EFFECTS OF BEDLOAD SAMPLER NETTING PROPERTIES ON HYDRAULIC AND SAMPLING EFFICIENCY

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Abstract Bedload samplers with coarse nets let small particles pass through the net, while samplers with fine nets have various problems capturing fine and coarse gravel bedload. Using samplers with nets of different mesh sizes may facilitate capture of a wider range of bedload particle sizes. However, preliminary evidence suggests that sampled transport rates are influenced by mesh size as well as by other net properties that tend to change with mesh size. Hence, a user would need to know and adjust for those differences before combining transport rates sampled with different mesh-width nets. To further investigate effects of netting properties on flow hydraulics and sampled transport rates, this study compares water throughflow and gravel transport sampled with two different mesh-size nets attached to non-flared bedload traps. One bag is a flexible, non-precision net with a 3.6 mm mesh width, the other bag is a stiff 1.18 mm precision mesh. The 1.18 mm net had a slightly better throughflow as long as the net remained empty, attributable to its slightly larger percent open area. Adding a substantial—but not uncommon—volume of 10 liters of organic material to the 1.18 mm net retarded and ponded the approach flow considerably because the organic material accumulated at the end of the cylindrical net where it blocked throughflow from exiting. The funnel-shape taken by the 3.6 mm net let most of flow exit shortly behind the bedload traps entrance, while captured solids traveled along the net bottom towards the bag end. The segregation of exiting flow from the accumulated material avoided major blockage of flow. In the 1.18 mm precision net, two hydraulic effects combined: higher through-flow for empty nets and compromised throughflow as organic material starts to accumulate at higher flow and transport. As a result, the 1.18 mm net sampled higher transport rates than the 3.6 mm net at low flow, while the 3.6 mm net sampled higher rates at higher flow.

INTRODUCTION

Coarse-bedded mountain streams transport a wide range of bedload particle sizes from sand to cobbles, but most bedload samplers can capture only a limited range of particle sizes. The sampler opening sets the upper limit of collectable particles, while the mesh width sets the lower limit. Large opening samplers with a large volume collection bag or basket and a coarse mesh of 4 to 25 mm collect only coarse particles, such as basket (Nanson 1974) or net-frame samplers (Bunte 1996, Whitacker and Potts 2007a,b), bedload traps (Bunte et al. 2004, 2007, 2008, 2010 a and b) or hanging baskets (Rickenmann et al. 2012). Those samplers provide satisfactory measurements of medium and coarse gravel or cobble transport rates but yield no information on transport of sediment finer than the mesh width. Samplers intended to capture coarse sand and

fine gravel typically have 0.2 to 0.5 mm mesh width bags. However, sand and fine organic particles quickly clog those bags, and the approximately 5-liter volume bag attached to small pressure difference samplers fill quickly when transport rates are high. Clogging and filling limit a sampler bag's water through-flow rates and sampling efficiency (Druffel et al. 1976; Johnson et al. 1977; Beschta 1981, 1983). Sampling times are typically kept to 2 minutes or less to avoid mesh clogging and bag overfilling, but if sampling times are too short to integrate over the natural fluctuations of bedload transport rates (Gomez et al. 1989; Turowski 2011) transport rates are overestimated when transport is low and underestimated when transport is high (Bunte and Abt 2005, Singh et al. 2009). Increasing both mesh and bag size alleviates the fast clogging and bag filling (Beschta 1981, 1983; O'Leary and Beschta 1981), and the subsequently higher throughflow rates increase sampled bedload rates. However, for a flared sampler body that is designed to have a hydraulic efficiency > 1 to compensate for the retardation of flow velocity in the fine-mesh and small-volume bag, increasing hydraulic and sampling efficiency via a coarser and larger bag to mitigate clogging might overcompensate.

Considering the limited range of particle sizes that can be representatively captured with a specified sampler body and bag, capturing a wider range of bedload particle sizes seems to require combining samples collected with nets of different mesh diameters. However, transport rates sampled using nets with different mesh widths differ (Beschta 1981, 1983; O'Leary and Beschta 1981). Furthermore, differences in mesh width are tied to changes in other net properties such as thread width, mesh shapes, and net stiffness, all of which can further affect hydraulic efficiency. An example of how the relation between mesh width and thread width affects a net's throughflow capacity is given below.

The percent open area A_o is a measure that relates the mesh opening width w to the thread width d in woven nets, or to the width of the knitted strands surrounding mesh openings in knitted nets, respectively (Figure 1a). Bunte and Swingle (2009) attached various nets with opening sizes of 0.5 to 3.6 mm to bedload traps, measured flow depth at the entrance of bedload traps deployed in a gravel/cobble bed stream, and showed that ponding of the approach flow increased with

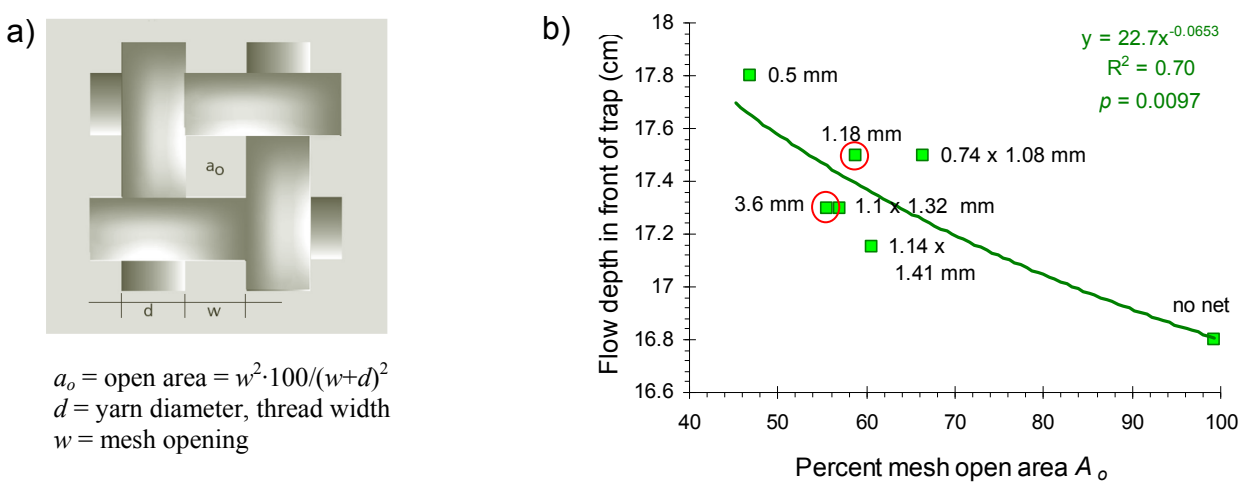

Figure 1: Schematic diagram of netting dimensions (from www.Sefar.com; slightly altered) (a). Negative relation between upstream ponding of flow and a net's percent open area A_o. Numbers next to data points indicate the mesh opening width w; note that not all meshes are square. The two circled nets were used in this study (a).

deceasing percent mesh open area A_o (Figure 1b). Scatter in the relation of ponding vs. A_o is attributed to concomitant netting properties such as being knitted vs. woven which determines mesh shapes and netting stiffness and whether mesh and net shapes change with increasing flow.

If throughflow rates, and hence sampled transport rates, differ between nets, then samples from different nets cannot be combined without first quantifying how those nets affect the sample outcome. However, systematic studies on how different nets affect sampled transport rates are rare. In this study we compare upstream flow hydraulics and sampled bedload rates between a 3.6 mm and a 1.18 mm mesh-width net attached to bedload traps with non-flared openings. Of the nets tested by Bunte and Swingle (2009), the 1.18 mm net was attractive because it would extend the size range collectible in bedload traps to coarse sand and pea gravel, while the square and precise mesh shape should give a precise lower limit of sampled particle size, and the sturdy nylon material suggested durability. The 0.5 mm nylon precision net was not included in this study because of its known propensity for immediate clogging and ponding (Bunte and Swingle 2003).

METHODS

Properties of the two study nets The 3.6 mm mesh-width net is knitted in a hole-pattern from thin, lightly twisted nylon yarn and is the original netting with which bedload traps were designed. This non-precision netting—called knotless Raschel (www.deltanetandtwine. com) and used for catfish farming—is very stretchable (and hence handles well). Mesh holes have a parallelogram shape when being gently stretched at low flows but become almost square when being fully stretched at moderate flows (Figure 2a). The bag, sewn as a cylinder, stretches to a funnel shape when subjected to flow (Figure 2b). The 1.18 mm mesh-width net is precision netting woven from 0.36 mm diameter nylon monofilament thread (www.Sefar.com). This netting is relatively stiff and unstretchable (Figure 2c), and the square mesh shape and the sewn cylindrical net shape are retained at all flows (Figure 2d). Both nets are about 1.2 m long. Properties of the two nets are summarized in Table 1.

Table 1: Characteristics of the two netting materials tested with bedload traps.

Netting material	Formal description	Open mesh width w (mm)	Width of thread or strand d (mm)	Ratio w/d	Open area A_o (%)	Smallest collectable 0.5 phi size class (mm)
hole-pattern knitted from thin, twisted nylon yarn, non-precision	Raschel 210d/9	3.6 - 5 based on stretching	1.23	2.9	56	4
Square mesh woven from nylon monofilament, precision	Sefar 06-1180/59	1.18	0.36	3.3	59	1.41

Field site The field comparison was carried out during snowmelt runoff at Fool Creek, a small step-pool mountain stream near Fraser in central CO. The reach-averaged gradient is 0.044 m/m, channel width is 1.3 m. The surface D_{16}, D_{50}, and D_{84} particle sizes are 12, 52, and 122 mm; 2% of the surface particles are smaller 2 mm and 11% and smaller 8 mm. The channel has a plane-bed morphology with low steps at the site, but turns to step-pool morphology about 10 m upstream. In the step-pool reach, the stream has carved a tortuous path around numerous large woody debris (LWD) pieces and created miniature forced bars. Storage and release of sediment around those semipermeable LWD dams causes highly variable transport rates.

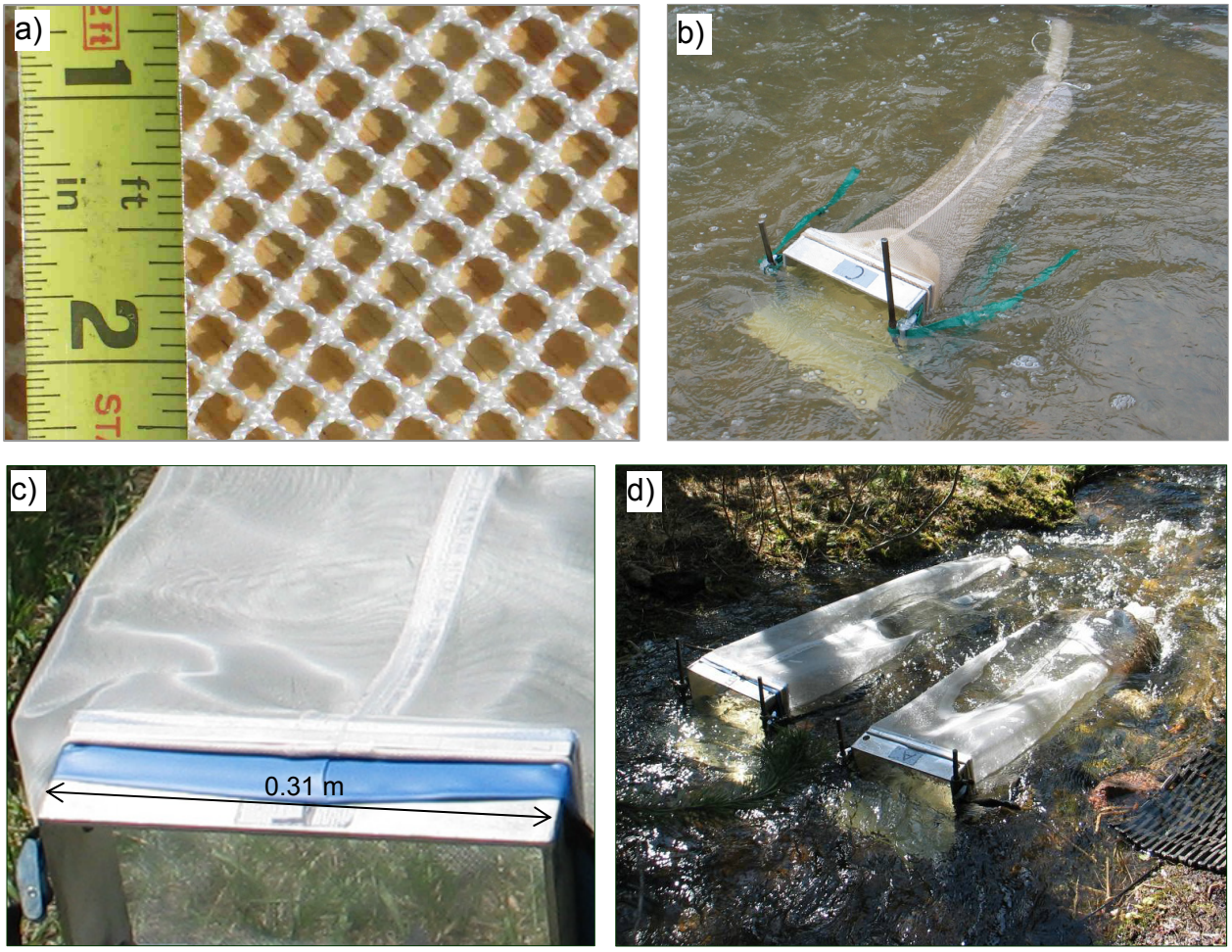

Figure 2: Detail of the 3.6 mm knitted nylon Raschel non-precision netting as the material is stretched to pull the meshes open into almost square shapes (a). The net—attached to a bedload trap—stretches to a funnel shape when subjected to flow (b). Detail of the 1.18 mm precision net woven from monofilament thread (c). The unstretchable 1.18 m nets—attached to bedload traps—retain a square mesh and cylindrical bag shape in all flows (d).

Bedload sampling Bedload traps have a 0.2 by 0.3 m frame to which a sampling net is attached. To cover the lateral variability of bedload transport, two bedload traps were installed next to each other on the channel bed, which resulted in a 0.2 m trap spacing, much tighter than the 0.8 to 1.2 m distance typically kept between neighboring bedload traps in wider streams. A set of two bedload traps with either the 3.6 mm (Figure 3a) or the 1.18 mm netting attached (Figure 3b) was alternately deployed for one-hour sampling times. When the 1.18 mm net visibly started to bulge at about 50% bankfull flow, sampling time was reduced to 30-40 minutes. Bedload samples were collected in flows of 20 to 80% of bankfull.

Data pairing To compare transport rates between the two netting materials, samples from both nets were sorted into data pairs collected no more than an hour apart. On some occasions, transport rates from two consecutive samples collected with the same net were averaged before pairing. In order to plot samples with zero transport, they were assigned a transport rate of 1E-6 g/s which is more than an order of magnitude less than the smallest sampled rate.

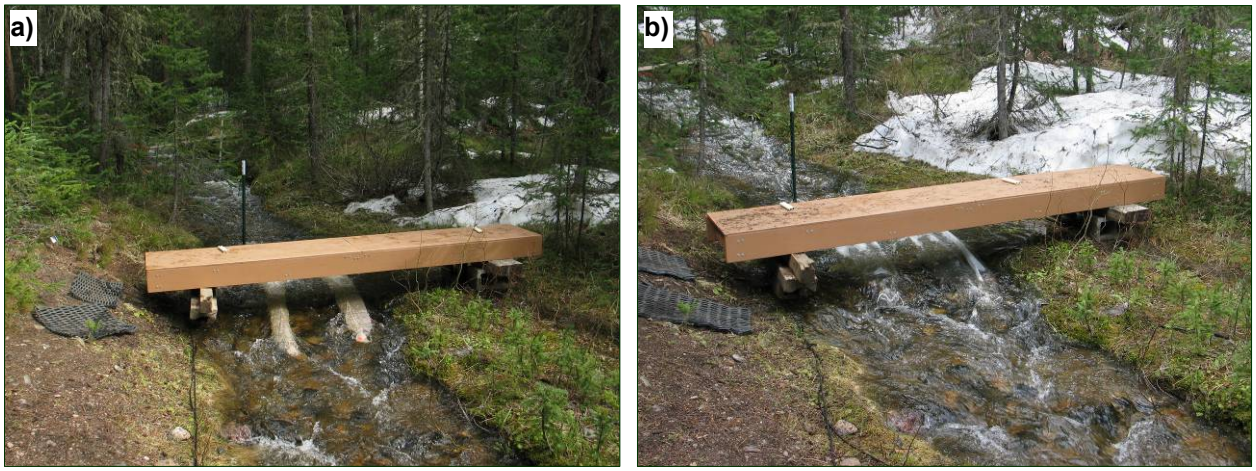

Figure 3: Fool Creek bedload sampling cross-section with footbridge and two bedload traps installed: the original 3.6 mm mesh width nets (a) and 1.18 mm precision nets (b).

Measurements of flow depth and velocity Flow depth as well as the mean vertical flow velocity at 0.6 of the flow depth was measured at distances of 0, 0.15, 0.305, and 0.61 m in front of the ground plates along the center line of the two traps with either the 3.6 mm or the 1.18 mm net attached. Flow depth was measured with a ruler and flow velocity with a Marsh-McBirney electromagnetic current meter. Depth measurements have an error of approximately 5 mm; the error in the velocity measurements was not estimated. The operator moved on a footbridge and a wooden plank placed across the stream in order not to disturb the flow. Pieces of tape on the upstream and downstream sides of the plank marked the measuring locations of 0.305 and 0.61 m in front of the traps. Flow depth and velocity were measured for three conditions: 1) at the bare ground plates with no trap installed, 2) with traps installed but empty, and 3) with traps to which 10 liters of organic material (mostly scales of conifer tree cones) had been added. The amount of organic material typically collected in Rocky Mountain streams in 1-hr bedload trap samples ranges from less than 0.1 to more than 20 l over a highflow season (Bunte et al. 2015, poster session, this volume). A 10-l volume—substantial, though not uncommon—fills about 20% of the net's volume. The measurements were repeated on two different days with flows of 0.17 and 0.20 m^3/s (57 and 67% Q_{bf}) and resulted in 48 individual measurements of flow depth and of flow velocity per net and day, a total of 192 measurements. At a discharge of 0.17 m^3/s, flow depth approached the upper rim of the sampling frame at the right trap and reached to about 75% of the frame height on the left trap. At a discharge of 0.2 m^3/s, flow started to overtop the upper rim of the right trap and reached to about 80% of the frame height on the left trap.

RESULTS AND DISCUSSION

Analysis of flow hydraulics in front of bedload traps

Effect of bedload trap presence on upstream flow hydraulics Compared to a bare ground plate, presence of a bedload trap generally caused ponding which increased the upstream flow depth and reduced the vertical mean flow velocity. The addition of organic material to the net further increased ponding, and retarded flow as shown in all plots of Figure 4. However, the degree of ponding and retardation, and the upstream extent of these effects, are determined not only by the netting properties, but also by the local flow hydraulics.

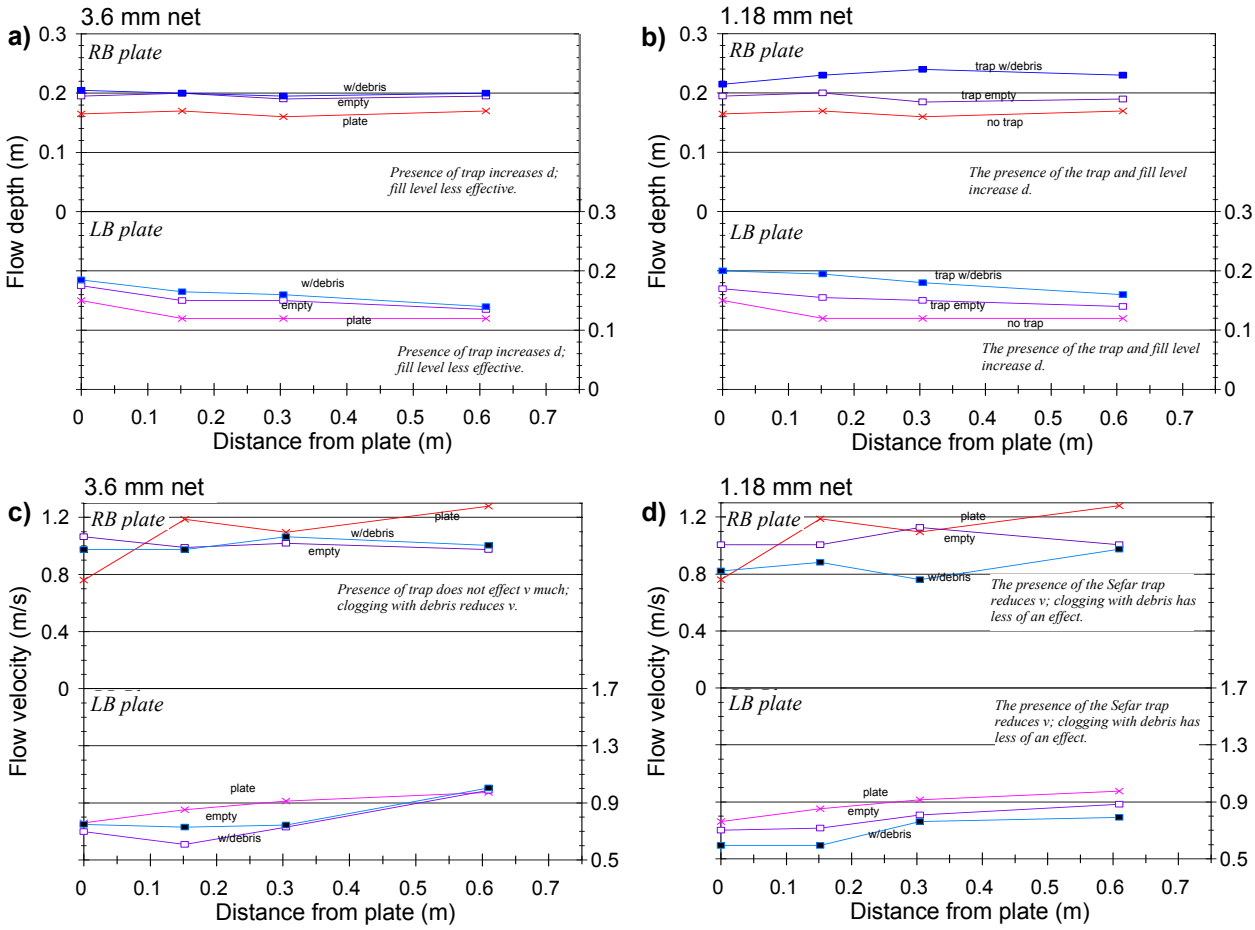

Figure 4: Flow depth (a, b) and mean flow velocity at 0.6 *h* (c, d) measured at a discharge of 0.17 m^3/s at four locations in front of the right and left bedload traps fitted with the 3.6 mm net (a, c) and the 1.18 mm net (b, d). Reddish lines refer to bare ground plates with traps removed. Purple lines refer to empty traps, and bluish lines to traps filled with 10 liters of organic debris.

For example, flow was deeper and faster at the RB plate and overtopped the RB trap, while 25% of the LB trap height protrudes through flow. There may also be hydraulic interference be-tween the two traps due to their close spacing. In order to integrate over local effects and focus on the general effects exerted by the netting properties, this study averaged the measurements of flow depth and flow velocity over all four longitudinal locations and over the left and right traps.

Average ponding and reduction in mean flow velocity For the two sampled flows of 0.17 m^3/s (Figure 4) and 0.20 m^3/s (not shown because patterns are very similar to those at 0.17 m^3/s), empty traps fitted with the original 3.6 mm net increased flow depth in front of the traps by about 18% and 20%, respectively, compared to the flow depth measured over the bare ground plates. The addition of 10 liters of organic material produced only a minor increase in flow depth for the 3.6 mm net (Table 2). Compared to flow depth on the bare plates, bedload traps with organics raised flow depth by 23%. Traps with empty 1.18 mm nets increased flow depth similarly by 18% for the lower flow and to slightly more (22%) at the higher flow. In contrast to the 3.6 mm traps, the 10 liter of organics added to the 1.18 mm nets increased flow depth by an additional 19 and 15% such that compared to the bare plates, traps with organics increased flow depth by 40%.

The response of retardation of flow velocity is similar to that of ponding (Table 2). Again, compared to the bare ground plate, an empty trap with a 3.6 mm mesh reduced the mean flow velocity by 10 and 13% at the two flows, and adding the organic material retarded the flow just slightly more. Empty traps with 1.18 mm nets reduced mean flow velocity a few percent less than empty 3.6 mm nets (about 7 and 10%), possibly due to the slightly higher open area of the 1.18 mm net (59%) compared to the 3.6 mm nets (56%). However, the added organic material reduced flow velocity in the 1.18 mm nets by another 15% in both flows, while the effect of organic material in the 3.6 mm nets was again minor.

Table 2: Average effect of empty and filled bedload traps fitted with the original 3.6 mm and the 1.18 mm nets on upstream flow depth and mean flow velocity at two discharges *Q*.

	Empty trap *vs*. no trap		Added 10 l of org. mat. *vs*. empty trap		Trap with 10 l of org. material vs. no trap	
	$Q = 0.17$ m^3/s	$Q = 0.2$ m^3/s	$Q = 0.17$ m^3/s	$Q = 0.2$ m^3/s	$Q = 0.17$ m^3/s	$Q = 0.2$ m^3/s
Percent increase in flow depth						
Orig. 3.6 mm nets	18.3	20.7	4.3	1.6	23.4	22.7
1.18 mm nets	17.9	22.4	19.1	14.8	40.4	40.6
Percent decrease in flow velocity						
Orig. 3.6 mm nets	- 9.5	- 12.9	2.4	- 3.2	-7.4	-15.7
1.18 mm nets	- 7.4	- 10.3	- 14.7	- 15.0	-21.0	-23.7

The pronounced effect of captured organic material on flow ponding and retardation in the 1.18 mm precision nets is caused by the stiffness of the net material which makes the net retain its cylindrical shape at all flows. Organic material that enters the net accumulates along the upper back part of the bag, where most of the water would otherwise exit, and obstructs water through-flow (Figure 5a, c). A similar response was observed at a 0.5 mm precision net that bulged and ponded flow within minutes of deployment in low to moderate flow (Bunte and Swingle 2003), suggesting that fine-meshed, stiff precision nets should not be used when organic material is in motion. The original 3.6 mm bedload trap net, by contrast, stretches to a funnel shape, and most of the flow exits the net just shortly behind the trap frame (Figure 5b). Organic material and bedload is directed to travel along the bottom of the net, and both accumulate in the narrow net end (Figure 5d) where solids do not have much effect on flow hydraulics near the trap entrance.

Comparison of fractional transport rates At the lowest transporting flows when small gravel particles were just starting to move, the non-precision 3.6 mm net collected either no particles or lower rates of the 4 - 5.6 mm size class than the 1.18 mm net (Figure 6a). The nominal 3.6 mm mesh size probably lets flat particles of the 4-5.6 mm size class pass when meshes still have a parallelogram shape before they are fully stretched by flow. Adding to the particle escape is the fact that the first 4 – 5.6 mm bedload particles in motion also tend to be the flatter and less voluminous specimens of the size class. At higher flows when meshes are fully stretched and almost square, the 3.6 mm net is believed to capture particles of the 4-5.6 mm size class representatively.

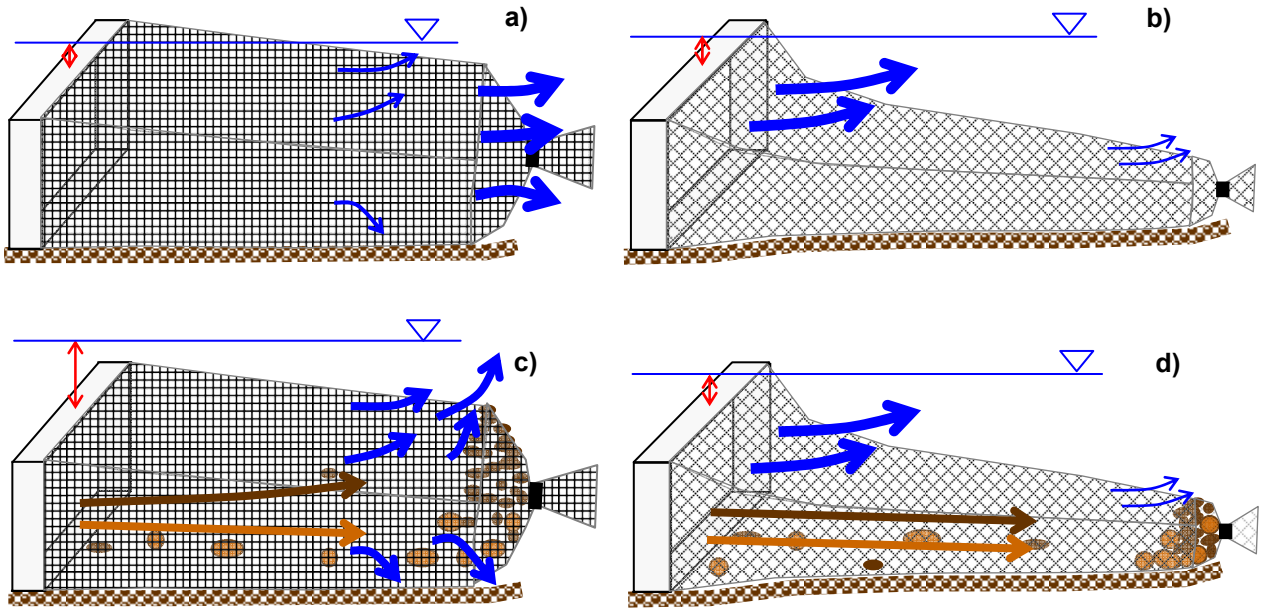

Figure 5: Sketches of flow and solid transport through the 1.18 mm precision net (a) and through the stretchable 3.6 mm Rachel (b) in the absence of organic material. Organic material added to the nets accumulated in the net end and blocked the exit of flow in the stiff 1.18 mm net (c) but not in the flexible, funnel-shaped 3.6 mm net (d). Blue arrows indicate water through-flow, dark brown arrows indicate the path of organic material, beige arrows indicates the bedload path.

At low transport, the 3.6 mm net often contained no 5.6 - 8 mm particles (Figure 6b), while the 1.18 nets had captured one or several. Similar observations held for the 8 - 11.2 (Figure 6c) and the 11.2 - 16 mm size class (Figure 6d). As suggested by the measured flow velocity, the 1.18 mm net with a 59% open area retarded throughflow less at very low flows than the 3.6 mm net with a slightly lower open area of 56%. Thus, absent high organic concentrations, the 1.18 mm net performed better at lower flows. At moderate transport rates, both nets collected all size bed-load fractions at similar rates, i.e., within a factor of about ±4 of each other, given Fool Creek's fluctuating transport. At the highest sampled transport rates, the 3.6 mm net tended to collect higher transport rates than the 1.18 mm net in all size fractions.

<u>Ratios of transport rates collected with the two nets</u>

Ratios of transport rates collected in the 3.6 mm vs. the 1.18 mm net for fractional and total bed-load transport (excluding zero samples) plotted vs. discharge (Figure 7a) show that the 1.18 mm net yields higher transport rates than the 3.6 mm net at the lowest flows, which is expected because the 1.18 mm net has a slightly higher percent open area and retards flow slightly less than the 3.6 mm net (Table 2). As discharge exceeds about 0.21 m^3/s (70% of bankfull flow), the 3.6 mm net started collecting higher rates than the 1.18 mm net for all particle size classes. The switch is attributed to the capture of organic material typically transported in Rocky Mountain streams during snowmelt runoff, and with increasing flow those organics comprise increasingly larger proportions of the solid transport (Bunte et al. 2015, this volume). Captured organic material accumulates in the bag ends where it blocks flow from exiting the 1.18 mm nets. As a consequence, the 1.18 mm nets start to bulge at their downstream ends (Figure 7b), pond, and retard flow at the net entrance, and decrease sampling efficiency.

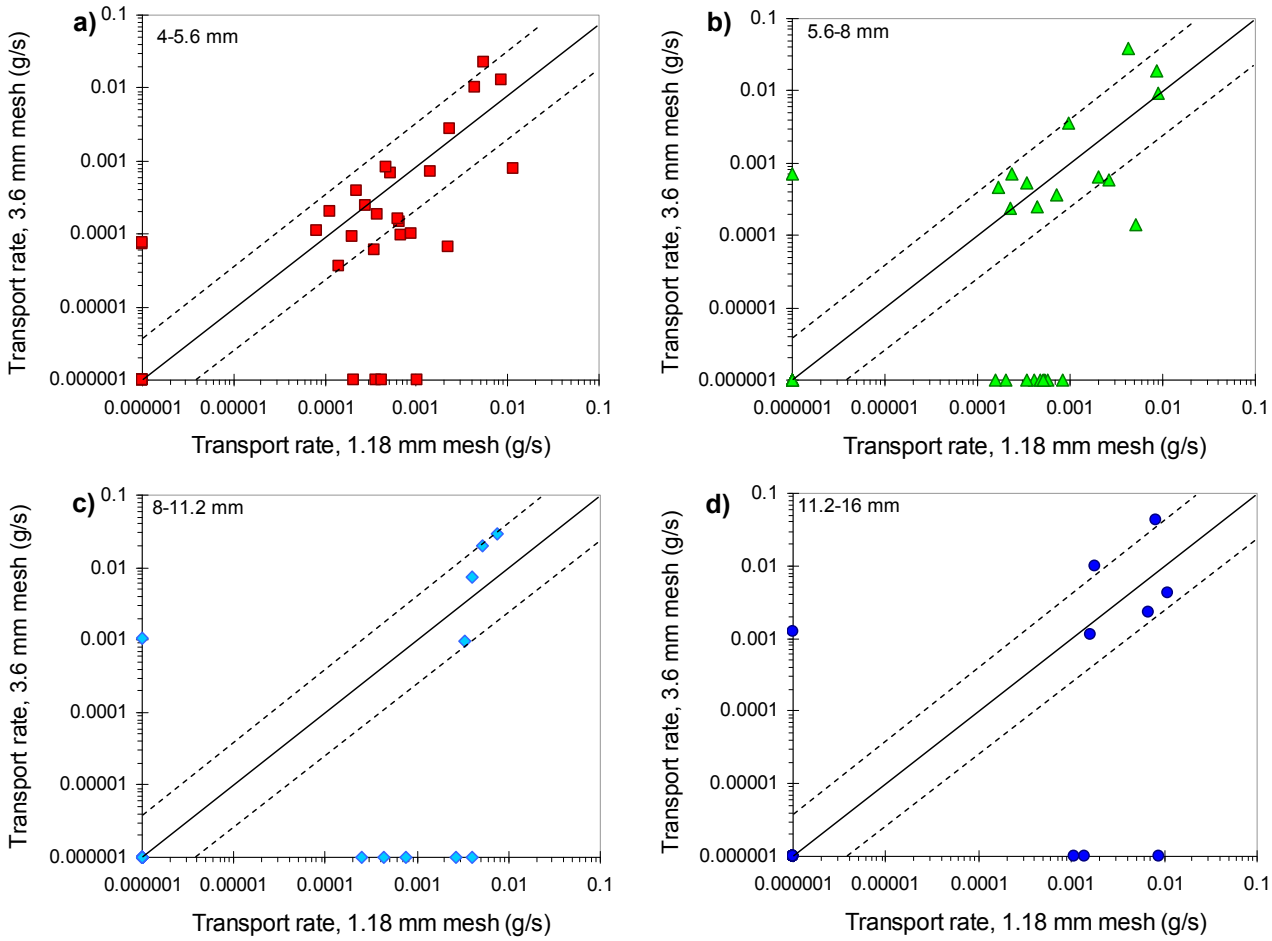

Figure 6: Pair-wise comparison of fractional transport rates collected with the two bedload trap nets. Samples that do not contain a particle were assigned the transport rate of 0.000001 g/s and plotted along the x- and y-axes. The solid diagonal line is the 1:1 line. Stippled lines indicate a factor 4 range above and below the 1:1 line.

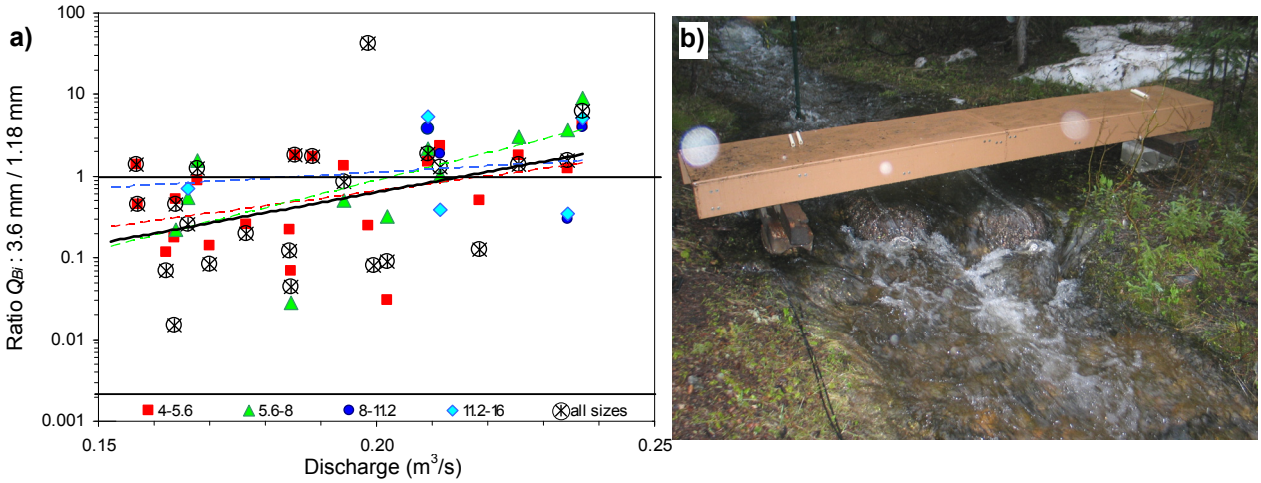

Figure 7: Ratios of transport rates collected in the 3.6 mm vs. the 1.18 mm net for fractional and total bedload transport (a). The 1.18 mm precision nets bulge when the start capturing organic material and pond water upstream (b).

SUMMARY AND CONCLUSION

- The study shows interactions between different netting properties and how they affect flow ponding and retardation, throughflow, and sampled transport rates.

- Hydraulic and sampling efficiency differs between nets of different mesh width even though both netting materials have percent open areas that are not very different.

- Netting stiffness affects hydraulic and sampling efficiency. Stiff nets that retain a near-cylindrical bag shape at all flows are prone to throughflow blockage by organic material, and respond with bulging, ponding, and retardation of flow, as well as with a reduction in sampled transport rates. Flexible nets segregate the paths of water throughflow and solid transport in the net such that solids accumulate where they have much less effect on hydraulic and sampling efficiency.

- At low flows, the 1.18 mm net measured higher transport rates of fine gravel particles with fewer zero samples than the 3.6 mm net. Both nets approach similar transport rates in moderately high flows (70% of bankfull), but in higher flows, the 3.6 mm yields higher rates than the 1.18 mm net. This switch in sampling efficiency between the two nets has implications on sampled gravel transport relations which increase more steeply with flow (i.e. the bedload rating curve slope) if the 3.6 mm net is used rather than the 1.18 mm net.

- The study showed that responses of hydraulic and sampling efficiency to netting properties are complex. Hydraulic efficiency is a response to the combined effects of the percent open area of the mesh, increasing flow, the shape taken by the net in flowing water, and net clogging and blockage which typically intensify with higher flow, higher transport rates of organic material, and longer sampling time.

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