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Check dam and polyacrylamide performance under simulated stormwater runoff

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ABSTRACT

High levels of turbidity and fine suspended sediments are often found in stormwater discharges from construction sites even when best management practices (BMPs) for sediment control are in place. This study evaluated turbidity reduction by three check dam types: 1) rock check dam representing a standard BMP, 2) excelsior wattle representing a fiber check dam (FCD), and 3) rock check dam wrapped with excelsior erosion control blanket (rock + excelsior ECB) representing an alternative FCD. Three check dams (all same type) were installed in a lined, 24-m ditch on a 5–7% slope and three consecutive simulated stormwater flows were run in the ditch. Additional tests were performed by adding granular polyacrylamide (PAM) on the check dams in the same manner using two sediment sources differing in clay content. Without PAM treatment, significantly higher effluent turbidity (>900 nephelometric turbidity units (NTU)) exited the ditch with rock check dams than with excelsior wattles or rock + excelsior ECBs (<440 NTU). The extent of sediment deposition between the check dam types was in the order of excelsior wattle > rock + excelsior ECB > rock check dam, indicating better water pooling behind the wattle. The PAM treatment reduced turbidity substantially (>75% relative to no PAM treatment) for all check dam types and it was very effective in excelsior wattles (<57 NTU) and rock + excelsior ECBs (<90 NTU) even during the third storm event. This study demonstrates that the passive treatment of runoff with PAM on FCDs (or rock + excelsior ECB) in construction site ditches can be very effective for sediment retention and turbidity reduction.

1. Introduction

Construction activities can be major sources of sediment and turbidity discharges into developing watersheds, with erosion rates an order of magnitude higher than farming and several orders higher than undisturbed areas (Owen, 1975; Pitt et al., 2007). Even with sediment control measures such as silt fence and settling basins, there can be substantial discharges of fine sediment from construction sites (Line and White, 2001; McCaleb and McLaughlin, 2008; Kalainesan et al., 2009). The fine sediments can carry nutrients and pollutants and can increase turbidity in nearby receiving waters, which in turn has negative impacts on aquatic organisms by limiting sunlight penetration into the water (Clark et al., 1985).

In December of 2009, the United States Environmental Protection Agency (USEPA) proposed effluent limitation guidelines (ELGs) and issued a new standard that applies to stormwater discharges from construction and development activities (USEPA, 2009). A numeric turbidity standard was developed for construction activities that disturb 10 acres or more and passive treatment system (PTS) was considered to be a low-cost treatment technology in controlling effluent turbidity. The PTS involves the introduction of chemical flocculant to runoff by placing solid or granular forms of the flocculant in stormwater flow, thereby "passively" dissolving it into the water. This has been proven to work well on linear construction sites when granular polyacrylamide (PAM) was applied to natural fiber check dams (FCDs) (McLaughlin et al., 2009). As a result of a lawsuit, the USEPA withdrew the turbidity limit from the ELG (USEPA, 2012), but there remains a great deal of interest in cost-effective methods to reduce turbidity in construction site discharges.

Check dams have been widely used globally as hydrological structures for watershed management for various purposes such as sediment retention, water capture, groundwater recharge, and carbon retention (Agoramoorthy et al., 2008; Lu et al., 2012). At many construction sites in US, channels such as drainage ditches or

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Fig. 1. Experimental setup showing (a) a drainage ditch installed with rock check dams, (b) turbid water generation by adding sediments, and (c) application of polyacrylamide on an excelsior wattle.

swales are constructed to intercept stormwater runoff from slopes and route the runoff into sediment control measures. Check dams are installed across the channels to pool the water to reduce channel erosion. While check dams can be constructed of a variety of materials, the most common and standard practice for construction sites is a rock check dam made up of large stones placed at intervals in the channel. Another best management practice (BMP) is to use FCDs made of natural fibers such as straw, coir, wood fiber (excelsior) or compost (King and McLaughlin, 2009). Sediment retention by conventional erosion and sediment control BMPs such as mulching, erosion control blanket (ECB), silt fence, check dams and sediment basins can be as high as 80–90% (Benik et al., 2003; Hayes et al., 2005). However, the turbidity in water exiting sediment control measures is often in the range from hundreds to even thousands of nephelometric turbidity unit (NTU) due to the presence of suspended clay-size particles that are not easily settled (Line and White, 2001; McCaleb and McLaughlin, 2008).

Studies have shown beneficial effects of anionic PAM in controlling soil erosion and turbidity in construction site runoff. The use of PAM in agriculture and environmental land management was extensively reviewed by Sojka et al. (2007). Applying PAM to slopes has reduced erosion up to 98% and turbidity up to 82% (Flanagan and Chaudhari, 1999; Hayes et al., 2005). The addition of PAM to turbid water pumped into a stilling basin reduced total suspended solids (TSS) by 80% and turbidity by 88% compared to untreated discharges (Bhardwaj and McLaughlin, 2008).

With the interest in limiting turbidity in stormwater discharges from construction sites, it is important to develop practical and effective methods for treating turbid water at the sites. Previous field studies (McLaughlin et al., 2008, 2009) suggested that FCD may outperform rock check dam in reducing ditch erosion, and adding PAM on FCD can significantly reduce turbidity. However, the efficiency of rock check dams and FCDs in controlling turbidity has not been compared directly under controlled conditions. The objectives of this study were to 1) compare the turbidity reduction by a standard rock check dam with a conventional FCD and alternative FCD (fabric-wrapped rock check dam) with and without PAM treatment, and 2) evaluate the flocculation performance of these check dams with the addition of granular PAM as affected by repeated storm events and sediment types.

2. Materials and methods

This study was conducted at the Sediment and Erosion Control Research and Education Facility (SECREF) in Raleigh, NC. A 24-m ditch was constructed on a 5–7% natural slope and lined with plastic tarps (Fig. 1). It was 0.9 m wide and 0.9 m deep with a 0.46-m H-flume installed at the lower end. The experimental setup consisted of three check dams (all same type) installed in series with the top of each check dam even with the bottom of the check dam above it. The actual spacing between check dams was determined to be 8 m based on the height of each check dam type and the slope of ditch line (King and McLaughlin, 2009). The three check dam types were: 1) rock check dam as a standard BMP, 2) excelsior wattle as a conventional FCD, and 3) rock check dam wrapped in excelsior ECB (rock + excelsior ECB) as an alternative FCD (Fig. 2). The standard rock check dam, composed of Class B stone (0.23–0.30 m in diameter), was installed across the entire width of the ditch similar to the standard design of North Carolina Department of Transportation (NCDOT, 2006). The center of each rock check dam was constructed with a low point (weir) 0.45 m high in the middle and a "tail" extending 0.75 m downslope. For the rock + excelsior ECB, a single-net ECB (American Excelsior Company, Rice Lake, WI) was laid on the bottom of the ditch, the rocks piled on top similar to the standard rock check dam, and the ECB was pulled back over the rocks and anchored with several rocks on

Fig. 2. Check dam types tested: (a) excelsior wattle, (b) rock check dam wrapped with excelsior erosion control blanket (ECB), and (c) rock check dam.

the lower side. For the excelsior wattle, it was cut into sections to snugly fit into the sides of the ditch and stapled down using 0.2 m landscape staples. Excelsior wattles were 0.46 m in diameter when installed but they were loosely packed and tended to compact down to 0.30–0.35 m during testing.

For the PAM treatment, we used a granular product (APS 705, Applied Polymer Systems, Inc., Woodstock, GA) that has been widely used in our region. This product contains a proprietary mixture of anionic polymers of different molecular weights and charge densities and it has been found to be more effective at flocculation than other single polymers (McLaughlin and Bartholomew, 2007). The PAM was applied by hand at the rate of 60 g per check dam (Fig. 1c). After applying the PAM, the check dams were sprinkled with water to simulate rainfall that would occur naturally in an actual site prior to concentrated flow coming into a ditch.

A ditch test consisted of three consecutive, simulated stormwater flows coming into the entrance pipe of the ditch (Fig. 1b). The duration of each storm was 20 min and water was introduced from a storage pond (~900 m^3) through a 0.3-m diameter pipe. Each storm consisted of 4 min of flow at 0.014, 0.028, 0.057, 0.028, and 0.014 $m^3\ s^{-1}$ simulating an increasing and decreasing storm event over a 20-min period. The highest flow was similar to peak flows expected from a 0.45-ha construction site for a 2-year storm event in the area. The flows were regulated with a gate valve located in the pipe near the storage pond. To generate turbid water, a total of 242 kg sediment was added to the delivery pipe by hand during each 20-min storm event. The sediment was added in proportion to flow to achieve approximately 6000 mg L^{-1} of TSS at all flows. This sediment concentration is within the typical TSS range (1000 to 16,000 mg L^{-1}) found in construction site discharges in NC (Line and White, 2001; McCaleb and McLaughlin, 2008). Two sediment sources were used to generate turbid water (Table 1). Sediment 1 was collected from a local construction site and it was used for both no PAM and PAM treatment. Sediment 2 was a fill soil from a local construction site and it was only used for PAM treatment to further test the efficacy of PAM in reducing turbidity between check dam types (Table 2).

An automatic water sampler (Teledyne ISCO 6712 portable sampler, Lincoln, NE) was placed next to each check dam with the intake installed at the immediate downstream (Fig. 1a). Samples were taken every minute with four samples composited into one bottle. Collected samples were analyzed for turbidity using an Analite NEP turbidity meter (McVan Instruments, Melbourne, Australia). For the turbidity measurement, samples were shaken for 10 s and turbidity readings were taken after 30 s of settling. Measured turbidity readings were corrected daily using a standard curve generated with formazin solutions of known turbidity.

Table 1
Particle size analysis for study sediments.

Sediment	Source	Texture	Sand (%)	Silt (%)	Clay (%)
1	Local construction site	Loam	45	38	17
2	Local construction site	Clay loam	32	31	37

Depth and length of sediment deposited above (up slope of) each check dam were measured after the third storm event. In order to approximate the amount of sediment deposited, a sediment deposition index (SDI) was calculated by multiplying depth immediately uphill from the check dam by length of the deposit. While SDI does not represent the absolute amount of sediment deposited, it was useful in comparing relative extent of sediment deposition between check dam types.

Statistical analyses of the data were conducted using the Mixed Procedure model in SAS (Version 9.1; SAS Institute, Cary, NC, USA). The three main treatment factors were check dam type, dam position, and simulated storm event with turbidity set as a repeated measurement (Table 2). Statistical differences of means were tested by Least Square Difference with a probability level of 0.05.

3. Results

3.1. No PAM treatment

All of three main treatments (check dam type, dam position, and storm event) significantly affected effluent turbidity ($P < 0.05$), while storm event was the most significant factor ($P < 0.0001$). When averaged across three storms, effluent turbidity (i.e., turbidity in ditch outlet after the third dam) after both excelsior wattles and rock + excelsior ECBs was significantly lower (<440 NTU) than that found after rock check dams (Fig. 3). There was no significant difference in effluent turbidity between excelsior wattles and rock + excelsior ECBs. In general, turbidity in the ditch effluent increased with each additional storm event for all the check dam types tested, but only the rock check dams had a significant increase in effluent turbidity during successive storm events (Fig. 4). For instance, all of the three check dam types had similar effluent turbidity level (<412 NTU) during the first storm

Table 2
Experimental design and PAM treatments for ditch test.

Sediment	PAM treatment	Check dam (3 types × 3 locations)		Storm event
		Type	Position	
1	With and without PAM	Excelsior wattle	Upstream (1st)	Three consecutive (1st, 2nd, 3rd)
2	PAM only	Rock + Excelsior ECB	Mid-stream (2nd)	
		Rock check dam	Downstream (3rd)	

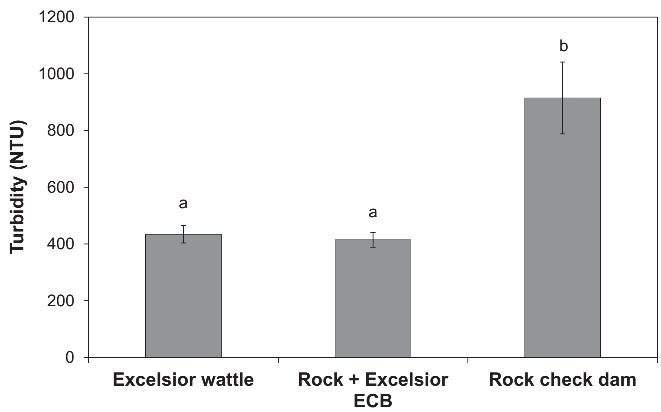

Fig. 3. Mean effluent turbidity for check dam types averaged across the three simulated storm events with no PAM treatment. Error bars represent standard error of the mean. Means followed by same letters are not significantly different ($P < 0.05$).

event. During the successive storm events (i.e., 1st vs 3rd storm), however, effluent turbidity increased by >300% for rock check dams while it increased only 122–144% for excelsior wattles and rock + excelsior ECBs. This result indicated that rock check dams were more susceptible to turbidity discharge over time due to the larger openings in its structure. Our results are in agreement with McLaughlin et al. (2009) who found a better performance of FCDs compared to rock check dams in linear roadside projects in the mountains of NC.

The characteristics of sediment deposition varied by check dam type and location (Table 3). Sediment deposition was the greatest at the first check dam and decreased as heavier fractions tended to be captured in upstream dams. At the first check dam, excelsior wattle and rock + excelsior ECB produced significantly greater sediment deposition than rock check dam in both depth and length. Excelsior wattle showed significantly higher sediment deposition than other two types, but there were no significant differences at the third check dam. Overall, the extent of sediment deposition was in the order of excelsior wattle > rock + excelsior ECB > rock check dam.

3.2. PAM treatment

Adding PAM to the check dams reduced turbidity as much as 93% compared to the untreated dams, even for the rock check dams

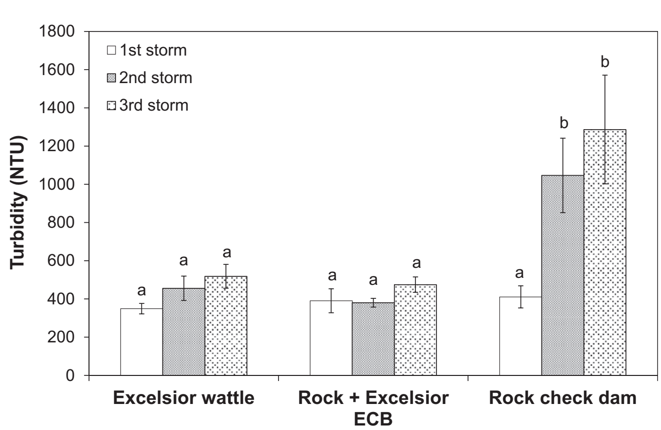

Fig. 4. Mean effluent turbidity for check dam types in three consecutive storm events with no PAM treatment. Error bars represent standard error of the mean. Within each check dam type, means followed by same letters are not significantly different ($P < 0.05$).

(Fig. 5). It was notable that the PAM treatment either on excelsior wattles or rock + excelsior ECBs reduced effluent turbidity below 90 NTU even during the third storm event. This suggests that the PAM applied to the excelsior materials was still providing substantial flocculation during successive storm events. A more detailed look at excelsior wattle by storm event and check dam number (Fig. 6) showed that there was some loss of effectiveness during the third storm, but turbidity was still reduced substantially compared to no PAM treatment. The rock check dams appeared to perform similar to rock + excelsior ECB with the PAM treatment during the first and second storm event, but turbidity reduction was significantly diminished during the third storm event (Fig. 5).

Turbidity reduction by PAM treatment between check dam types was further tested using a clay loam (sediment 2) with identical sediment loading, flow conditions, and PAM application rate (Table 2). The higher clay content in sediment 2 resulted in higher effluent turbidity (38–4984 NTU) than sediment 1 (29–229 NTU) (Fig. 7). During the first storm event, substantial flocculation appeared to occur, with effluent turbidity below 70 NTU in all of the three check dam types. To a greater degree than sediment 1, there was an increase in the effluent turbidity with successive storm events and the flocculation efficiency of PAM decreased rapidly particularly with rock check dam. Over the course of the three storm events, the turbidity reduction by PAM in excelsior wattle and rock + excelsior ECB was diminished by two- to three-fold while that of the rock check dam was diminished by more than 10 fold. The relatively poor flocculation performance of PAM on rock check dam was likely due to the much smaller surface area for the PAM to adhere to and dissolve from.

An important environmental consideration in the use of PAM for stormwater management is the potential toxicity of PAM in the receiving water. If the applied PAM had dissolved over all of the three storm events in this study, the PAM concentration in water would have been 1.7 mg L^{-1} prior to reacting with suspended sediments. If all of the applied PAM had dissolved in the first storm event, the average concentration would have been approximately 5.3 mg L^{-1}. These values are at least 5–10 times lower than the no observable effect concentration (26.25 ppm) for 7-day chronic toxicity as reported by the supplier of the PAM product. These PAM concentrations are far below levels considered to be toxic, and most of the PAM would be adsorbed to the sediment and removed as it settled in the ditch or sediment basins (Lentz et al., 2002). In contrast, the turbidity levels in the untreated water would be considered far above known toxicity levels for aquatic organisms (Henley et al., 2000).

4. Discussion

The original numerical turbidity limit proposed by USEPA required the effluent turbidity of construction site stormwater to be <280 NTU in a daily average (USEPA, 2009). In this study, we demonstrated that granular PAM applied on excelsior wattles can maintain turbidity well below the turbidity limit under conditions similar to ours. The high surface area of excelsior material improved turbidity reduction due to increased PAM-water contact during storm events. We observed that the hydrated PAM on the surface of the excelsior formed a gelatinous pad, which still appeared to be active after the end of the repeated storm events.

Overall effluent turbidity in ditch outlet was reduced by 78–93% when PAM was applied to any check dam type compared to identical tests with no PAM treatment. Rock check dams could be treated with PAM but these were less effective and lost flocculation potential faster than other two types. More frequent PAM application may be needed when using rock check dams as a medium for PTS, and the rocks should be wetted prior to applying PAM to allow

Table 3
Sediment deposition measured by the deepest depth and the longest length after the third storm event. Within a column, values followed by same letters are not significantly different ($P < 0.05$).

Type	1st dam			2nd dam			3rd dam			Total SDI[b]
	Depth (m)	Length (m)	SDI[a]	Depth (m)	Length (m)	SDI[a]	Depth (m)	Length (m)	SDI[a]	
Excelsior Wattle	0.24a	2.41a	0.58a	0.17a	2.74a	0.47a	0.08a	1.37a	0.11a	1.16
Rock + Excelsior ECB	0.22a	3.73a	0.82a	0.08b	2.22ab	0.18b	0.07a	0.99a	0.07a	1.07
Rock	0.12b	0.56b	0.07b	0.11b	1.60b	0.18b	0.10a	0.91a	0.09a	0.34

[a] Sediment deposition index (SDI) was calculated by (depth × length).
[b] Total SDI was a summation of SDI in each of three check dams.

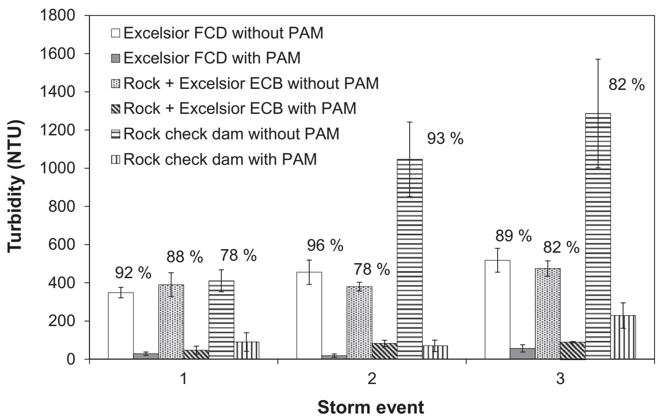

Fig. 5. Mean effluent turbidity for three successive, simulated storm events with and without PAM treatment. The numbers above each pair of bars reflects the turbidity reduction (%) by adding PAM. Error bars represent standard error of the mean.

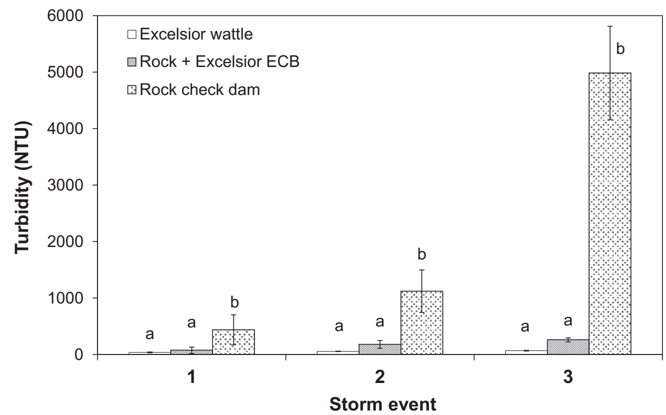

Fig. 7. Mean effluent turbidity for three check dam types with PAM treatment for the clay loam soil (sediment 2). Error bars represent standard error of the mean. Within each storm event, means followed by same letters are not significantly different ($P < 0.05$).

it to adhere to the surface. Our results suggest that wrapping rocks with an ECB can achieve turbidity reductions comparable to the excelsior wattle in situations where rock check dams are preferred. This provides a larger surface area for the PAM granules to adhere to and greater granule-water contact.

It is critical to install check dams correctly and to apply granular PAM in areas where the PAM will be in contact with runoff water (e.g., center of weir of FCD). We recommend installing ECBs under the FCDs to prevent erosion and to apply one-half of the PAM on the FCD and the remainder on the ECB, both above and below the FCD. This ensures PAM contact with both low flows, which may pass through the dam, and high flows when the water passes over the FCD. Stabilizing ditches using liners such as ECB would further prevent the channels from eroding and yield better flocculation performance of PAM compared to unlined ditches. It is also important that check dams are checked regularly (e.g., after each significant rainfall) for sediment accumulation and the need for reapplication of PAM to ensure the effectiveness of this BMP.

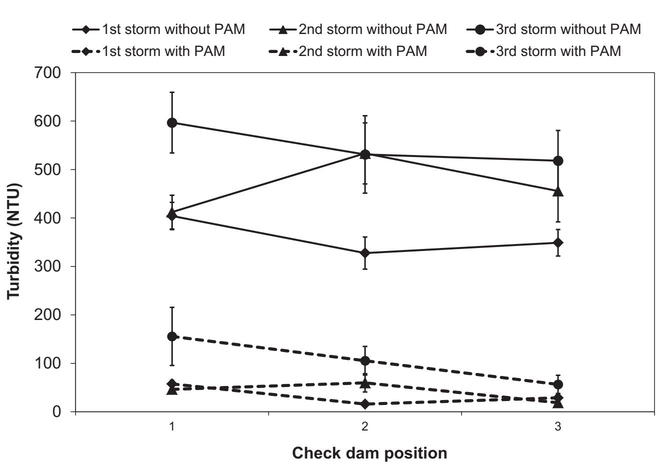

Fig. 6. Mean turbidity at each check dam position for each storm event for excelsior wattle with and without PAM treatment. Error bars represent standard error of the mean.

5. Conclusions

Fine particles that contribute to turbidity are not easily removed by conventional, gravity-based sediment control BMPs. In this study, both the excelsior wattle and rock + excelsior ECB check dams were effective in reducing turbidity as well as maximizing sediment capture. The PTS approach tested with a granular form of PAM greatly improved the performance of check dams in reducing turbidity. Our study suggests that PAM applied to either a FCD or a rock check dam wrapped with an ECB could be effective in both reducing sediment loading to basins and greatly reducing turbidity in stormwater discharges from construction activities.

Acknowledgments

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