Water Quality Improvements Using Modified Sediment Control Systems on Construction Sites

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Abstract. *A study of the water quality of discharges from three different sediment control systems was conducted on a large construction site in North Carolina. Samples were obtained during storm events at the outlets of 11 of these systems using automatic samplers. Turbidity and total suspended solids (TSS) were measured, and a storm-weighted average (SWA) was determined for the systems. Water discharged from five standard sediment traps with rock dam outlets and unlined diversion ditches with rock check dams had an SWA turbidity of 4,320 nephelometric turbidity units (NTU) and an SWA peak of 12,640 NTU over a total of 26 storm events. The representative TSS values were 4,130 and 11,800 mg* L^{-1} *, respectively. Measurements of runoff entering and exiting the traps suggested that heavy sediment was being captured, but turbidity was not reduced. Three traps with modifications including forebays, porous baffles, improved ditch stabilization (lining, additional check dams), and polyacrylamide application had SWA and peak turbidity of 990 and 1,580 NTU, respectively, over a total of 31 events. Total suspended solids were also much lower, at 740 and 1,810 mg* L^{-1} *, respectively. Three basins with these same modifications,* *but with surface outlets, had somewhat higher average SWA values (1,560 NTU, 820 mg L* $^{-1}$ *), suggesting that the outlet type may not improve discharge water quality above the benefits of the other modifications to the standard sediment trap. However, when one of the latter systems was at optimal function, turbidity was reduced to below the receiving stream water levels (<100 NTU). These results strongly suggest that relatively simple modifications of commonly employed sediment trapping systems can dramatically improve discharge water quality and reduce the impacts on receiving waters.*

Keywords. Polyacrylamide, Sediment, Total suspended solids, Turbidity.

Most construction sites are required to have sediment control devices to intercept and treat runoff prior to discharge, but the devices typically installed are generally inefficient. Trapping efficiencies greater than 90% have been estimated to be needed to meet common water quality standards, but this efficiency is not often met (Ward et al., 1980). A number of design factors can greatly affect how well sediment traps function. The length-to-width ratio has been shown to affect the dead storage volume, which is the area of a basin bypassed by most of the incoming flow (Chen, 1975; Griffin et al., 1985). A minimum length-to-width ratio of 2:1 was recommended by Barfield et al. (1983), Mills and Clar (1976), and the North Carolina Department of Environment and Natural Resources (NC DENR, 2006). The outlet design can also affect basin performance. A field study of typical sediment traps with gravel outlets determined that they trapped 59% to 69% of the incoming sediment over the course of up to 20 months (Line and White, 2001). Using similar surveying methods, McCaleb and McLaughlin (2008) found that these traps were capturing <40% of incoming sediment, but that large, well-stabilized basins with surface outlets could achieve up to 99% capture efficiency. A study of sediment basins on a Pennsylvania highway construction site suggested a trapping efficiency of <20%, and that sometimes the discharge had more sediment than the water entering the basin (Kalainesan et al., 2009). Under controlled conditions, sediment capture rates were improved by controlling discharge with a perforated riser (Fennessey and Jarrett, 1997; Ward et al., 1979; Edwards et al., 1999) or a floating skimmer (Millen et al., 1997). Modeling results have also indicated that surface outlets, such as skimmers, greatly increase sediment capture compared to either bottom or full water column dewatering (Ward et al., 1979).

Modifications within a sedimentation device can also improve efficiency. For example, solid baffles near the basin inlet reduce the mean flow velocity into the basin and disperse the inflow energy, reducing bypass flow and dead volume (Goldman et al., 1986). Baffles made of silt fence material with weirs cut in the fabric are commonly installed in sediment basins in North Carolina. Millen et al. (1997) suggested that silt fence baffles can improve sediment retention by diverting the flow through opposing weirs to increase the flow path and residence time. Barrett et al. (1998) demonstrated that the main mechanism of a silt fence for sediment trapping on slopes is the initial pooling that occurs; a similar effect may occur in sediment basins. Porous baffles have been found to capture flocculated soil after polyacrylamide (PAM) treatment, but the main effect found was improved flow characteristics for settling (Thaxton et al., 2004; Thaxton and McLaughlin, 2005). Porous baffles are now required in sediment traps and basins in North Carolina (NC DENR, 2006).

The objective of our research was to compare the turbidity and TSS being discharged from standard sediment control systems, consisting of rock check dams and sediment traps, with those modified to improve sediment capture on active construction sites. Because of the highly variable nature of active construction sites, discharges from multiple systems were monitored over many storm events in order to obtain statistically valid representations of the performance of these systems.

Materials and Methods

Site Description

The study was conducted on a large, linear construction project similar to conditions commonly found on construction sites in the southeastern U.S. The construction site was situated along a portion of the Interstate 485 project northwest of Charlotte, North Carolina. Multiple basins of each design were monitored from early 2003 to summer 2006 along sections that mostly paralleled or crossed Long Creek. The disturbed area was at least 60 m wide in all locations. Elevations and topography varied widely and often changed depending on the stage of construction around the individual basins. Typically, the highest point was no more than 10 m above the basins, and slopes ranged from <1% (roadbeds) to 50% or more during major grading operations. The surface soils were predominantly sandy clay loams or clay loams mapped as Cecil (fine, kaolinitic, thermic Typic Kanhapludults) or in the Enon-Helena-Vance (fine, mixed, semiactive, thermic Typic Hapludults) complex, but most of the time the exposed soil was either subsoil or a fill material from an unknown location and could change radically due to grading activities. Subsoils from other Piedmont areas were typically sandy loams with <20% clay (McLaughlin and Bartholomew, 2006).

Sediment Trapping Systems Evaluated

During basin monitoring, the watershed was often being changed, through either cutting or filling activities needed for highway construction. All of the basins were originally designed as traps to capture runoff from relatively small areas using the formula of 168 m^2 per hectare of drainage. In general, a "trap" is a ponding device with a rock dam outlet, while a "basin" has a solid dam and a riser barrel or similar outlet. We will refer to all of the ponding devices as "basins" for simplicity. The resulting sizes at each site varied but were close to 6 m long × 2.5 m wide × 1 m deep. Standard basins had rock outlets with weirs 1.5 to 2.5 m wide. Three basins had 7.6 cm diameter Faircloth skimmer outlets with 1.5 to 2.0 m geotextile-lined spillways.

Three sediment trapping systems were evaluated, with each system including the basin and the ditches leading up to it, as described below and in table 1. The first system was a standard sediment trap (ST), which had a rock dam outlet of large rock (0.23 to 0.30 m average diameter; Class B stone) with a 0.3 m layer of washed gravel (0.0045 to 0.025 m average diameter, AASHTO No. 57 stone) on the inside to reduce flow (fig. 1). The dam had a weir that was sized to pass a 10-year storm for the area draining to it, but the range in weir width was only between 1.5 and 2.5 m due to the similarities in design drainage areas among these traps. This design has been the standard sediment control device for many years. Runoff was directed to the basin in diversion ditches approximately 1 m wide and 0.5 to 0.75 m deep, unlined, and with rock (Class B stone) check dams. The rock check dams were spaced using the following equation: $S = 300 / \text{slope}$ (%), where$S$ is the spacing (ft). In most cases, this resulted in a spacing of at least 30 m (100 ft). Five ST systems were monitored during the study. Three were monitored for water quality only, and two had V-notch weirs installed below the outlets to monitor flow rates as well.

Table 1. Summary of characteristics of sediment trapping systems compared in this study.

Characteristic	Standard Sediment Trap (ST)	Modified Standard ST with Forebay and PAM Treatment (STFBPam)	Surface Skimmer Outlet, Forebay, and PAM Treatment (SkFBPam)
Outlet	Rock	Rock	Skimmer/spillway
Forebay	None	Rock	Earth dam with geotextile spillway
Porous baffles	No	Yes	Yes
Polyacrylamide (PAM)	None	Ditch (granular, solid blocks)	Ditch (granular, solid blocks)

		and forebay outlet (solid blocks)	and forebay outlet (solid blocks)
Diversion ditch	Unlined, rock check dams	Jute mesh lined, TSD check dams	Jute mesh lined, TSD check dams

Figure 1. Standard rock dam sediment trap (ST).

The second sediment trapping system (STFBPam) involved modifying the existing ST system with the addition of a forebay, porous baffles, and PAM treatment in the diversion ditches leading to the traps as well as in the forebay weir (fig. 2). Forebays were sized between 50% and 100% of the original dimensions of the trap or basin, depending on space available and stage of grading. The forebay was installed primarily to provide a location for PAM blocks, which were placed in a corrugated pipe in the weir between the forebay and the basin to protect them from the heaviest sediment. We had found in earlier trials that the blocks tended to become covered in sediment or buried when placed in ditches or basin inlets. Porous baffles were installed in selected traps and basins using a coconut erosion control blanket (C-125, North American Green, Evansville, Ind.) and a generic jute mesh material on the upstream face. This had previously been shown to greatly improve sediment capture (Thaxton and McLaughlin, 2005; Thaxton et al., 2004). The materials were either hung from a wire strung across steel post supports or on wood supports similar to saw horses. The baffles extended at least 0.15 m above the outlet weir and were anchored on the sides with 0.15 m landscape staples. The bottom of the material was trenched in and stapled using 0.15 m landscape staples.

Figure 2. Standard sediment trap with forebay and polyacrylamide (STFBPam).

Polyacrylamide was applied at several points in the system. One included the installation of solid blocks of PAM (APS 706, Applied Polymer Systems, Woodstock, Ga.) in the ditches leading to the basin. The blocks, weighing approximately 3.6 kg, are a proprietary mixture of PAM and other ingredients and are approved for use in North Carolina due to their low aquatic toxicity. The ditches were lined with jute mesh, chosen due to its low cost relative to other materials, to reduce erosion and to provide a surface for applied PAM powder to adhere to during rain events. Three to four check dams were installed between the existing rock check dams. The extra check dams were Triangular Silt Dikes (TSD, Triangular Silt Dikes, Midwest City, Okla.), which are triangular-shaped foam blocks 25 cm tall covered in a woven geotextile similar to silt fence material. The PAM blocks were installed on the downhill side of the TSDs, where the higher water velocity could accelerate dissolution of PAM from the blocks. In some cases, the blocks were inserted into 20 cm diameter corrugated pipe, which was placed in the center of the TSD to collect flow. This arrangement provided some protection of the PAM blocks from drying in the sun, which tends to reduce the rate of PAM dissolution from the blocks. A PAM block was also placed in the forebay outlet weir. Additional PAM (APS 705) was applied as a powder to the jute material in the ditches for a total of 0.2 to 0.5 kg per application. This was done within a two-day period after each runoff event at the same time samples were retrieved. There were three STFBPam systems monitored.

The third design (SkFBPam) was the same as the second design except that the rock dam outlet was replaced with a floating outlet (Faircloth skimmer, Faircloth and Son, Hillsborough, N.C.) and a lined spillway (weir) over a solid earthen dam as the principal outlets (fig. 3). This is a recent innovation that has been shown to improve sediment capture (Fennessey and Jarrett, 1997; Markusic, 2007) and that is now strongly encouraged or required throughout North Carolina and elsewhere (NC DENR, 2006). Three SkFBPam systems were monitored, all with 7.6 cm skimmers that dewatered at a rate of 11.5 m^3 h^{-1}.

Figure 3. Skimmer basin with forebay and polyacrylamide (SkFBPam).

One of the study systems was initially an SkFBPam system but was extensively modified as road construction progressed. These modifications were made by the construction staff to accommodate grading activities, but we continued to monitor basin discharges. Initially, it received water from a bare soil area that was graded and that had two diversion ditches directing runoff to it. We retrofitted it with a forebay of equal size (8 m × 4 m), installed three porous baffles in the forebay and one in the basin, and removed the rock outlet and installed a skimmer with a geotextile-lined spillway in the dam. We also lined the ditches with jute matting, installed additional check dams (straw wattles, TSDs), and applied PAM to the jute and check dams. The adjacent area began to receive fill material after a few months, eliminating one ditch and the forebay. Then the skimmer was removed, leaving the emergency spillway as the outlet. Finally, the earth dam was removed and a standard rock outlet was installed. The data from this system, which appear in table 2 as ST 1, were gathered during the period after this final modification. We will discuss the effects of each stage of modification on discharge water quality.

Monitoring Methods

Water sampling was accomplished using automatic samplers with the capability of measuring flow and rainfall (ISCO 6700, ISCO, Lincoln, Neb.). It was not always possible to measure flow rate or volume due to site constraints, but where it was measured we used 120° V-notch weirs installed below the rock outlet or in the spillway of the solid dams. Samples were obtained from a point just before the weir by installing a fence post and attaching the sampling tube just below the level of the weir bottom. The samplers were triggered by either basin water level (no weir) or flow through the weirs and were programmed to composite four samples into each of up to 24 bottles. The samplers were programmed to take a sample every 15 min (no weir) or 14 m^3 (weir). To be sure we had data representative of runoff events, only storms that generated at least five bottles (representing 20 samples) were included in our analysis. Flow from the skimmers was measured at the weir, which was placed so that flow from both the skimmer and the geotextile spillway passed through it.

The samples were brought to our laboratory at North Carolina State University within several days of each event. After shaking the bottles to resuspend the sediment, turbidity was measured using either a probe (Analite 160, McVan Instruments, Melbourne, Australia) or a meter (LaMotte 2020, LaMotte Co., Chestertown, Md.). The probe had a higher range (manufacturer specifications: 3,000 NTU max., 2% accuracy), but we found it less accurate at values below 200 NTU, so the meter (1,100 NTU max., 2% accuracy) was used for the less turbid samples. Initially, samples that exceeded 3,000 NTU were diluted to as low as 5%, resulting in a maximum measurement limit of 60,000 NTU for our instruments. However, this procedure was modified to a 10% dilution after the first year due to difficulties in reproducing the 5% dilution results. If a sample exceeded this range, then 30,000 NTU was used for calculations. The turbidity meters were calibrated daily against standards, and the readings were corrected in the data spreadsheet. Total suspended solids were measured by stirring the sample continuously and removing a subsample from all depths with a pipette, which was then filtered through a 0.45 μm filter (Clesceri et al., 1998).

For each system, the minimum, maximum, and average values for turbidity and TSS were calculated for each storm. In systems for which flows were measured, the flow-weighted averages were also calculated. The minimum, maximum, and average values for each system were calculated using a storm-weighted average. This was calculated by multiplying the average minimum, maximum, and overall average for each individual system by the number of storms monitored for that system, summing those, and dividing by the total number of storms (eq. 1):

(1)

where

SWA = storm-weighted average

avg = average value for system 1, 2, ..., *n*

n = number of storms monitored for system 1, 2, ..., *n* .

This provided a way to weight the data according to the strength of the monitoring for each individual system, as indicated by the number of storms successfully monitored. For example, averages from a system for which ten storms were monitored have twice the weight of a system with data from five storms.

Results and Discussion

In all cases, the watershed for each system that we monitored had been stripped of vegetation and was in some stage of being graded when monitoring was initiated. The watershed was usually 100% bare soil, the only exception being when grading stopped long enough for weeds to grow. Runoff was always diverted to the devices using ditches on the cleared area edge and sometimes within the area. The ditches were cut 0.5 to 1 m deep with vertical sides, unlined, and unvegetated, and as a result they likely contributed large amounts of sediment into the basins.

Comparisons of the turbidity and TSS results indicate substantial reductions in both in the water discharged with the modified systems compared to the ST systems (tables 2 to 4). The average turbidity and TSS for ST was more than four times the turbidity and TSS averages for STFBPam when the outlier storm is excluded from the latter. This final storm produced turbidity in excess of 30,000 NTU in all samples, possibly as a result of a different type of fill material being introduced to the site. Even with the final storm, the STFBPam TSS average was only 19% of the ST systems. The SkFBPam systems did not have as low an average turbidity as the STFBPam systems, primarily due to high turbidity for two storms in one of the three systems monitored. However, turbidity was still considerably lower than the ST systems, and TSS was nearly as low as the STFBPam systems.

Table 2. Turbidity and TSS in five ST basins.

System	Size (m, L × W)	No. of Storms [a]	Rainfall Range (mm)	Turbidity Average (NTU)			TSS Average (mg L^{-1})		
				Min.	Max.	Mean	Min.	Max.	Mean

1	8 × 4	4/3	19-101	2,110	23,840	7,520	2,110	23,850	7,170
2	6 × 2	4/4	6-49	1,430	9,560	2,830	530	10,870	1,590
3	6 × 2	5/5	6-45	1,930	8,240	3,000	2,010	4,430	5,590
4	8 × 3	3/3	2-70	290	30,000	12,440	180	47,170	10,820
5	6 × 2	10/10	2-50	570	6,380	1,870	270	6510	1060
		Storm-weighted average and 95% confidence interval		1,170 ± 580	12,640 ± 4,570	4,320 ± 1,870	870 ± 670	13,750 ± 7,900	3,950 ± 1,950

[a] Listed as number of storms where turbidity/TSS were measured.

Table 3. Turbidity and TSS in three STFBPam basins.

System	Size (m, L × W)	No. of Storms [a]	Rainfall Range (mm)	Turbidity Average (NTU)			TSS Average (mg L^{-1})		
				Min.	Max.	Mean	Min.	Max.	Mean
1	8 × 4	6/2	4-63	740	2,790	1,990	250	1,590	670
2	6 × 2	13/9	4-63	490	1,340	730	330	1,050	600
3	6 × 2	11/7	3-40	400	1,340	840	180	2,840	940
		System 3 including last storm [b]		2,860	3,730	3,270	890	3,590	1,450
		Storm-weighted average and 95% confidence interval		500 ± 230	1630 ± 290	1020 ± 310	260 ± 160	1810 ± 2000	740 ± 650

[a] Listed as number of storms where turbidity/TSS were measured.

[b] Turbidity from the last storm in one of the basins was much higher (>30,000 NTU in all samples) than the other 31 events, so averages were calculated both with and without data from that storm. The SWA does not include the last storm.

Table 4. Turbidity and TSS in three SkFBPam basins.

System	Size	Forebay	No. of	Rainfall	Turbidity Average	TSS Average (mg

	(m, L × W)	(m, L × W)	Storms [a]	Range (mm)	(NTU)			L $^{-1}$)		
					Min.	Max.	Mean	Min.	Max.	Mean
1	6 × 3	2 × 2	7/5	6-63	900	2,590	1,450	130	3,720	1,000
2	6 × 4	6 × 2	2/0	4-62	1,770	12,450	4,330	nd	nd	nd
3	6 × 4	6 × 2	10/8	7-90	310	3,040	1,080	290	1,750	710
			Storm-weighted average and 95% confidence interval		680 ± 1,130	3,870 ± 4,030	1,560 ± 710	230 ± 450	2,510 ± 1,250	820 ± 184
[a] Listed as number of storms where turbidity/TSS were measured.										

One of the most striking differences among these systems was in the peak values for both turbidity and TSS. The average high turbidity for ST was more than 12,000 NTU, while the average high values were less than 4,000 NTU for the other systems (tables 2 to 4). Similar reductions in these peak values were evident for TSS. An example of a storm event for an ST system is shown in figure 4, with flow and turbidity plotted together. The turbidity peaks tended to coincide with peak flows, as expected, which suggests that the effect of reducing the peak amount of sediment entrained in discharges from sediment control devices will be multiplied since it occurs during the highest flows. The peak values for this storm were more than 30,000 NTU, which is higher than our instruments can measure, so they are plotted as 30,000 NTU. In comparison, a storm of similar precipitation totals produced peak turbidities of less than 700 NTU for one of the STFBPam systems (fig. 5).

Figure 4. Example peak turbidity and flow for a standard trap (ST). Turbidity values above 30,000 NTU could not be accurately measured and are plotted as 30,000 NTU.

Figure 5. Example peak turbidity and flow for a standard trap with a forebay and polyacrylamide (STFBPam). Note the scales for flow and turbidity are different from those in figure 4.

The differences in discharge water quality among the systems could have been influenced by activities in their watersheds during the monitoring period, as well as by site characteristics (slope, soil type) and storm characteristics. For instance, the storm event in STFBPam 3, which raised the averages in table 3, had discharges with high turbidity (>30,000 NTU) and TSS (>3,500 mg L^{-1}), although there was only 14 mm of rain. This high turbidity was the direct result of a fill operation that added up to 10 m of soil directly adjacent to the ditches and trap, with unstabilized 50% or steeper slopes draining into them. In fact, this was the last storm we monitored because the ditches and trap were filled in as part of the next phase of grading. This amount of sediment clearly overwhelmed the system that we installed. In comparison, however, for many of the storm events monitored at the standard traps, the watersheds were at final grade with little active earth-moving activities, and the discharges still contained much more sediment compared to the other systems. There was no correlation between rain amount and turbidity in any of the three systems ($r^2 = 0.03$ to 0.08), further suggesting that earth-moving activities were a dominant variable in system performance. We did not fully explore rainfall intensity as a variable, but a review of average intensities suggested that this did not represent the rainfall or runoff patterns well. For example, two consecutive storms in July 2004 had similar average intensities (17.8 and 17.1 mm h^{-1}) and lengths (2.4 and 1.9 h) but dramatically different outlet flow peaks (0.28 and 0.09 $m^3 s^{-1}$). The wide range in minimum and maximum values and wide confidence intervals also provides evidence of the variability in water quality from the same treatment system or similar systems as a result of the complex interactions between site conditions and storm characteristics on active construction sites.

Our attempts to obtain representative samples of water entering the ST basins were often unsuccessful because the high sediment loads either clogged or buried the sampler intake tubing; therefore, in most cases, we did not attempt to sample inflow. However, there were five storms for which we did get samples both at the inlet and outlet of three different STs. The data suggest that the traps did not reduce runoff turbidity, and sometimes increased it (table 5). The overall average increase of 6% indicates that these systems are not effective for turbidity control. The reduction in TSS in traps 2 and 3 was negligible for these storm events, but trap 5 appeared to reduce TSS even when turbidity was increasing. This discrepancy could be an artifact of the analytical methods. Turbidity was measured 30 s after shaking the sample for 10 s as a way to standardize this measurement, which usually changes continuously as materials settle. This procedure would allow the sand and coarse silt, which do not contribute much to turbidity, to settle. The TSS samples were stirred prior to subsampling for filtration, so even the coarse fraction would be included in the analysis. This could explain why turbidity and TSS did not always follow the same pattern, depending on the source sediment particle size distribution. Kalainesan et al. (2009) also found that TSS could actually increase from inlet to outlet in construction site sediment basins.

Table 5. Turbidity and TSS for storm events in which both inlet and outlet samples were obtained in standard traps.

ST System	Date (month/day, 2006)	Rainfall (mm)	Turbidity			TSS		
			In (NTU)	Out (NTU)	Change (%)	In (mg L $^{-1}$)	Out (mg L $^{-1}$)	Change (%)
2	12/15	45	3,100	2,620	-10	870	840	-4
3	7/13	18	3,760 [a]	3,420 [a]	-10	3,020	3,100	6
5	5/26	17	11,480 [a]	11,200 [a]	-2	4,3810	11,850	-73
5	6/03	2	7,270 [a]	11,680 [a]	37	4,3230	6,340	-85
5	6/14	44	7,890 [a]	9,250 [a]	15	7,7760	14,250	-82

[a] Flow-weighted average.

To estimate changes in turbidity as runoff passed through two of the SkFBPam systems, we installed samplers at both the forebay outlet and the main outlet. These two systems both had PAM applied in ditches leading to the basin, as well as the forebay outlet weir, with one of the two ditches bypassing the forebay and flowing directly into the basin. The ditch flowing directly to SkFBPam 3 had almost no slope, which combined with high sediment loads to render the PAM treatments ineffective by burying them with sediment. Similar problems have been reported elsewhere (Auckland Regional Council, 2004). This partial treatment explained why turbidity increased in SkFBPam 3 as measured from forebay outlet to main outlet, while it decreased in SkFBPam 1 where the PAM treatment was effective in both ditches (table 6). The ditches with effective turbidity reduction had steeper slopes to provide higher velocities and turbulence, which helped to dissolve the PAM and increase contact with the sediment. Previous work has shown that the PAM blocks are effective under optimal conditions, including protection from heavy sediment that can coat them, keeping them moist between storm events, and maintaining good contact and mixing with storm water (McLaughlin, 2003). Similar ditch treatments (check dams and PAM powder) can also be very effective (McLaughlin et al., 2009).

Table 6. Average turbidity in forebay outlet and basin outlet for two skimmer basins with different levels of PAM treatment.

SkFBPam	PAM	Date	Rainfall	Turbidity

System	Treatment	(month/day, 2004)	(mm)	Forebay Average (NTU)	Outlet Average (NTU)	Change (%)
1	Forebay and basin	2/28	13	200	90	-55
		4/13	24	260	150	-42
		6/14	63	7,530	3,760	-50
3	Forebay only	6/14	63	580	5,270	808
		9/13	69	610	1,010	65
		9/20	36	550	1,070	94

One basin was modified extensively during our monitoring in 2005 (see the Materials and Methods section), allowing for some analysis of the effect of these modifications. Because the changes to the system coincided with changes in activity in the watershed, the differences in discharged water quality cannot be completely attributed to the basin configuration changes. However, trends were certainly obvious over this period. With the full SkFBPam system in place, turbidity was reduced 82% to 99% from inlet to outlet for the three storms with substantial turbidity at the inlet and samples at the outlet (3/22, 4/8, 4/12; table 7). Turbidity was reduced by 30% to 98% at the forebay outlet, for an average of 64% over the six storms with samples at the inlet and forebay outlet. The combination of PAM (blocks, powder) in the ditches along with a forebay with three porous baffles and a surface (spillway) outlet apparently functioned well, reducing turbidity by an order of magnitude or more. We observed heavy deposits of sediment in front of the first baffle within just a few storms. During this period, this SkFBPam system reduced turbidity better than any of those listed in table 4, possibly due to the larger forebay and better PAM treatment in the somewhat steeper and longer diversion ditches.

Table 7. Turbidity in a SkFBPam basin discharge as it was modified during the project.

Treatment[a]	Date (month/day, 2005)	Precipitation (mm)	Average Turbidity (NTU)			
			In	Forebay Outlet	Surface Outlet	Rock Outlet
1	3/8	17	116	81	63	Skimmer and

	3/16	20	na	124	32	spillway outlet in place
	3/22	14	4,360	437	54	
	3/27	17	2,152	987	na	
	3/31	11	654	386	na	
	4/8	14	3,705	1,047	466	
	4/12	27	4,286	93	776	
2	6/7	15	Forebay removed, fill starts		5,819	
	6/9	30			14,208	
	6/27	57			18,166	Spillway alone
	7/11	13			13,867	
	7/18	5			11,061	
3	7/28	19	Outlet converted to rock dam			5,294
	8/8	26				8,210
	10/17	101				12,319
	11/21	49				2,874

[a] Treatment 1 = Ditches lined, extra check dams, and PAM in two ditches and forebay spillway. Treatment 2 = One ditch and forebay filled in, eliminating PAM treatment. Treatment 3 = Slope drains with PAM blocks in them.

Starting in May, the area adjacent to the basin began to receive fill materials, which required the removal of the forebay and one of the two diversion ditches. As a result, substantial increases in turbidity were evident (6/7 and thereafter, table 7) when the adjacent area received fill materials, creating steep slopes of bare soil. Most of the sediment coming into the basin originated from the fill area, while the remaining diversion ditch became isolated and conveyed little water to the basin. This limited the potential for PAM treatment of most of the runoff coming to the basin. For three storms (6/27 to 7/18), the skimmer was removed by the construction staff, but the primary discharge point was still the spillway over the dam. After the July 18 event, the outlet was converted to a standard rock dam, so the only modification remaining was a single porous baffle, which sagged badly and probably did not function properly. By the July 28 event, most of the flow to the trap was from slope drains and sheet flow from the slopes. Turbidities decreased compared to the previous month, due to the increasing stability of the watershed, the influence of the PAM blocks in the slope drains, or both. However, average turbidities remained one to two orders of magnitude higher than when the full system was intact, suggesting that the PAM blocks were likely covered in sediment and generating little PAM in the storm flows.

During the March and April period, while the full treatment system was in place, we also installed automatic samplers to monitor the adjacent stream at points just upstream and downstream from the construction site. This basin was one of four discharging directly to the stream, while the other three were standard traps. There were four events for which samples were obtained from all three points in the system and both upstream and downstream, plus one more event that was missing only the inlet samples due to the sampler intake being buried. There was a great deal of variability in turbidity during each storm event, but the basin outlet had significantly lower turbidity than the receiving stream for two events and the forebay outlet for one additional event (table 8). Even more striking was the attenuation of peak turbidities at the system inlet. The full treatment system brought the peak turbidity down to less than that of the upstream water for the first three storms and less than peak turbidity in the downstream water for the next two. The inlet peak turbidities for the third and fifth events were obtained by doing one extra dilution, which we did not do routinely, in order to make these comparisons. Comparing the upstream and downstream turbidities also illustrates the influence of the construction site on the stream, generally increasing turbidity by an order of magnitude. The downstream peaks of up to 13,000 NTU and the corresponding TSS are several orders of magnitude greater than values previously shown to affect aquatic organisms (Newcombe and Jensen, 1994; Reid et al., 1999). Construction site discharges containing much less sediment have been shown to affect benthic macroinvertebrates (Ehrhart et al., 2002).

Table 8. Turbidity (NTU) means and maxima in a basin and an adjacent stream during five storm events when the ditch treatments, forebay, porous baffles, and skimmer were in place. Means followed by different letters are significantly (p = 0.05) different within each event. Downstream samples were impacted by discharges from three standard sediment traps in addition to the monitored basin.

Storm Event Date (month/day, 2005) and Precipitation (mm)	Forebay Inlet		Forebay Outlet		Basin Outlet		Stream Above Project		Stream Below Project	
	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.
3/8 (17)	116	335	81	122	63	69	57	72	326	4,106
3/16 (20)	--	--	124 b	480	32 a	80	79 b	199	309 c	1,075
3/22 (14)	4,360 [a]	56,461	437 c	2,915	54 a	233	111 b	278	454 c	2,783

4/6 (14)	3,705	12,362	1,047	5,691	466	2,161	179	626	1,901	13,578
4/12 (27)	4,286 c	37,177	93 a	125	776 bc	2,660	97 a	369	623 bc	3,526

[a] Not included in analysis due to extreme variability.

Conclusions

Conventional sediment traps on construction sites have been shown to remove 35% to 60% of incoming sediment, with the remaining being discharged. We found that five of these devices on active construction sites had an SWA turbidity of 4,320 NTU and an SWA peak of 12,640 NTU over a total of 26 storm events. The representative TSS values were 4,130 and 11,800 mg L $^{-1}$, respectively. Measurements of runoff entering and exiting the traps suggested that the larger particles were being captured but the turbidity was not reduced. These values far exceed those shown to affect aquatic organisms. Over a total of 31 events, three sediment trapping systems with modifications including forebays, porous baffles, ditch lining, and PAM application had SWA turbidity and peak turbidity of 990 and 1,580 NTU, respectively. Total suspended solids were also much lower, at 740 and 1810 mg L $^{-1}$, respectively. These results strongly suggest that relatively simple modifications of sediment control systems can dramatically improve their capture efficiency and reduce the impacts of construction activities on nearby streams and lakes. Having large areas of disturbed soil open for months, as in the case of this study, will likely present a challenge to any sediment control system even when optimized.

Although there was clear evidence of improvements through the combination of elements in the experimental systems, greater reductions are both possible and needed. This was demonstrated for one SkFBPam system, which reduced turbidity below receiving stream levels before the system was systematically dismantled during the construction process. On an active construction site, the two experimental systems we tested would have to be regularly maintained and adjusted to have significant impacts on fine, suspended sediment. Polyacrylamide dosing prior to the basins can be very effective, and ensuring that this is occurring is an important part of maintenance. This can be challenging if the water conveyances are also carrying heavy sediment loads that bury PAM blocks or powder spread on a liner or check dam, or if low slopes prevent adequate flows for dissolving and mixing the PAM. However, lining ditches, installing extra check dams, and using forebays can create opportunities to use PAM in many settings.

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