Does the Birkbeck type bedload sediment trap effect local flow velocity?

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[1] ***Abstract* -- A series of experiments was conducted to determine to what extent a trap for bedload sediment effects local flow velocity. The Birkbeck type bedload pit sampler consists of a metal box with internal load cell for continuous weighing of trapped bedload sediment. It is installed in streams and flumes in order to capture and weigh the amount of bedload sediment being transported in the flow. Sediment enters the trap through an aperture in the top surface. A model of the bedload sediment trap was tested in a flume in the Mountain StreamLab located in the Center for Ecohydraulics Research at the University of Idaho in Boise. Two variations of the trap were built: a standard aperture opening and a full width opening. Each variation was tested with two conditions: trap empty and trap half-full of sediment. Velocity was measured by Particle Imaging Velocimetry (PIV) for three flow rates. It was determined that trap entrance treatment and the volume of trapped sediment cause a measureable difference in the velocity of the approaching flow.**

I. INTRODUCTION

Every year, significant damage is sustained by infrastructure (including transportation facilities) during flood events in steep mountain streams. In addition to high water, these floods erode stream banks and beds in some reaches, and deposit sand, gravel, and cobbles in other reaches. A local and recent example is the extreme damage to highways in Vermont resulting from Tropical Storm Irene. In addition to damage to the built infrastructure, these events cause extensive damage to the natural stream environment. The damage happens from both removal and deposition of sediment.

While erosion and deposition are natural processes, mankind's activities have exacerbated their outcome. Artificial straightening of a stream reach to accommodate highways, bridges, and railroads often results in erosion and deposition in other reaches of the channel. The restoration of stream corridors and environments requires accurate predictions of sediment transport. Climate change will probably result in more variability of storm types and precipitation amounts. As a result, it becomes more important to be able to accurately predict the transport of sediment in steep mountain streams.

However, existing computational tools are inadequate to accurately predict sediment transport in steep mountain streams. Traditional equation models (which were designed for lower gradient streams) over predict sediment transport in steep channels by several orders of magnitude [1], [2]. Previous attempts to derive sediment transport equations for steep channels also over predict it [1], [2].

Reference [3] proposed a model to improve predictions of sediment transport. This model was developed in a flume study using spherically shaped roughness elements. These models would be improved by validation using flume results with naturally shaped sediments.

Sediment transport rates are difficult to measure in the field and better sediment capture techniques are needed. Birkbeck type bedload sediment traps [4] have been employed worldwide in a number of channels [5], [6]. See Figure 1. The effectiveness of these traps in capturing a representative sample is not well known. Nor is the effect of these traps on local flow fields.

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Figure 1. Birkbeck Bedload Sediment Trap Boxes at the Reynolds Creek Experimental Watershed.

II. EXPERIMENTAL APPARTUS

The research work was conducted in the Mountain StreamLab located in the Center for Ecohydraulics Research at the University of Idaho in Boise [7].

The flume used in this research has an overall length of 22 meters. The bed of the flume is 2 meters wide and is constructed of steel plate. Bed walls measure 1.2 meters tall and are clear tempered glass. The flume can be adjusted for slope from 0.2 % to 10 %. Flow is provided by 2 variable speed pumps. Flow circulates from the concrete sump at the flume outlet (volume = 242,000 liters, 64,000 gallons) through pumps and valves to the flow straightening box at head of the flume. Sediment can be metered into the flow approximately 6 meters downstream of the head box, using a conveyor belt system fed by three bins with metered outlets. The length of the flume that can be used for sediment studies is about 15 meters, with the remainder of the flume consisting of the head box, straightening box, and tail gate. The tail gate can be adjusted from zero degrees to 90 degrees from horizontal. A sediment trap at the outlet captures sediment in a trench, which transmits it by auger to a dedicated pump system. The outlet from the sediment pump can be directed into various types of sediment buckets or into a sediment bag. Sediment is weighed electronically in the sediment trap.

Flow velocity can be measured by two systems.

1) A stereoscopic particle image velocimetry (PIV) system with megapixel resolution and 15 Hz frame rate. High end visualization software processes and displays PIV results.
2) An acoustic Doppler velocimeter (ADV) system that provides down-looking and side–looking capabilities.

Flow rates may be set manually or by a computer interface, with the low flow system providing metered volume flow rates between 0.6 and 60 liters/second (0.021 to 2.1 CFS) and the high flow rate system providing metered volume flow rates between 60 and 850 liters/second (2.1 to 30 CFS, or 942 to 13,460 gpm). The flume is equipped with a custom designed, computer controlled instrumentation platform and can simultaneously measure multiple processes.

III. PROCEDURE

Sediment for this experiment consists of very coarse gravels and cobbles (2 inches to 6 inches, 51 mm to 152 mm). The available volume of sediment provided a depth of 9 cm. Sediment was delivered to the flume in ½ cubic yard bags using the overhead rail crane. The sediment was placed by hand.

The site for the bedload sediment traps is about 7.5 meters downstream of the sediment feed. This site is designated as flume station 8.40 meters. Model 1 of the sediment trap (Figures 2 &3) was used by John Boyd. It is described as a Birkbeck-type. Model 1 has inside dimensions of 190mm X 190mm X 190mm, with a lid with an aperture measuring 80mm X 80mm. Model 2 of the sediment trap (Figure 4) had the same inside dimensions but without a lid. In both models, the top of the box was recessed about two centimeters below the assumed top of the sediment layer (see Figure 2). That is, it extended seven centimeters above the floor of the flume.

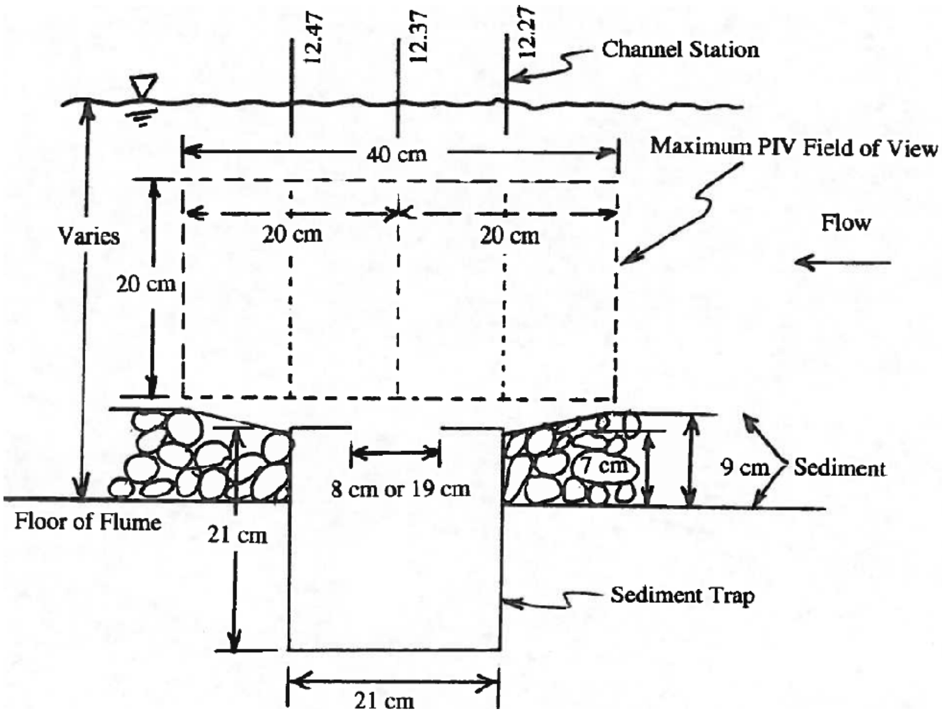

Figure 2. Placement of sediment traps and PIV fields of view

Figure 3. Sediment trap Model 1 shown empty (Birkbeck type)

Figure 4. Sediment trap Model 2 shown half-full of small gravel (Open top)

Water surface elevations were measured at flume stations 3.0, 6.5, and 10.5 in vertical stilling tubes which were connected to perforated plastic tubes laid across the flume bed.

In this experiment, two PIV cameras with megapixel resolution and 15 Hz frame rate were attached to opposite sides of the instrumentation platform. Each camera was directed downstream at a horizontal angle of about 75 degrees from the centerline. A laser sheet in the vertical plane was provided by a Double Pulse Nd:YAG laser delivered through a boroscope. DaVis version 8.1.4 software processed the images and calculated velocity.

It was desired that no movement of sediment should take place during the experiments. One of the challenges was to find flow rates and slopes that did not cause sediment movement. Preliminary calculations of shear stress were performed for a range of slopes and flow rates. These assumed an estimated value of Shield's dimensionless critical shear stress equal to .03. This calculation was used to predict initiation of movement for the smallest size of sediment (D = 2 inches = 51 mm). A range of flow rates were tried in the flume. Based on no observed sediment motion, the following three flow rates were selected (Table I).

Table I. Flows used in the experiment

Flow Designation	Flow rate (gpm/ lps)	Bed Slope	Depth (m)	Area (m^2)	Velocity Average (m/s)	Froude Number
A	5225 / 330.0	.005	.215	.430	.768	.539
B	7750 / 489.3	.007	0.244	0.488	1.003	0.648
C	7450 / 470.3	.013	0.192	0.385	1.223	0.891

For each flow rate (A, B & C), data was collected for each trap configuration (aperture and open top) and for two conditions (empty and half-full).

During each experimental run, the flow rate and slope were set. The tail gate was adjusted to obtain equal flow depths at flume stations 3.0 and 6.5. The goal was to create uniform flow approaching the sediment trap site at flume station 8.40. For flow C, total depths (at flume stations 3.0 and 6.5) were within 3% of one another. Usually the difference in total flow depths was less than 1% for flows A and B.

In all cases, the flow depth at flume station 10.5 (furthest downstream) was less than or equal to the average flow depth at the other two locations. For flows A and B, the total water depth at flume station 10.5 averaged 94% of the depths at the 3.0 and 6.5. For flow C, the total water depth at flume station 10.5 averaged 97% of the depths at the 3.0 and 6.5. It was assumed that this drawdown was caused by the effects of the sediment trap and the tail gate. If the tail gate was raised, the water depths at flume stations 3.0 and 6.5 became less uniform.

The following data was collected for each run: Flow rate, slope, total water depth at flume stations 3.0, 6.5, and 10.5, and instantaneous velocities by PIV. The measurement area was in a vertical plane that extended through the trap centerline, extending from the upstream face of the trap to the downstream face of the trap. The dimensions of the measurement area were 20 cm by 20 cm. There were twelve combinations of flow rate and trap treatment: three flow rates (A, B, & C) and four trap treatments (aperture with empty trap, aperture with half-full trap, open top with empty trap, open top with half-full trap). As shown in Fig 1, there were three camera placements (velocity fields) for each of the twelve combinations. The camera placements used a coordinate system that was based on the location of the instrumentation platform. Under this system, the three camera locations were 12.27 (upstream face of the trap), 12.37 m (center of the aperture), and 12.47 (downstream face of the trap). Note that the center of the aperture corresponds to flume station 8.4 m.

Each data run took about 25 minutes. Each data run produced 4000 sets of instantaneous photographs. High end visualization software processed and displayed PIV results. It took about 9 hours to compute results for each run. This calculation resulted in time-averaged velocity measurements at over 5500 locations. Successful velocity measurement required extremely clean water. To obtain good photographs, the water was seeded with 18 micron hollow glass beads with a Specific Gravity of 0.6. The flume at the measurement site was draped to exclude light and reduce spurious reflections.

IV. RESULTS

Figures 5 shows velocity profiles for flows A, B & C. For each flow, the velocity is shown at instrumentation platform stations 12.27, 12.37, and 12.47. Each graph shows velocity profiles for four situations: aperture with trap empty (AE), aperture with trap half-full of small gravel (AG), open top with trap empty (OE), and open top with trap half-full of small gravel (OG). For each flow, the highest velocity occurs at the upstream face (12.27). For flows A & B, the fastest velocities occur with the AE case and the slowest velocities occur with the OE case. The other two cases (AG and OG) produce velocities between these extremes. However, velocities over OG are always faster than over AG.

For flow C, the results are not as consistent. The case with the fastest velocity is AE, except for the lower portions of the flow at 12.47 (the downstream face). Velocities over the OE case are not always the slowest. However the velocities over OG are always faster than over AG.

It can be concluded that the trap with the aperture and empty box (AE) provides the least resistance to flow. The trap with the open top and empty box (OE) usually provides the most resistance. For the cases with the box half-full of small gravel, the trap with the aperture provides more resistance than the trap with the open top.

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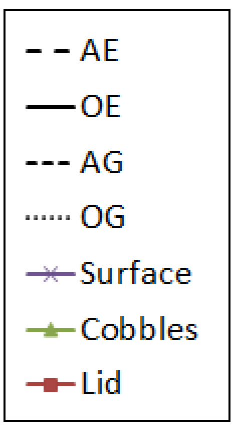
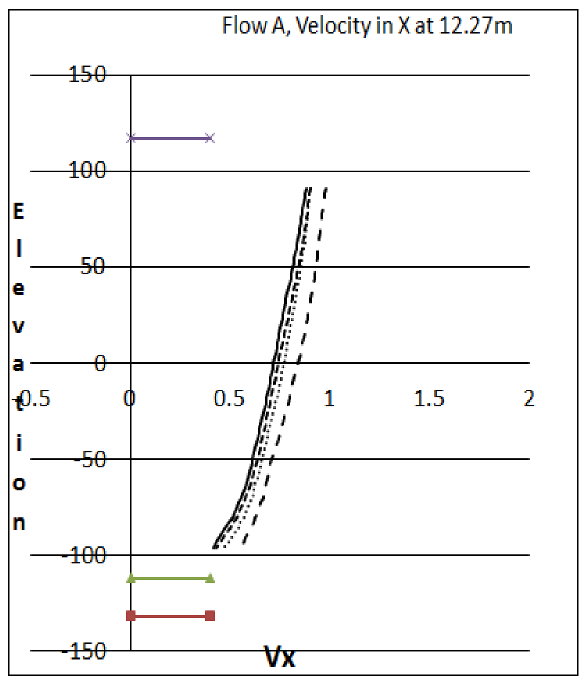
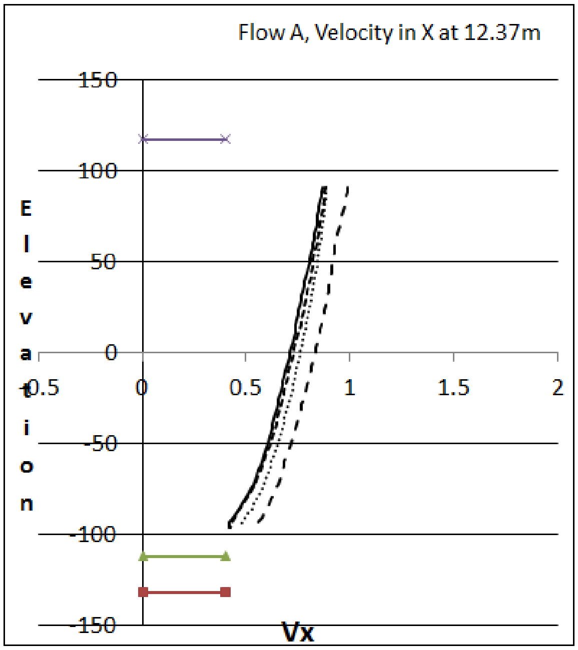
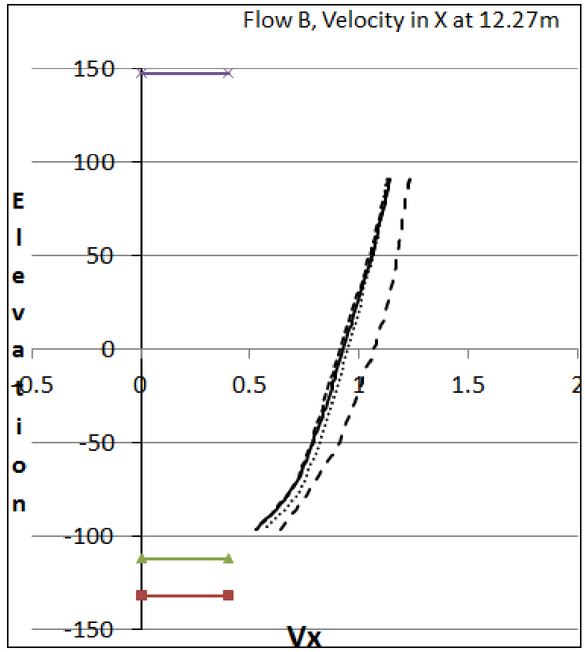
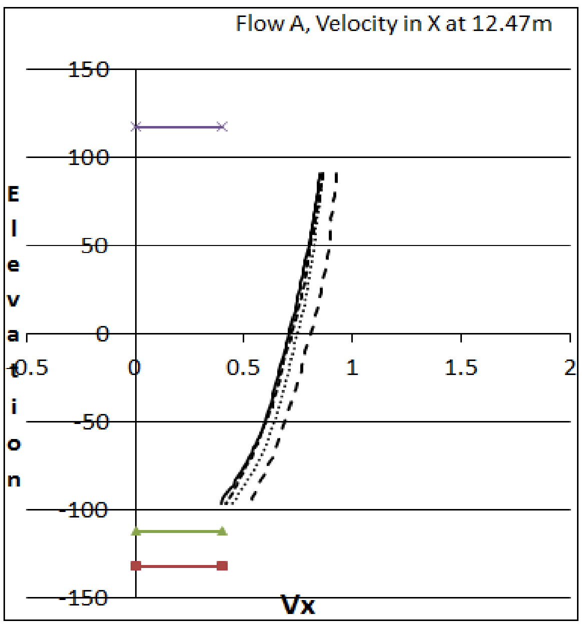
Legend for velocity graphs. AE = aperture with empty box, OE = open top with empty box, AG = aperture with half-full box, OG = open top with half-full box. Velocities are in m/s, depth is in cm.

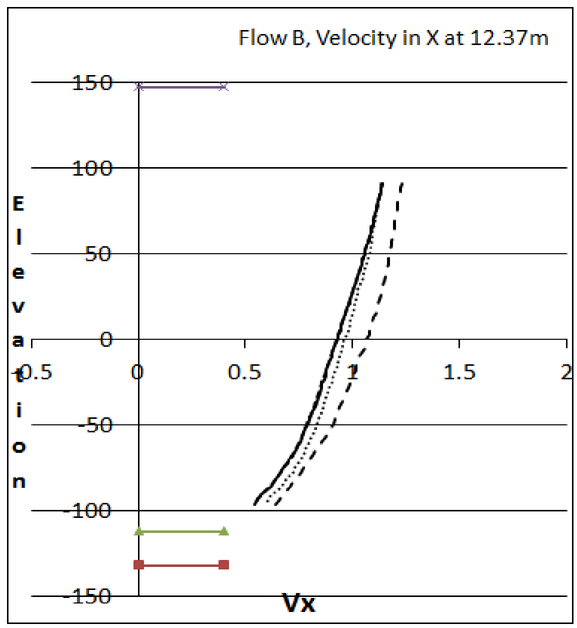


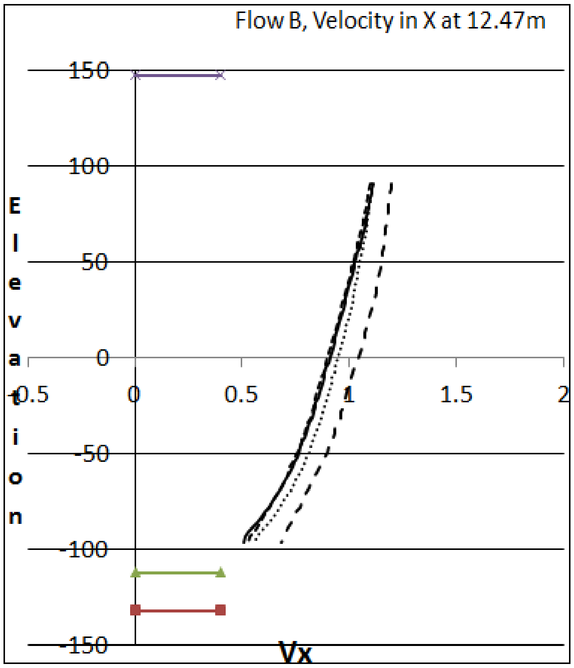


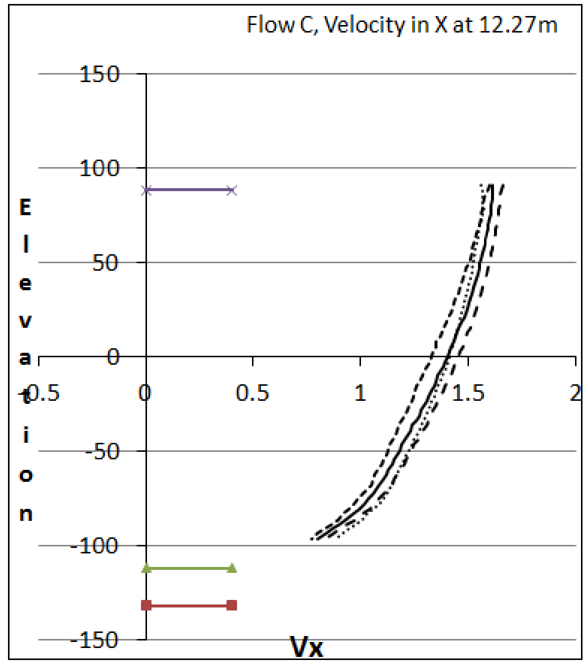

Flow A, Velocity in X at 12.37m
150
100
50
0
-50
-100
-150
-0.5
0
0.5
1
1.5
2
Elevation
Vx

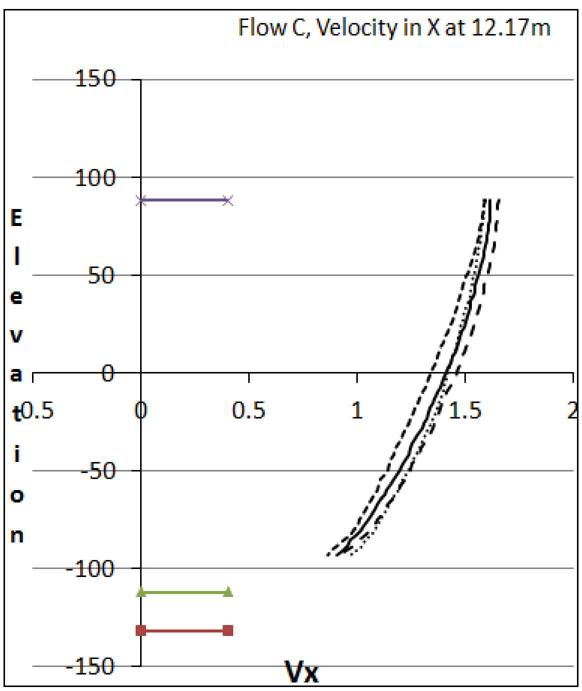

Flow B, Velocity in X at 12.27m
150
100
50
0
-50
-100
-150
-0.5
0
0.5
1
1.5
2
Elevation
Vx

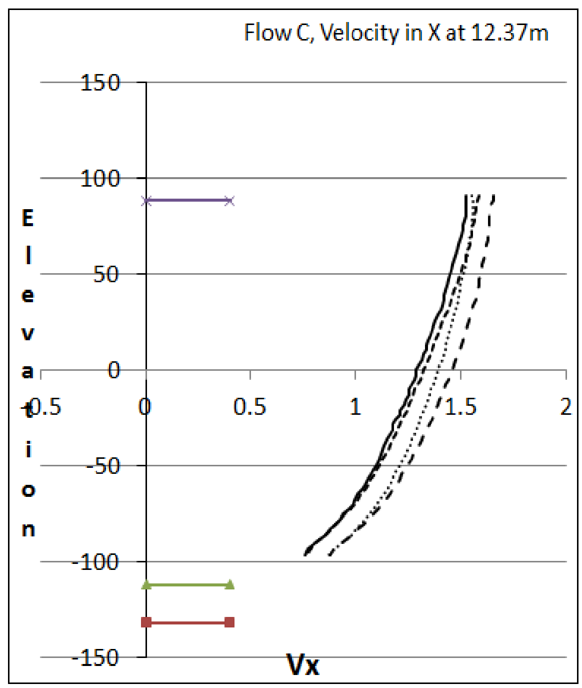

Flow A, Velocity in X at 12.47m
150
100
50
0
-50
-100
-150
-0.5
0
0.5
1
1.5
2
Elevation
Vx

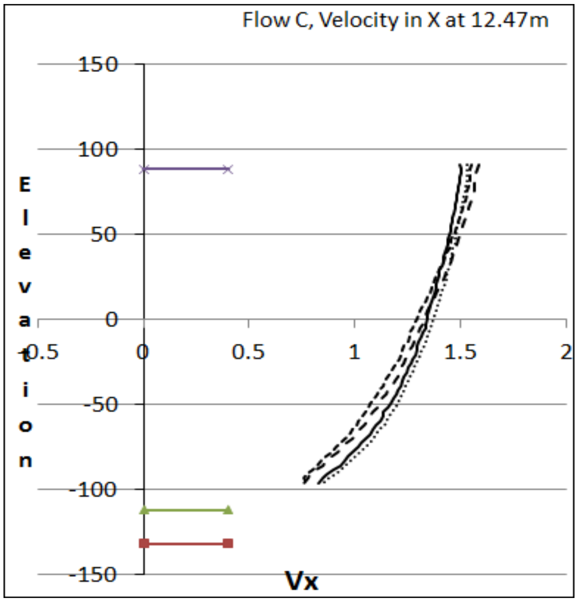

Flow B, Velocity in X at 12.37m
150
100
50
0
-50
-100
-150
-0.5
0
0.5
1
1.5
2
Elevation
Vx


Flow B, Velocity in X at 12.47m
Elevation
Vx
150
100
50
0
-50
-100
-150
-0.5
0
0.5
1
1.5
2


Flow C, Velocity in X at 12.27m
Elevation
Vx
150
100
50
0
-50
-100
-150
-0.5
0
0.5
1
1.5
2


Flow C, Velocity in X at 12.17m
Elevation
Vx
150
100
50
0
-50
-100
-150
-0.5
0
0.5
1
1.5
2


Flow C, Velocity in X at 12.37m
Elevation
Vx
150
100
50
0
-50
-100
-150
-0.5
0
0.5
1
1.5
2



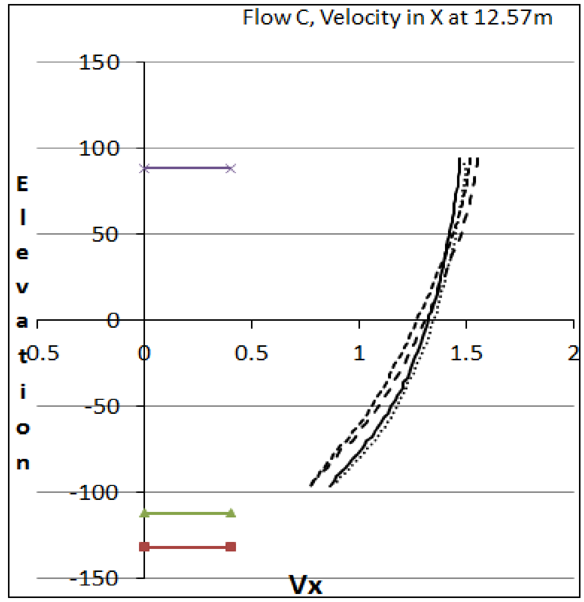


Figure 5. Velocity profiles for three flows.

Table 2 below compares the average velocity in the cross section (flow/area) to the average of the PIV velocity profiles. This table uses the averages of the depths at flume stations 3.0 and 6.5 to calculate the cross section area. It also shows that case AE produces the fastest velocities, and case OE produces the slowest velocities. Cases OG and AG produce similar results, with OG producing faster velocities than AG.

Table 2. Average Velocities

				Y total m (to flume bed)			Y	Area	V avg			V avg	
							m (to						
Flow	Treatment *	Q gpm	Q cms	3	6.5	10.5	cobbles)	m2	m/s	Slope	Fr	PIV	V PIV/V avg
A	ae	5225	0.330	0.315	0.312	0.297	0.2235	0.447	0.738	0.0051	0.498	0.8044	1.091
A	ag	5225	0.330	0.314	0.31	0.295	0.222	0.444	0.743		0.503	0.7044	0.949
A	oe	5225	0.330	0.314	0.313	0.296	0.2235	0.447	0.738		0.498	0.6894	0.935
A	og	5225	0.330	0.318	0.315	0.3	0.2265	0.453	0.728		0.488	0.7347	1.009
B	ae	7750	0.489	0.339	0.337	0.327	0.248	0.496	0.986	0.007	0.632	1.019	1.034
B	ag	7750	0.489	0.342	0.341	0.327	0.2515	0.503	0.972		0.619	0.9015	0.927
B	oe	7750	0.489	0.343	0.342	0.325	0.2525	0.505	0.968		0.615	0.9038	0.933
B	og	7750	0.489	0.345	0.344	0.328	0.2545	0.509	0.961		0.608	0.9352	0.973
C	ae	7450	0.470	0.290	0.28	0.282	0.195	0.39	1.205	0.0131	0.872	1.3948	1.157
C	ag	7450	0.470	0.290	0.28	0.278	0.195	0.39	1.205		0.872	1.2772	1.060
C	oe	7450	0.470	0.290	0.283	0.285	0.1965	0.393	1.196		0.862	1.247	1.042
C	og	7450	0.470	0.292	0.285	0.285	0.1985	0.397	1.184		0.849	1.3368	1.129

V. CONCLUSIONS

Trap entrance treatment and the volume of trapped sediment cause a measureable difference in the velocity of the approaching flow. In most cases, the velocity difference is in the order of 10% to 15%. The trap with the aperture and empty box (AE) provides the least resistance to flow. The trap with the open top and empty box (OE) usually provides the most resistance. For the cases with the box half-full of small gravel, the trap with the aperture provides more resistance than the trap with the open top.

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