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Hydrodynamic and Sediment Capture Assessment of Various Baffles in a Sediment Retention Pond

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Abstract. *We assessed the relative improvement to the sediment trapping effectiveness of a permanent-pool sediment retention pond due to the installation of baffles composed of different materials commonly used on construction sites. A suite of experiments was performed at the Sediment and Erosion Control Research and Education Facility (SECREF) at North Carolina State University in which an acoustic Doppler velocimeter was used to record steady-state flow velocity data at 50 grid points within the pond at three steady input flow rates. Hydrodynamic data was taken for three different baffle materials and for free flow. The experiments were repeated with a characterized soil injected upstream at a fixed rate. At the completion of each baffle experiment, particle size distribution was determined for sediment deposits at fixed points in the pond bed. Analysis of the hydrodynamic data suggests that all baffles greatly reduced and diffused flow compared to an open pond. The jute/coir baffle outperformed a standard silt fence with weirs and a tree protection fence (tripled over to reduce porosity). Results from soil composition analysis, exit* *turbidity measurements, and estimates of the captured volume per baffle configuration confirm that the jute/coir baffle is the most effective in improving sediment retention in the pond.*

Keywords. Retention pond, basin, pond, baffles, hydrodynamics, sedimentation.

Introduction

The sediment retention pond is a widely used device for trapping total suspended solids from a disturbed watershed. Effluent sediments and pollutants from construction sites, surfaces mines, and existing urban areas alter downstream ecosystems by reducing both benthic populations (Gray & Ward, 1982; Cairns & Dickson, 1971) and species richness and diversity (Erhardt, et. al., 2002; Mayack & Waterhouse, 1983; Cline, et. al., 1982). Small catchments, such as a retention pond, provide sufficient time of residence for solids within an available volume to be removed from the effluent flow. Nominally, colloidals, clays, silts, and very fine sands escape capture in retention structures due to their very small settling velocities (Haan, et. al., 1994), regardless of shape (Graf, 1971; Simons & Senturk, 1992), unless they aggregate either through natural or artificially induced flocculation (Chen, 1975; Camp, 1937). Federal (e.g., EPA, 1986) and state (e.g., NCDENR, 1995) government agencies have issued retention pond design guidelines based on widely implemented design methodologies such as that developed by Brune (1953) which relates pond trapping efficiency to the ratio of pond capacity and the average annual rainfall from the source watershed. Previous work has been aimed at increasing retention pond trapping efficiencies through pond geometry optimization (e.g. Goldman, et. al., 1986; Griffin et. al., 1985; Barfield, et. al., 1983; Mills & Clar, 1976; Chen, 1975) or through improved dewatering methods - e.g. perforated riser (Fennessey & Jarrett, 1997), floating skimmer (Millen, et. al., 1997).

Baffles installed in a sediment pond increase sediment retention rates by reducing and diffusing the inflow momentum, therefore minimizing dead zones and increasing the pond's "hydraulically effective width" (Chen, 1975). The use of silt fencing as baffles in sediment ponds has become a more common occurrence in North Carolina. One study has suggested that silt fence baffles can improve sediment retention (Millen, et. al., 1997) by diverting the flow through opposing weirs to increase the flow path and residence times. Recent work by Barrett, et. al. (1998), however, suggested that geotextiles not originally designed for hydrodynamic applications may meet or exceed the sediment capture effectiveness of silt fences baffles in sediment retention applications. As part of our studies in the use of the flocculent polyacrylamide (PAM) in sediment ponds, we also investigated porous baffles composed of jute with coir backing which allow much higher flows through the material than the silt fence. We observed an obvious reduction in turbulence compared to open, or free flow, conditions. The purpose of this study was to confirm this observation with measurements of flow velocities with jute/coir baffles in the pond and to compare this to flows in the open pond and the pond with silt-fence baffles installed. In addition, we included a third baffle composed of tree protection fence which was folded into three layers to more closely simulate the porosity of the jute/coir baffle but without the highly fibrous nature of that material.

Methods

A 2:1 rectangular, 23-m^3 retention pond with a 1-m permanent pool was constructed at the Sediment and Erosion Control Research and Education Facility (SECREF) (McLaughlin, et al. 2001) at North Carolina State University. Water from an upstream source pond was piped through a variable control valve to an H-flume that fed the water into the retention pond. The H-flume was 0.96 m tall, 1.92 m wide and 4.8 m long. It was constructed of a rigid fiberglass frame and leveled such that the flow volume was proportional only to the head height, allowing for accurate inflow rates to be measured using an Isco™ (Isco, Inc. 4700 Superior St., P.O. Box 82531, Lincoln, NE, 68504) 6712 portable sampler with an Isco™ 730 bubble flow module set in the H-flume configuration. Two wire baffles, 0.20 m high, were installed in the base of the H-flume to reduce flow turbulence prior to flow rate measurement. A 92-cm long trapezoidal funnel was attached to the outflow side of the H-flume to feed water into the pond at an average spill height not exceeding 0.30 m. The retention pond was roughly rectangular in shape, measuring 8.0 m in length (from intake to spillway), 5.2 m in width on average, and 0.92 m deep at its deepest point at the center. The water exited the pond over a 1.10-m wide plywood weir at the top of the dam which had a 50% slope. The slope of the dam and the earthen back wall did not exceed 0.5. The side slopes averaged 80% and the front slope did not exceed 40%. The floor and walls of the pond were lined with geotextile fabric secured with landscape staples to prevent soil detachment within the pond. In addition, rubber sheeting was stapled onto the intake wall to prevent erosion as the water entered the pond.

Experiments were performed with baffles made from three different types of materials: silt fence, tree protection fence, and jute/coir. The jute/coir material was a comprised of standard 4 x 100 jute mesh backed by woven coir erosion control blanket (North American Green C-125), joined with zip ties along the top and bottom edges and at several locations throughout the baffle. The medium weight, polyethylene orange tree protection fence had rectangular openings of 0.10 m x 0.050 m. It was folded into three layers and secured with zip ties along the top and bottom edges and at various locations throughout the baffle to reduce its effective permittivity to be closer to that of the jute/coir material. The silt fence material was a standard woven polypropylene fiber with 670 threads/m. A fourth set of experiments was performed for the free flow case with no baffles installed.

For the experiments that included baffles, three parallel baffles were installed at 0.92 m intervals centered roughly on the pond's midpoint and perpendicular to the axis of the pond as defined by the inlet and outlet midpoints (see Fig. 1). The baffles were supported three metal stakes spaced evenly across the pond width and were secured with landscape staples along the pond floor and walls to prevent water from "leaking" around the edges. Each silt fence baffle had one 0.30-m x 0.30-m weir centered 0.75 m from the center axis of the pond. The weir on the first silt baffle was set to the left of the pond's axis relative to the flow direction, the second to the right, and the third to the left. Once installed, the height of the jute/coir and the tree baffles exceeded the pond surface height by at least 0.10 m. The pond surface height and the height of the installed silt baffles were roughly equivalent during the 14 L/s experiments; however, in the 28 L/s experiments, water occasionally overtopped the baffles at various locations. During the 42 L/s experiments, the water consistently overtopped the baffles by approximately 50 mm.

In order to take velocity measurements in the pond, a wooden frame was constructed above the pond. Two telephone poles were laid perpendicular to the flow direction across the width of the pond. Grid rails made of 2" x 6" treated lumber were mounted onto the telephone poles and leveled. A Sontek™ (Sontek/YSI, Inc. 6837 Nancy Ridge Rd., Ste. A, San Diego, CA, 92121) 10 MHz ADV-1 acoustic-Doppler velocimeter was secured to a vertical mount that was free to slide along an aluminum frame which itself could slide along the grid rails (see Figure 1-A). The three fluid velocity spatial components and the corresponding signal-to-noise ratios were taken using the velocimeter at depths of 0.13 m and 0.26 m below the still ponded water surface for 25 points per depth corresponding to a 5 x 5 data sampling grid (Figure 1-B). The data sampling grid was defined with a right-handed coordinate system where the positive x-axis (longitudinal) is oriented in the downstream mean flow direction and the y-axis (transverse) is positive starting from the far right grid point as seen from the pond inlet facing downstream. For analysis, the x-grid positions were labeled 1 through 5, with x-grid position 1 being nearest the inlet. The grid was centered at the pond's center point as to minimize boundary effects. As a result of the installed baffle locations, the pond was divided into four "cells" such that a minimum of five points along the transverse direction would be sampled by the velocimeter per cell (Figure 1-B). At least 1,024 timed data points were taken per position at a sampling rate of 25

Hz with an acoustic frequency of 1MHz. The unfiltered data was then processed using the WinADV program version 1.849 (Wahl, 2001).

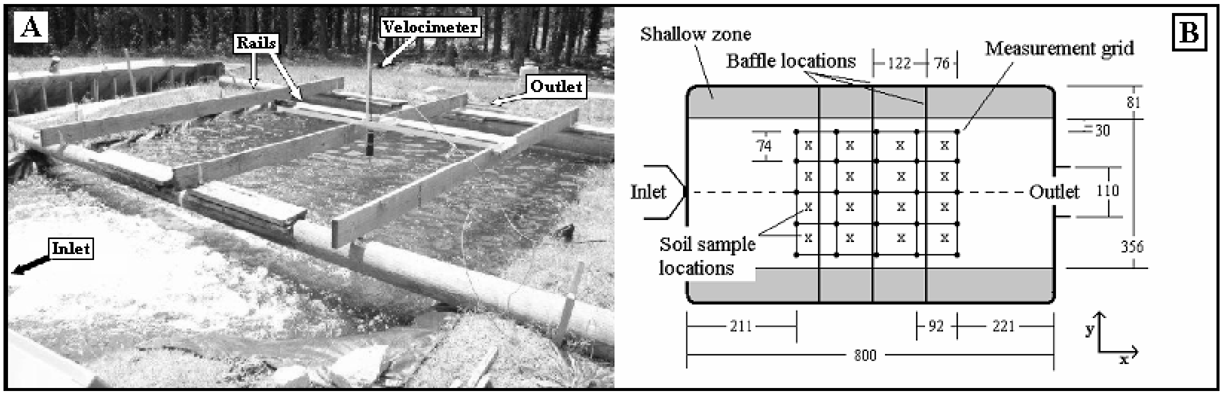

Figure 1. (A) Picture of the sediment retention pond used in the experiments. (B) Geometry of the retention pond and the location of the 5x5 data acquisition grid, as well as the soil sample locations. All measurements are in centimeters.

For each of the baffle configurations tested, pond flow data were taken at three fixed intake flow rates: 14 L/s, 28 L/s, and 42 L/s. The intake flow rates were monitored during each test and the intake control valve was adjusted as needed to maintain the flow rate to within 10% of the target rate for each test. Measurements were taken only when the flow at the outlet equilibrated at the intended flow rate. Source pond water level and time of day were recorded at the beginning and the end of each run. Source pond water temperature remained between 26^0C and 28^0C for all experiments performed.

All "clear water runs" were repeated with a previously characterized soil being injected upstream at a rate of ~5.6 kg/minute (hereafter identified as the "sediment laden runs"). Water samples were taken at the outlet at timed intervals with an Isco™ 712 sampler and later analyzed for turbidity levels. Hydrodynamic data as described above was collected and compared to the clear water runs. After the experiments were performed for each baffle configuration, the pond was drained and sediment accumulation depths were measured at 16 points along the pond bottom within the data acquisition grid (see Figure 1-B). Sediment accumulation depths were also measured at the point of peak accumulation which, in every case, was located on the intake side of the 1st x-grid position. These depths were used to derive estimates of the volume of captured sediment per baffle configuration. 40g- soil samples were also taken at these locations and analyzed for sand, silt, and clay composition via the standard hydrometer method (Loch, 2001). For each of the samples, the silt and clay were removed and the remaining sand was sieved into 6 bins corresponding to the standard sieve sizes of 1000, 500, 250, 106, 63, and 53 µm. As a result, a representative grain size, D_{50}, was obtained at each sample location and compared to the captured grain size projected from the hydrodynamic data.

Results and Discussion

Hydrodynamics

Mean Flow

Using the method of Reynolds decomposition (e.g. Tennekes and Lumley, 1972), the measured flow velocity at grid position *i* (with coordinates (*x*, *y*, *z*)), each having three spatial components, *j*, is decomposed into a mean flow velocity, *V*, and flow velocity fluctuations, *v*.

$$\widetilde{V}_{i,j} = V_{i,j} + v_{i,j} \quad ; \qquad i = (x, y, z);\ j = \{e_1, e_2, e_3\} \tag{1}$$

The mean flow velocity at each location is computed by time-averaging the *n=1,024* timed data points acquired by the velocimeter.

$$V_{i,j} = \frac{1}{n}\sum_{\tau=1}^{n} \widetilde{V}_{i,j}(\tau) \quad ; \quad n = 1024 \tag{2}$$

$$|V_i| = \sqrt{\sum_{j=1}^{3} V_{i,j}^2} \tag{3}$$

Equation (3) defines the mean flow velocity magnitude at grid location *i*.

To quantify the generalized downstream reduction in flow field intensity for each baffle configuration, the mean flow velocity magnitudes (equation (3)) were depth-averaged at each grid location and the resulting depth-averaged values at the five transverse grid points per x-grid position were averaged together to yield V'_x – a representative velocity of the flow as a function of downstream distance. The process was repeated for each of the inflow rates. The result of this analysis shows that, with baffles installed, the transverse- and depth-averaged mean flow velocity magnitude per x grid position, V'_x, diminished significantly beyond the first baffle and incrementally at each successive downstream location (see Figure 2), with the jute/coir baffle performing best.

The tree fence and jute/coir materials were observed to distribute the flow evenly across the width of the pond, increasing the pond's hydraulically effective width. This can be quantified by calculating the transverse variation of the depth-averaged mean flow velocity magnitudes at each x grid position.

$$\mathrm{var}_x = \frac{n\sum_{y=1}^{n}\left|V_{i=(x,y,\bar{z})}\right|^2 - \left(\sum_{y=1}^{n}\left|V_{i=(x,y,\bar{z})}\right|\right)^2}{n(n-1)}; \quad n = 5 \tag{4}$$

When the transverse variance of each baffle configuration is averaged longitudinally and expressed as a percentage of the free flow, the jute/coir baffles exhibited a relative transverse variance of 27%, the tree fence baffles 34%, and the silt fence baffles 95%. The low transverse variance of the jute/coir and tree fence baffles indicate a rapidly diffused and stable mean flow across the full width of the pond, in support of observations. Although the transverse variance of the silt fence baffle configuration is roughly equivalent to the free flow case, no large scale recirculations were observed. Therefore, the high transverse variance in the silt fence baffle setup is due most likely to two factors: (1) the weirs introduced localized jets of mean and turbulent flow as the water passed through them and (2) the low permittivity of the silt fence geotextile establishes a high pressure gradient across the baffle, causing moderately intense flows to occur at unpredictable locations as overtopping or through weak points in the baffle structure.

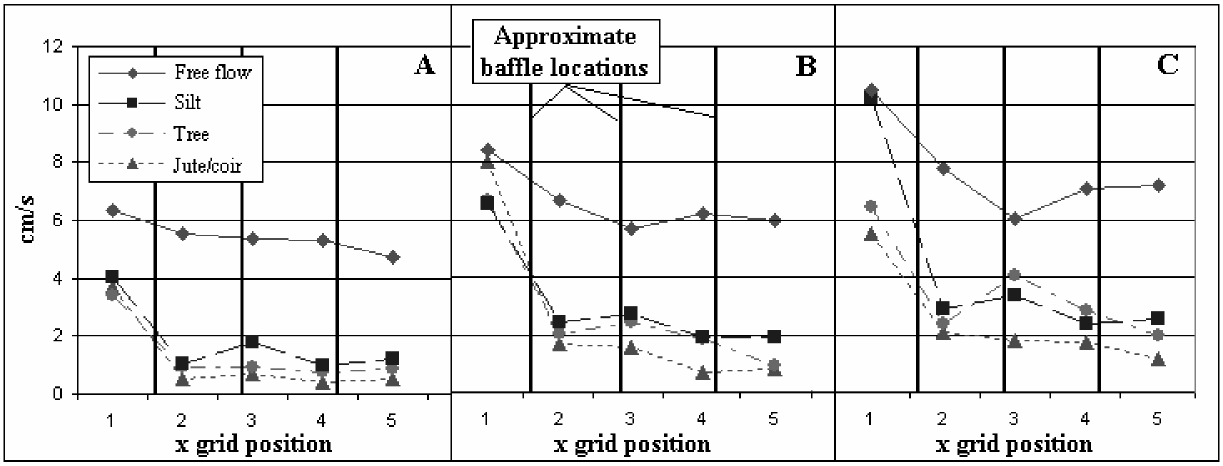

Figure 2. The depth-averaged mean flow velocity magnitude for (A) 14 L/s, (B) 28 L/s, (C) 42 L/s, averaged along the 5 transverse points per x grid position.

Vertical Flow Structure

The depth-averaged vertical velocities for each baffle configuration at 28 L/s for the clear water runs are shown in Figure 3. Similar patterns existed for each baffle configuration for the sediment laden runs and for the 14 L/s and 48 L/s flow rates, except for the silt fence to be discussed below. The free flow field exhibited a pond-wide rotation about the axis of flow direction in which water rose (brown color in figure 3) in the center and fell (blue-green color in figure 3) along the pond walls. For each of the baffles, at least two flow direction-parallel rotations were established in the intake cell (prior to the 1st baffle) due to the confinement of turbulent energy by the 1st baffle. For the tree and jute/coir baffles, vertical rotations were significantly reduced beyond the 1st baffle.

For the silt fence at 28 L/s and 42 L/s flow rates, large flow direction-orthogonal rotations developed between the baffles, which did not develop for the 14 L/s flow rate (Figure 4, sediment laden runs). This indicated that independent zones of rotational flow between the baffles, energized by the shear stress from overtopping flow, may inhibit new sediment from entering, reducing the pond volume accessible for sediment capture (Figure 5). Because independent zones of flow direction-orthogonal rotation between baffles did not develop at the lowest flow rate (Figure 4-A), it is feasible to postulate that, for higher expected flow rates, a larger baffle separation distance would be necessary to inhibit the formation of the vortices of rotation in these zones, thus maximizing sediment capture. For higher baffle permeabilities, such as that for the jute/coir, these zones did not develop nor were they encouraged by overtopping which did not occur, independent of flow rate or baffle separation distance.

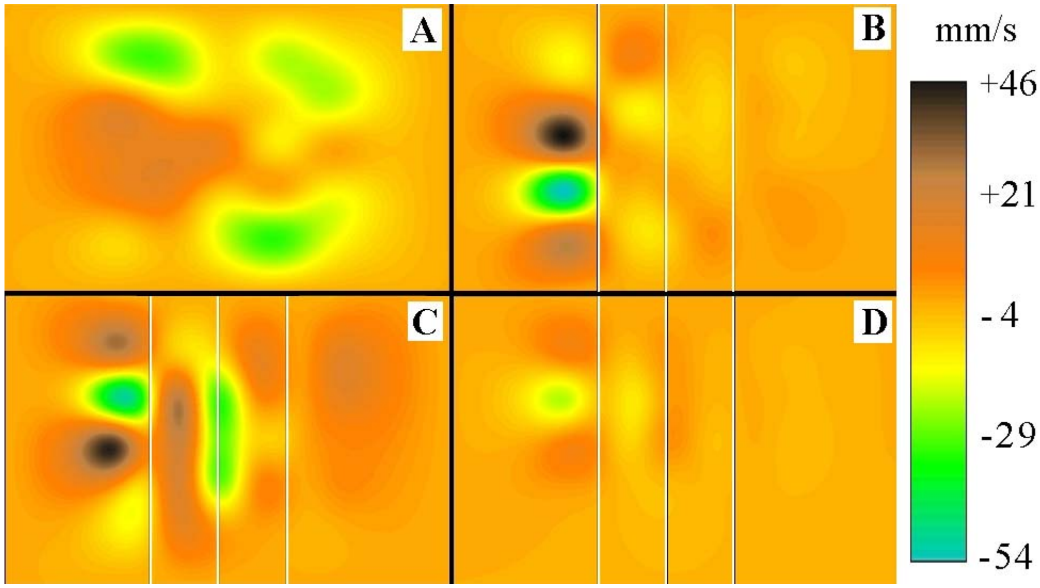

Figure 3: Depth-averaged vertical velocities at 28 L/s (clear water runs) for (A) free flow, (B) tree protection fence, (C) silt fence, and (D) jute/coir baffles. Approximate baffle locations are indicated by white lines. Flow is left to right.

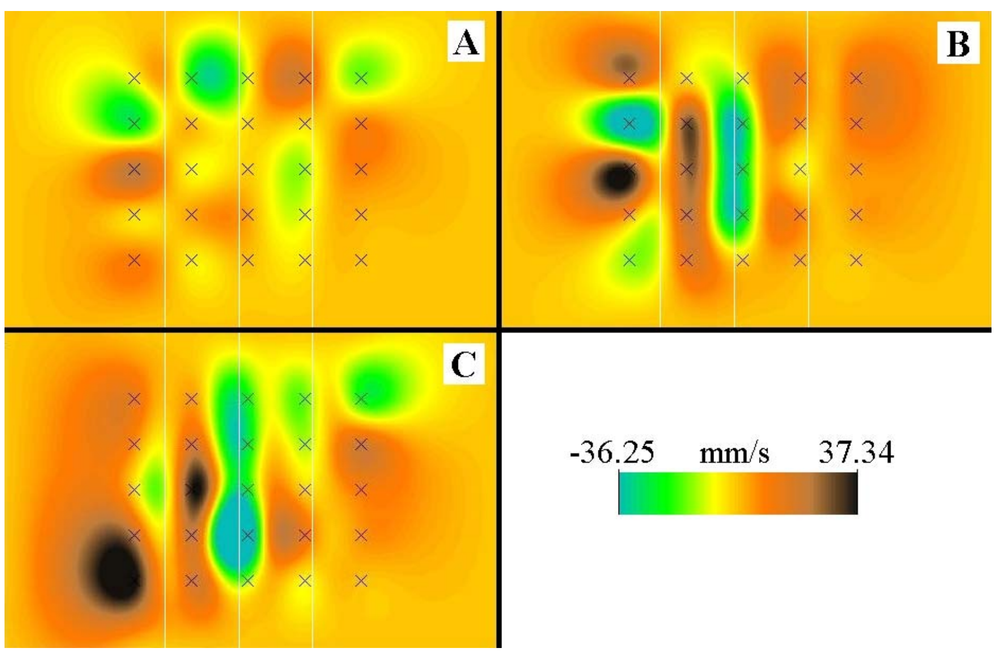

Figure 4: Depth averaged vertical velocities for the silt fence baffle (sediment laden runs) at (A) 14 L/s, (B) 28 L/s, and (C) 42 L/s. Approximate baffle locations are indicated by white lines. Flow is left to right. Note that the scale is different than that of Figure 3.

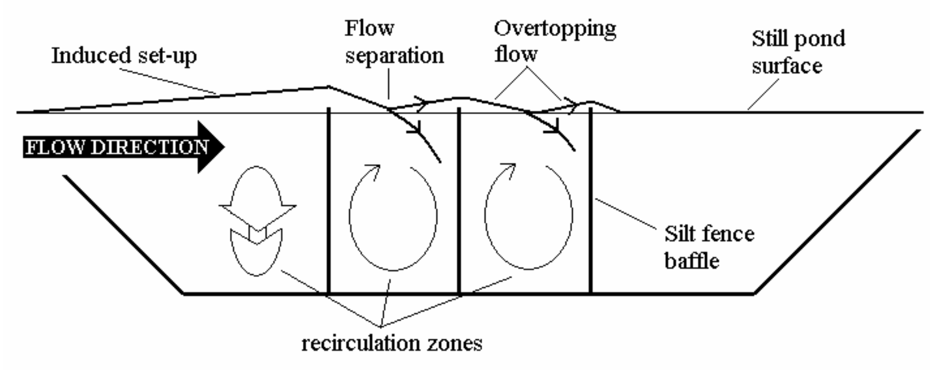

Figure 5: Vertical velocity data presented for the silt baffle suggests that, at 28 L/s and 42 L/s flow rates, independent zones of flow direction-orthogonal rotation ("sub basins") developed, inhibiting new sediment from entering the sub basins. The sub basins were energized by the shear stress applied by the overtopping flow observed at 28 L/s and 42 L/s flow rates (silt baffle only).

Sediment Capture

The outflow for the free flow configuration was observed to be comprised of a combination of recirculated flow and flow that streamed directly to the pond outlet (e.g. Griffin, et. al., 1985; Haan, et. al., 1994). For simplicity, however, we assume in this analysis that the e_1-(longitudinal) component of the flow velocity, averaged over all 50 grid locations, represents the actual downstream flow field for each baffle configuration:

$$V_1 = V_{j=e1} = \frac{1}{n}\sum_{i=1}^{n} V_{i,j=e1} \qquad ;\ n=50 \text{ grid locations} \tag{5}$$

By equating the conventional Stoke's setting velocity for spherical grains at small Reynolds numbers (Re < 1.0) (e.g. Daily and Harleman, 1966) with the ratio of pond depth, *h (=92 cm)*, to minimum residence time, $T_r = L/V_1$ (L=distance from intake to near-exit sample locations=580cm), the captured grain diameter can be projected for each baffle configuration as:

$$D(V_1) = \sqrt{\frac{18\nu}{g(SG-1)}\frac{h}{T_r}}\ . \tag{6}$$

where SG=2.65 is the specific gravity of quartz grains, d is the grain diameter in cm, g=980 cm/s is the acceleration of gravity and ν=0.008513 cm^2/s is the kinematic viscosity of water at 27^{0}C. By averaging $D(V_1)$ over all flow rates, we assumed that $D(V_1)$ represents a median capture size that is comparable to a representative grain size (D_{50}) from the hydrometer and sand sieving analysis of samples taken at distance L. Results are summarized in Figure 6-A.

The hydrometer and sand sieve analysis of the soil samples, taken at each grid location, i, yield a representative grain size, $D_{50,i}$:

$$D_{50,i} = f_i^{sand}\overline{d}_i^{sand} + f_i^{silt}\overline{d}_i^{silt} + f_i^{clay}\overline{d}_i^{clay}\ . \tag{7}$$

Here, f is the fraction of sand, silt, and clay of the 40g sample as determined from the hydrometer analysis, and:

$$\bar{d}_i^{clay} = 1.00; \quad \bar{d}_i^{silt} = 26.0; \quad \bar{d}_i^{sand} = \frac{1}{w_i^{sand}} \sum_{j=1}^{6} w_{i,j}^{sand} \bar{d}_j \qquad (8a)$$

where

$$\begin{aligned} w_i^{sand} &= \text{weight of sand sample} \\ w_{i,j} &= \text{weight of sand in bin } j \\ \bar{d}_j &= \text{median diameter of sand bin } j = \{1500, 750, 375, 178, 85, 58\mu m\} \end{aligned} \qquad (8b)$$

The transverse-averaged D_{50} at the x- grid position nearest the exit compares well to the projected median captured grain size $D(V_1)$ (equation 6) for the jute/coir baffle (see Figure 6-A). The e_1-component of the flow velocity, averaged over all grid locations, is progressively less representative of the actual flow for the tree fence baffle, silt fence baffle, and free flow cases respectively (moving left-to-right in Figure 6-A). This result corresponds to that suggested by the transverse variances in mean flow velocity and verifies that the jute/coir baffle best incorporates more of the pond volume in sediment capture. In addition, a rough estimate of the captured sediment volume, normalized by the amount of sediment injected over the duration of each set of baffle experiments, shows that the jute/coir and tree fence baffle configurations capture more sediment than the silt fence baffle or the free flow case (Figure 6-B). The captured sediment volume was calculated by interpolating between the 16 grid points at which sediment accumulation depths were measured (see Figure 1-B). Since significant amounts of sediment settled outside of our measurement grid, the volume estimates are less than actual and are therefore intended solely for comparison between the different baffle configurations. The exit turbidity, averaged over the duration of each set of baffle experiments, correlates to the relative D_{50} capture performance of each baffle.

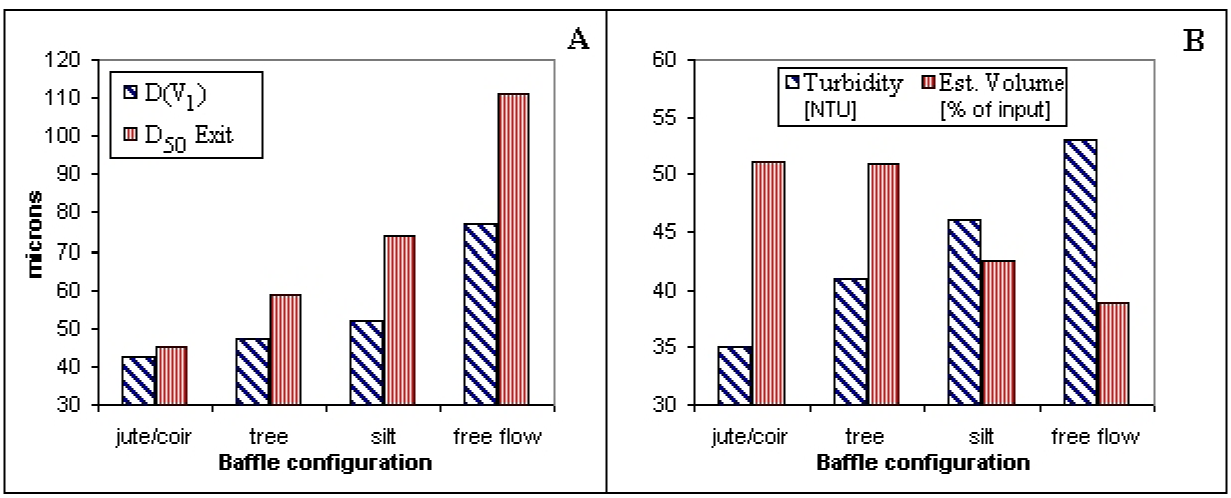

Figure 6. (A) The projected median grain capture diameter ($D(V_1)$) (based on Stoke's settling and the measured flow velocities) compared to the D_{50} computed from the soil samples at the x-grid location nearest the exit. (B) The measured turbidity and estimated volume within the measurement grid expressed as a percent of the volume of sediment injected per baffle configuration.

Conclusions

In all cases, the inclusion of baffles in a sediment basin greatly reduced flow velocities and turbulence and increased sediment capture. Among the baffle materials tested, the jute/coir baffles out performed the tree protection fence and especially the silt fence in diffusing the inflow momentum such that more of the pond volume participates in the sediment settling process. This is evidenced by the greatly reduced mean flow velocity magnitude, the small transverse variance in mean flow velocity magnitude, and the minimal vertical velocity structure beyond the intake cell for the jute/coir baffles. We found that the first baffle, located near the intake, provided most of the benefit, with marginal reductions in velocities and turbulence with each additional baffle.

Calculation of a representative grain size, D_{50}, from analysis of soil samples taken at the near-exit downstream location confirms the hydrodynamic findings, as does the measured outlet turbidity and relative sediment capture volume from each baffle configuration. Analysis of the turbulence in the pond is under way, as well as an attempt to functionally correlate sediment capture effectiveness with baffle material permeability (Thaxton & McLaughlin, in preparation).

Although most small silts and clays will escape capture regardless of the existence of baffles, our current findings strongly suggest that the jute/coir baffle provides considerable improvements in the sediment trapping effectiveness of the sediment basin.

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