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16. Abstract
On December 1, 2009, the US Environmental Protection Agency (EPA) published a rule in the Federal Register establishing non-numeric and, for the first time, numeric effluent limitation guidelines (ELGs). The numeric ELGs included a turbidity limit of 280 nephelometric turbidity units (NTU) and sampling requirements for stormwater discharges from construction sites that disturb 20 or more acres of land at one time. At that time, the EPA required Texas to implement these new requirements when the Texas Commission on Environmental Quality (TCEQ) renewed their Texas Construction General Permit (CGP) in 2013. Due to litigation regarding the initial numeric ELG implementation, the EPA put numeric ELGs on hold in 2011 and on April 13, 2013, proposed to withdraw the numeric ELG as a requirement.

This project was initiated in 2010 to prepare the Texas Department of Transportation (TxDOT) for changes to the CGP regarding the monitoring and sampling of their construction site to meet the anticipated numeric ELG requirements. The scope of the project was modified due to EPA's actions. However, in light of anticipated future numeric limits, the project's monitoring and testing experiments proceeded to 1) determine "typical turbidity" representative of TxDOT's construction site discharges, 2) collect performance data on innovative erosion and sediment control measures that might be expected to achieve the discharge standard, and 3) provide update to TxDOT's Stormwater Managements Guidelines for Construction Activities.

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Effluent Limitation Guidelines, Stormwater, Turbidity, Flocculants, Coagulants, ELG, Erosion Control, Sediment Control

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

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INTRODUCTION

During the last two decades, there has been an increasing recognition by policy makers of water quality impairment issues associated with sediment laden stormwater discharge from construction sites. These issues led to several revisions and updates to the Clean Water Act of 1972. In December 2009 the US Environmental Protection Agency (EPA) issued new nationwide discharge and monitoring standards for construction site stormwater runoff. These new standards are the Effluent Limitations Guidelines and Standards for the Construction and Development Point Source Category, known as the C&G Rule (74 FR 62995, 2009) (*1*). These standards established non-numeric and, for the first time, numeric effluent limitation guidelines (ELGs) and new source performance standards to control the discharge of pollutants from construction sites. This new rule also specified that owners/operators of permitted construction activities must:

- Implement erosion and sediment controls.
- Stabilize soils.
- Manage dewatering activities.
- Implement pollution prevention measures.
- Prohibit certain discharges.
- Utilize surface outlets for discharges from basins and impoundments (*1*).

The 2009 C&G Rule required that all sites disturbing 20 or more acres of land at one time sample stormwater discharges and comply with a turbidity limitation of 280 nephelometric turbidity units (NTU). At the time of the 2009 C&G Rule, all state environmental agencies were required to incorporate these new regulations into their National Pollutant Discharge Elimination System (NPDES) permits for construction activities when their construction general permits (CGP) were re-issued. The Texas Commission on Environmental Quality (TCEQ) was set to renew its Texas Pollutant Discharge Elimination System (TPDES) CGP in 2013 and anticipated incorporating the numeric ELGs into its permit. The C&G Rule excluded projects covered under an individual permit rather than being covered under the TPDES permit. These new regulations would have been effective for any individual permit issued after February 1, 2010. In light of the anticipated new requirements, the Texas Department of Transportation (TxDOT) was preparing to meet the new regulatory requirements.

EPA's decision to regulate turbidity through a numeric standard was based on the agency's conclusion that turbidity is an "indicator pollutant," which will help identify other pollutants coming from construction sites (*1*). The numeric ELGs set forth in EPA's 2009 C&G Rule consisted of the following:

- Turbidity limit does not apply to stormwater discharges from storms that exceed the local two-year, 24-hour storm.
- On construction sites where the numeric limit applies, the rule requires contractors to collect numerous stormwater runoff samples from all discharge points during every rain event and measure the NTU level(s).
- If the average NTU level of the samples taken over the course of a day exceeds the "daily maximum limit" of 280 NTU on any given calendar day, then the site is in violation of the federal limitation requirement.

EPA supposed that this standard could be met with passive treatment technologies, rather than the advanced treatment systems, which EPA used as the technology basis for the draft limit of 13 NTU.

The ELGs mandated by the EPA were considered a technology 'floor' that all permittees would have been required to meet. As previously stated, each individual state regulatory agency would have been required to include these minimum performance standards in their re-issued construction general permit, and be allowed and encouraged to adopt more aggressive requirements if they chose to do so. This left a number of requirements and decisions to the authority of TCEQ.

As the EPA was preparing to make this new rule effective, they received petitions from the National Association of Home Builders (NAHB), the Utility Water Act Group, and the Wisconsin Builders Association for reconsideration of the rule. These petitions pointed out a potential error in the calculation of the numeric limit. After examining the dataset underlying the 280 NTU limit, EPA concluded that it improperly interpreted the data and, as a result, the original calculations used to establish the ELG were no longer adequate to support the 280 NTU numeric effluent limit. The progress of the C&G Rule is as follows:

- The EPA submitted a proposed rule to revise the turbidity limitation to the Office of Management and Budget (OMB) in December 2010.
- The EPA withdrew this proposal from OMB to seek additional performance data from construction and development sites.
- On January 4, 2011, the EPA acknowledged the error in calculating the 280 NTU effluent limit and issued a direct final rule staying the limit until corrected. Because the numeric limit for turbidity has been stayed, EPA and authorized states are no longer required to incorporate the numeric turbidity limitation and monitoring requirements into their permits.
- On September 2, 2011, EPA filed a status report with the court indicating that it withdrew the new numeric limit from OMB "to seek additional data on treatment performance from construction and development sites."
- In December 2012, NAHB and EPA settled this matter. EPA has agreed to propose a rule that vacates the numeric limit and modifies certain best management practice (BMP) requirements. Furthermore, EPA will finalize the rule by February 2014, at which time NAHB will formally drop its lawsuit (*2*).
- On April 1, 2013, EPA decided to vacate the numeric standard and to add provisions to improve the flexibility of the best management practices. EPA has added a definition for "infeasible" that has a two part focus: 1) whether a control is "technologically possible"; OR 2) whether it is "economically practicable and achievable in light of best industry practices" (*3*).

C&G RULE CHANGES AND PROJECT FOCUS IMPACTS

This research project was initiated to prepare TxDOT for the anticipated changes to the CGP regarding the monitoring and sampling of their construction sites to meet EPA's numeric ELG requirements. Another objective of this research project was to assist TCEQ with decisions regarding the monitoring, sampling, and site management requirements of the EPA C&G Rule by presenting the research results through TxDOT. Reducing sediment from stormwater runoff is extremely beneficial to the quality of water sources. There was little doubt that the new regulations mandated by EPA would have dramatically improved the nation's waters if developed and enforced correctly. Included in the original project objectives were the following:

- Develop monitoring/sampling protocols.
- Conduct statewide field testing to determine effectiveness of recommended practices and sampling protocols.
- Develop and conduct training/workshops for monitoring and sampling protocols.

TxDOT revised the project scope due to changes in the C&G Rule during the early stage of the project. The PMC eliminated the above listed tasks from the project scope as they were deemed premature at this time. However, there is still the generally accepted probability that the EPA will eventually implement a numeric limit of some sort. In that, TxDOT decided to continue with the data collection regarding construction site stormwater discharge and controlled testing of various coagulant materials. Three research institutes, Texas A&M Transportation Institute at College Station, the University of Texas at Austin, and Texas Tech University in Lubbock, collaborated on the statewide data collection and experimentation regarding differences in climate, soil types, slopes, and other factors that affect the performance of erosion and sediment control measures. The project focused on the remaining tasks:

- Review of literature and current state agency practices.
- Controlled testing of coagulants.
- Construction site field monitoring.
- Revision of TxDOT's *Stormwater Managements Guidelines for Construction Activities*.

One of the many issues regarding the sampling or monitoring requirements that may be promulgated by EPA in the future is the potential for substantial costs, direct and indirect, to permittees. These costs tend to be higher when associated to linear projects such as highways. The scale and geometric configuration of highway projects typically crosses multiple watersheds and, consequently, a large number of possible discharge locations. It may not be cost effective to monitor all stormwater runoff from most highway construction sites. For example, a typical 5-mile long TxDOT construction site might be required to collect and sample more than 50 different locations. Future monitoring and sampling protocols will need to address these issues.

LITERATURE REVIEW

STATE AGENCY CONSTRUCTION GENERAL PERMITS

There are a number of states that have adopted turbidity construction runoff standards. These states were identified to determine what these standards are and what practices have been used by the respective departments of transportation (DOT) to meet these requirements. At the time of the 2009 C&G Rule, authorized states were to incorporate the new rule requirements into their reissued CGP, including any applicable numeric limits. For states needing to finalize their CGP before the effective date of the corrected numeric limit, EPA advised them to issue their permit without the numeric limit. Table 1 lists the CGP expiration dates for each state. EPA encouraged these states to consider a shorter permit term in order to incorporate the corrected limit sooner than five years. For states finalizing their CGP after the effective date of the corrected numeric limit, but have to propose their permit prior to the effective date of the corrected numeric limit, EPA encouraged them to pursue an approach similar to the one EPA intends to follow so that they are assured of the ability to include the corrected limit in their final permit.

Table 1. State CGP Expiration Dates.

State	Expiration Year
South Dakota, Maine, Alabama, Michigan, Indiana, North Dakota, Pennsylvania, North Carolina	2009 or already expired
Connecticut, New York, Tennessee, Oregon, Washington	2010
Delaware, Wyoming, South Carolina, Vermont, Wisconsin, Arkansas, Kansas, Montana, New Hampshire, New Mexico, Idaho, Massachusetts	2011
Missouri, New Jersey, Colorado, Oklahoma, Nevada, Iowa, Hawaii, West Virginia, Nebraska	2012
Arizona, Ohio, Texas, Utah, Georgia, Illinois, Minnesota, Rhode Island, Maryland	2013
Florida, Kentucky, Virginia, California, Louisiana	2014

NUMERIC LIMITS BY OTHER STATES

While the EPA vacated their ruling on the numeric effluent limit for now, many states already initiated a numeric limit, sampling programs, and analysis for sediment-related pollutants. While the majority of states have not established a statewide standard, several states have their programs well underway. These existing program values range from percent total suspended solids (TSS) removal, NTU limits, pH range limits, and removal of pollutants compared to pre-construction levels. Many more states have established *post-construction* standards. A table listing each state and its current numeric standards for active construction sites is included as Appendix A. The researchers did not include monitoring/sampling requirements for impaired waters or specific water bodies such as cold water streams, etc.

TYPICAL RUNOFF TURBIDITY FROM CONSTRUCTION SITES

Previous studies showed a wide variance in runoff turbidity in roadway construction projects (*4, 5, 6*). Based on the literature reviewed, the values ranged from 10 to 28000 NTU. The California Department of Transportation (CALTRANS) monitored 15 highway construction sites over a period between 1998 and 2000 (*7*). They selected 15 monitoring sites to represent a wide range of CALTRANS construction site characteristics, considering construction type (e.g., roadway widening, new highway construction), construction activities (e.g., bridge, rail), sampling location, and BMP in place. Their study reported turbidity readings from 15 to 16,000 NTU with an average turbidity of 702 NTU.

McLaughlin's 2002 research (*8*) monitored three construction sites in North Carolina. The selected sites were constructed on 1:2 fill slope of loam, 1:4 cut slope of loam, and 1:4 fill slope of sandy loam, respectively. McLaughlin treated every site with two different surface controls—polyacrylamide (PAM) only and PAM+mulch+seed. Runoff turbidities from those six conditions varied from 11 to 5900 NTU through seven rainfall events. The sites treated with PAM+mulch+seed produced less turbid water than the sites of PAM only. For example in 1:4 cut slope site, the average turbidity was 2272 NTU in the PAM only site and 182 NTU in the PAM+mulch+seed site (refer to Appendix B for more detail).

McLaughlin and Jennings focused on the performance of erosion and sediment control measures on construction sites (*9*). For erosion control measures, they installed excelsior erosion control blanket, hydromulch, and straw on active construction sites and monitored runoff turbidities for four to six rainfall events by site. The maximum turbidity in the tests reached over 24,000 NTU. Sites treated with sediment control measures, including 14 types of sediment traps and basins, yielded 8 to 30,000 NTU of runoff. They also monitored final outlets discharging to nearby streams and found 116 to 2950 NTU of average daily turbidity (see Appendix B).

EXISTING CONSTRUCTION SITE SAMPLING PROGRAMS

California, Washington State and Oregon have established effluent limits and sampling procedures for their construction sites. Following is a brief description of each program.

California Construction Site Sampling Requirements

The California Environmental Protection Agency State Water Resources Control Board's Construction General Permit includes a risk-based permitting approach by requiring project site risk assessment (*10*). This risk assessment is based on two criteria:

- Project sediment risk is assessed based on site characteristics (slope steepness, soil type, etc.) and project scheduling (wet/dry season, construction work window, etc.). The Revised Universal Soil Loss Equation (RUSLE) is used to determine the sediment risk.
- Receiving water risk is assessed based on whether or not the receiving water is listed on 303(d) list, been released a total maximum daily load (TMDL) for sediment, or chosen as Cold/Spawn/Migratory.

The results of the two risk assessments classify the project site into risk levels 1 – 3 as shown in Table 2. Sampling and monitoring requirements are varied by risk levels.

Table 2. California's Project Risk Level Matrix.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="3">Sediment Risk</td></tr>
<tr><td>Low</td><td>Medium</td><td>High</td></tr>
<tr><td rowspan="2">Receiving Water Risk</td><td>Low</td><td>Level 1</td><td colspan="2">Level 2</td></tr>
<tr><td>High</td><td colspan="2">Level 2</td><td>Level 3</td></tr>
</table>

Visual Monitoring

All projects, regardless of risk level, require quarterly visual inspections at three levels—non-storm, storm-related, and post-storm. Non-storm inspections are conducted to check stormwater control devices. Storm-related inspections must be done by visually observing stormwater discharges at all discharge points within two business days following a rain event. Post-storm inspections must be conducted to recognize the effectiveness of stormwater control devices.

Effluent Monitoring

Sites selected as risk levels 2 or 3 require sampling and effluent analysis. Sampling must be conducted after a rainfall event over 0.5 inches at the time of discharge. The sampling requirements are as follows:

- Risk level 1 requires visual monitoring.
- Risk level 2 requires effluent sampling.
  - Turbidity: 250 NTU numeric limit
  - pH: 6.5 – 8.5
- Risk level 3 requires effluent monitoring and bio-assessment (limited cases).
  - Turbidity: 500 NTU numeric limit
  - pH: 6.0 – 9.0
- Risk level 2 and 3 monitoring
  - A minimum of three samples per day must be collected from discharge sites following a qualifying rain event (half inch or more at the time of discharge) (*10*).

Washington State Construction Site Sampling Requirements

The stormwater monitoring program of the Washington State Department of Ecology suggests the basics for site inspections and stormwater sampling. The program determines whether or not BMPs are working correctly and explains the proper protocol to measure the turbidity of discharge from construction projects.

Sampling Methods

The program suggests two methods to measure turbidity, 1) transparency tube method and 2) turbidimeter method. Water sampling is not required in construction projects that disturb less than one acre. Sites of one to five acres may use either method. Turbidimeter method is required for projects with disturbed areas greater than five acres. Construction projects that use 1000 cubic yards of concrete must sample for pH. Also, the Washington Department of Ecology may demand additional monitoring for projects that release into a 303(d) listed water body or designate a TMDL.

Turbidity and transparency samples are collected at all stormwater discharging points including ditches, pipes, drains, and detention/retention pond discharges. Samples for pH monitoring must be collected before discharge occurs. The program requires weekly sampling and within 24 hours of a rainfall when stormwater discharge occurs. This protocol intends to make all samples representative of the total discharge from the project site.

The program suggests three sampling methods—single grab sample, time-proportionate sample, and flow-proportionate sample. Any of these methods can be used as long as it achieves a representative sample of the stormwater runoff. Some principles for sampling are listed in the program such as:

- Use clean gloves and collection bottles.
- Avoid disturbing flow bottom.
- Avoid touching the opening of the bottle.
- Hold bottle to make flows come from upstream directly into the bottle.
- Stand downstream.
- Keep bottle lids off the ground.
- Label each sample instantly after collection.
- Capture a sample with a scoop in order not to disturb bottom settlements (*11*).

Visual Monitoring

The Washington State monitoring program requires visual inspection by experts for possible signs of erosion, suspended sediment, turbidity, discoloration, and oil sheen in stormwater runoff.

Oregon Construction Site Sampling

Oregon uses a 160 NTU benchmark for stormwater runoff turbidity on construction sites. Oregon Department of Environmental Quality's *General Permit National Pollutant Discharge Elimination System Stormwater Discharge Permit 1200-C* (*12*) includes analysis of the runoff turbidity from construction sites to determine if BMPs perform effectively to meet the turbidity benchmark. The permit describes minimum measurement requirements for the monitoring, including when and where measurements should be monitored, how samples should be collected, and what needs to be inspected.

The Oregon permit designates three major areas of interest for turbidity measurements on construction sites and requires corrective action if the turbidity is too high at these areas. These locations include:

- Locations where the discharge eventually leads to surface waters either directly or through a conveyance system.
- Fifty feet downstream from discharge points that lead to surface waters.
- Any place where the discharge into surface waters is greater than half of the width of the collecting water body (*12*).

Visual Inspection

Oregon requires visual inspection and turbidity measurement. The visual inspection of erosion and sediment controls is conducted differently depending on the site condition as follows:

- In active construction sites, visual inspection should be conducted every day when stormwater runoff exists.
- Visual inspection should be done once before the construction is completed or the site becomes inaccessible.
- When the site is inactive for longer than seven days, inspection should be done every other week.
- When the site becomes inaccessible due to severe weather, inspection is recommended once a day if possible.

Visual inspections should describe the color and clarity (turbidity). The color should be compared to nearby surface waters, and any sheen or floating material in the runoff should be visually inspected. If the site is inaccessible, inspection should be recorded downstream of the discharge point.

Sampling and Turbidity Measurement

Turbidity should be measured at all discharge points where stormwater flows directly or indirectly to surface water. At least one sample representative of the stormwater runoff should be collected at every monitoring point. A field turbidimeter should be used to measure turbidity.

Sampling frequency and condition is conducted once a week when stormwater runoff is present. Sampling instruction states that samples should be taken before the runoff reaches another body of water or substance in order to ensure the representativeness of samples. The permit suggests the grab sampling method and instructs that each sample collected over a period of time not to exceed 15 minutes.

CONTROLLED TESTING OF COAGULANTS

One sediment reduction treatment demonstrating much promise is the use of settling agents known as coagulants, such as polyacrylamide (PAM), chitosan, alum, and gypsum. When added to the stormwater flow these products reduce the charges on the colloidal clay suspensions allowing them to flocculate or clump/mass together and, therefore, settle out of suspension. The terms coagulation and flocculation are often used interchangeably; however, coagulants are the products used to destabilize the charged colloidal particles, and flocculation is the mixing of these products to promote the agglomeration of the stabilized particles. Research indicates that these agents can substantially reduce the turbidity of discharged stormwater.

Performance evaluations of coagulants were conducted at the Texas A&M Transportation Institute's (TTI) Hydraulics, Sedimentation, and Erosion Control Lab (HSECL), using an indoor rainfall simulator (erosion control tests) and a sediment retention device testing flume (sediment control tests). The Center for Transportation Research in Water Resources (CTR) at The University of Texas in Austin conducted laboratory tests using different soils and coagulants. Erosion and sediment control tests evaluated the field application performance of flocculants (PAM) used in conjunction with standard erosion and sediment control products. The objective of CTR testing was to develop an understanding of how soil characteristics and polymer properties affect the amount of turbidity reduction that can be achieved through flocculation.

EROSION CONTROL PERFORMANCE USING COAGULANTS

Facility and Equipment

The indoor rainfall simulator at the HSECL has two soil beds that can be adjusted to any desired slope up to 1:2 (or 50 percent). The rainfall simulator provides a water drop size distribution and impact velocity typical of severe storms that occur in Texas and the Gulf Coast regions of the country. The rainfall simulator is designed to subject test beds of selected soil fill to very destructive rainfall characteristics and high rainfall rates. Simulated rainfall is dropped from a height of 14 ft above the test bed which provides 85–90 percent terminal velocity with an average drop size of approximately 4.4 mm.

Researchers conducted erosion control performance evaluation tests using PAMs and rolled erosion control blankets in the HSECL indoor rainfall simulator. The test parameters were as follows:

- Test bed: 30 ft × 6 ft on 1:3 slope.
- Rainfall duration and rate: 30 minutes at 3.5 inches/hr.
- Soil type: clay (tests on sand plots were excluded because PAM is known as less effective on sandy soils).
- Soil moisture: less than 70 percent (determined by a Kelway model 36 moisture meter).

Researchers measured total sediment loss and turbidity from each test. Midway through the testing process researchers changed the turbidity measurement method from an automated monitoring system to a manual grab sampling. The initial automated system was designed to record turbidity at one minute intervals using the Hach SOLITAX® model TS-line sc (see Figure 1) in situ turbidity sensor. After recognizing that the flow rates from test runoffs were too low to acquire reliable readings from the sensor, researchers grabbed samples at five minute intervals and measured turbidity using the Hach 2100N turbidimeter shown in Figure 2. The total sediment loss was measured using a consistent protocol through the entire test procedure.

The Hach SOLITAX® model TS-line sc sensor was connected to a Hach model sc100 controller system. Datacom software available on the Hach website enabled the retrieval of the turbidity data from the controller system to a field laptop. Specifications of the turbidity sensor are as follows:

- Measuring range: 0.001 to 4000 NTU.
- Accuracy: less than 1 percent of reading or ±0.001 NTU, whichever is greater.
- Signal average time: user selectable ranging from 1 to 300 sec.

Figure 1. Hach SOLITAX® Model TS-line sc in situ Turbidity Sensor and Controller.

The specifications of the Hach 2100N turbidimeter used for the grab-sample tests are as follows:

- Measuring Range: 0 to 4000 NTU with ratio on.
- Accuracy: ± 2 percent of reading plus 0.01 NTU from 0 to 1000 NTU.
- ±5 percent of reading from 1000 to 4000 NTU.
- Lamp Type: Tungsten.
- Operating temperature range: 0 to 40°C.
- Regulatory: EPA method 180.1.
- Repeatability: ± 1 percent of reading or ± 0.01 NTU, whichever is greater.
- Resolution: 0.001 on lowest range.
- Response Time: 6.8 sec with signal averaging off; 14 sec with signal averaging on.
- Sample cell compatibility: 25 mm round; 12, 13, 16, and 19 mm round with optional adapter kit.

Figure 2. Hach 2100N Turbidimeter.

Materials and Methodology

TTI researchers evaluated the performance of PAMs for erosion control using the HSECL's indoor rainfall simulator where they compared PAM-treated conditions with non-treated conditions. Erosion control testing used two PAM products and three types of rolled erosion control blankets (ECB) (i.e., jute, excelsior, and straw) as shown in Figure 3. A total of eight treatments were tested as follows:

- Bare ground vs. PAM on bare ground.
- Jute ECB vs. PAM on jute ECB.
- Excelsior ECB vs. PAM on excelsior ECB.
- Straw mulch ECB vs. PAM on straw mulch ECB.

PAM products are generally recommended to use with ECBs because a sole application of PAM results in limited performance. This study tested the performance of two PAM products, PAM1 and PAM2, in conjunction with ECBs consisting of jute, excelsior, and straw.

PAM1 is an anionic polyacrylamide copolymer. Technical specifications are as follows:

- Viscosity: 2410 cps.
- Insoluble: 4–5 maximum.
- Residual acrylamide (ppm): < 500 (0.05 percent).
- Dry content percentage: 90.0 minimum.
- Anionic charge percent: 30 ± 1.0.

- Approximate molecular weight: 12–15 mg/mol.
- Maximum concentration: 5g/l.
- Recommended application rate: 9 lb/acre (1:3 slope).

PAM2 is another anionic linear copolymer of acrylamide. The specification for this product is as follows; however, some proprietary information (including anionic charge percent and molecular weight) was not made available by the manufacturer:

- Bulk density: 40–50 lb/ft^3.
- Percent moisture: 15 percent maximum.
- pH 0.5 percent Solution: 6–8.
- Recommended application rate: 20–35 lb/acre (1:3 slope, clay soil).

The jute ECB used was 100 percent polypropylene. Its technical information is as follows:

- Polypropylene 1/8 inch square mesh.
- 2.5 oz/yd^2.
- Multifilament and tape yarn weave.
- Photo degradable.

The excelsior ECB consists of a 100 percent certified weed free straw matrix stitched to a single net. Its technical information is as follows:

- Stitch spacing: 2 inches on center.
- Unit weight: 8.0 oz/yd^2.
- Thickness: 0.28 inch.
- Tensile strength, MD: 4.8 lb/inch.

The straw ECB used is a 100 percent agricultural straw blanket with straw fibers stitched between two photodegradable nets using photodegradable thread. Its technical specifications are as follows:

- Mass/unit area: 8.3 oz/yd^2.
- Tensile strength: 75 lb/ft.

- Thickness: 0.25 inch.
- Light penetration: 16 percent.
- Water absorption: 461 percent.
- Elongation, MD: 21.6 percent.
- Permissible shear stress: 1.75 lb/ft.
- Permissible rate of flow: 6 ft/sec.

(a) Jute ECB	(b) Excelsior ECB	(c) Straw ECB

Figure 3. Tested Erosion Control Blankets.

Table 3 presents the PAMs and erosion control blanket application specifications. PAM1 was applied with excelsior blanket and straw blanket, and on bare soil. These treatments were applied in liquid form using a hydroseeder because the application rates were not great enough for broadcast treatment. PAM2 was applied with the jute ECB. Since PAM2 caused clogging of a hand-held hydroseeder, researchers broadcasted the PAM2 powder on the jute ECB netting.

Table 3. PAM Application Specifications.

Treatment	PAM Application Rate	PAM Application Method
PAM1	9 lb/ac	Hydroseeder
PAM1 + Excelsior ECB	9 lb/ac	Hydroseeder
PAM1 + Straw ECB	9 lb/ac	Hydroseeder
PAM2 + Jute ECB	25 lb/ac	Broadcast

Performance Test Procedure

The TTI research team conducted the following procedures for the preparation of the soil filled test beds, installation of materials, and rainfall simulation process:

- Till soil-filled test bed and bring to a saturation point of less than 70 percent.
- Level the test bed using heavy equipment and a pipe drag. When leveled, compact the test bed soil fill cross-slope using a 150-lb hand roller. When last measured with a nuclear density meter in 2010, clay compaction was 89.3 percent of optimal density.
- Install test materials using exact manufacturer's instructions for staple pattern and/or rate per acre for spray on products. For this study, researchers applied the PAM products using a broadcast or hydroseed method.
- Test ECB materials the same day of installation.
- Roll the prepared test bed into the rainfall simulator and lift into position (1:3 slope) using the overhead drum hoist.
- Conduct simulated rainfall for 30 minutes per test bed at a rainfall rate of 3.5 inches per hour (198 gallons water added for each test).
- Collect all water and sediment using containers or collection sacks.
- Allow collected water and sediment to settle overnight to enable the separation of the water and sediment.
- Decant and weight the separated water for each container.
- Collect three random 1 pint grab samples from the sediment containers after weighing and take these samples to the HSECL index testing laboratory to completely dry to determine the percent moisture content.
- Subtract the moisture percentage of the grab samples from the total sediment loss weight. For example a dried 100-lb sample of sediment had 25 percent water. Subtract the 25 percent from the total batch weight. Record the 75-lb dry weight as actual soil loss.
- Repeat the process after a 24-hour waiting period from the previous rainfall test. Repeat the exact same rainfall test and subsequent soil weighing and moisture determination process two more times for two consecutive days on each of the test beds. The testing process consists of three simulated rainfall events on three consecutive days.

- Combine the dry sediment loss from all three tests to determine total soil loss.
- Average the soil loss from all three rounds to determine a final total sediment loss.

Figure 4 shows an example of how the erosion control testing uses the in situ turbidity sensor on a weir box to collect turbidity and flow rate data automatically.

Figure 4. Erosion Control Performance Tests Using Coagulants.

Results

Results showed that PAM did not perform well on 1:3 clay soil slopes. Maximum turbidities of all tested ECB treatments were very high, ranging from 3450 to 9037 NTU. The turbidity of the effluent from the bare soil plot reached 52857 NTU. Average dry soil losses overall agreed with turbidity results (see Table 4).

The efficiency of PAM could not be determined with these tests. Although PAM showed a lower turbidity and average dry soil loss on bare soil and excelsior ECB than untreated counterparts, the differences were negligible considering their higher turbidities. Furthermore, PAMs performed worse on the jute and straw ECBs. This result was unexpected because a straw ECB is typically considered as an excellent performer in clay soil slope control (see Table 5).

Table 4. Maximum Turbidity from Erosion Control Performance Tests.

Surface Condition	No PAM Treated	PAM Treated	Difference
Bare soil	52857 NTU	51987 NTU	−870
Jute ECB	over 4040* NTU	over 4040* NTU	NA
Excelsior ECB	3603 NTU	3450 NTU	−153
Straw ECB	4180 NTU	9037 NTU	+4857

* over the capacity of the in situ turbidity sensor

Table 5. Average Dry Soil Loss from Erosion Control Performance Tests.

Surface Condition	No PAM Treated	PAM Treated	Difference
Bare soil	175.50 lb	163.10 lb	−12.40
Jute ECB	17.25 lb	19.05 lb	+1.80
Excelsior ECB	6.97 lb	5.43 lb	−1.54
Straw ECB	0.40 lb	10.17 lb	+9.77

Several potential reasons came from the observation of tests. First, broadcast application might limit the efficacy of PAMs. The PAM2 hand-broadcasted on the jute ECB did not develop obvious flocculation during the tests; consequently, the dry soil loss of its effluent was nearly equivalent with the untreated jute ECB. However, the PAM1 applied with the hydroseeder on straw ECB created very viscous flocculation from the plot surface to the outlet. It was expected that those flocculated sediments were stuck into the straw ECB, but in reality, the sediment clogs appeared too heavy to be held on the blanket surface, particularly with the heavy design storm (3.5 inches/hr). Also, the PAM1 appeared to facilitate more flocculation by softening surface soil.

SEDIMENT CONTROL PERFORMANCE TESTING USING COAGULANTS

The performance of PAM in sediment controls or sediment retention devices (SRD) was evaluated by comparing a PAM-treated wattle with non-treated wattle. Tests were conducted at the HSECL using the SRD flume.

Facility and Equipment

The SRD flume has a 12-ft upper flume and a 2-ft lower flume as shown in Figure 5. The soil-filled area is 4-ft wide soil-filled and is used to install the material according to manufacturer's specifications. The reservoir is a 1600-gal polypropylene cylindrical tank with a conical hopper bottom with a 6-inch butterfly valve. A 3-phase electric motor and double mixing paddles ensure proper mixing of the sediment-laden test water. The reservoir continually mixes slurry of well-graded artificial sediment. Turbidity meters monitor influent and effluent concentrations. Flow meters monitor influent and effluent flow rates. The SRD flume is made up of three distinct zones: the retention zone, the installation zone, and the collection zone. The overall length of the channel is 18 ft.

- The retention zone is a longitudinal section of a cylinder 25 ft in diameter 12 ft long, and 15 ft wide with a maximum depth of 2.5 ft. The channel maintains a constant 3 percent slope. The concrete flume has a waterproofing grout surface.
- The installation zone is a 4-ft opening between the retention zone and collection zone with metal sliding gates on either side. The installation zone can be filled with any type of test soil. The proposed soil for testing SRD's is high plasticity index (PI) clay. The surface of the clay in the installation zone was shaped to match the profile of the channel.
- The designed shape of the collection zone matches the retention zone except it is only 2 ft long. The collection zone provides an area to channel the flow toward the collection and monitoring system.

Figure 5. Sediment Retention Device Testing Flume.

Turbidity is measured with the Hach SOLITAX® model TS-line sc in situ turbidity sensor connected to the Hach SC100 controller.

Two ISCO® model 4230 bubbler flow meters monitored the flow at inlet and outlet of the SRD flume. This bubbler flow meter uses an internal air compressor to force a metered amount of air through a bubble line submerged in the flow channel. The flow level is accurately determined by measuring the pressure needed to force air bubbles out of the line. Its brief specifications are as follows:

- Range: 0.1 to 10 ft.
- Level measurement accuracy: ±0.005 ft from 0.1 to 5.0 ft.

Materials and Methodology

The tested wattle was a composite of wood fibers and crimped man-made fibers encased in a heavy duty, knitted cylindrical tube as shown in Figure 6. The design capacity and ponding volume of tested wattles are as follows:

- Height: 4.25 inches.
- Design capacity: 65 gal.
- Ponding volume: 59–63 gal (non-treated) and 66 gal (treated).

Figure 6. Wattle Used for Performance Testing.

The tests controlled the mass loading of inflow and measured the difference in the mass loading of outflow. The controlled properties of the inflow are as follows:

- Sediment: Silica (Sil-Co-Sil® 49) 12.5 lb and ball clay 12.5 lb.
- Water volume: 70 gal.
- Slurry concentration: 2000 mg/L.

The mass loading of outflow was estimated using flow rate and turbidity monitored at the one minute resolution. The following data was recorded and calculated for each product evaluation:

- Flow-through rate (cfs).
- Maximum flow rate at gallons per minute (gpm).
- Ponding volume (gal).
- Turbidity (NTU) at inlet and outlet.
- Suspended sediment concentration (SSC) (mg/L) at inlet and outlet.
- Mass loading (lb).
- Removal efficiency as percentage.

Performance Test Procedure

The TTI research team conducted the following procedures for the preparation of the SRD flume, installation of materials, and flume flow process. Table 6 shows the results of the SRD flume tests using the treated and untreated wattles.

- Researchers cleaned the SRD flume and resurfaced the soil in the installation zone to match the flume profile.
- The SRD was installed in the installation zone according to manufacturer's instructions.
- The turbidity probes and bubbler tubes were connected to the appropriate locations at inlet and outlet.
- A mix of 12.5 lb of SIL-CO-SIL®49 and 12.5 lb of ball clay was placed in 1500 gal of water to create sediment-laden water having a SSC of 2000 mg/L. The sediment laden water was continually stirred in the mixing tank throughout the test.
- The water slurry was released into the flume, at a flow rate defined by the SRD flow category, by controlling the butterfly valve on the mixing tank. The entire 1500 gal of sediment-laden water was emptied into the flume.
- The test monitoring continued until there was no water retained behind the SRD.
- Three repetitions of this test were conducted on SRD before removing it from the installation zone.

Table 6. Design Capacity and Ponding Volume of Wattles.

Sediment Retention Device	Test Round	Height Inches (cm)	Design Capacity Gal (L)	Ponding Volume Gal (L)
Wattle – untreated	1	4.25 (10.8)	65 (246)	59 (223)
	2	4.25 (10.8)	65 (246)	60 (227)
	3	4.25 (10.8)	65 (246)	63 (238)
Wattle – treated	1	4.25 (10.8)	65 (246)	66 (250)
	2	4.25 (10.8)	65 (246)	66 (250)
	3	4.25 (10.8)	65 (246)	66 (250)

CONTROLLED COAGULANT TESTS

Recent field use and research indicates that soil characteristics have an important bearing on the effectiveness of specific coagulants and that no single type is effective in reducing sediment from all sediment sources. For coagulants to be effective on TxDOT construction sites laboratory testing determined effectiveness and dosing of various coagulants for various soil types. Researchers conducted tests on a variety of soil types representative of those encountered statewide in highway construction projects. The coagulants evaluated included a variety of polymers, chitosan, and other chemicals.

Soil Sampling

Seven soil samples were collected at highway construction sites from across the state of Texas through collaboration with The University of Texas at Austin, Texas A&M Transportation Institute, and Texas Tech University. Grab samples of soils were collected from spoil piles. The spoil piles are representative of the fill material typically used in the construction of highways and are most vulnerable to being transported in the stormwater runoff from construction sites. Midwest Laboratories, Inc. (Omaha, Nebraska) analyzed the properties of these seven soil samples as shown in Table 7. As is standard practice in soil analysis, the designation of sand, silt, and clay is based on the weight percent in various particle size ranges, with sand being all material > 62.5 µm, clay being all material < 2 µm, and silt being everything in between.

Table 7. Selected Properties of Soils Used in Laboratory Tests.

Sample	pH	Ca (mg/ kg)	Mg (mg / kg)	CEC[a] (meq / 100g)	Organic Matter (%)	Sand (%)	Silt (%)	Clay (%)
183ANBC	8.2	4618	149	24.9	1.1	28	36	36
College Station	9.28	3956	231	22.2	1.6	38	40	22
W Loop	8.3	3222	434	20.7	0.7	52	28	20
127 Lub	7.8	2066	509	16.6	0.7	58	22	20
Hearne I	4.8	1195	371	17.8	1.5	18	30	52
Hearne II	7.8	569	64	3.5	0.2	86	6	8
E Texas	5.0	621	134	7.4	0.5	60	12	28

[a] Cation exchange capacity

Modified Synthetic Stormwater Runoff

A modified synthetic stormwater runoff was created for each soil sample such that it had a turbidity of 1500 NTU (±300 NTU). The turbidimeter used for synthetic runoff and jar tests was a Hach Ratio/XR Turbidimeter (Hach Company, Loveland, CO) and has an upper limit of 2,000 NTU. Therefore, 1500 NTU was selected as a standardized value, so that a comparison could be made between modified synthetic runoff of similar initial turbidities. By creating a set of samples with similar turbidity but from different soil types, the laboratory evaluation could focus on the effects of the soil characteristics directly and exclude the effects of overall particle (mass) concentration.

The modified synthetic stormwater runoff was prepared through an iterative approach.

- A six liter soil suspension of 15 g/L was prepared in the decanter shown in Figure 7.
- This soil suspension was then rapid mixed mechanically for five minutes.
- The suspension was then allowed to settle for 2 minutes and 37 seconds. This time allows large particles that would typically settle out quickly in runoff to settle out of the modified synthetic stormwater runoff being created. Accounting for Stokes' Law and the height of the ports on the decanter, 2 minutes and 37 seconds should allow all particles 25 µm and larger to settle out of the suspension.

- A sample of the soil suspension was then taken and measured for turbidity. If the soil suspension's turbidity was less than 1,200 NTU, then a known amount of soil was added to the suspension and the process was iterated.
- This process was repeated until the soil suspension's turbidity fell within the specified range of 1,200 to 1,800 NTU.
- Once this target turbidity was obtained, the process was iterated one more time without adding any soil and after 2 minutes and 37 seconds, the soil suspension was decanted into a large storage container.
- This process was repeated at least three times such that over nine liters of modified synthetic stormwater, runoff was created for each soil for use in laboratory tests.

Figure 7. Decanter Used to Remove Large Particles from Soil Suspension.

Flocculants

The nine flocculant products used in this study covered a range of molecular weights and charge densities (see Table 8). The molecular weight of the polyacrylamides ranged from 0.2 to 14 mg/mol, and the charge densities ranged from neutral to 50 percent anionic molar charge. Cationic PAM products were not included in this study due to their toxicity to aquatic life. Researchers included a cationic polymer, chitosan, in this study due to its effectiveness as a positively charged polymer. Stock solutions of PAM (0.1 g/L and 10 g/L) were prepared with DI water and stirred for 24 hours at room temperature.

Table 8. Molecular Weight and Charge Density of Flocculants.

PAM Type	Molecular Weight (mg/mol)	Charge Density (%)
SF N300	15	Neutral
LMW SF N300	6	Neutral
A 110	10-12	16
A 130	10-12	33
A 150	10-12	50
A 110 HMW	10-14	16
Cyanamer P-21	0.2	10
Chitosan	NA	Positive
APS #705	NA	NA

Test Procedure

The research team used a Dekaport Cone Sample Splitter (Rickly Hydrological Company, OH) to create homogeneous samples of the modified synthetic runoff for each individual jar test. The large collection container was mixed well, and the contents were poured into the top of the splitter. The splitter divided the modified synthetic runoff into 10 Erlenmeyer flasks. From these flasks, 200 mL of modified synthetic runoff were measured and poured into the jars for testing. The jars were specially constructed from acrylic, with a square cross-section 5.15 cm (2.03 inches) per side. Mixing was provided through a standard jar test apparatus (Phipps and Bird, Richmond, VA) with paddles cut down to a length of 3.4 cm (1.34 inches).

The jar tests comprised a rapid mix, slow mix, and settling period. The tests performed in this study emulated the conditions that are likely to be encountered in the field as well as possible; these conditions generally mean very short detention times in any treatment unit. Therefore, the duration of rapid mix, slow mix, and settling period were much shorter than a typical jar test done for drinking water treatment. The process was as follows:

- Each jar was rapidly mixed on a magnetic stirrer for one minute to ensure that all of the particles were suspended prior to the start of the jar test.
- The initial turbidity was then measured on a sample.
- A specific dose of flocculant was then added during the rapid mix (1000 rpm) on a magnetic stirrer for 15 seconds.
- The jar was then moved onto the jar test apparatus where it was slow mixed (60 rpm) for 5 minutes.

- The slow mix was followed by a 5 minute settling period.
- After this time, the final turbidity was measured on a sample taken from the top 2.5 cm of the jar.

A matrix of jar tests tested each modified synthetic stormwater runoff with each type of polymer. For each combination, a series of jar tests was run with polymer doses of 0.03, 0.1, 0.3, 1.0, 3.0, and 10.0 mg/L to determine the effect that dose had on the resulting turbidity. In some circumstances, jar tests were run with higher doses up to 300 mg/L to determine the dose at which overdosing occurs. A control with no polymer added was also included for each suspension.

CONSTRUCTION SITE FIELD MONITORING

The objective of the field monitoring portion of this project was to develop an understanding of typical turbidity values of runoff from highway construction sites as a function of site conditions and rainfall characteristics. To accomplish this objective, research teams monitored eight active TxDOT construction sites located in the Austin, Bryan, College Station, Hearne, and Lubbock areas to determine the level of turbidity reduction the current TxDOT measures achieved. This geographic distribution of monitoring sites ensured that most environmental aspects located in geographically different areas of the state were examined. The research teams from Texas Tech University and The University of Texas coordinated sampling in Lubbock and Austin areas, respectively. The research team from Texas A&M Transportation Institute conducted monitoring and sampling in the College Station, Bryan, and Hearne areas.

This monitoring task can be classified into two stages. Initially during 2010 to 2012, researchers collected samples using the grab sample method from EPA's and other states' stormwater sampling guidelines recommendations. After recognizing the limitations of these grab sampling methods, such as significantly different turbidity readings by collection time and runoff flow rate, the researchers switched to an automatic sampler at one site. The turbidity reading protocol was also changed between the two stages. The initial protocol did not estimate turbidity value over 4,000 due to the capacity of the Hach 2100N turbidimeter. The later protocol estimated these values using a dilution method to determine turbidity when high turbidity values were observed.

STUDY AREAS

Austin

The CTR research team collected runoff samples from three highway construction projects in the northwest suburbs of Austin, Texas, between November 2010 and March 2012. The three construction projects are listed below:

- Austin Project 1 located on the eastbound shoulder of FM 1431 near the crossing with Spanish Oak Creek added an additional traffic lane and shoulder to an existing road.

- Austin Project 2 located along FM 2769 west of RR 620 converted an existing two-lane rural road into a four-lane road divided by a median.
- Austin Project 3 was the extension of US 183A in Cedar Park that constructed a new controlled access highway.

Lubbock

The Texas Tech team collected runoff samples from discharge points located on two TxDOT sites chosen in the Lubbock area (see Figure 8 and Figure 9) as follows:

- Lubbock Project 1 located on the Marsha Sharp Freeway had a watershed area of approximately 160 acres with one discharge point.
- Lubbock Project 2 located on the West Loop 289 had a watershed area of approximately 52 acres.

Figure 8. Lubbock Project 1 – Marsha Sharp Freeway.

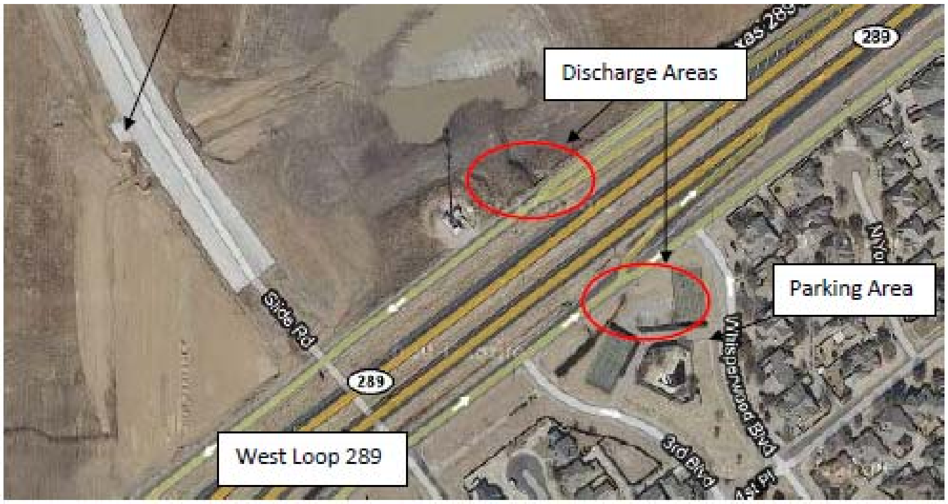

Figure 9. Lubbock Project 2 – West Loop 289.

For the Lubbock Project 1 at the Marsha Sharp Freeway location, rills in the slope led to a playa lake in Mackenzie Park. Researchers collected samples when water flowed in these rills. In most cases, when the storm did not produce enough rain for adequate runoff, puddles formed at the bottom of the slope around a culvert or silt fence. When necessary, researchers collected the samples at this location. Figure 10 shows the changes to the site over the course of the project. The culvert at the Lubbock Project 1 location connected to the playa at the end of sample collection no longer provided a puddle that allowed for collection at the beginning of the project. Instead, researchers collected from puddles behind silt fences.


Figure 10. Lubbock Project 1 Discharge Locations.

At the Lubbock Project 2 West Loop 289 location researchers collected samples on the side that flowed into the playa, just where the water left the culvert and entered the stream bed.

This site was difficult to reach at times and required the use of a pole to reach the runoff stream. The other side of the Lubbock Project 2 discharged toward the neighborhood tennis courts. Researchers collected grab samples as the water left the two culverts and formed puddles. The Lubbock Project 2 location resulted in at least three samples collected for each rainfall event.

Figure 11 shows the actual discharge locations where sample collection began and when testing ended. Site conditions changed between beginning and end of sample collection, which resulted in slight changes of how and where to take samples safely. Initially the culvert at the Lubbock Project 2 location to the playa had a bare earth channel bottom. At the end of sample collection the culvert had a gabion cover requiring the sampling personnel to use a pole to collect a sample inside the culvert.

Figure 11. Lubbock Project 2 Discharge Locations.

College Station

The College Station research team collected runoff samples from a highway construction site located at the intersection of FM2818 and FM2154 in College Station, Texas (CS Project). The CS Project consists of three watersheds. Two of them flow to natural creeks, and the third flows to a nearby housing construction site.

CS Project Watershed 1 is a 4.21 acre drainage area equipped with a 1000-ft long vegetated swale and a 0.2 acre detention basin. The vegetation in this drainage area was disturbed and contained several soil stockpiles. The swale and detention basin needed maintenance. For example, the tall, naturally established grasses covered the swale with a steep gully down the center. This swale/gully became a potential source of additional sediment from the drainage area to the detention basin. Figure 12 shows the structure of CS Project Watershed 1 and the sampling points for this location. Sample '1.g' collection point was at the culvert between the swale and the detention basin. Sample collection point ‘1’ is the discharge from the detention basin toward the outside of the construction boundary. Figure 13 shows CS Project Watershed 1 sampling points.

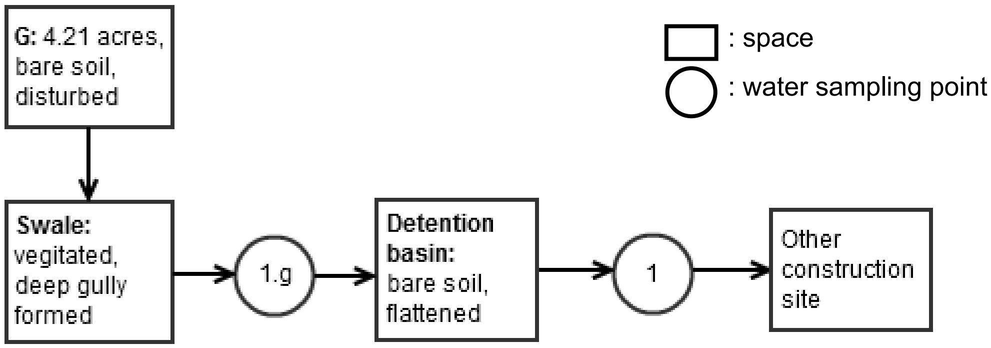

Figure 12. CS Project Watershed 1 Structure and Sampling Locations.

Figure 13. CS Project Watershed 1.
Left – Culvert and Detention Basin, Right – Discharge from the Detention Basin.

CS Project Watershed 2 is comprised of a 3.41 acre drainage area with a vegetated swale. Figure 14 shows the structure of the watershed and turbidity values by sampling point. Researchers collected samples at ‘2.f’ at the culvert to the swale and sample ‘2’ is the discharge from the swale to adjacent creek. To see the influence of the discharge from the construction site on the creek, the research team decided to collect samples before it mixed with the construction site discharge (2.org) and the creek water after mixed (2.mix). However, researchers could not collect ‘2.mix’ because of the unsafe field conditions. Figure 15 depicts the site conditions.

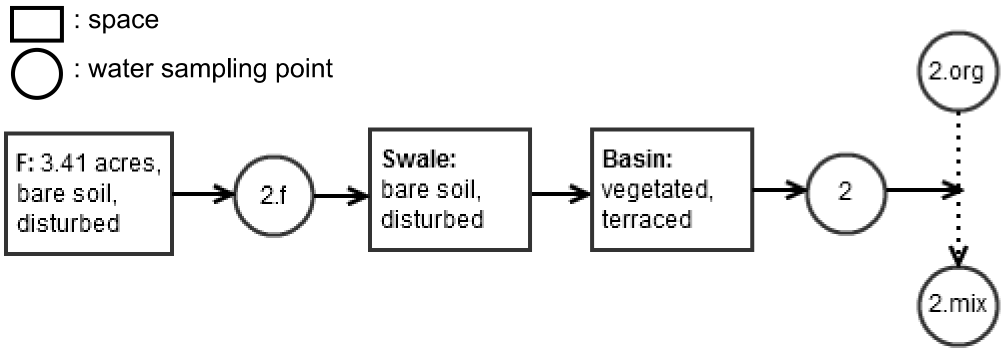

Figure 14. Structure of CS Project Watershed 2.

Figure 15. CS Project Watershed 2.
Left – Creek (before Construction Site Outlet) Where Water Is Already Turbid
Right – Discharge from Construction Site to Creek.

Watershed 3 was comprised of two drainage areas and a vegetated swale with five silt fences installed. The swale connects to a creek through a vegetated channel. The two drainage areas in this watershed are relatively flat and well tilled. This makes the areas act like a detention basin and can hold a large amount of rainfall runoff. However, the drainage areas release turbid water once the rainfall volume exceeds the capacity due to the bare soil. See Figure 17 to Figure 19.

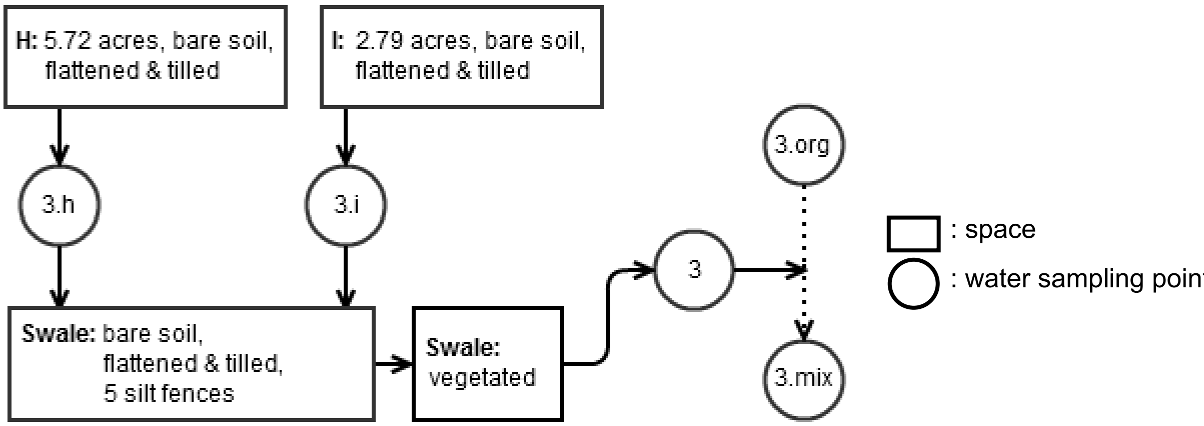

Figure 16. Structure of CS Project Watershed 3.

Figure 17. CS Project Watershed 3 Vegetated Channel and Discharge to Creek.

Figure 18. CS Project Watershed 3 Relatively Flat Drainage Area with Loose Bare Soil.

Figure 19. CS Project Watershed 3 Swale with Silt Fence on Bare Soil.

Hearne

The College Station research team collected runoff samples at the Highway 6 widening project between Hearne and Calvert, Texas. The Hearne Project site is a 6-mile-long linear project that crosses seven stream locations. The site had a paved road surface; however, the roadside vegetation was not fully established. To separate the influence of the ongoing construction site, researchers excluded the roadside section with fully vegetated cover. There were five outlets selected for monitoring at this location.

One challenge in monitoring this site was the difficulty in separating and defining the net influence of the construction site on stormwater discharge quality because the site contained multiple drainage areas covering a far wider area than the project construction site. Researchers selected five monitoring points for five outlets, but confirmed only two as originating from the construction site.

Hearne Project Watershed 1 is a 10.8 acres linear-shape drainage area which has a vegetated swale and a rock check dam. The swale is designed to discharge the stored water to nearby grass field in the form of sheet flow, while, the outlet to stream is protected by a rock check dam (Figure 20).

Figure 20. Hearne Project Watershed 1 Swale with Rock Check Dam.

Hearne Project Watershed 2 is a 501.6 acre drainage area that provides drainage beyond the construction site boundary. Two channels merge and contribute to the final outlet in this watershed. One is a concrete-paved channel from the construction site and the other is an underground culvert from the outer construction site (Figure 21). A rock check dam exists near the inlet of the concrete channel. Adjacent slopes have almost fully established vegetation except some large bare soil surface areas.

Figure 21. Hearne Project Watershed 2 Concrete-Paved Channel.

Hearne Project Watershed 3 is a 36,368 acre natural drainage area that includes a major creek. The creek is protected by a perimeter silt fence. The creek bank is a flat clay area with sparse vegetation (see Figure 22).

Figure 22. Hearne Project Watershed 3 Turbid Natural Creek.

Hearne Project Watershed 4 has eight drainage areas that are linked together by a 5-mile long swale fed by numerous culverts. The total area is approximately 260 acres. The swale is covered by rock/concrete riprap (see Figure 23). This watershed includes a creek which typically conveys water from adjacent 1,714 acres of natural drainage area; however, the creek remained dry because of the lack of rainfall.

Figure 23. Hearne Project Watershed 4 Swale Covered by Rock Riprap.

Hearne Project Watershed 5 is 359.5 acres and serves an area much larger than the construction site. A linear-shape swale following the road cuts across a natural creek in this watershed. The swale is directly connected with the creek through culverts and holds water at all times. The swale plays a role as a retention basin designed to discharge to an adjacent grass field in the form of sheet flow. The outlet to stream is protected by a rock check dam (Figure 24).

Figure 24. Hearne Project Watershed 5 Swale Used as a Retention Basin.

Bryan

The Bryan Project study area was a lane expansion project for State Highway (SH) 47. Researchers collected samples from six outlets in four sub-watersheds. Bryan Project Watershed 1 and 2 are located on the north side of the construction site. Both areas are linear shape swales with a bare soil surface. Silt fence surrounded the site's drop inlets (see Figure 25).

Figure 25. Bryan Project Watershed 1 on Left and Watershed 2 on Right.

Bryan Project Watershed 3 had a detention basin type of outlet with bare soil surface. The outlet collects runoffs from both sides of the road construction site, and therefore has three sampling points, including the collection point from each north and south side and the final outlet toward the adjacent natural creek. The final outlet is blocked with silt fence, but the device is less effective due to the large amount of concentrated water (see Figure 26). The researchers used an automatic sampling system at the final outlet location.

Figure 26. Bryan Project Watershed 3 Collection Points.
Left – North Side, Middle – South Side, Right – Final Outlet and Detention Area.

Bryan Project Watershed 4 is located at the south side of the construction site as shown in Figure 27. The area is a grassy channel slope. Runoff flows collected in this area were less turbid due the vegetated surface. The outlet is connected to the adjacent private reservoir and had multiple silt fences installed.

Figure 27. Bryan Project Watershed 4.

SAMPLING METHODS

Manual Sampling

The research team started collecting samples at the identified discharge locations after rainfall events. When possible, samples of runoff leaving the project boundary were also obtained. Whenever possible, researchers collected grab samples during the rain events. If the rain ended, researcher obtained samples from the sedimentation pond with retained runoff. The collection process was as follows:

- Samples were collected downstream of the discharge location using a clean collection bottle with the opening facing in the direction of the flow.
- Care was taken to ensure the bottle did not overflow and the sampling site was not disturbed by agitating particles upstream.
- For low flows, a scoop was used to capture a sample so that the bottom settlements were not disturbed, and for hard to reach locations, a pole was attached to a bottle to retrieve a sample, both are recommendations from other state protocols (*8*).
- A single grab sample from each sampling location was considered sufficient.

Automatic Sampling

Automatic sampling done at the Bryan Project used an ISCO 6712 sampler shown in Figure 28. Samples were collected once every hour after activated at a certain level of runoff flow. An ISCO 730 bubbler flow module was attached to the sampler and read flow depths once every five minutes for selected rain events. The research team returned to the HSECL with the samples to read their turbidities within 48 hours using the Hach 2100N turbidimeter used for the grab samples.

Figure 28. ISCO 6712 Sampler and ISCO 730 Bubbler Flow Module.

Turbidity Measurements

Runoff sample analysis followed EPA method 180.1 with two modifications. The method was developed for less turbid samples, i.e., drinking water, groundwater, etc., so the method refers to a range of turbidity from 0 to 40 NTU. The first modification in the methodology was to utilize this method using the Hach 2100N turbidimeter, which has a range of 0 to 4,000 NTU. The samples were immediately transported to the lab, where they were analyzed for turbidity or stored in the 4°C cold room to be analyzed within 7 days. This was the second modification to the method as the methodology requires the analysis to be performed within 48 hours. Typically, samples were analyzed within 48 hours, but for some sampling events, analysis was performed after 48 hours. Therefore, a 7-day limit was utilized as the timeframe for sample analysis. Researchers gently shook the samples and allowed the bubbles to dissipate prior to performing the turbidity measurements.

RESULTS

Grab Sampling in Austin

Severe drought conditions have persisted in central Texas since September 2010, making stormwater runoff sampling difficult. Over the three project sites, 15 samples were collected on 10 dates during the study period. As shown in Table 9, turbidity levels ranged from 35.5 to > 4,000 NTU. Researchers collected samples from within the limits of construction. The construction sites did not always discharge stormwater at the sampling time due to sediment control practices, dry soil conditions, low rainfall intensities, and timing of sampling trips.

Management practices used on sampled areas of the construction project included silt fencing and sedimentation ponds. Due to the limited number of samples, it is difficult to make conclusions about the effectiveness of particular management practices. The data shows that the turbidity varies based on rainfall intensity, duration of rainfall, amount of bare soil, best management practices, and various other factors. The turbidity observations were consistent with a previous study in the Austin area, which documented turbidity values ranging from 79 to 2,160 NTU in runoff from highway construction sites (*13*). Overall, the data suggests that the runoff from construction sites is very turbid, and existing control practices may have difficulty consistently meeting any new regulatory threshold that EPA and/or TCEQ may implement in the future.

Table 9. Turbidity in Construction Site Runoff in Austin Area.

	Austin Project 1		Austin Project 2		Austin Project 3	
Date	**Rainfall (mm)**	**Turbidity (NTU)**	**Rainfall (mm)**	**Turbidity (NTU)**	**Rainfall (mm)**	**Turbidity (NTU)**
11/2/2010	4.3	2440.0	2.8	420.0	-	-
1/15/2011	7.1	35.5	3.6	66.2	-	-
1/15/2011	13.2	53.2	6.9	445.0	-	-
5/12/2011	17.8	203.0	37.8	>4000	10.7	>4000
5/25/2011	-	-	-	-	7.9	1256
6/22/2011	-	-	-	-	34.8	>4000
10/8/2011	-	-	-	-	6.9	>4000
10/9/2011	-	-	-	-	48.5	>4000
11/8/2011	-	-	-	-	4.8	565.0
11/15/2011	6.9	66.7	-	-	6.6	1083.0

Grab Sampling in Lubbock

During the course of the study, four rainfall events occurred that allowed for sample collection at both the Lubbock Project 1 at the Marsha Sharp Freeway and Lubbock Project 2 at West Loop 289. March 4, May 11, and August 11, 2011 were the three days that samples were obtained for both. Researchers collected one sample on July 12, 2011, at the Lubbock Project 1 location only. For the three times samples were collected at both sites, four total samples for each rainfall event were collected—one at the Lubbock Project 1 location and three at the Lubbock Project 2 location.

Turbidity values observed in the field ranged from 20 NTU up to around 10,600 NTU. For all measurements the field turbidimeter read larger values than the lab turbidimeter. Table 10 shows a brief synopsis of the values read for each sample collected. The samples collected on March 4th were not collected by the main operator on the project, therefore, the sample collecting personnel did not have access to the field turbidimeter, and measurements were only performed in the lab.

Table 10. Turbidity in Construction Site Runoff in Lubbock Area.

	Turbidity (NTU) by Sampling Location			
Date	**Lubbock Project 1**	**Lubbock Project 2 playa**	**Lubbock Project 2 small tennis**	**Lubbock Project 2 large tennis**
3/4/2011	21.6	1889	252	60.2
5/11/2011	2205	601	226	49.0
7/12/2011	>4000*	-	-	-
8/11/2011	4280	225	170	145
9/15/2011	235	32.2	22.9	238

* A dilution series was performed on this sample in the lab machine only and produced a final 10,600 NTU reading.

Grab Sampling in College Station

Samples from 12 rainfall events were collected in the CS Project site. Researchers collected the first three samples during construction, the remaining after the road opened to the public. The major difference between the two periods was the surface condition of drainage area. Turbidity was reduced significantly in both outlets after an application of mulch on the roadside surface even though vegetation was not yet established (see Table 11).

Table 11. CS Project Watersheds 1 and 2 Turbidities Readings of Samples.

Date	Rain (inches)	Sampling Time	Turbidity (NTU)		Surface Condition
			Watershed 1	Watershed 2	
12/24/2010	0.66	raining	3903	-	Disturbed bare soil
1/9/2011	1.69	1-hr later	860	833	
1/16/2011	0.70	raining	1647	354	
2/3/2012	4.11	6-hr later	12	56	Mulched but no vegetation established
2/4/2012	2.15	1-hr later	51	68	
2/10/2012	0.20	1-hr later	N/F	52	
2/13/2012	0.54	1-hr later	29	72	
2/15/2012	0.45	1-hr later	82	129	
2/18/2012	1.16	1-hr later	48	79	
3/10/2012	2.62	3-hr later	4	17	
3/20/2012	2.38	raining	13	61	
3/29/2012	2.27	2-hr later	60	71	

Note: N/F means "no flows"

An interesting note is that the detention basin showed different performance by sampling timing. Turbidity was reduced through the detention basin when collected after an hour (1/9/2011), whereas, collection during rainfall events (12/24/2010 and 1/16/2011) showed increased levels. This difference is probably due to the one hour interval allowing for sedimentation to occur in the detention basin. During rainfall events, some of the sediment may be redistributed within the basin and therefore discharge may be representative of this action.

Watershed 2 showed an improved turbidity level between the drainage area and the outlet (from 354 to 143 NTU). Two reasons can be considered for this:

- The swale condition.
- The existence of a terraced vegetation basin.

Other watersheds of CS Project site showed that a swale or detention basin on bare soil surface does not improve turbidity but becomes a source of additional sediments. This watershed also had a bare soil swale adjacent to drainage area. However, the swale is not long and has a flatter center line gradient so it was not expected to add as much sediment. Most of all, this watershed was equipped with a high-performing sediment control method, a terraced vegetated basin which was located between the upper swale and the lower creek. The terraced vegetated area appeared able to:

- Disperse the concentrated flow of the swale though the flat area.
- Reduce the flow rate.
- Capture sediments.

Table 12 shows turbidities in the CS Project Watershed 3. Runoff samples from the drainage area 'i' show a large disparity in turbidity between two different rain events (i.e., 1338 NTU in the first event and 182 NTU in the second at the sample point '3.i') even though the surface conditions were almost consistent during that period. This is probably due to the difference in precipitation volume, 1.69 inches for the first event and 0.7 inches for the second.

Table 12. CS Project Watershed 3 Turbidities of Samples.

Date	Rain (inches)	Sampling Time	Turbidity (NTU)					Surface Condition
			3.h	3.i	3	3.mix	3.org	
12/24/2010	0.66	raining	1334					Tilled bare soil
1/9/2011	1.69	1-hr later	1863	1338	1991	163	142	
1/16/2011	0.7	raining	197	182	358	75	67	
2/3/2012	4.11	6-hr later	4	7	19	32	30	Mulched but no vegetation
2/4/2012	2.15	1-hr later	19.3	11	7	37	38	
2/10/2012	0.20	1-hr later	6	8	N/F	-	-	
2/13/2012	0.54	1-hr later	11	18	19	47	11	
2/15/2012	0.45	1-hr later	44	25	73	80	30	
2/18/2012	1.16	1-hr later	22	12	12	-	-	
3/10/2012	2.62	3-hr later	15	3	40	-	-	
3/20/2012	2.38	raining	37	20	11	-	-	
3/29/2012	2.27	2-hr later	15	7	5	104	36	

The swale installed with five silt fences on bare soil surface did not help reduce turbidity. The turbidity at the final outlet ('3' in Figure 28) in both rain events is greater than the turbidity of discharge from the drainage area '3.h' and '3.i'. This indicates that the series of swales is an additional source of sediments at first glance. However, the turbidity of the accepting creek was not changed much by the construction site discharge (e.g., 21 NTU from 142 to 163 NTU in the first rain event). Silt fences in the swale held a large volume of water and discharged at the significantly lower flow rate, thus the absolute amount of sediments per time may be lower at the end (see Figure 17 and Figure 19). However, this type of detention is not efficient or effective during rain events beyond the silt fence's capacity. This method will not be able to reduce the flow rate in but, rather has the risk of discharging higher rate of turbid flow when the silt fences fail.

Grab Sampling in Hearne

Samples from three rainfall events were collected in the Hearne Project site due to the draught condition over its relatively short construction period. Another difficulty in monitoring and sampling the Hearne Project was that the site rarely produced a significant quantity of runoff. The research team could not collect more samples although there were more than five visits in addition to the three successful collections. Table 13 presents turbidity at eight sampling points located at the Hearne Project.

Table 13. Hearne Project Turbidities of Samples.

Date	Rain Inches	Sampling Time	Turbidity (NTU)							
			1	2	2.mix	2.org	3	3.org	4	5
6/22/2011	1.64	1-hr later	N/F	104	410	472	N/F	1862	814	1394
11/15/2011	1.07	raining	N/F	1316	3100	1681	>4000	-	>4000	1472
1/9/2012	0.80	1-hr later	N/F	130	150	166	N/F	35	688	144

Note: N/F means "no flows"

When researchers collected the first sample an hour after rain ceased in Hearne Project Watershed 1, the swale was at near capacity with turbid water (368 NTU) but there was no noticeable discharge to offsite. Researchers collected the swale water because the water was supposed to flow out of the project boundary during a rain event. However, overflows to offsite were found even during rainfall events as shown in Table 13. This Hearne Project Watershed 1 seemed to convey the stormwater to the adjacent watershed rather than off-construction site because it is located upstream.

In Hearne Project Watershed 2, researchers collected samples at the channel from construction site (sample 2), out of construction site (2.org) and the final outlet to offsite (2.mix). In this watershed, the turbidity of construction site discharge was lower than flows from offsite. The turbidity level was extremely high during rainfall, but seemed to reduce quickly. This is probably due to the condition of the adjacent slopes. Large bare soil areas were easily disturbed during rainfall events; however, the sediments would settle down quickly to adjacent vegetated areas after rainfall ceased.

Hearne Project Watershed 3 was the most environmentally sensitive area in the Hearne site as the runoff from this watershed directly flowed to the nearby creek. Hearne Project Watershed 3 had two sampling points—one at the outlet from the construction site (sample 3) and the other from the natural creek (3.org). This watershed seems to develop a small amount of stormwater flows to the outlet. Although the creek shore is located lower than adjacent half-vegetated slopes, no noticeable ponding was found on the area even during a rainfall event. There were no outflows from the small outlet under the silt fence when monitoring the site one hour after rainfall ceased. Only a streak of outflow was found in the monitoring right after the rainfall, but the turbidity was extremely high over 4000 NTU. The creek water showed various turbidity levels (35 to 1862 NTU), which seemed to depend on rainfall intensity and volume.

Stormwater turbidities at the Hearne Project Watershed 4 were high, over 688, but showed low flow rates during the monitoring period. The research team could not confirm if this flow came from only the construction site or from another area. Hearne Project Watershed 5 seemed to be more affected by out-of-construction site conditions, and its turbidity level appeared to be affected by rainfall characteristics. The samples collected on 1/9/2012 showed a significantly lower turbidity when the rainfall had a lower intensity over a longer period of time.

Grab Sampling in Bryan

Samples from 11 rainfall events were collected in the Bryan Project site. Bryan Project Watersheds 1 and 2 rarely produced any discharges. This may be due to the fact that their drainage areas were large, flat, and pervious so most stormwater produced in the area was either absorbed, infiltrated, or stored on-site. Bryan Project Watershed 3 produced very turbid runoff levels due to discharges from the southbound area ("3.south" in Table 14). The southbound area had disturbed bare soil conditions. While silt fence protected discharge from the area, it was easily overtopped in the initial period (until 1/9/2013). The runoff from this area was significantly reduced after the drainage area was flattened during construction. The Bryan Project Watershed 4 had an established grass channel and produced minimal amounts of less turbid water.

Table 14. Bryan Project Turbidities of Samples.

Date	Rain (Inches)	Sampling Time	Turbidity (NTU)					
			1	2	3.south	3.north	3	4
7/10/2012	0.09	1-hr later	334	116	N/F	N/F	N/F	N/F
7/13/2012	1.84	1-hr later	277	106	N/F	-	8400	209
12/27/2012	0.25	1-hr later	N/F	N/F	N/F	144	314	N/F
1/4/2013	0.19	1-hr later	N/F	N/F	2068	99	254	46
1/8/2013	1.1	3-hr later	N/F	N/F	N/F	N/F	303	N/F
1/9/2013(1)	3	raining	649	N/F	5102	-	2829	239
1/9/2013(2)	3	raining	-	N/F	9017	-	4455	191
2/6/2013		raining	N/F	N/F	N/F	-	743	46
2/10/2013		raining	2907	5239	6558	-	2086	51
4/3/2013		1-hr later	779	N/F	218	-	792	N/F
4/19/2013		2-hr later	N/F	N/F	N/F	127	238	35

Note: N/F means "no flows"

Automatic Sampling from Bryan

The Bryan Project successfully used automatic samplers for three rainfall events among six attempts (see Figure 29–Figure 31). Results presented a wide variance in turbidity by the discharge flow rate as shown in Table 15. The maximum turbidity reached 21,355 NTU in the most intense rainfall event occurring on 1/9/2013. This implied that the time of grab sampling would significantly change the turbidity estimate from a construction site.

Table 15. Bryan Project Turbidity Change by Time Using Data from Automatic Sampling.

Time (hr)	Turbidity by Date (NTU)		
	2/6/2013	2/18/2013	3/11/2013
0	743	777	23663
1	417	502	5987
2	347	3328	2103
3	215	1128	407
4	189		157
5	179		80
6	173		53
7	162		27

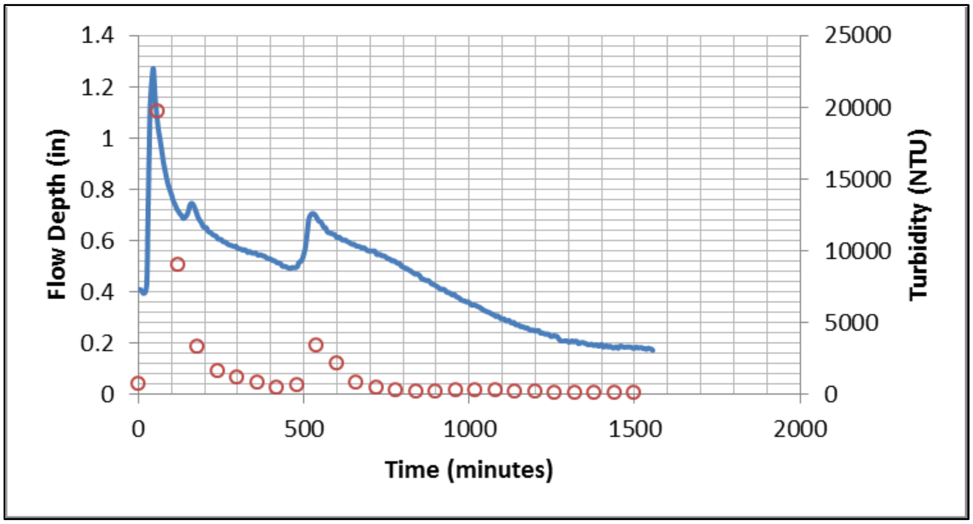

Figure 29. Bryan Project Automatic Sampling Turbidity and Flow 1/9/2013.

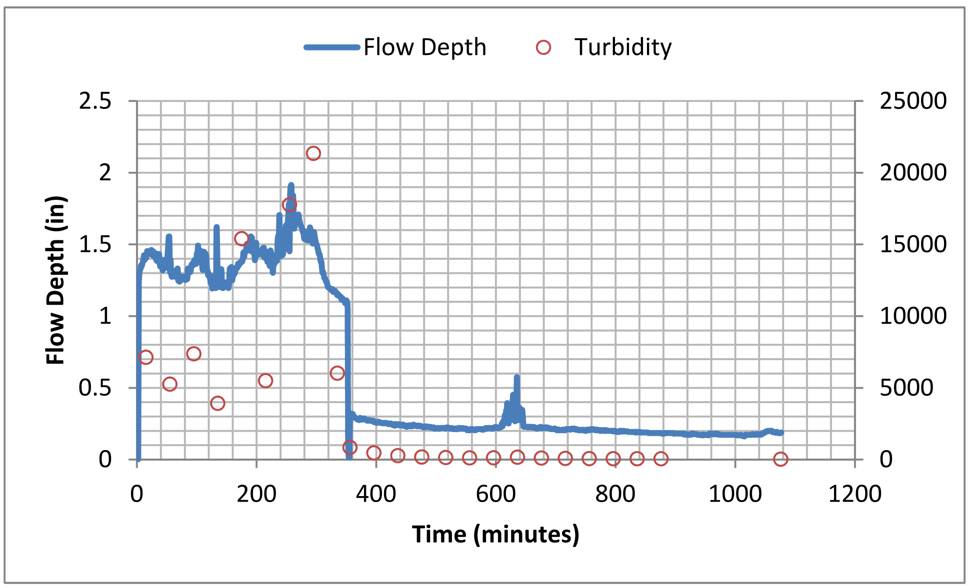

Figure 30. Bryan Project Automatic Sampling Turbidity and Flow 4/2/2013.

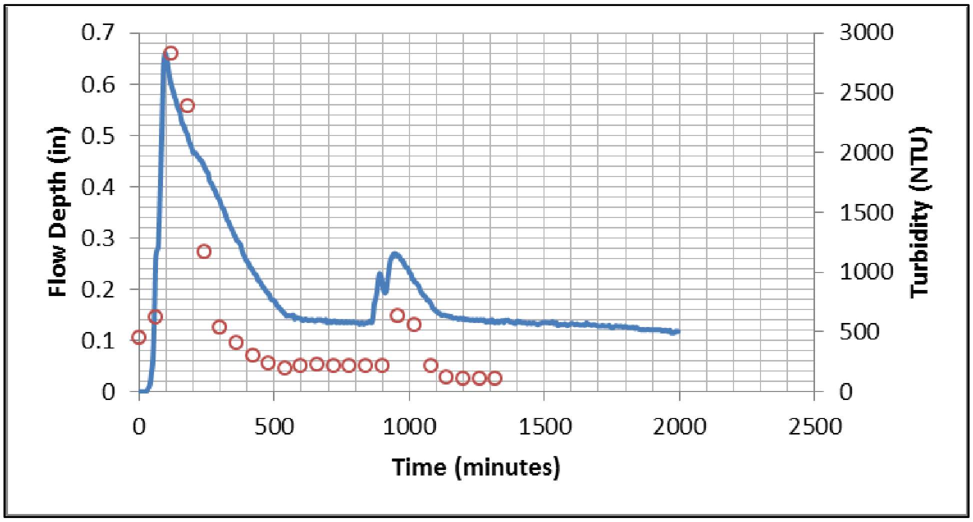

Figure 31. Bryan Project Automatic Sampling Turbidity and Flow Depth 4/19/2013.

CONCLUSIONS AND FINDINGS

CONTROLLED TESTING OF COAGULANTS

Polyacrylamide for Erosion Control

The PAM application used in this evaluation was not effective in significantly reducing turbidity or soil loss on clay soils with 1:3 slopes. Maximum turbidities of all tested ECB treatments were very high, ranging from 3,450 to 9,037 NTU. The turbidity of the effluent from the bare soil plot reached 52,857 NTU. Average dry soil losses overall agreed with turbidity results.

Due to the high range of turbidity the efficiency of PAM could not be determined. Although PAM showed a lower turbidity and average dry soil loss on bare soil and excelsior ECB than untreated counterparts, the differences were negligible. Furthermore, when applied with jute and straw erosion control blankets the reduction in turbidity decreased. This result was unexpected because straw ECBs are typically considered excellent performers in a 1:3 clay soil application. These results are shown in Table 16 and Table 17.

Table 16. Maximum Turbidity from Controlled Erosion Control Tests.

Surface Condition	No PAM Treated	PAM Treated	Difference
Bare soil	52,857 NTU	51,987 NTU	-870
Jute ECB	over 4,040* NTU	over 4,040* NTU	NA
Excelsior ECB	3,603 NTU	3,450 NTU	-153
Straw ECB	4,180 NTU	9,037 NTU	+4,857

* exceeds the capacity of the Hach SOLITAX in situ turbidity sensor

Table 17. Average Dry Soil Loss from Controlled Erosion Control Tests.

Surface Condition	No PAM Treated	PAM Treated	Difference
Bare soil	175.50 lb	163.10 lb	-12.40
Jute ECB	17.25 lb	19.05 lb	+1.80
Excelsior ECB	6.97 lb	5.43 lb	-1.54
Straw ECB	0.40 lb	10.17 lb	+9.77

Several potential reasons could contribute to the test results. First, broadcast application might limit the efficacy of PAM. The PAM2 hand-broadcasted on jute ECB did not develop any visible flocculation during the tests; as a result, the dry soil loss of its effluent was equivalent with the untreated jute ECB. Meanwhile, the PAM1 applied with the hydroseeder on the straw ECB created highly viscous flocculation from the soil surface to the discharge outlet. It is speculated that those flocculated sediments adhered inside the straw ECB, but in reality the sediment clogs appeared too heavy to be held on the blanket's surface, particularly when using the heavy design storm of 3.5 inches per hour. Also, the PAM1 appeared to facilitate more flocculation by softening the surface soil. This was most likely due to the high viscosity caused by the application of PAM1.

Polyacrylamide for Sediment Control

To compare the sediment removal efficiency of treated and untreated sediment retention devices, wood fiber wattles were installed in SRD test flume. Mass loading of the outflow was estimated using flow rate and turbidity monitored at the one minute resolution. The following data was recorded and calculated to determine removal efficiency:

- Flow-through rate (cfs).
- Maximum flow rate (gpm).
- Ponding volume (gal).
- Turbidity at inlet and outlet (NTU).
- SSC (mg/L) at inlet and outlet.
- Mass loading (lb).
- Removal efficiency (%).

Test results demonstrated that PAM treated sediment control devices were significantly more successful at reducing sediment from sediment laden water than untreated SRDs. The removal efficiencies of PAM treated wattles ranged from 8 percent to 18 percent improvement. Table 18 shows these results.

Table 18. Sediment Removal Efficiency of Untreated and PAM Treated Wattles.

Sediment Retention Device	Test Round	Mass In lb (kg)	Mass Out lb (kg)	Removal Efficiency %
Wattle – untreated	1	1.3 (0.58)	0.69 (0.31)	46
	2	1.4 (0.65)	0.79 (0.36)	45
	3	1.6 (0.71)	0.85 (0.39)	46
Wattle – PAM treated	1	1.47 (0.67)	0.54 (0.24)	63
	2	1.54 (0.70)	0.61 (0.28)	61
	3	1.47 (1.47)	0.67 (0.30)	54

Coagulation and Dosing of Polyacrylamides

The flocculation tests were performed to understand the soil characteristics, polymer characteristics, and doses that promote flocculation. Researchers generated turbidity curves as a function of polymer dose added for each modified synthetic stormwater runoff. Comparison of these curves and the soil characteristics gives insight about the interactions between the PAM and the particles in the modified synthetic stormwater runoff.

Interparticle bridging is commonly accepted as the mechanism by which PAM interacts with soils to destabilize particles. Since particles are negatively charged, they repel one another. Interparticle bridging may overcome this repulsion if the polymer is able to span the distance between two particles, thereby forming a floc. The polymer's ability to bridge two particles is referred to as its grappling distance and is a function of its molecular weight. The higher the molecular weight of the polymer, the longer it's grappling distance. Therefore, flocculants with higher molecular weights are expected to be more effective at promoting flocculation due to their improved ability to bridge particles.

Figure 32 shows the turbidity curves for the modified synthetic stormwater runoff of WLoop soil for the polymers P-21, A-110, and A-110 HMW. The objective of these tests was to determine how molecular weight effects turbidity reduction. PAM P-21 is clearly ineffective at reducing the turbidity. It also had the lowest molecular weight of 0.2 Mg mol^{-1} indicating a minimum grappling distance to effectively bridge particles in the suspension may exist. A-110 had a higher molecular weight of 10-12 Mg mol^{-1} and was effective at reducing the turbidity below 280 NTU. A-110 HMW had a molecular weight of 10-14 Mg mol^{-1} and has a similar turbidity curve to A-110. This result is expected since A-110 and A-110 HMW have a similar range of molecular weights. However, A-110 HMW was observed to be more viscous than A-110 when working with these polymers during the experiments. The greater viscosity indicates that A-110 HMW does have a higher molecular weight than A-110, since viscosity is a surrogate measure for the molecular weight. The similar turbidity curves of A-110 and A-110 HMW support the concept that a minimum molecular weight may be required to promote interparticle bridging. The similarity also implies a plateau effect may exist, where an increase in molecular weight above 10 Mg mol^{-1} does not increase the effectiveness of the anionic PAMs.

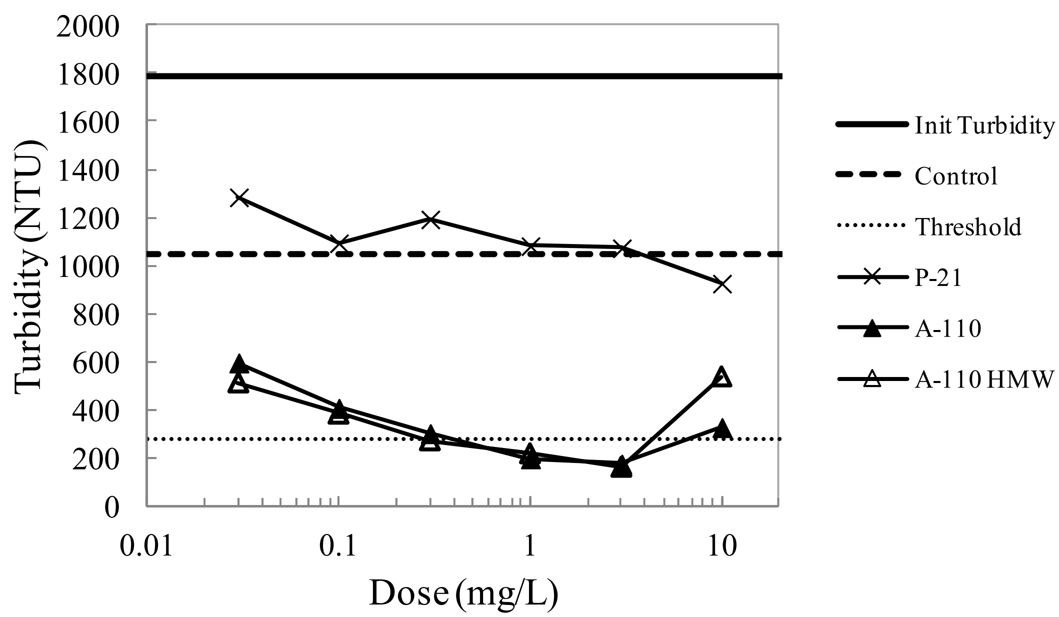

Figure 32. Impact of Molecular Weight on Turbidity Reduction for Modified Synthetic Stormwater Runoff for WLoop Soil.

The effect of charge density on flocculation is shown in Figure 33. The non-ionic PAM, SF N300, is the most effective polymer. A-110, which has a charge density of 16 percent, is less effective than the non-ionic PAM, but is more effective than A-150, which has the highest charge density of 50 percent. The turbidity curves clearly indicate that as charge density increased, the effectiveness of PAM decreased. This trend occurred in all the synthetic runoff samples that were tested. Intuitively, this trend is expected. The particles are negatively charged; therefore, the addition of an anionic PAM would increase the negative charge on the particle surfaces, making them more difficult to flocculate. Flocculation will occur if the grappling distance of the PAM is able to overcome these repulsive forces. The addition of a non-ionic

PAM, however, does not increase the charge of the particles and therefore it would be expected to be the most effective.

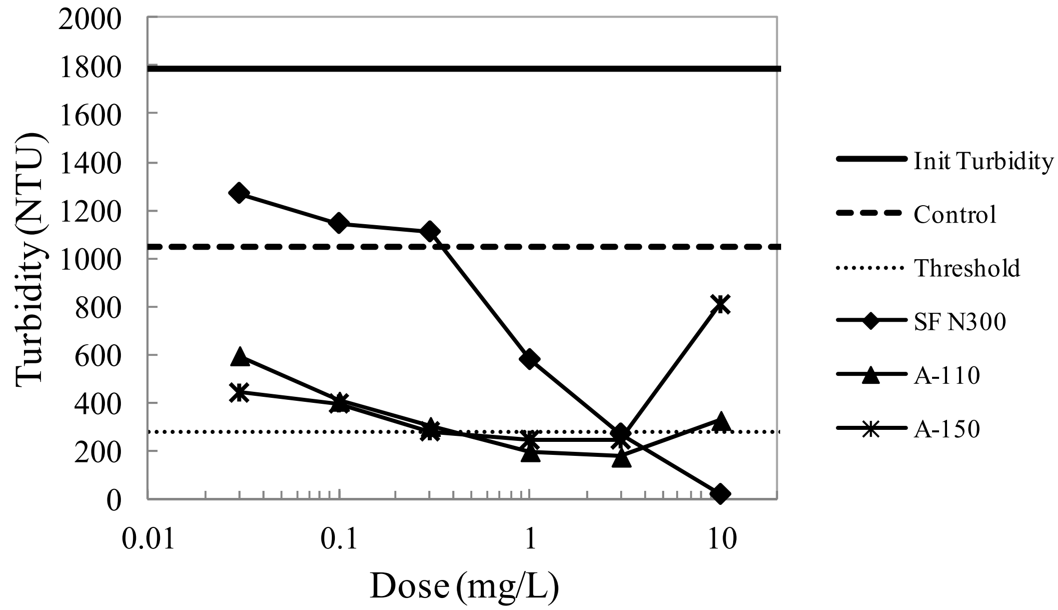

Figure 33. Effect of Charge Density on Flocculation for Modified Synthetic Stormwater Runoff Using Wloop Soil.

Furthermore, Figure 33 shows a difference between the optimal dose of anionic PAMs and non-ionic PAMs. The optimal dose for SF N300 was 10 mg/L (see Appendix B) compared to the optimal dose for the anionic PAMs of 3 mg/L. The optimal dose for the anionic PAMs and the non-ionic PAMs varied between 1-3 mg/L and 10 mg/L, respectively, for all the synthetic runoff tested. Their study observed the optimal dose for anionic PAMs was lower than those of non-ionic PAMs for kaolinite suspensions. The lower optimal dose was a result of the anionic PAMs' ability to form loops and tails due to their anionic charge, while the non-ionic polymer was not able to form these loops and tails. Figure 32 demonstrates that the optimal dose for anionic PAM is lower than that of non-ionic PAM for synthetic runoff.

Figure 34 shows the polymers that were most effective in reducing the turbidity of the synthetic runoff was WLoop. The non-ionic PAMs, SF N300, and LMW SF N300, reduced the turbidity to 20 and 55 NTU, respectively. The molecular weight of these PAMs was 15 and 6 Mg mol^{-1}, respectively. SF N300, with its higher molecular weight, was more effective than the LMW SF N300 for all the runoff tested. This confirms the previous trend found with anionic

PAMs, which indicated that higher molecular weights are more effective to a certain threshold. APS #705 was also effective at promoting flocculation and reduced the turbidity to 23 NTU at its optimal dose. The turbidity curve of APS #705 was nearly identical to the curve of SF N300 indicating APS #705 may have similar charge characteristics to the non-ionic PAM. Furthermore, the flocs created by APS #705 were similar to all the PAMs in that they were "fluffy." These fluffy flocs are indicative of interparticle bridging. The flocs formed by chitosan were denser. The denser flocs are expected to be observed as the mechanism of particle destabilization with chitosan is a combination of charge neutralization and interparticle bridging.

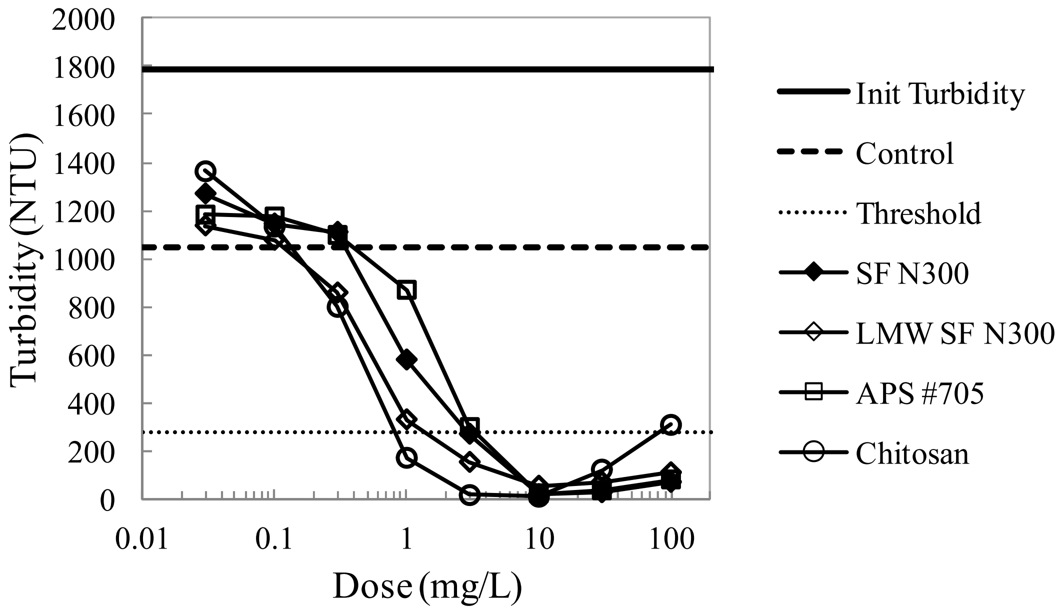

Figure 34. Most Effective Flocculants for Modified Synthetic Stormwater Runoff Wloop.

The optimal dose of chitosan was 3 mg/L, beyond which restabilization occurred. The optimal dose associated with chitosan depends on its mechanism of particle destabilization. When charge neutralization is the dominant mechanism of particle destabilization, the optimal dose will be the dose at which the zeta potential is zero. The cationic polymer will adsorb to the surfaces of the particle, which neutralizes the charge of the particle until it is zero. Restabilization will occur when the adsorption of chitosan to the particles causes the particles to have a net positive charge, thereby causing particles to repel one another. When interparticle bridging is the dominant mechanism of particle destabilization, overdosing of chitosan will be the same as overdosing with PAM. Restabilization will occur when the adsorption sites on the particle are saturated by chitosan to the extent that flocs are prevented from forming. The optimal dose of chitosan was found to range from 1 to 10 mg/L for all the synthetic runoff tested, which indicates the mechanism of particle destabilization may be different for the various samples of synthetic runoff.

Restabilization of the non-ionic PAMs and APS #705 is a result of overdosing the synthetic runoff, which is the same restabilization that occurs for chitosan when interparticle bridging is its mechanism of particle destabilization. Researchers observed the restabilization of the non-ionic PAMs and APS #705 for all the synthetic runoff tested beyond the optimal dose of 10 mg/L. The non-ionic PAMs, APS #705, and chitosan were the most effective at promoting flocculation for all the synthetic runoff tested. In particular, SF N300, APS #705, and chitosan reduced the turbidity of the synthetic runoff below 280 NTU for all the synthetic runoff tested. The LMW SF N300 reduced the turbidity below 280 NTU for all but one synthetic runoff, E. Texas soil, and was the lease effective of these four polymers.

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APPENDIX A: STATE NUMERIC STANDARDS FOR CONSTRUCTION SITES

State	Numeric Effluent Standards for Active Construction Sites
Alabama	No statewide standard but 2011 ALR 100000 CGP requires construction site monitoring and sampling for turbidity. Alabama Department of Environmental Management. 2011. *National Pollution Discharge Elimination System General Permit ALR 100000*. http://www.adem.alabama.gov/programs/water/waterforms/ALR10CGP.pdf.
Alaska	No statewide standard Alaska Department of Environmental Conservation. 2011. *Alaska Pollutant Discharge Elimination System General Permit for Discharges from Large and Small Construction Activities AKR 100000.* http://dec.alaska.gov/water/wnpspc/stormwater/docs/Final_2011_ACGP_(20110519)_w_app.pdf.
Arizona	No statewide standard. Arizona Department of Environmental Quality. *Arizona Pollutant Discharge Elimination System General Permit for Stormwater Discharges Associated with Construction Activity to Waters of the United States.* June 2013. http://www.azdeq.gov/environ/water/permits/download/2013_cgp.pdf.
Arkansas	No statewide standard - 80% removal of TSS from post-construction only. Arkansas Department of Environmental Quality. *General Permit No. ARR150000*. http://www.adeq.state.ar.us/water/branch_permits/general_permits/stormwater/construction/pdfs/ARR150000_permit.pdf
California	Draft Construction General Permit includes turbidity levels of 1,000 NTU. If Active Treatment Systems are used, a daily average of 10 NTUs is noted. California State Water Resources Control Board, Division of Water Quality. 2010. *National Pollutant Discharge Elimination System General Permit for Storm Water Discharges Associated With Construction and Land Disturbance Activities, CAS000002*. http://www.swrcb.ca.gov/board_decisions/adopted_orders/water_quality/2012/wqo2012_0006_dwq.pdf.
Colorado	No statewide standard. Colorado Department of Public Health and Environment. 2007. *CDPS General Permit Stormwater Discharges Associated With Construction Activity, Permit No. COR-030000.* http://www.cicacenter.org/pdf/copermit.pdf=1251808459293&ssbinary=true.
Connecticut	No numeric standard. Turbidity monitoring required at least once a month during construction activity if there is discharge.

State	Numeric Effluent Standards for Active Construction Sites
	Connecticut Department of Energy and Environmental Protection. *General Permit for the Discharge of Stormwater and Dewatering Wastewaters from Construction Activities*. 2013. http://www.ct.gov/deep/lib/deep/permits_and_licenses/water_discharge_general_permits/storm_construct_gp.pdf. Accessed 2013.
Delaware	No statewide standard. Delaware Department of Natural Resources and Environmental Control. http://www.dnrec.delaware.gov/swc/Pages/SedimentStormwater.aspx. Accessed 2013.
Florida	No statewide standard. State of Florida, Department of Environmental Protection. *Generic Permit for Stormwater Discharge from Large and Small Construction Activities*. 2009. http://www.dep.state.fl.us/water/stormwater/npdes/docs/cgp.pdf. Accessed 2011.
Georgia	New CGPs GAR100001 and GAR100002, effective 9-2013, require site monitoring and sampling. Georgia Environmental Protection Department of Natural Resources. 2013. NPDES General Permit No. GAR100001 for Stand Alone Construction Projects and NPDES General Permit No. GAR100002 for Infrastructure Construction Projects. http://www.gaepd.org/npdes/. Accessed 2013.
Hawaii	No statewide standard. Hawaii Department of Health. *NPDES General Permit Authorizing Discharges of storm Water Associated with Construction Activity.* 2007. http://health.hawaii.gov/cwb/files/2013/04/HAR1155.pdf.
Idaho	No statewide standard. Uses EPA CGP. Idaho Department of Environmental Quality http://www.deq.state.id.us/permitting/water-quality-permitting/npdes.aspx. Accessed 2013.
Illinois	No statewide standard Illinois Environmental Protection Agency, Division of Water Pollution Control. 2013. *National Pollutant Discharge Elimination System General NPDES Permit For Storm Water Discharges From Construction Site Activities, General NPDES Permit No.ILR10.* http://www.epa.state.il.us/water/permits/storm-water/general-construction-permit.pdf. Accessed 2013.

State	Numeric Effluent Standards for Active Construction Sites
Indiana	No statewide standard. Indiana Department of Environmental Management. Article 15. *NPDES General Permit Rule Program.* 1996. http://www.in.gov/idem/4902.htm.
Iowa	No statewide standard - 80% removal of TSS from post-construction only. Iowa Department of Natural Resources. 2007. *NPDES General Permit No. 2 for Storm Water Discharge Associated with Industrial Activity for Construction Activities.* http://www.iowadnr.gov/portals/idnr/uploads/water/stormwater/guidanceno2.pdf. Accessed 2011.
Kansas	No statewide standard. Kansas Department of Health and Environment. *Kansas Water Pollution Control and National Pollutant Discharge Elimination System Stormwater Runoff From Construction Activities General Permit*. 2012. http://www.kdheks.gov/stormwater/download/Const%20SW%20Issued%203-2-2012%20Packet.pdf. Accessed 2013.
Kentucky	No statewide standard - 80% TSS reduction compared to pre-construction levels. Kentucky Energy and Environment Cabinet. 2009. *Kentucky Pollutant Discharge Elimination System (KPDES) General Permit For Stormwater Discharges Associated With Construction Activities (KYR10).* http://water.ky.gov/permitting/General%20Permit%20Fact%20Sheets/FinalPermitKYR10000RTC_2_.pdf. Accessed 2011.
Louisiana	No statewide standards related to construction sites. Louisiana Department of Environmental Quality. 2009. *General Permit for Discharge of Storm Water from Construction Activities Five (5) Acres of More, LAR100000.* http://www.deq.louisiana.gov/portal/Portals/0/permits/lpdes/pdf/FINAL%20LAR100000.pdf. Accessed 2011.
Maine	No statewide standard. Maine Department of environmental Protection. 2006. *General Permit – Construction Activity Maine Pollutant Discharge Elimination System (MPDES).* http://www.maine.gov/dep/land/stormwater/2006mcgp.pdf. Accessed 2011.

State	Numeric Effluent Standards for Active Construction Sites
Maryland	No statewide standard. Maryland Department of the Environment.2009. *General Permit for Stormwater Associated with Construction Activity.* http://www.mde.maryland.gov/programs/Permits/WaterManagementPermits/WaterDischargePermitApplications/Documents/2014GP-FactSheet.pdf. Accessed 2013.
Massachusetts	No statewide standard-uses EPA Construction General Permit. Massachusetts Energy and Environmental Affairs. http://www.mass.gov/eea/agencies/massdep/water/wastewater/stormwater.html#4. Accessed 2011.
Michigan	No statewide standard. Michigan Department of Environmental Quality. http://www.michigan.gov/deq/0,4561,7-135-3313_3682_3716---,00.html. Accessed 2013.
Minnesota	No statewide standard. Minnesota Pollution Control Agency. 2013. *General Permit Authorization to Discharge Stormwater Associated With Construction Activity under the National Pollutant Discharge Elimination System/State Disposal System Program, Permit No. MN R 100001.* http://www.pca.state.mn.us/index.php/view-document.html?gid=18984. Accessed 2013.
Mississippi	No statewide standard; however, has ACT9 (LCGP) Optional Monitoring, which was changed to optional due to changes in C&G Rule. Mississippi Department of Environmental Quality Office of Pollution Control. 2011. Large Construction General Permit. *http://www.deq.state.ms.us/MDEQ.nsf/pdf/epd_ConstructionStormWaterGeneralPermit(5acresandgreater)/$File/05General.pdf*. Accessed 2013.
Missouri	The effluent limitation for Settleable Solids from a stormwater outfall discharging shall not exceed 2.5 ml/L per Standard Method 2540 F, except immediately following the local 2-year, 24-hour storm event. The Settleable Solids limit is not enforceable during or greater that the local 2-year, 24-hour storm event. Missouri Department of Natural Resources. *Missouri State Operating Permit, General Operating Permit MORA00000*. 2012. http://www.dnr.mo.gov/env/wpp/permits/issued/RA00000.pdf. Accessed 2013.

State	Numeric Effluent Standards for Active Construction Sites
Montana	No statewide standard. Montana Department of Environmental Quality. 2012. *General Permit for Storm Water Discharges Associated with Construction Activity.* http://www.deq.mt.gov/wqinfo/MPDES/StormwaterConstruction.mcpx. Accessed 2013.
Nebraska	No statewide standard. Nebraska Department of Environmental Quality. 2008. *Authorization to Discharge Under the National Pollutant Discharge Elimination System (NPDES) General NPDES Permit Number NER110000 for Storm Water Discharges from Construction Sites to Waters of the State of Nebraska.* http://www.transportation.nebraska.gov/letting/Forms/NPDES%20General%20Permit.pdf. Accessed 2013.
Nevada	No statewide standard. Nevada Department of Conservation & Natural Resources. 2007. *Stormwater General Permit NVR 100000.* http://ndep.nv.gov/docs_07/nvr100000_permit07.pdf. Accessed 2013.
New Hampshire	No statewide standard. New Hampshire. 2012. *EPA National Pollutant Discharge Elimination System General Permit for Discharges from Construction Activities*. http://www.epa.gov/npdes/pubs/cgp2012_finalpermit.pdf. Accessed 2013.
New Jersey	No statewide standard – post-construction standard only. New Jersey Department of Environmental Protection. *Permit to Discharge Stormwater from Construction into the Surface Waters of the State of New Jersey*. 2011. http://www.state.nj.us/dep/dwq/pdf/5g3_factsheet.pdf. Accessed 2011.
New Mexico	No statewide standard. New Mexico. 2012. *EPA National Pollutant Discharge Elimination System General Permit for Discharges from Construction Activities*. http://www.epa.gov/npdes/pubs/cgp2012_finalpermit.pdf. Accessed 2013.
New York	No statewide standard. New York State Department of Environmental Conservation. 2010. *SPDES General Permit for Stormwater Discharges from Construction Activity.* http://www.dec.ny.gov/docs/water_pdf/gpsconspmt10.pdf. Accessed 2011.

State	Numeric Effluent Standards for Active Construction Sites
North Carolina	No statewide standard. North Carolina Department of Environment and Natural Resources Division of Water Quality. 2006. *General Permit to Discharge Stormwater under the National Pollutant Discharge Elimination System*. http://cicacenter.org/pdf/ncpermit.pdf Accessed 2011.
North Dakota	No statewide standard. North Dakota Department of Health. 2009. *Authorization to Discharge under the North Dakota Pollutant Discharge Elimination System.* http://www.ndhealth.gov/WQ/Storm/Construction/NDR10per20091001F.pdf Accessed 2011.
Ohio	No statewide standard. Ohio Department of Natural Resources. 2013. *General Permit Authorization for Storm Water Discharges Associated with Construction Activity under the National Pollutant Discharge Elimination System.* http://www.epa.ohio.gov/Portals/35/permits/OHC000004_GP_Final.pdf. Accessed 2013.
Oklahoma	No statewide standard. Oklahoma Department of Environmental Quality – Water Quality Division. 2012. *General Permit OKR10 for Stormwater Discharges from Construction Activities Within the State of Oklahoma.* http://www.deq.state.or.us/wq/wqpermit/docs/general/npdes1200c/permit.pdf. Accessed 2013.
Oregon	No statewide standard. Oregon Department of Environmental Quality. 2010. *General Permit – National Pollutant Discharge Elimination System Stormwater Discharge Permit.* http://www.deq.state.or.us/wq/wqpermit/docs/general/npdes1200c/permit.pdf. Accessed 2011.
Pennsylvania	No statewide standard. Pennsylvania Department of Environmental Protection. 2010. *General Permit for Coverage Under General NPDES Permit For Stormwater Discharges Associated with Construction Activities.* http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-91750/3150-PM-BWEW0280%20Fact%20Sheet.pdf . Accessed 2011.
Rhode Island	No statewide standard – post-construction standard only. Rhode Island Department of Environmental Management. 2013. *General Permit for Stormwater Discharge Associated with Construction Activity.* http://www.dem.ri.gov/pubs/regs/regs/water/ripdesca.pdf. Accessed 2013.

State	Numeric Effluent Standards for Active Construction Sites
So. Carolina	No statewide standard. South Carolina Department of Health & Environmental Control. 2012. *NPDES General Permit for Stormwater Discharges from Construction Activities.* http://www.scdhec.gov/environment/water/swater/docs/CGP-permit.pdf. Accessed 2013.
So. Dakota	No statewide standard. South Dakota Department of Environment and Natural Resources. 2010. *General Permit for Storm Water Discharges Associated with Construction Activities.* http://denr.sd.gov/des/sw/IPermits/ConstructionGeneralPermit2010.pdf. Accessed 2011.
Tennessee	No statewide standard. Tennessee Department of Environment & Conservation. 2011. *General NPDES Permit for Discharges of Stormwater Associated with Construction Activities (Permit No. TNR100000).* http://www.tennessee.gov/environment/water/docs/wpc/tnr100000.pdf. Accessed 2011.
Texas	No statewide standard - concrete batch plants only. Texas Commission on Environmental Quality. 2013. *General Permit to Discharge Under the Texas Pollutant Discharge Elimination System (Permit No. TXR105000).* http://www.tceq.texas.gov/assets/public/permitting/stormwater/TXR150000_CGP.pdf. Accessed 2013.
Utah	No statewide standard. Utah Department of Environmental Quality Division of Water Quality. 2010. *Storm Water General Permit for Construction Activities.* Permit No. UTR300000. http://www.waterquality.utah.gov/UPDES/docs/2008/07Jul/GeneralConstructionPermiUTR3000000t.pdf. Accessed 2011.
Vermont	2008 Construction General Permit notes a 25 NTU limit for moderate-risk sites. Vermont Agency of Natural Resources. 2008. *General Permit for Stormwater Runoff from Construction Sites.* http://www.anr.state.vt.us/dec/waterq/stormwater/docs/construction/sw_cgp_amended_final.pdf. Accessed 2011.

State	Numeric Effluent Standards for Active Construction Sites
Virginia	No statewide standard. Virginia Department of Environmental Quality. 2009. *General Permit for Discharges of Stormwater from Construction Activities*. http://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/CGPvar10.pdf . Accessed 2011.
Washington	Turbidity shall not exceed 5 NTU over background turbidity when the background turbidity is 50 NTU or less, or has more than a 10 percent increase in turbidity when the background turbidity is more than 50 NTU. Washington State Department of Ecology. 2010. *National Pollutant Discharge Elimination System (NPDES) and State Waste Discharge General Permit for Stormwater Discharges Associated with Construction Activity.* http://www.ecy.wa.gov/programs/wq/stormwater/construction/permitdocs/cswgppermit120110.pdf Accessed 2011.
West Virginia	No statewide standard. West Virginia Department of Environmental Protection. 2012. *State of West Virginia Department of Environmental Protection Division of Water and Waste Management.* http://www.dep.wv.gov/WWE/Programs/stormwater/csw/Documents/Final_Signed_2012_CSW_General_Permit.pdf. Accessed 2013.
Wisconsin	Construction sites must implement erosion and sediment controls to reduce to the maximum extent practicable 80% of the annual sediment load. Wisconsin Department of Natural Resources. 2011. *Wisconsin Pollutant Discharge Elimination System General Permit for Construction Site Storm Water Runoff*. http://dnr.wi.gov/topic/stormwater/documents/fact_sheet_wi-s067831-4_sept_2011.pdf. Accessed 2011.
Wyoming	No statewide standard. Wyoming Department of Environmental Quality. 2011. *General Permit to Discharge Storm Water Associated with Construction Activity Under the Wyoming Pollutant Discharge Elimination System (WYPDES).* http://deq.state.wy.us/wqd/wypdes_permitting/wypdes_storm_water/downloads/LCGP_2011_final.pdf. Accessed 2011.

APPENDIX B: TYPICAL RUNOFF TURBIDITY FOR ROAD CONSTRUCTION PROJECTS FROM PREVIOUS STUDIES

Source	Construction Type	Location State	Sampling Year	Runoff Turbidity			Remark
				Min	Max	Mean	
Kayhanian et al. (7)	Roadway / Highway	CA	1998-2000	15	16000	702	15 sites
McLaughlin (8)	1:2 fill slope	NC	2001	50	5600	1638	PAM
	1:2 fill slope	NC	2001	25	4000	634	PAM+mulch+seed
	1:4 cut slope	NC	2001	200	5900	2272	PAM
	1:4 cut slope	NC	2001	50	400	182	PAM+mulch+seed
	1:4 fill slope	NC	2001	11	2000	360	PAM
	1:4 fill slope	NC	2001	18	500	116	PAM+mulch+seed
McLaughlin and Jennings (9)	Highway	NC	2004-2005	77	28160	2950	Final outlet
	Highway	NC	2004-2006	6	18223	1647	Final outlet
	Highway	NC	2004-2007	6	2272	159	Final outlet
	Highway	NC	2004-2008	3	9409	1178	Final outlet