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THE EFFECTS OF LARGE ORGANIC DEBRIS UPON CHANNEL MORPHOLOGY: A FLUME STUDY

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ABSTRACT: In streams draining forested mountain catchments, large organic debris can have an important effect upon sediment storage, channel morphology, and aquatic habitat. Large debris often causes localized scour of the streambed, thereby increasing diversity in channel dimensions. A flume study was conducted to evaluate the interaction between (1) water discharge, (2) positioning of debris above the stream bed and (3) size of debris in relation to the depth and size characteristics of scoured pools. A cylinder, representing the stem of a fallen tree, was positioned horizontally across the flume and flows were incrementally increased from 0 to 27 L s^{-1}. Cylinder diameters of 6, 10, 15 and 20 cm were evaluated at elevations 0, 5, 10 and 15 cm above an erodible bed consisting of 5.4 mm (d_{50}) gravels. During increased flows, scour of the gravel bed occurred as water was deflected underneath the cylinder; a relative maximum in pool depth typically occurred when flow overtopped the cylinder. Further increases in flow also increased pool depth but at a much slower rate; additional flows caused primarily a downstream expansion in the size of pool. Vertical velocity profiles at the deepest portion of the pool were of irregular shape. Average bottom velocities (within 2 cm of the bed) were lower in the pool than either upstream or downstream, however, flow at the bottom of the pool was highly turbulent. Results demonstrate the extent to which simulated large organic debris can create localized bed scour in a two dimensional system. The relatively rapid scour experienced within a narrow range of flow also illustrate a mechanism by which slugs or waves of bed material may be released for downstream transport.

INTRODUCTION

In recent years, research results have increasingly identified the importance of organic debris in affecting channel morphology. This debris exists in a variety of shapes, sizes and quantities. For example, debris loadings have been found to range from 2.6 to 79 tonnes per 100 m (0.9 to 26 tons per 100 ft) along undisturbed stream channels in the Pacific Northwest (1). Depending upon the management practices used, logging can modify these debris volumes to levels ranging between 60 to 360 percent of prelogging concentrations.

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Of particular importance, is the occurrence of large organic debris which can be defined as tree boles > 20 cm in diameter with rootwads attached. Tree branches over 20 cm in diameter would also qualify as large organic debris (2). Historically, streams of approximately 4th through 7th order in the Pacific Northwest were used to transport logs from the forest by the use of splash dams and log drives. These streams were typically "improved" before a log drive by removing naturally existing debris and obstructions (3). During the 1970's, forest harvesting activities along many of the lower order channels (1st through 4th) often resulted in reduced quantities of organic debris due to stream cleanup activities. This depletion of large organic debris may have important short- and long-term implications regarding channel characteristics, sediment routing and aquatic habitat (4, 5).

The presence of large organic debris in a channel will generally increase bed roughness and thus increase the localized dissipation of the stream's potential energy. In some instances, the debris may sufficiently obstruct flows and sediment transport so that deposition of sediment may occur immediately upstream. For example, Megahan (6) found the volume of sediment stored in mountain channels of the Idaho Batholith was 15 times greater than the annual sediment yield; logs representing the most important type of obstruction. Similarly, Mosley (7) found large debris created local base levels in a New Zealand forest stream where coarse sediment remained stored for long periods. In other instances, however, flows deflected by large organic debris may result in localized scour of the bed and banks of a channel. Even in this situation, the presence of large debris would be to effectively increase the overall roughness of a reach and slow the routing of sediment from upchannel sources. Where debris accumulations in and along channels have been removed, large volumes of bed material may be released downstream (7, 8).

Although the importance of large organic debris to instream habitat values is becoming increasingly recognized (2, 3, 9) little is known about the hydraulic effects of this debris and its role in affecting channel characteristics. Scour of bed material as water flows around large debris is a complex process which encompasses highly variable flow patterns. An example is illustrated in Fig. 1 of a large tree which has fallen into a channel at right angles to the direction of flow. Flows depicted at (a) are largely deflected over the tree stem, whereas at (b) and (c) most water is forced underneath the stem. At (d) the tree is having essentially no effect on flow patterns. As flow levels change, the relative effectiveness of various parts of the tree

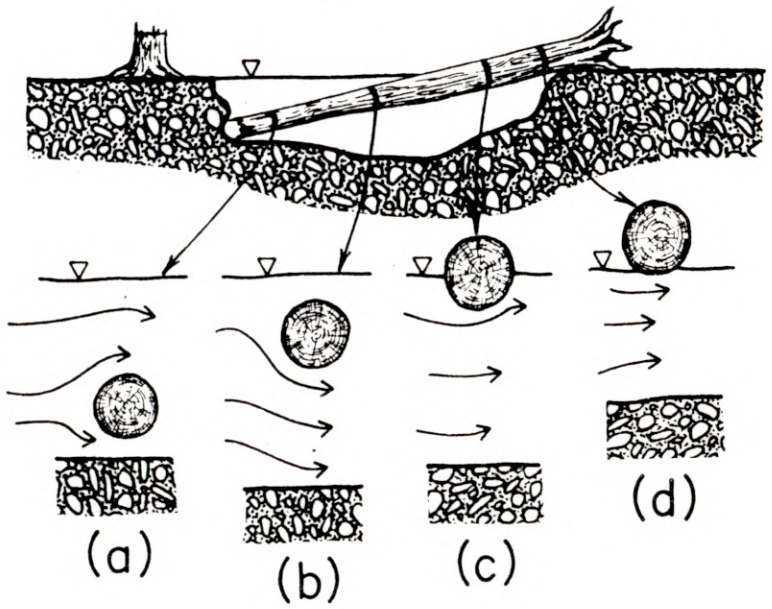

FIG. 1 - Influence of large organic debris upon flow streamlines at bankful stage.

for deflecting flows will change accordingly. Only vertical flow deflections are emphasized in Fig. 1 whereas a lateral component may also be important in natural channels. An evaluation of bed changes associated with large debris would provide important insights regarding its role as a modifier of streambed morphology in natural channels. Hence, this flume study was undertaken to assess the effects of debris size, placement (height above the bed) and flow magnitude upon the amount of scour (i.e., pool formation) in a gravel bedded channel.

EXPERIMENTAL DESIGN

A 0.132 m wide, 0.6 m deep and 10 m long flume, with a full depth viewing section along the middle 4.5 m of channel, was utilized in this study (10). A centrifugal pump recirculated water from 1.5 m^3 holding tank; water tempertures were maintained between 18 and 20°C during all tests.

Two plexiglass plates, 0.3 m in height, were installed approximately 4 m apart in the channel and the area between was filled to a depth of 0.3 m with well sorted gravel having a median particle diameter (d_{50}) of 5.4 mm. Flows were then increased to 27 L s^{-1}, the maximum used during the study, and the gravels between the plates degraded several centimeters until a stable bed resulted. The surface of the resultant bed was uniform and with a slope of 0%.

At the beginning of each experimental run, the relatively uniform and flat gravel bed was reformed. A metal cylinder was then positioned at one of four heights above the bed surface, i.e., the bottom of the cylinder was placed at elevations of either 0, 5, 10 or 15 cm in reference to the bed. Flows were then incrementally increased, starting from zero, to 1, 3, 5, 9, 13, 17, 20, 23 and 27 L s^{-1}. After each increase, the flow was held constant until changes in the gravel bed had ceased. Once the bed had stabilized at a given flow, water and bed elevations were recorded. Because of its relatively narrow width, only vertical deflections of flow and resultant scour was evaluated. Localized scour of the gravel bed, when it occurred, took place soon after the flow was increased; the bed typically stabilized within 2 hr. Selected velocity profiles were determined with a Kent-Lea miniflow probe (10 mm diameter propellor). After the full range of flows and resultant changes in the gravel bed had been measured, the uniform and flat gravel bed was restored and the cylinder repositioned for the next experimental run. Four

cylinder diameters, i.e., 6, 10, 15 and 20 cm, were individually evaluated at each of the four positions.

RESULTS AND DISCUSSION

Pools were scoured in the gravel by the action of flowing water deflected downward as it moved under the simulated debris (i.e., cylinder). An example of the complexity of velocity profiles resulting from the presence of a cylinder is illustrated in Fig. 2. At location (a) the velocity profile is relatively uniform vertically and averages approximately 85 cm s^{-1}. A sharp decrease in velocity occurs in the lower 10 cm of the profile. In contrast, profile (b) has relatively low velocity in the upper portions of the profile, as a result of the cylinder's influence. A relatively high velocity component or submerged jet is shown in the lower 10 cm of the profile. At (c) the submerged jet has increased in complexity but is the major feature of the profile. Similarly, Chatterjee and Gosh (11) found velocity profiles of a submerged horizontal jet over an erodible bed to be highly variable and complex. Even though the profile at (c) was measured at the deepest location in the pool, average velocities within 5 cm of the bed are less than half of those measured at other locations. At location (d) relatively high velocities are still found in the middle of the profile as velocities begin to reestablish the pattern shown in (a).

The relatively low average velocities within 5 cm of the bed for profile (c), Fig. 2, had an important influence on the scour and transport of gravels. Individual gravel particles, would often be initially lifted vertically and then carried downstream by saltating and/or rolling along the bed. The bottom of the pool was thus a zone of exceptionally high turbulence and velocity pulsations. As an indication of relative turbulence along the bed at each location, velocity fluctuations (Δu) over 1 second intervals (Δt) were determined from recorded output of the miniflow current meter. These results indicated that relative turbulence, expressed by $\Delta u/\Delta t$, was 1.7 to 2.5 times greater at the bottom of the pool than at other profile locations. This turbulent flow was capable of scouring and removing gravels even though average velocities might indicate otherwise.

The 16 experimental runs (4 cylinder diameters x 4 elevations above the bed) indicated that the amount of scour (i.e., an increase in maximum pool depth or pool volume) increased non-linearly with increased water discharge. The changes in pool characteristics and morphology are shown in Figs. 3, 4, 5

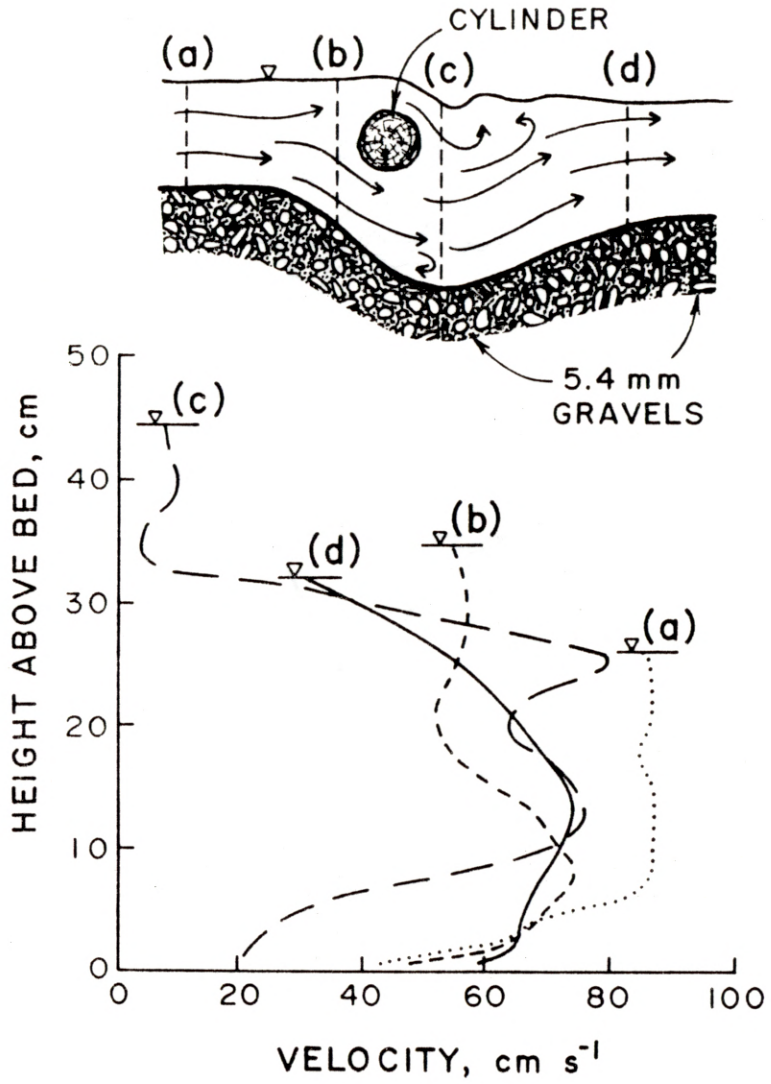

FIG. 2 - Definition sketch and associated velocity profiles for 15 cm diameter cylinder positioned 10 cm above the original bed; water discharge at 27 L s^{-1}.

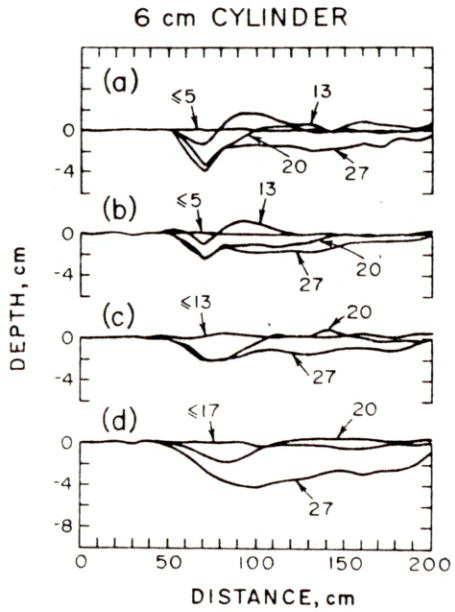

FIG. 3 - Bed profiles resulting from 6 cm diameter cylinder positioned (a) 0, (b) 5, (c) 10 and (d) 15 cm above the bed at the 55 cm channel distance; numbers indicate water discharge in L s^{-1}.

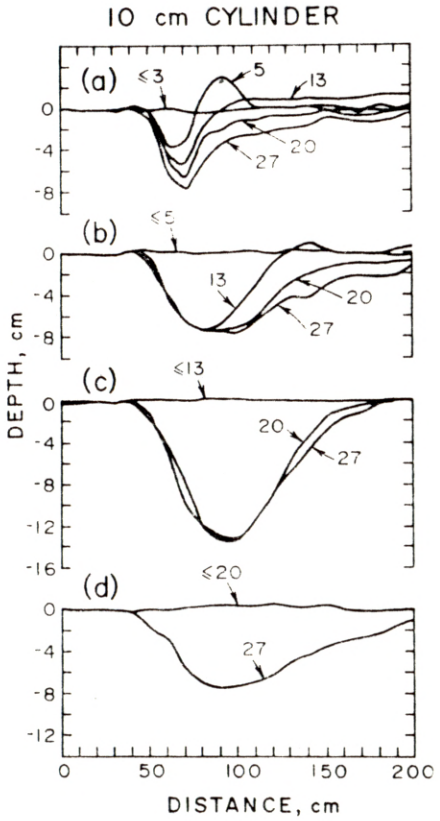

FIG 4 - Bed profiles resulting from 10 cm diameter cylinder positioned (a) 0, (b) 5, (c) 10 and (d) 15 cm above the bed at the 55 cm channel distance; numbers indicate water discharge in L s^{-1}.

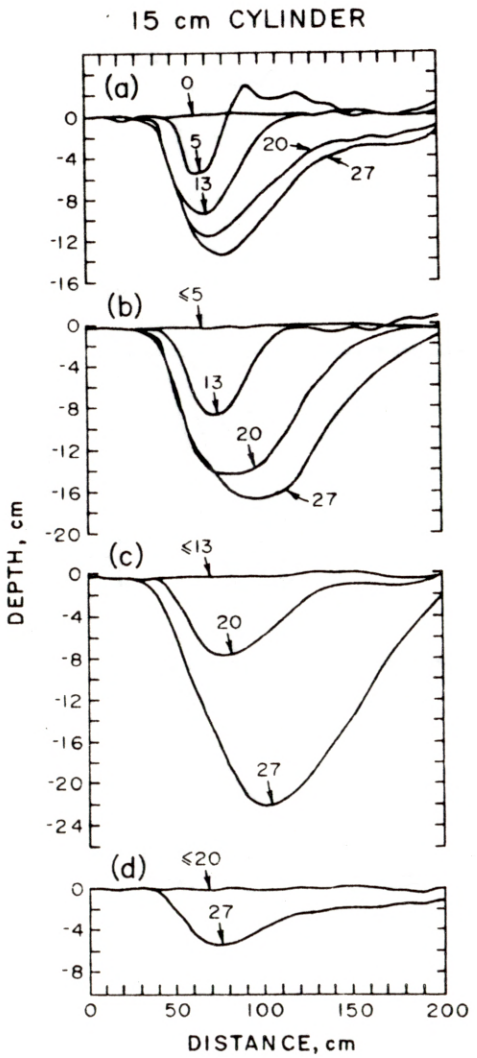

FIG. 5 - Bed profiles resulting from 15 cm diameter cylinder positioned (a) 0, (b) 5, (c) 10 and (d) 15 cm above the bed at the 55 cm channel distance; numbers indicate water discharge in L s^{-1}.

and 6 for the 6, 10, 15 and 20 cm cylinders, respectively; only selected bed profiles are shown. Several distinct response patterns developed as flows were incrementally increased during a particular run.

When the bottom of the cylinder was at the same elevation as the original bed and flows were incrementally increased, scoured gravels would form wave-like accumulations immediately downstream. For example, Fig. 4-(a) shows a pool has begun to form at a flow of 5 L s^{-1}. Immediately downstream lies an accumulation of gravel from the pool. Incrementing the flow to 13 L s^{-1}, increased the depth and size of pool immediately under the cylinder and caused approximately a centimeter of deposition immediately downstream on top of the original bed. Increased flow resulted in additional scour along the entire longitudinal section affected by the cylinder. Similar patterns are seen in Figs. 3, 5 and 6.

When the bottom of a cylinder was positioned at the same height as the gravel bed, the maximum depth of scour (in relation to cylinder diameter) increased relatively uniformly with increased flow (Fig. 7-(a)). Above a discharge of 20 L s^{-1} all cylinders had at least part of the flow going over the top. At this discharge and above, the larger cylinders appear to be consistently more effective at creating deeper pools. This would be expected because of the larger vertical cross-section associated with the larger cylinders and a greater proportion of the flow being forced underneath. The general flattening of the curves at the higher discharges (Fig. 7-(a)) indicate that there would be little additional effect on pool depth if flows were increased further.

When cylinders were positioned above the bed, there was a tendency for pool depths to increase relatively rapidly as flows were incrementally increased. Once the cylinder was overtopped by water, however, continued deepening was not as rapid or stopped entirely, even though flows were increased. This feature is shown in Fig. 7 ((b), (c) and (d)) where many of the relationships appear to have distinct break points. Instead of the pool becoming deeper at higher flows, the available stream power was being used to increase pool size in a downstream direction (Figs. 3, 4, 5 and 6). A similar effect was noted by Abt and Ruff (12) in a study evaluating scour of cohesive material at a culvert outlet.

There was a tendency for the longitudinal location of maximum depth to shift downstream as a particular pool was scoured during a run. Similarly, when a particular cylinder was positioned higher above the bed, the location

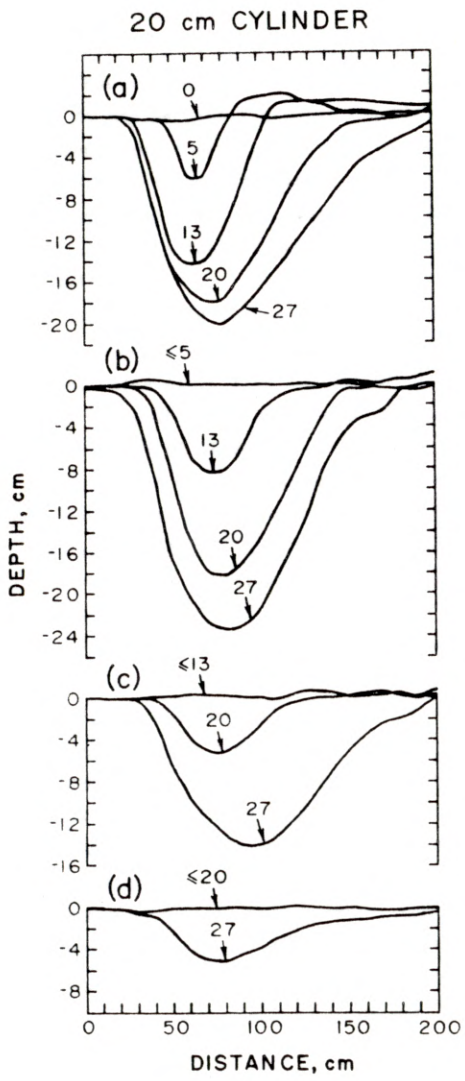

FIG. 6 - Bed profiles resulting from 20 cm diameter cylinder positioned (a) (b) 5, (c) 10 and (d) 15 cm above the bed at the 55 cm channel distance; numbers indicate water discharge in L s^{-1}.

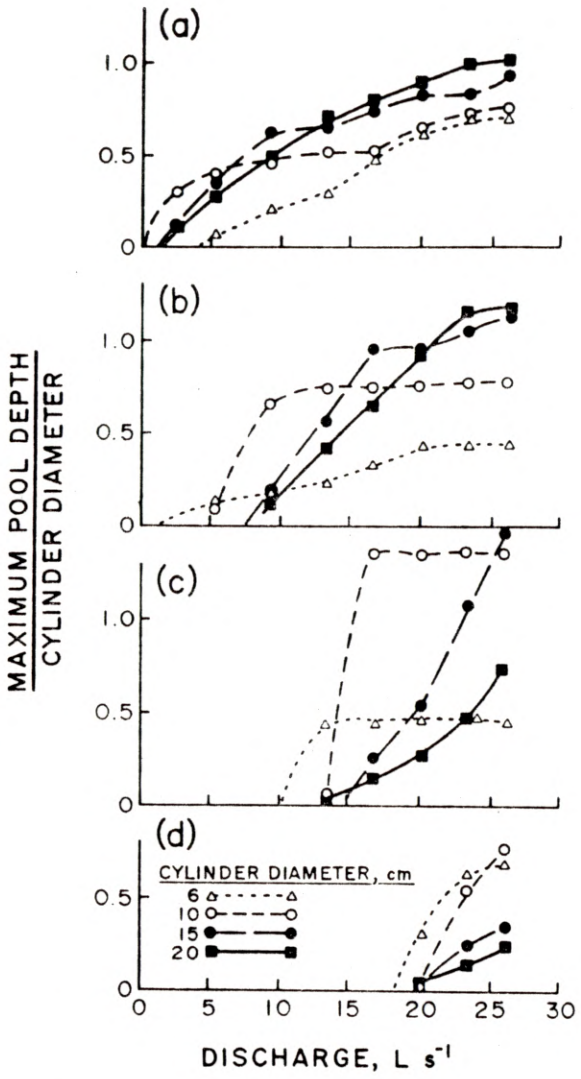

FIG. 7 - Maximum pool depth (expressed as a ratio of cylinder diameter) as influenced by water discharge and cylinder diameter for cylinder positioned (a) 0, (b) 5, (c) 10 and (d) 15 cm above the original bed.

of maximum depth would occur farther downstream. Although the scoured pools would usually start with a symetrical longitudinal profile, this was often lost as pool size increased.

The pronounced changes in maximum pool depth, Fig. 7, which occurred over relatively small changes in water discharge indicate the sensitivity of bed scour processes to seemingly subtle changes in flow. If this situation also occurs in mountain streams, it may partially explain why high temporal variability in bedload transport rates are common. A tree falling into a channel, the trapping of floatable organic debris by an existing log, a readjustment of large organic debris, or some other localized change in hydraulic conditions could result in relatively rapid scour of the channel and the release of a pulse of bed sediments.

The depth and size of pools scoured in the gravel bedded flume resulted from a complex interaction between cylinder diameter, cylinder position above the bed, and water dishcarge. At a given flow and height of cylinder above the bed, the greatest amount of scour was associated with the largest cylinders. This would imply, that trees of large diameter may be needed in natural streams if large pools are needed to improve the availability and quality of aquatic habitat. Because the organic debris would also provide at least partial cover during low flow, such pools may have more desirable characteristics for fish than pools formed from water overflowing logs, gabions, boulders, or other similar obstructions in a channel.

Pool depths did not exceed 1.5 times the cylinder diameter in any of the 16 test runs. Yet, field observations of Pacific Northwest streams indicate that where organic debris deflects streamflow underneath, the resultant pool depths can be several times that of the tree diameter. The cylinders used in this study had smooth surfaces. Tree boles, on the other hand, seldom have a perfectly circular cross-section, often have rough bark or woody surfaces, and may have limbs protruding. All of these features would increase the effective roughness of the organic debris and may partially explain the occurrence of relatively deep pools in natural channels. Furthermore, contracted channel banks, due to other woody debris, roots, or erosion resistant bank materials, might increase the convergence of flow streamlines underneath a log and accentuate the focus of stream energy so that scour is increased.

The results illustrated in Fig. 7 support the idea that hydraulically "rough" debris would be more effective in affecting scour depths, particularly when debris (i.e., cylinders) are positioned above the bed (i.e., (b), (c) and

(d), Fig. 7). During initial scour, and before the cylinders are overtopped by the flow, the maxumum pool depth (expressed as a ratio of cylinder diameter) is generally associated with the relatively small cylinders. These smaller diameter cylinders cause a more abrupt change in flow and result in greater relative scour.

The presence of large organic debris, as simulated by the cylinders used in this study, has the capability for increasing diversity in channel dimensions. Although sediment inputs were not fed into the channel during any of the test runs reported herein, several trials were conducted whereby gravels (d_{50} = 5.4 mm) were added to the flume upstream of an existing cylinder-pool configuration. The result was immediate aggradation along the upstream bed. Gravels that arrived at the pool were rapidly routed through the pool and additional bed aggradation occurred downstream. These trials indicated that once a pool has formed, by flows deflected underneath an obstruction, it will remain even during periods of high bed material transport. Although the greater turbulence and flow deflection can increase localized scour and energy dissipation, an overall reduction in bed material routing through a reach will apparently occur.

Observations during the study indicated that flow underneath a cylinder was creating significant hydrodynamic forces. The cylinder was in effect operating as an airfoil due to the relatively high velocity water flowing underneath (Fig. 2), however, the "lift forces" in this case were operating downward. This downward force would tend to counteract bouyancy forces of a submerged wooden stem. It would also act to increase the effective frictional resistance to downstream movement at each end where the stem is in contact with the bed or banks. How important this effect is in maintaining debris positioning in streams is not known. However, these hydrodynamic forces, in addition to gravitational forces, may help to explain why large organic debris often becomes buried in the bed and banks of natural channels.

SUMMARY

A flume study was undertaken to obtain a two-dimensional assessment of the interaction of debris size and height above the bed, and water discharge, in relation to changes in longitudinal profiles of a gravel bedded channel. Results indicate bed scour responded nonlinearly to changes in these factors. Several principles of pool formation are identified which may be useful to land managers and fisheries biologists attempting to increase habitat diversity in natural channels.

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