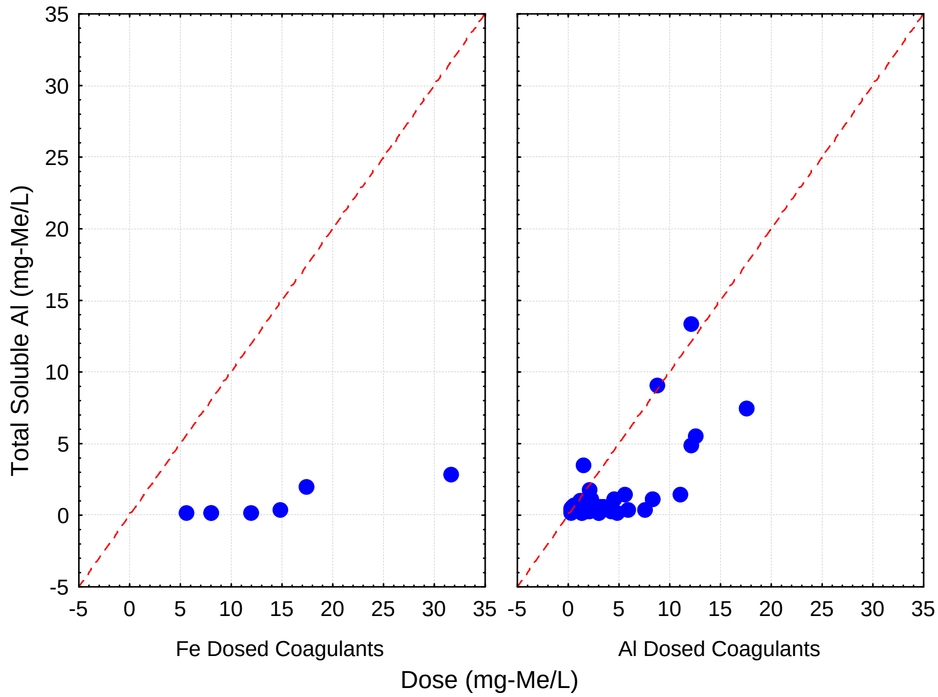


Figure 8-3 Increasing Soluble Metal Under Overdosing Conditions.

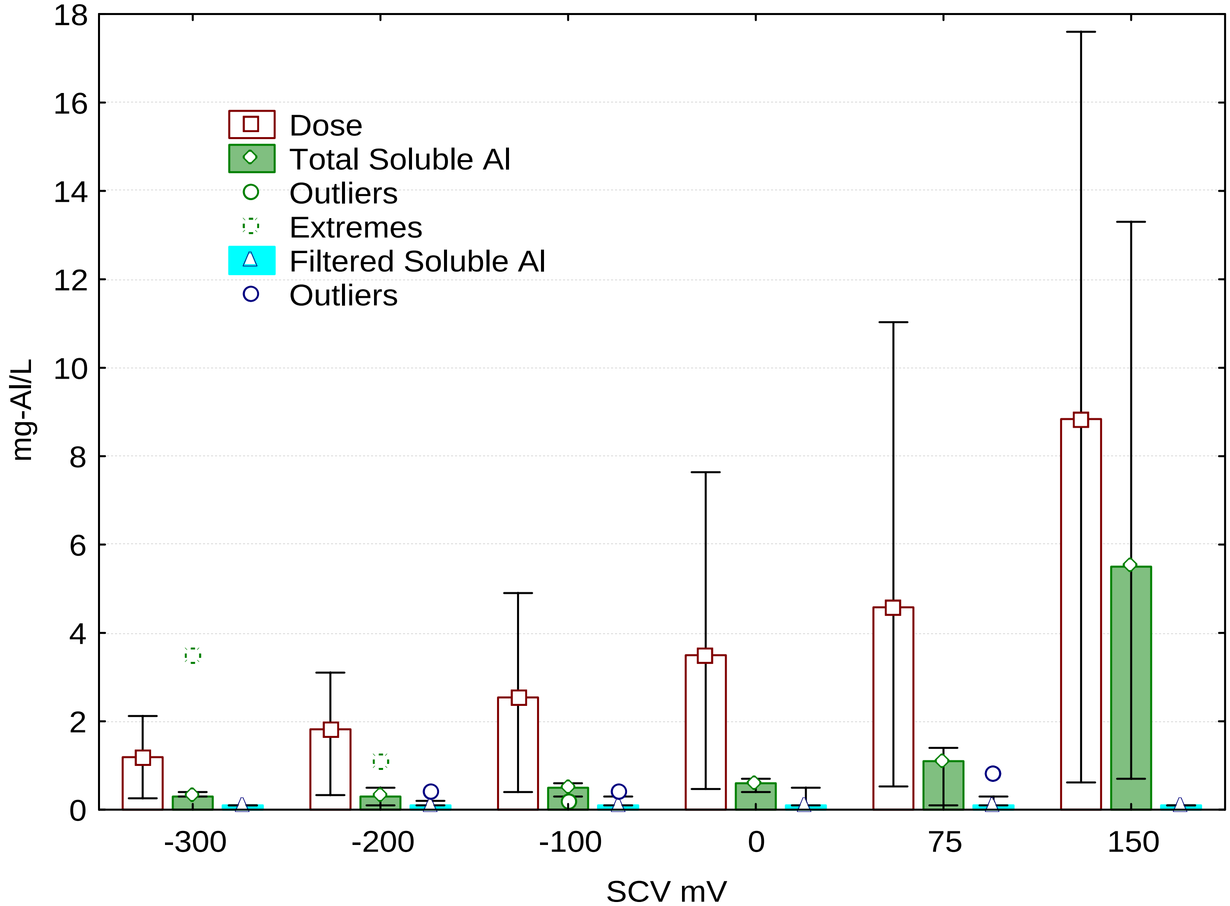


Figure 8-4 Unfiltered Soluble Aluminum Increases for Different Dosing Levels Corresponding to Streaming Current Values.

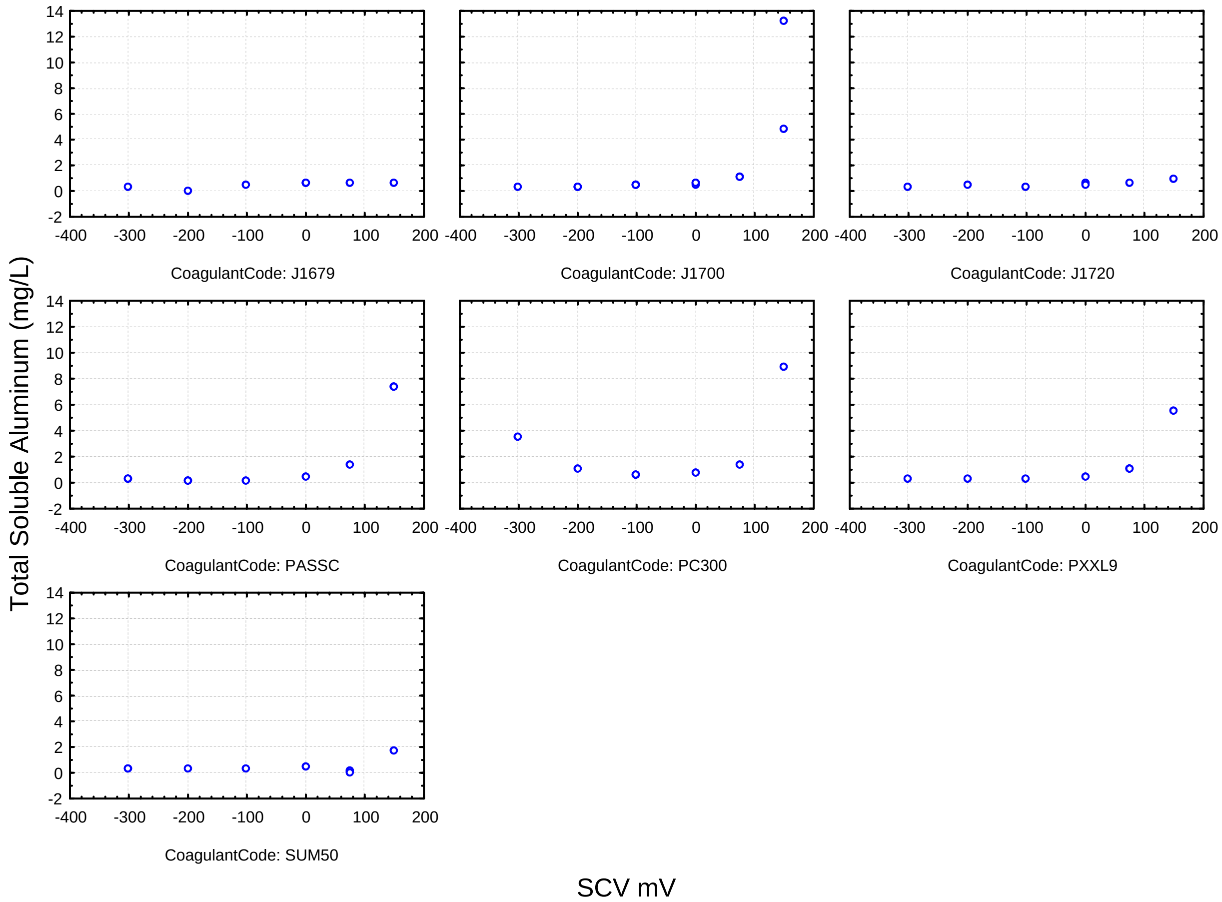
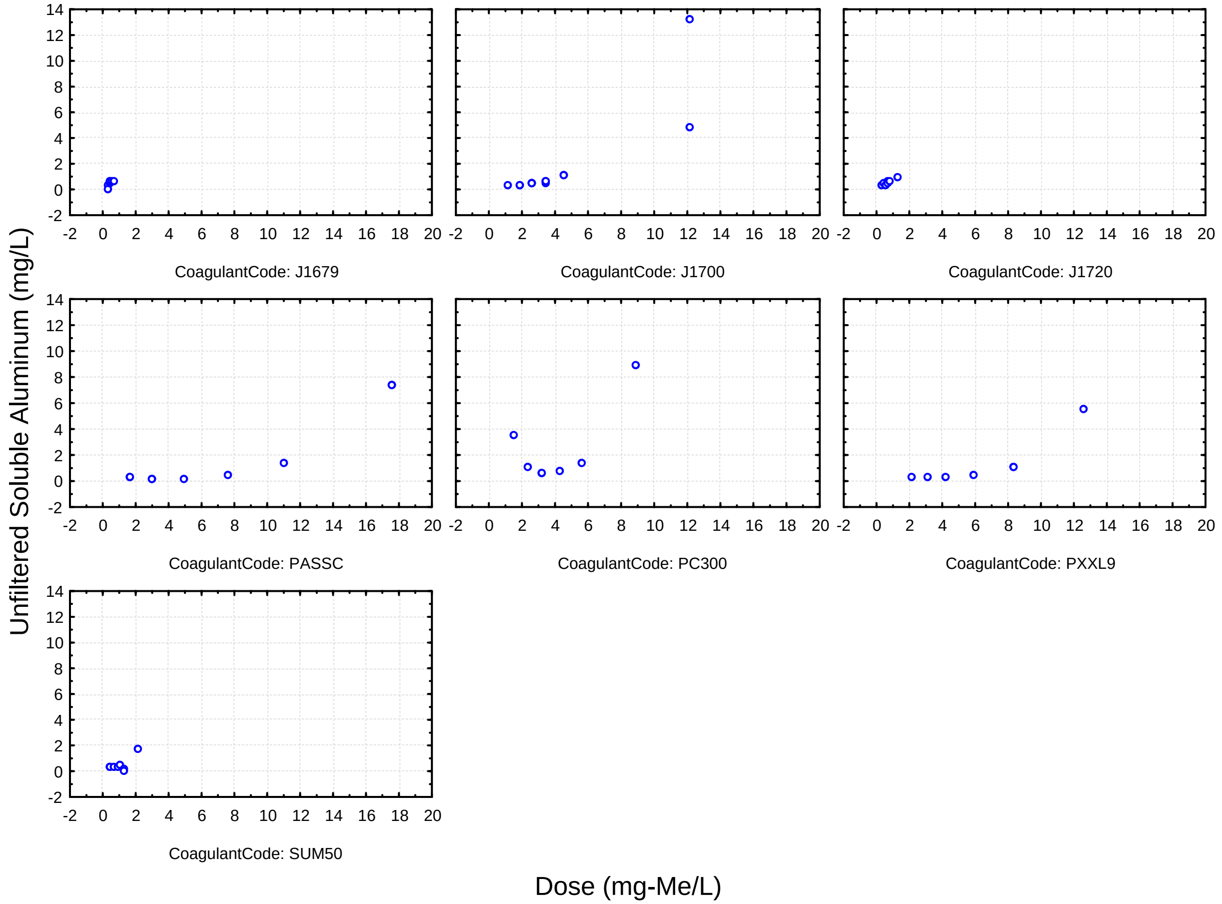


Figure 8-5 Unfiltered Soluble Aluminum increases for Different Chemical Dosing Levels



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.

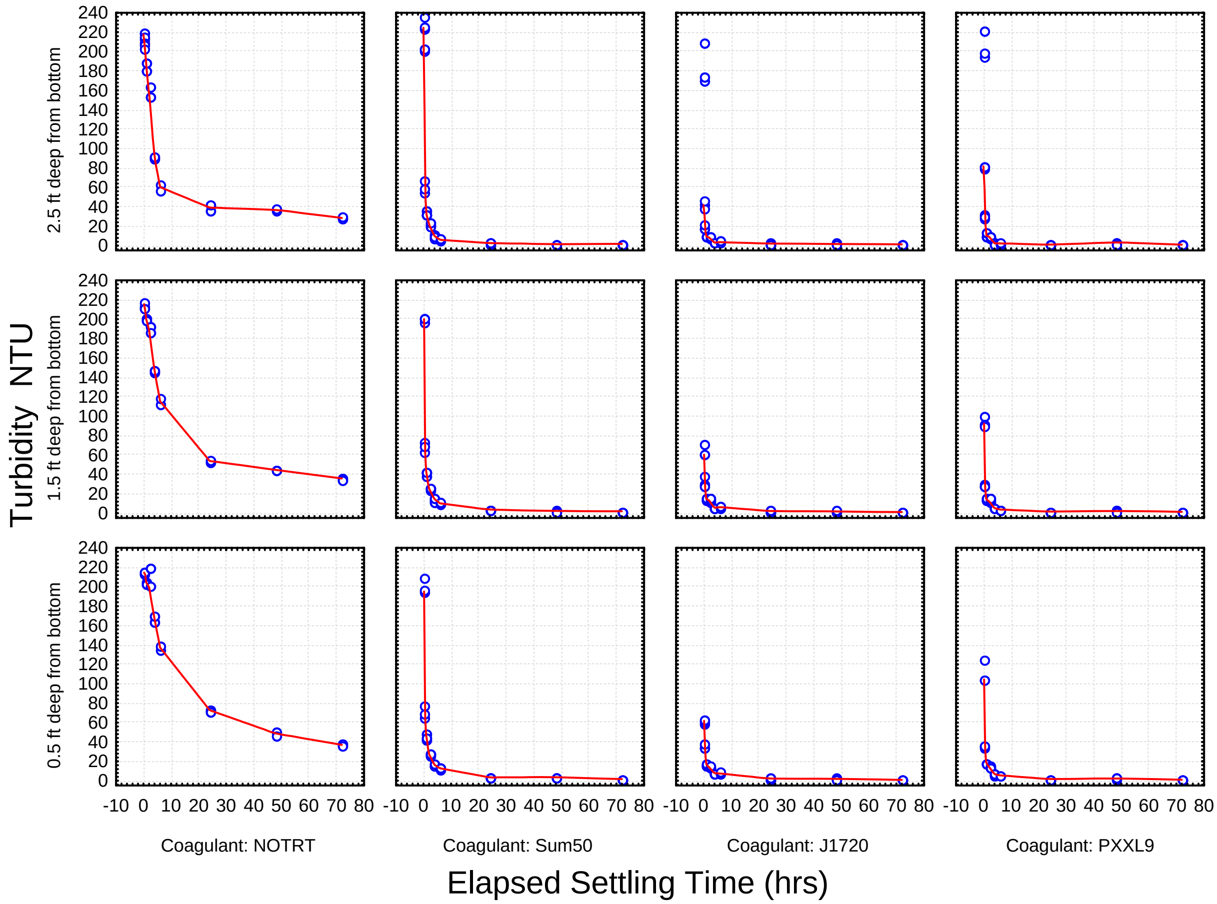
Table 9-2 Turbidity and Phosphorus Levels During Settling Column Test

	Elapsed Time (hrs)	No Treatment			Treatment								
					PXXL9			J1720			SUM50		
		Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N
Turbidity (NTU)	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
		Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N
Total P (ppm)	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
		Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N	Means	Std.Dev.	N
Filtered Total P (ppm)	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

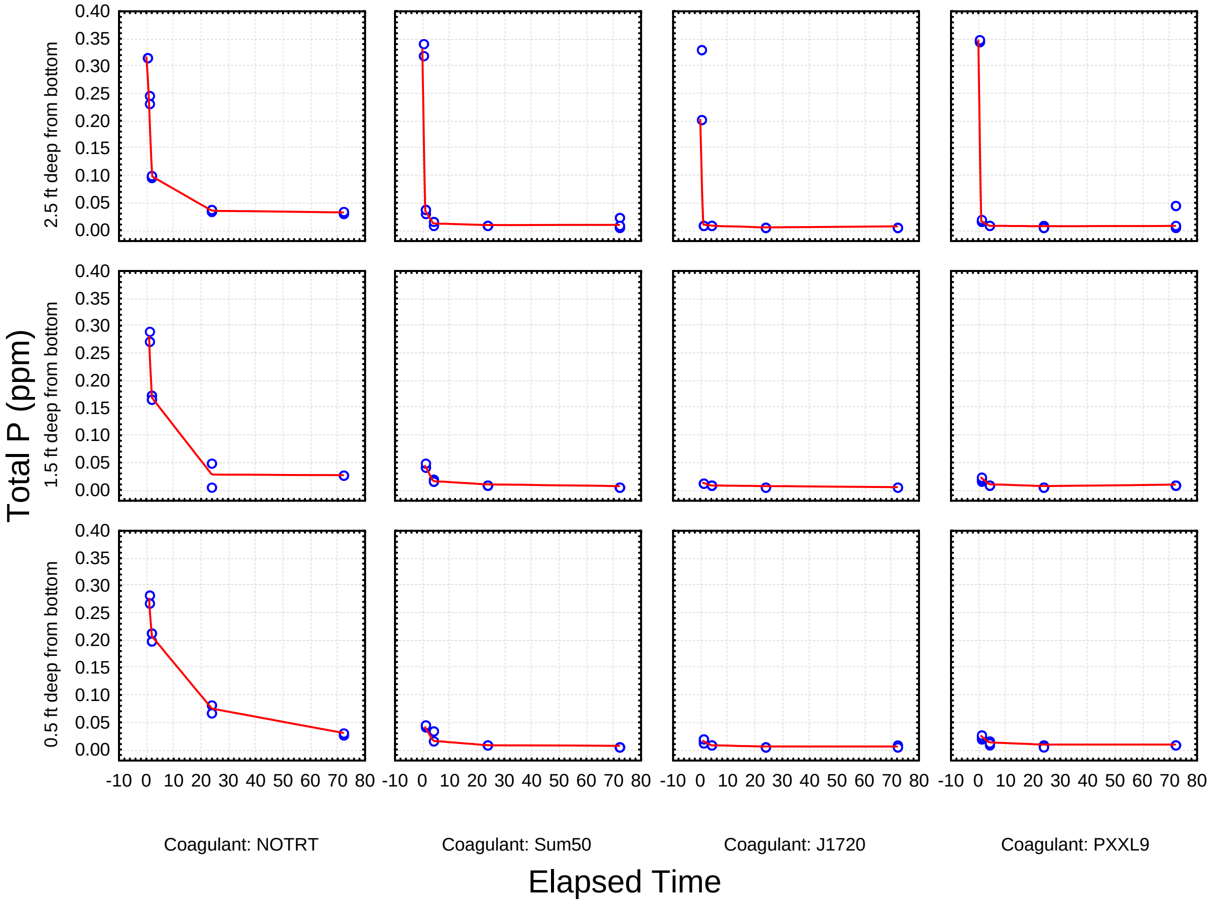
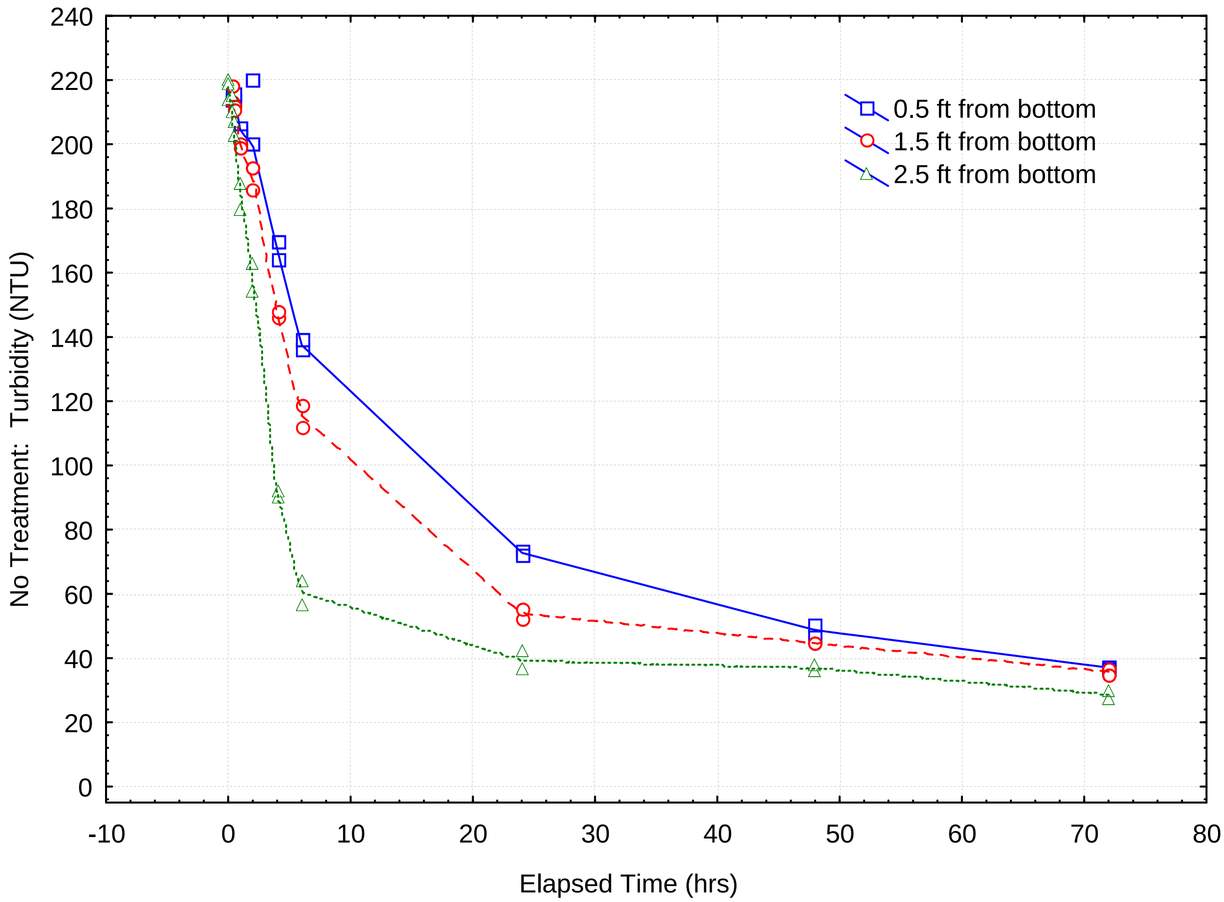


Table 9-3 ANOVA Analysis

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)

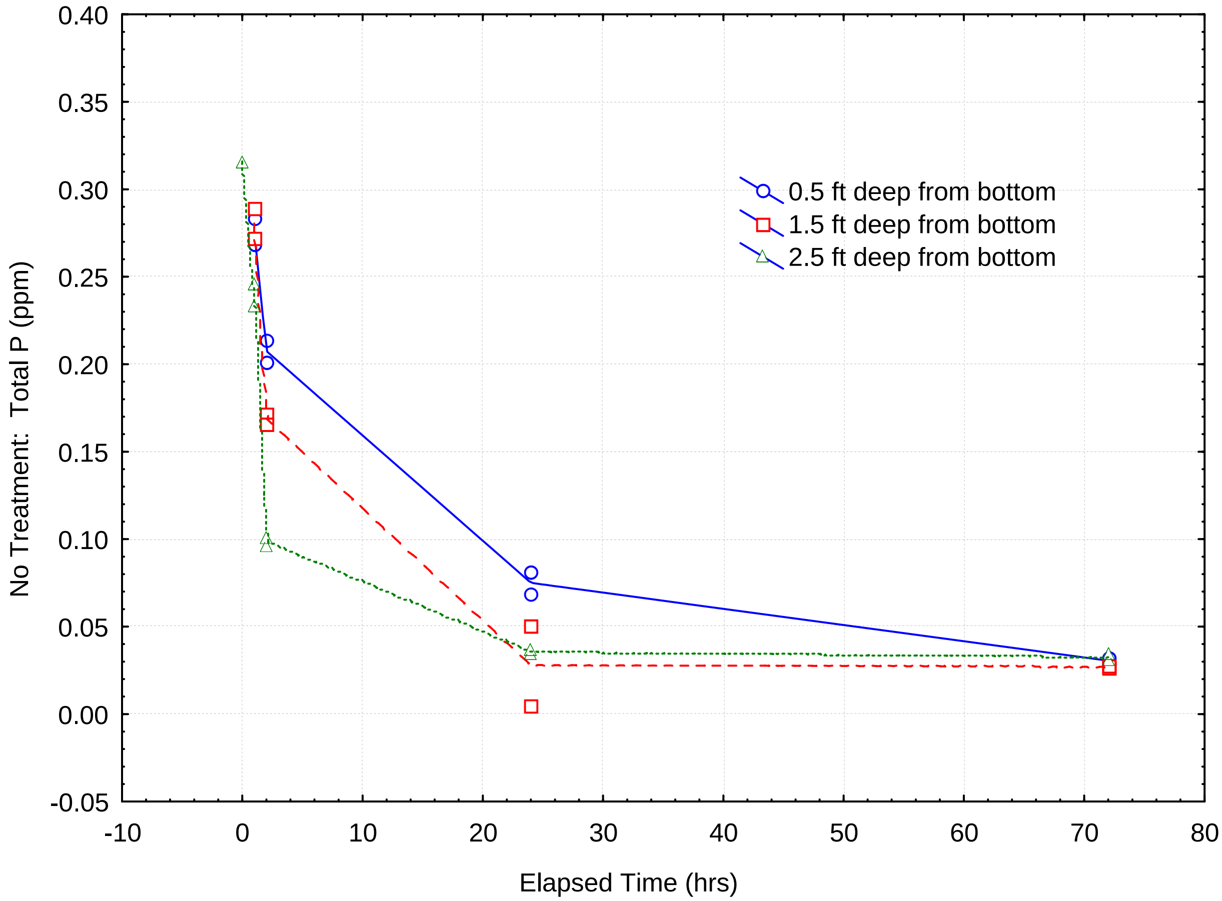


Figure 9-5 Turbidity at Different Depths for a PAX-XL9 Treated Storm Water

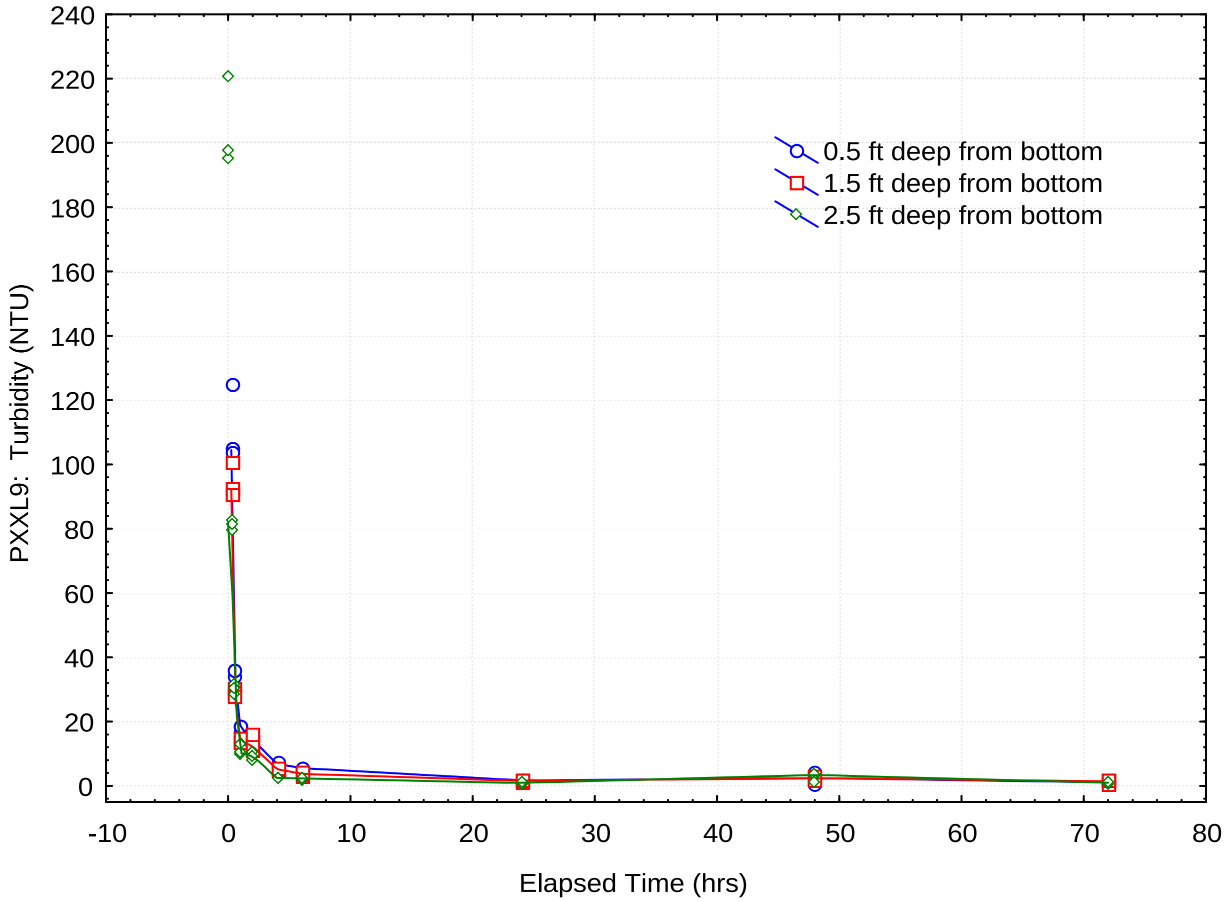
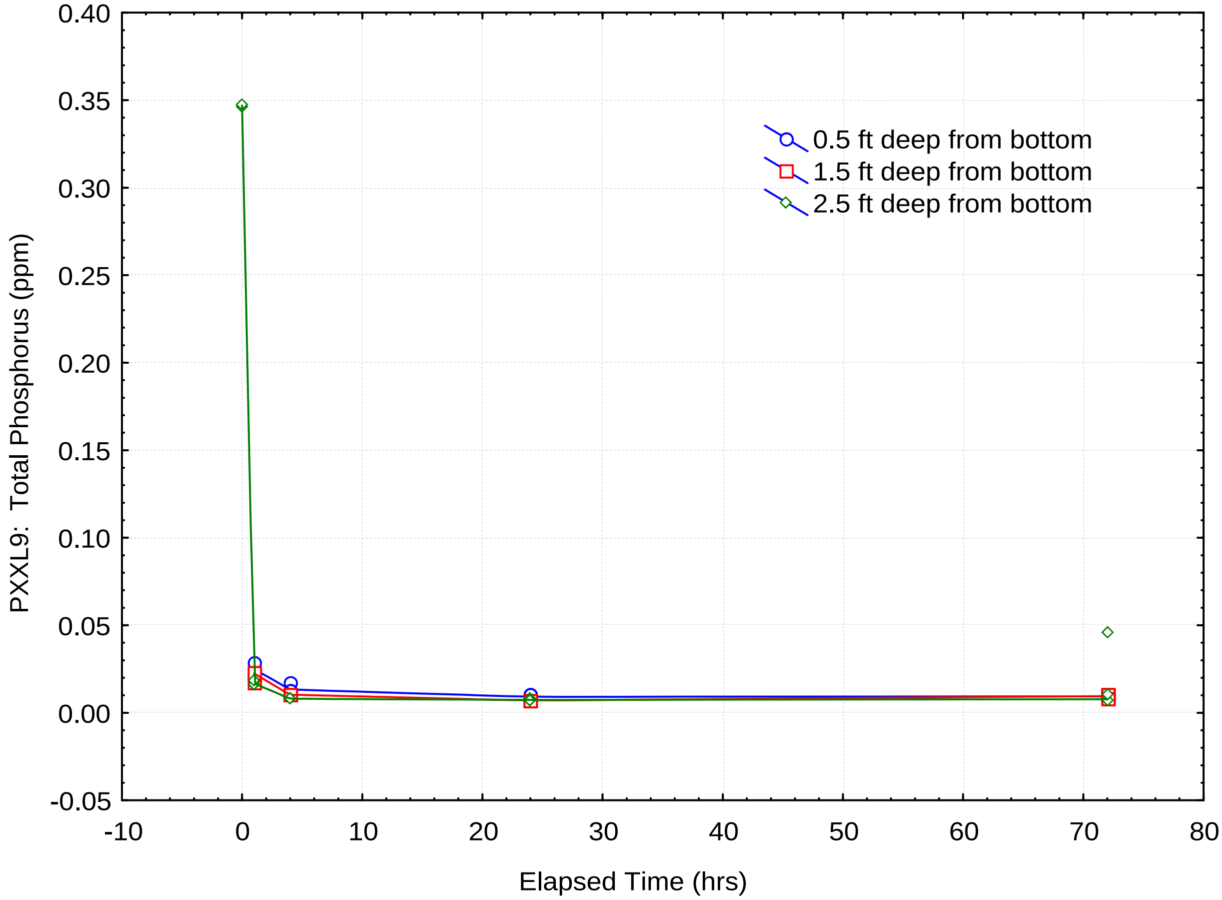


Figure 9-6. Total P at Different Depths for a PAX-XL9 Treated Storm Water



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 Environmental Research Center 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 Environmental Research Center.

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 Environmental Research Center 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.

Properties

DatasheetFontHeight:	8	DatasheetFontItalic:	False
DatasheetFontName:	Arial	DatasheetFontUnderline:	False
DatasheetFontWeight:	Normal	DatasheetForeColor:	33554432
DateCreated:	6/28/2004 1:26:30 AM	DefaultView:	Datasheet
Description:	Lists coagulants and there properties. 8 Jan 03 pamb.	GUID:	{guid {3FD13EDC-F2B0-44A1-9022-EEC88D4B03C8}}
LastUpdated:	4/18/2006 4:09:36 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	33	TabularCharSet:	0
TabularFamily:	34	Updatable:	True

Columns

Name	Type	Size
CoagulantCode	Text	255
CoagulantName	Text	255
Chemical Class	Text	255
Basicity Rank	Text	255
Al Rank	Text	255
Metal	Text	255
Group	Text	255
Generation	Double	8
Grouping	Text	255
Min Basicity	Single	4
Max Basicity	Single	4
Ave Basicity	Single	4
Min % Metal	Single	4
Max % Metal	Single	4
Ave % Metal	Single	4
Sulfate %	Single	4
Min pH	Single	4
Max pH	Single	4
Ave pH	Single	4
Min SG	Single	4
Max SG	Single	4
Ave SG	Single	4
Min % Al2O3	Single	4
Max % Al2O3	Single	4
Max NSF dose	Single	4
Vendor	Text	150
Caltrans	Text	50
NSF Designation	Text	150

Properties

DateCreated:	6/28/2004 1:26:30 AM	DefaultView:	Datasheet
Description:	Charge Titration Data for lab studies	GUID:	{guid {35AFB131-7CFB-41AD-A914-980A3BCA7070}}
LastUpdated:	2/22/2006 2:48:19 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	2855	Updatable:	True

Columns

Name	Type	Size
CTFilename	Text	50
CTRunID	Text	50
CTDate	Date/Time	8
RunNo	Integer	2
ExperimentType	Text	50
Experimenter	Text	50
CTMPTaskNo	Text	50
CoagulantCode	Text	50
SWCode	Text	50
ReplicatedRunCode	Integer	2
ProbeSerialNo	Text	50
StormwaterVol	Single	4
CTSampleID	Text	50
TimeFlag	Text	50
TimeEntered	Date/Time	8
SampleNumber	Integer	2
IncrVolAdded	Single	4
TotalVolAdded	Single	4
Dose ULCoag/L	Single	4
Dose MGCoag/L	Single	4
Dose MGMetal/L	Single	4
RoundedDose MGMetal/L	Double	8
SCV	Single	4
ZeroFlag	Text	50
SettlingTime	Single	4
pH	Single	4
Temperature	Single	4
Turbidity	Single	4
TurbidityAfterSettling	Single	4
Conductivity	Single	4
Comment	Memo	-
CoagulantName	Text	255
Chemical Class	Text	255
Basicity Rank	Text	255
Metal	Text	255
Min Basicity	Single	4
Max Basicity	Single	4
Ave Basicity	Single	4
Min % Metal	Single	4
Max % Metal	Single	4

Ave % Metal	Single	4
Sulfate %	Single	4
Min pH	Single	4
Max pH	Single	4
Ave pH	Single	4
Min SG	Single	4
Max SG	Single	4
Ave SG	Single	4
Min % Al2O3	Single	4
Max % Al2O3	Single	4
Max NSF dose	Single	4
Vendor	Text	150
Caltrans	Text	50
NSF Designation	Text	150

Properties

DateCreated:	6/28/2004 1:26:32 AM	DefaultView:	Datasheet
Description:	DANR Analyses for lab studies (jar tests)	GUID:	{guid {9C7B9BA2-9087-4F2F-933D-DC2ECD61D663}}
LastUpdated:	2/22/2006 12:35:19 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	178	Updatable:	True

Columns

Name	Type	Size
JTSampleID	Text	255
LabSampleID	Text	255
SampleID	Double	8
FilterFlag	Text	255
QCCODE	Text	255
TKN mg/L	Double	8
Sol Fe ppm	Double	8
Fe DQ	Text	255
Alkalinity	Double	8
Sol Al ppm	Double	8
Al DQ	Text	255

Properties

DatasheetFontHeight:	8	DatasheetFontItalic:	False
DatasheetFontName:	Arial	DatasheetFontUnderline:	False
DatasheetFontWeight:	Normal	DatasheetForeColor:	33554432
DateCreated:	6/28/2004 1:26:32 AM	DefaultView:	Datasheet
Description:	Data Qualifier descriptions	GUID:	{guid {BDC10D79-D7DB-4FE4-BF85-2FF3AE371EB1}}
LastUpdated:	2/22/2006 12:39:41 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	34	TabularCharSet:	0
TabularFamily:	34	Updatable:	True

Columns

Name	Type	Size
DQID	Text	50
DQdescriptor	Memo	-
ManualAutoFlag	Text	50

Properties

DateCreated:	6/28/2004 1:26:32 AM	DefaultView:	Datasheet
Description:	Field QAQC related to jar test (sample collection by jar tester)	GUID:	{guid {2DD4EB76-BBD9-4FF3-B650-2153C423CEFF}}
LastUpdated:	2/22/2006 12:43:34 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	121	Updatable:	True

Columns

Name	Type	Size
SubmittalNo	Text	50
COCNo	Text	50
RunID	Text	50
RunDate	Date/Time	8
JTSampleID	Text	255
ParaType	Text	255
CalcConc	Double	8
QCCode	Text	50
BlankConc	Double	8
DupConc	Double	8
AvgDupConc	Double	8
DupDiff	Double	8
Dup%RPD	Double	8
Dup%RSD	Double	8

Properties

DateCreated:	6/28/2004 1:26:33 AM	DefaultView:	Datasheet
Description:	Analytical Data for jar tests	GUID:	{guid {77F70F31-7F44-4229-929B-66855939232E}}
LastUpdated:	2/22/2006 2:05:24 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	2217	Updatable:	True

Columns

Name	Type	Size
SubmittalNo	Text	50
SubmittalDate	Date/Time	8
COCNo	Text	50
COCDate	Date/Time	8
COCLab	Text	50
ChemistID	Text	50
RunDate	Date/Time	8
RunID	Text	50
AnalysisOrder	Integer	2
AliasSampleID	Text	255
LabSampleID	Text	255
JTSampleID	Text	255
TrayNo	Integer	2
Analyte	Text	50
ParaType	Text	255
Value	Double	8
MeasurementUnit	Text	50
CalcConc	Double	8
ConcUnit	Text	50
Dilution	Double	8
QCConc	Double	8
SpikeConc	Double	8
QCCode	Text	50
DQQualifiers	Text	255
Comment	Text	255
PreCalAbs	Double	8
CalcR2	Double	8
AnalyticalMethod	Text	50

Properties

DateCreated:	6/28/2004 1:26:34 AM	DefaultView:	Datasheet
Description:	Experimental data for jar tests	GUID:	{guid {650CC252-C7BA-4FD3-8FD5-511543E30010}}
LastUpdated:	2/22/2006 2:11:39 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	1904	Updatable:	True

Columns

Name	Type	Size
JTFilename	Text	50
JTRunID	Text	50
JTDate	Date/Time	8
ExperimentType	Text	50
CTMPTaskNo	Text	50
StormwaterVol	Single	4
Rapid Mix RPM	Integer	2
Rapid Mix Duration	Integer	2
Slow Mix RPM	Integer	2
Slow Mix Duration	Integer	2
JTSampleID	Text	50
RunNo	Text	50
StartTime	Date/Time	8
ControlSampleID	Text	50
SWCode	Text	50
CoagulantCode	Text	50
CoagulantVolDose	Single	4
CoagulantName	Text	255
Chemical Class	Text	255
Metal	Text	255
Ave Basicity	Single	4
Ave % Metal	Single	4
Ave pH	Single	4
Ave SG	Single	4
Dose mgME/L	Single	4
Dose MGCoag/L	Single	4
SCV mV	Single	4
ReplicateNo	Long Integer	4
TimeSettled	Single	4
Turbidity	Single	4
pH	Single	4
Temp	Single	4
Comment	Memo	-

Properties

DateCreated:	6/28/2004 1:26:35 AM	DefaultView:	Datasheet
Description:	QAQC related to laboratory analyses of samples collected by jar tester personnel.	GUID:	{guid {4536FD63-D72F-4E1A-A65F-AB62ADD6CDC7}}
LastUpdated:	2/22/2006 2:14:17 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	1617	Updatable:	True

Columns

Name	Type	Size
SubmittalNo	Text	50
COCNo	Text	50
RunID	Text	50
RunDate	Date/Time	8
AnalysisOrder	Integer	2
TrayNo	Integer	2
JTSampleID	Text	255
ParaType	Text	255
CalcConc	Double	8
QCCode	Text	50
BlankConc	Double	8
StdConc	Double	8
Std%Rec	Double	8
Spike	Double	8
SpikeConc	Double	8
SpikeDupConc	Double	8
AvgSpikeConc	Double	8
Spike%Rec	Double	8
DupSpike%Rec	Double	8
Spike%RPD	Double	8
Spike%RSD	Double	8
DupConc	Double	8
AvgDupConc	Double	8
Dup%RPD	Double	8
Dup%RSD	Double	8
DupDiff	Double	8

Properties

DateCreated:	2/22/2006 1:59:28 PM	DefaultView:	Datasheet
Description:	Defines Parameters and their codes	GUID:	{guid {DB830ABB-36C7-4F6C-999F-46E640064B7E}}
LastUpdated:	2/22/2006 1:59:54 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	42	Updatable:	True

Columns

Name	Type	Size
ParaCode	Text	50
ParaDefinition	Text	255
Parameter	Text	50

Properties

DateCreated:	6/28/2004 1:26:35 AM	Description:	Defines QAQC terms
LastUpdated:	2/22/2006 12:39:52 PM	NameMap:	Long binary data
OrderByOn:	True	Orientation:	Left-to-Right
RecordCount:	20	Updatable:	True

Columns

Name	Type	Size
QCCode	Text	50
QAQCDescriptor	Text	200
Frequency	Integer	2
Comment	Text	150
Location	Text	150
Blank	Text	50
Spike	Text	50
Dup	Text	50
Standard	Text	50

Properties

DateCreated:	6/28/2004 1:26:35 AM	DefaultView:	Datasheet
Description:	Settling Column Data	GUID:	{guid {75798914-B1F3-4888-96B2-90C2165E82AF}}
LastUpdated:	2/22/2006 2:43:05 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	337	Updatable:	True

Columns

Name	Type	Size
Coagulant	Text	255
Date	Date/Time	8
Rack Set	Text	255
Elapsed Time	Double	8
Time Note	Text	255
Distance from bottom	Double	8
IntDist	Double	8
Distance Note	Text	255
Column	Text	255
Turbidity NTU	Double	8
UTP ppb	Double	8
FTP ppb	Double	8
Col height ft	Text	255
General Comment	Text	255
UAL	Double	8
UFE	Double	8
FAL	Double	8
FFE	Double	8
non filterable solid	Double	8
Alkalinity	Double	8
UTKN	Double	8
FTKN	Double	8

Properties

DateCreated:	6/28/2004 1:26:36 AM	DefaultView:	Datasheet
Description:	Results of analyses of real and synthetic stormwater	GUID:	{guid {25BC484D-8075-4495-A974-4B5F235414A7}}
LastUpdated:	2/22/2006 2:44:23 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	50	Updatable:	True

Columns

Name	Type	Size
JTFilename	Text	50
JTRunID	Text	50
JTDate	Date/Time	8
ExperimentType	Text	50
CTMPTaskNo	Text	50
StormwaterVol	Single	4
Rapid Mix RPM	Integer	2
Rapid Mix Duration	Integer	2
Slow Mix RPM	Integer	2
Slow Mix Duration	Integer	2
JTSampleID	Text	50
RunNo	Text	50
StartTime	Date/Time	8
ControlSampleID	Text	50
SWCode	Text	50
CoagulantCode	Text	50
CoagulantVolDose	Single	4
CoagulantName	Text	255
Chemical Class	Text	255
ReplicateNo	Long Integer	4
TimeSettled	Single	4
Turbidity	Single	4
pH	Single	4
Temp	Single	4
Comment	Memo	-
Min Basicity	Single	4
UTPppb	Double	8
UBGppb	Double	8
AdjUTP	Double	8
UTP>FTP	Text	255
FTPppb	Double	8
UTPDQ	Text	255
UTPComment	Text	255
UBGDQ	Text	255
UBGComment	Text	255
FTPDQ	Text	255
FTPComment	Text	255
ContTurb	Single	4
ContUTP	Double	8
ContFTP	Double	8

Turbo	Double	8

Properties

DateCreated:	2/22/2006 2:47:19 PM	DefaultView:	Datasheet
Description:	Summary of stormwaters created or used.	GUID:	{guid {10BB5C3E-38C2-4ABC-B387-AB77BDA7CE70}}
LastUpdated:	2/22/2006 2:47:30 PM	NameMap:	Long binary data
OrderByOn:	False	Orientation:	Left-to-Right
RecordCount:	12	Updatable:	True

Columns

Name	Type	Size
SWCode	Text	50
Type	Text	50
DateCreated	Date/Time	8
Stormwater source	Text	50