Environmental Hydraulics of Large Woody Debris in Streams and Rivers

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ENVIRONMENTAL HYDRAULICS OF LARGE WOODY DEBRIS IN STREAMS AND RIVERS

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ABSTRACT: Although awareness of the habitat value of large woody debris in streams has promoted a more environmentally sensitive approach to its management, present guidelines are largely intuitive and do not contain advice for conducting quantitative hydraulic investigations. This review of the literature provides information to assist management, and highlights deficiencies in current knowledge. Hydraulically, debris act as large roughness elements that provide a varied flow environment, reduce average velocity, and locally elevate the water-surface profile. This can significantly increase flood travel time. The significance of debris is scale-dependent. For example, the hydraulic effects are often drowned out in a large flood on a large river. Some hydraulic models can be used to predict the effect of debris removal or reinstatement. A challenge for research is the development of a hydraulically and biologically meaningful definition of debris geometry that can be readily used in the field. When more is known about the physical and biological significance of debris in rivers, a detailed cost-benefit analysis on its management should be undertaken.

INTRODUCTION

The use of rivers for navigation and water supply has often involved periodic or regular removal of obstructions as a part of so-called river improvement, river clearing, or channelization schemes. Fallen trees, usually termed snags, are a common obstruction. The extensive removal of snags (termed either as snagging or desnagging) to improve river navigability has been a common practice in many countries for over a century (Peterson et al. 1987). Desnagging has also been justified on the grounds that it maintains or improves water conveyance, either for flood control or irrigation supply; reduces bank erosion; rejuvenates channels; lessens the risk of damage to bridges; improves recreational amenity (swimming, boating, and water skiing); or removes barriers to fish migration (Harmon et al. 1986; Bisson et al. 1987; Gippel et al. 1992).

Traditionally, snag management has been regarded as an engineering or economic problem and, because of this narrow focus, most snag removal has been undertaken with little regard for the direct or indirect effects on aquatic fauna. The wider environmental role of snags is more widely appreciated now (Shields and Nunnally 1984). Several reviews of the literature have demonstrated that snags provide physical habitat for aquatic fauna, play a major role in stream channel geomorphological processes, contribute significantly to the dissolved and particulate load of stream water, retain fine particulate matter for biological processing, provide thermal refuges for fish, and contribute to the aesthetic value of a waterway (Marzolf 1978; Harmon et al. 1986; Bisson et al. 1987; Sullivan et al. 1987). Originally, the term snag was used in a derogative sense to refer to the hazard fallen wood presented to navigation; but, given the now-recognized multifunctional (and positive) role of fallen wood in streams, the term is no longer appropriate. Preferred terms are large woody (or organic) debris or coarse woody (or organic) debris. The abbreviation debris is used in this paper to refer to woody material in stream channels that is by convention sized larger than 0.1 m in diameter and 1.0 m in length (Keller and Swanson 1979; Andrus et al. 1988).

Concern over the undesirable effects of debris removal has led to various recommendations for, and in many places adoption of, a more sensitive approach to its management [e.g., McConnell et al. (1980), "Stream" (1983), Bilby (1984), Shields and Nunnally (1984), Andrus et al. (1988), "A guide," *Environmental* (1990), Lawrence (1991)]. In some areas, degraded stream systems are being rehabilitated (Gore 1985; Osborne et al. 1993), and to hasten ecological recovery this can involve replacing debris in previously cleared rivers. Large-scale reintroduction of debris or surrogate enhancement structures to streams has been under way in certain areas of the United States for some time (Swales and O'Hara 1980; Lisle 1981; Gore 1985; House and Boehne 1985; Sedell et al. 1991). In addition, several U.S. states have declared riparian-vegetation mangement rules, which are partially intended to ensure an ongoing supply of debris to streams (Graf 1980; Andrus et al. 1988; Sedell et al. 1991). These efforts should speed ecological recovery, but it is likely that ongoing maintenance, in the form of management of in-channel debris or selective logging of riparian vegetation, will be economically and ecologically desirable, especially if flood mitigation is an issue of concern (Graf 1980; Rainville et al. 1985; Bisson et al. 1987).

A common problem in the management of debris in rivers is how to trade off between the need to maximize the volume of wood in the channel for ecological benefits and the need to minimize the volume of wood in the channel to lower flow resistance. Quantitative information on the volume, geometry, and characteristics of the wood required to maintain adequate habitat is generally lacking in the literature. However, the typical distribution of debris in relatively undisturbed rivers and streams [see reviews in Harmon et al. (1986) and Gippel et al. (1992)] might be used as the upper limit of what is ecologically useful. Fig. 1 shows measured values of debris volume loading as a function of basin area for streams that have received little or no disturbance. The range of values is quite large, and it is a challenge for ecological research to define the lower limit of the volume of debris required to maintain ecological functioning in various environments. Similarly, for regulated rivers, it is important to be able to define the upper limit of debris volume that can remain, or be placed, in the channel without compromising the hydraulic efficiency required for conveying flows for irrigation or for mitigating flood risk. In spite of the wealth of scientific and engineering literature available on river hydraulics, guidelines for debris management still rely on a degree of intuitive judgement, and these guidelines lack advice on techniques for conducting a

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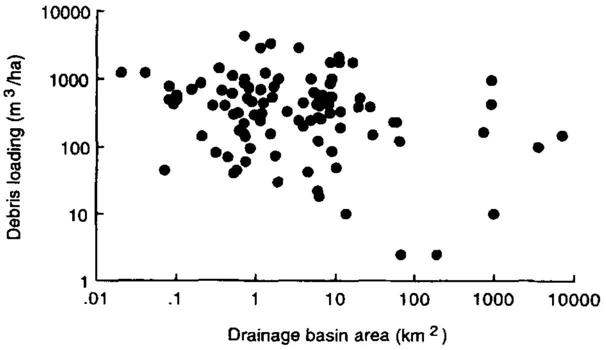

FIG. 1. Measured Values of Debris Volume Loading as Function of Basin Area for Streams that Received Little or No Disturbance [from Gippel et al. (1992)]

reliable quantitative analysis of the hydraulic aspects of the works.

This paper is a review of the literature concerned with the hydraulic and hydrologic significance of debris in streams and rivers. The paper does not include a detailed review of the biologic, geomorphic, and water-quality roles of debris in streams; instead, it integrates relevant knowledge on these aspects with information on the hydraulic and hydrologic significance of debris. Reviews of the environmental significance of debris can be found in the aforementioned literature, particularly in Harmon et al. (1986). The purpose of this paper is to provide information to assist in the prudent management of debris, and also to identify deficiencies in knowledge that warrant research.

EFFECT OF DEBRIS ON FLOW RESISTANCE

One approach to the quantification of the hydraulic effect of debris is to use a flow resistance equation, whereby it is assumed that the resistance debris offers to flow is expressed by a roughness coefficient, or friction factor. The hydraulic resistance of debris varies as a function of the flow depth. Beven et al. (1979) found that when debris is large in relation to flow depth, the roughness coefficient is abnormally high (Manning's $n > 1$), even compared with values of supposed extreme roughness [quoted by Leutheusser and Chisholm (1973), Wakhlu (1974), Hicks and Mason (1991)]. As the flow depth increases, debris on the channel bed becomes structurally submerged and its significance as a roughness element reduces. On an upland stream reach containing a debris dam, Gregory et al. (1985) measured a reduction in n from 1.02 to 0.31 as flow increased, and an even lower value was anticipated near the banktop flow level. Beven et al. (1979), Lisle (1986), and Shields and Smith (1992) measured a large decrease in the Darcy-Weisbach friction factor as discharge increased. Shields and Smith (1992), Lisle (1986), and Hecht and Woyshner (1987) observed that the channel roughness of cleared and uncleared reaches converged at high flows. Indirect support for these findings is provided by investigations of downstream hydraulic geometry, which show that roughness generally decreases as channels increase in size (while the size of debris is essentially spatially constant) [e.g., Wolman (1955), Leopold and Miller (1956)]. In contrast, for channels heavily obstructed by trees and debris, Petryk and Bosmajian (1975) found that the density of obstructions remained constant with the flow depth, resulting in an increasing Manning's n value with discharge; Jarrett (1984) noted that, after initially decreasing with an increasing flow stage, n increased when flows reached the dense vegetation growing on the side slopes.

Subcritical flow generally prevails in large lowland rivers, and n values would be expected to lie within the normal range of 0.025–0.15 defined by Chow (1959). The reviews by Shields and Nunnally (1984) and Gippel et al. (1992) suggested that there is no simple relationship between the removal of obstructions and the reduction in Manning's n. The contribution of debris to a channel's roughness depends on many factors including the size and shape of the channel, the stage of the flow, bedforms, bank irregularities, and the degree of meandering (Chow 1959). Petryk and Bosmajian (1975) derived an equation to predict Manning's n as a function of the density of large woody vegetation in the channel bed, hydraulic radius, Manning's n due to boundary roughness, and vegetation drag coefficient. Van Velzen (1992) also considered drag force in a model of the roughness effects of trees on flowing water. Measured resistance was greater than that predicted by the model, probably because of the unrealistic characterization of the vegetation structure (Van Velzen 1992). In stream channels, interference from nearby obstructions (Nagai and Kurata (1971) and the effect of blockage (Shaw 1971) on the drag coefficient need to be considered. The degree of blockage is measured as the ratio of the projected area of the debris and the cross-sectional area of the flow.

Shields and Gippel (1995) developed a method for estimating the effects of debris on flow resistance in rivers on the basis of debris density, channel geometry, mean flow velocity, and blockage-dependent debris drag coefficients. Resistance due to bed material, bars, and bends were also considered. Verification studies found that computed friction factors were within 30% of measured values for lowland straight sand-bed reaches of the Obion River, Tennessee, and within 38% of measured values for reaches of the meandering, gravel-bed Tumut River, N.S.W., Australia. These results are promising, but the procedure does not account for local flow contraction and expansion and makes use of uncertain, empirically derived coefficients.

Although it is possible to compute roughness coefficients in cases of large-scale debris roughness in which flow is critical and supercritical, they are really "apparent" coefficients. Such conditions give rise to abnormally large flow-resistance coefficients, such as those measured by Beven et al. (1979) and Gregory et al. (1985). The Manning equation is not strictly applicable to this case, since it was developed to describe open-channel situations with fully turbulent flow where friction is controlled by surface drag from the bed sediments, instead of from drag from large obstacles like debris. The Manning equation also attaches significance to the channel hydraulic radius, which may be hydraulically irrelevant if the channel is heavily obstructed by debris. It would be more appropriate to relate flow resistance to indices of relative roughness, which has been done for boulders in mountain streams. The work on boulder-bed streams has found that spacing can be an important factor in determining resistance (Mirajgaoker and Charlu 1963), but other factors may include orientation of long axis with flow direction (Dandekar and Modi 1983), boulder size and shape, and channel geometry (Bathurst 1978). Because smaller roughness elements have a decreasing influence as the flow depth increases, Bathurst (1978) indicated that only those elements that jut through the flow need to be considered. In addition, smaller elements often lie in the wake of larger elements (Dandekar and Modi 1983). Three flow equations tested by Thorne and Zevenbergen (1985) were found to overpredict velocity by about 30%.

Kadlec (1990) concluded that the consideration of drag on single objects is the most appropriate approach to describing water flow in emergent vegetated wetlands, and this may also be true for stream channels heavily obstructed by debris. Gippel et al. (1992) developed such an approach, which used empirically derived data on debris drag coefficients and con-

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sidered the blockage effect. Initial testing of the method on the Tumut River, Australia, found that the estimates of water-surface elevation due to debris were close to measured values (Gippel et al. 1992).

EFFECT OF DEBRIS ON VELOCITY DISTRIBUTION

Hydraulic diversity created and maintained by debris enhances fish species diversity by providing habitat, through a range of flow conditions, for a variety of species and age groups (Sullivan et al. 1987; McMahon and Hartman 1989; Rabeni and Jacobson 1993). Macroinvertebrates also benefit from the structural complexity provided by debris (Minshall 1984). Dead-water zones are important for fish because they provide areas for resting and for refuge during floods (Bisson et al. 1987), and they are the preferred habitat for newly emerged fish (Sullivan et al. 1987). The best feeding sites for fish are low-velocity zones adjacent to higher-velocity flows or eddies, which provide a concentrated source of food (Sullivan et al. 1987). Hydraulic diversity is not generated simply by the flow pattern around the debris per se, but also by the morphological features associated with the presence of debris, such as plunge pools, dammed pools, lateral scour pools, backwater pools, and gravel bars (Keller and Tally 1979; Beschta and Platts 1986; Bisson et al. 1987; Andrus et al. 1988).

Beschta and Platts (1986) provided some schematic diagrams of flow directions around various types of obstruction. Keller and Swanson's (1979) detailed maps of flow direction around debris illustrate the hydraulic diversity it creates. Koehn (1987) observed increased flow diversity in an artificially restored reach of the Ovens River, Victoria, Australia, with the main habitat improvement being a substantial increase in the area of channel flowing at less than 0.2 m/s. Plan view isovel maps in Gore (1985), Sullivan (1986), and Smith et al. (1992) also show the effect of debris in creating a varied pattern of velocity distribution. The plan view distributions of mean velocity in the vertical during storm flow at two of Sullivan's (1986) sites in western Washington are shown in Fig. 2.

Shields and Smith (1992) reported that removal of debris from the Obion River, which is 18–23 m wide and 4–5 m deep, produced more-uniform flow, and less of the channel was occupied by eddies and regions of reduced velocity. Gippel et al. (1992) measured the velocity distribution at three cross sections in the Tumut River, a large lowland Australian river, at banktop flow (approximately 100 m^3/s) before and after debris removal. One of the cross sections is reproduced in Fig. 3. Large zones of virtually dead water occurred immediately downstream of debris, while diverted water flowed at velocities of up to 2 m/s. Removal of debris distributed the flow more evenly across the river, contracted or eliminated the dead-water zone, and reduced the maximum velocity to approximately 1.6 m/s.

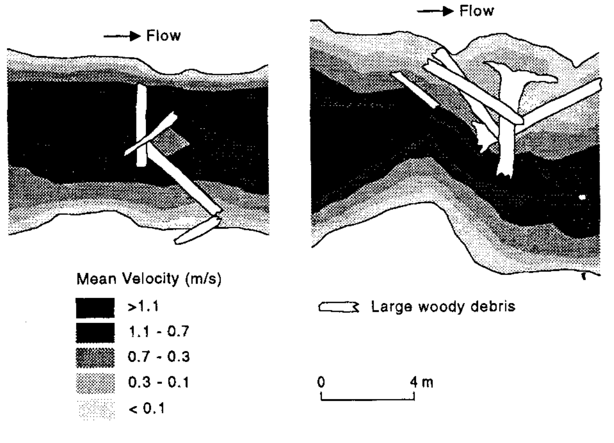

FIG. 2. Plan View Mean Vertical Velocity Distributions at Two Sites on Streams in Western Washington during Stormflow [from Sullivan (1986)]

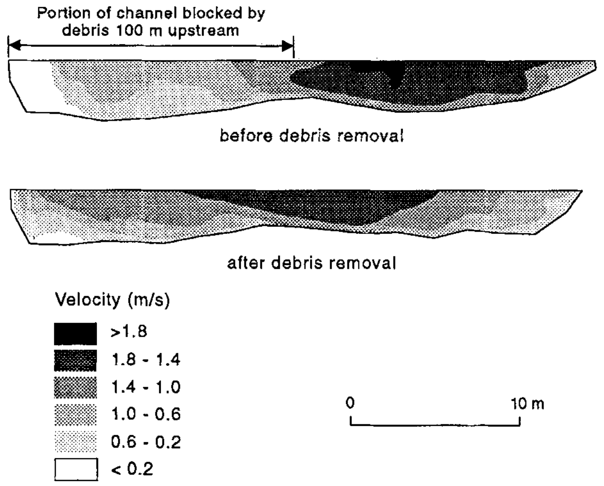

FIG. 3. Cross-Section Velocity Distribution at Site on Tumut River, Australia, at Banktop Flow before and after Debris Removal [from Gippel et al. (1992)]

EFFECT OF DEBRIS ON STREAM HYDROLOGY

Debris is often removed on the assumption that achievement of a significant reduction in channel roughness will allow higher mean flow velocity and thereby increase the channel capacity (Nunnally 1978; Bhowmik 1984; Brookes 1985; Smith and Shields 1990; Shields and Smith 1992). Increased capacity is usually sought for lowering flood frequency, improving drainage of flood waters, or allowing higher flows in regulated rivers. These changes can have adverse ecological impacts. A reduction in the area of low velocity suitable for fish would most likely accompany an increase in mean velocity. Reduced overbank flooding frequency can seriously impact fish species that require seasonal access to floodplain wetlands for spawning and nursery habitat in order to complete their life cycles, and many other species benefit from food washed from the floodplain into the river by floods (Welcomme 1989).

There is some direct and indirect evidence in the literature for higher mean-flow velocity after debris removal. For low flows, MacDonald and Keller (1987) reported a local increase in velocity of up to 250% as a result of the removal of debris accumulation. Shields and Smith (1992) measured the reach mean velocity at low flow (4 m^3/s) in cleared sections of the Obion River, Tennessee, to be 0.38 m/s. In uncleared sections of the same river the mean velocity was 0.25 m/s. At discharges greater than 10 m^3/s, there was no statistical difference in velocity between cleared and uncleared reaches. Mason et al. (1990) also found that the increase in mean velocity from the debris removal in Chicod Creek, North Carolina, depended on flow stage. For example, before debris removal the mean velocity corresponding with a channel cross-sectional area of 1 m^2 was 0.12 m/s. After debris removal, the velocity for this stage increased to 0.46 m/s. Mean velocity increases were less for overbank flows and, for the highest measured floods, removal of debris made no difference to mean flow velocity.

Increased mean flow velocity means that for the same discharge, river stage is reduced. The Murray-Darling Basin Commission (unpublished report) calculated a theoretical reduction in water level of 0.3–0.4 m for a maximum regulated flow on the River Murray, Australia, after the removal of approximately 200 debris formations per kilometer. Later

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analysis of high flow records indicated a reduction of approximately 0.2 m. The flood study of Guillou and Uecker Inc. (*Flood* 1984) predicted local stage reduction of up to 1.0 m for 1–10% exceedance probability floods, following the removal of debris from Spring Creek, Illinois. Nunnally (1978) cited an investigation by the U.S. Geological Survey that indicated a 0.6 m reduction in the height of the 5% exceedance probability flood after partial stream channel clearing. Taylor and Barclay (1985) predicted a reduction in the stage of the 50% exceedance probability flood of 0.05 m by desnagging a heavily congested (debris blockage ratio was 0.16) reach of the Deep Fork River, Oklahoma. For the 20% and 10% exceedance probability floods, they predicted stage reductions of approximately 0.1 m. The effect of debris removal was limited in this case because most flood flow was conveyed by an anabranch that bypassed the blocked original channel. For clearing an upstream reach, which had not been bypassed, the predicted flood stage reductions were only 0.003–0.006 m, but here the debris blockage ratio was only 0.0003 (Taylor and Barclay 1985).

Theoretical flood calculations by Klaassen and van der Zwaard (1973) on the floodplain of the Meuse River, Netherlands, demonstrated that for an overbank flood at a height of 14.4 m, clearing woody vegetation from the floodplain would cause a fall in water level of only 0.075 m. Similarly, on the lower Tisza River, Hungary, Laczay (1992) calculated that partial deforestation of the floodplain would not result in a statistically significant reduction in water-surface elevation for design floods, because flow velocities were generally low on the floodplain (approximately 0.2 m/s), and the smooth tree trunks appeared to have lower-than-expected flow resistance.

A desnagged channel with increased capacity can convey higher discharges within its banks, so it follows that there should also be a statistical reduction in the frequency and duration of overbank flooding. However, many claims to the achievement of this effect lack supportive evidence [e.g., Strom (1962), Shattock (1966), Keller and Hoffman (1977), Graf (1980)]. It is difficult to isolate the hydrological significance of debris removal from channels using historical flow records because of possible concurrent changes in catchment conditions, which also affect hydrological processes. Erskine et al. (1990) found that at Rosedale on the Latrobe River, Victoria, Australia, a decrease in the stage height of banktop flow of 0.5 m coincided with a period of intensive desnagging. Erskine et al. (1990) reasonably concluded that this fall in stage height for a given discharge represented a large fall in the frequency of overbank floods. However, this reduction in flood frequency cannot be attributed solely to reduced roughness (and increased mean velocity) as a result of desnagging, because apparently the channel has also increased in cross-sectional area.

It is possible that by removing debris, the normal downstream attenuation of the flood wave may be reduced, and flood peaks may be higher. Increasing channel capacity may therefore cause increased flooding, particularly downstream of the desnagged reach (Swales 1982; Drummond and Tilleard 1982). The modeling work of Kikkawa et al. (1975) on the Gono River, Japan, predicted a 2–9% increase in peak discharge in areas just downstream of river improvements, although the works did involve substantial modification of the channel cross section. Mason et al. (1990) measured a statistically significant reduction in median-flood duration from 22 hr to 14.2 hr after debris removal on Chicod Creek, North Carolina, and this was associated with an increase in the magnitude of peak discharge.

Gregory et al. (1985) investigated the effect of debris on the travel time of flow peaks in a highland stream in Hampshire, England. Although debris was found to influence travel time significantly at low flows, at high discharges the effect was drowned. For example, along a 4-km channel reach, comparing the situation with and without debris, the difference in travel time at peak flow (1.0 m^3/s) was only 10 min, but at low flow (0.1 m^3/s) it was over 100 min (Gregory et al. 1985). Mason et al. (1990) found that flood peaks in Chicod Creek, prior to debris removal, occurred on an average of 13.7 hr before those in a nearby, similar, control stream. After debris removal in Chicod Creek, the flood peaks arrived on an average of 20.7 hr earlier than in the control stream, but this difference was not statistically significant.

Large debris accumulations have a damming effect, which locally elevates the water-surface profile. Instead of being treated simply as roughness elements, large obstructions can be incorporated in backwater profile computations as geometric elements within the channel (Shields and Nunnally 1984). Hogue (1981) reported that individual blockages on Spring Creek, Illinois, were observed to cause local, but cumulative, increases in the elevation of the water-surface profile of 1.0–1.3 m. On the Tumut River, Australia, Gippel et al. (1992) measured local increases in water-surface elevation at near banktop discharge (approximately 100 m^3/s) of 0.1–0.2 m, because of debris accumulation with blockage ratios of 0.3–0.4. Debris with blockage ratios less than 0.1 did not cause a measurable increase in water-surface elevation. Over a relatively undisturbed 775 m reach of the Thomson River, Victoria, Australia, which had a debris loading of 33 m^3/ha (95 items of debris), Gippel et al. (1992) calculated that the debris caused only a 0.2% (0.01 m) increase in the water-surface elevation at banktop flow. This was a case of relatively small debris (median diameter of 0.45 m) scattered on the bed of a large river (mean width of 48 m and mean depth of 4.2 m), so that the maximum blockage ratio of the debris items was 0.1 and the median value was only 0.004. The largest item of debris accounted for 21% of the estimated total increase in water-surface elevation, and the 10 largest items of debris accounted for 68% of the estimated total increase.

EXPERIMENTAL HYDRAULIC STUDIES

The many confounding influences present in streams and rivers make field-based investigation of the hydraulics of large-scale roughness difficult, and it is not surprising that the problem has also been investigated by controlled laboratory experimentation. Two quite different approaches are apparent in the literature. Many flume experiments have considered numerous, identical roughness elements arranged uniformly across the bed [e.g., Morris (1955)]. This approach reveals the effects of uniformly distributed roughness elements on broad flow patterns, but does not attempt a quantitative explanation of the detailed hydraulic processes. However, this approach could provide information on how to arrange debris in rivers to minimize resistance for a given desirable debris volume. The alternative approach is to focus attention on the hydraulics of a single roughness element [e.g., Ranga Raju et al. (1983)]. The aim is to derive predictive relations between flow conditions and characteristics of the roughness element, and also to quantify the effect of interference from adjacent roughness elements or confinement within channel walls.

Multiple Roughness Elements

Morris (1955) defined three types of flow over roughness elements on the basis of an index of roughness spacing (λ) to roughness height (k). When λ/k is large, isolated-roughness flow occurs, and when λ/k is small, skimming flow occurs.

Wake-interference flow is intermediate between these types of flow, when the roughness elements are sufficiently close that the zones of vortex separation and dissipation associated with each element are not completely developed before the next element is encountered. A stable vortex occupies the groove between roughness elements when λ is less than k. When λ is larger than k a typical flow-separation phenomenon occurs, with a continual succession of vortices growing and washing downstream. By observing flow over Perspex square-sectioned strips in a flume, Knight and Macdonald (1979) quantitatively classified flow patterns on the basis of λ/k. Semismooth turbulent flow occurred at $33 > \lambda/k > 13.9$, when the roughness elements were too widely spaced to significantly influence one another. Quasi-smooth flow occurred at $\lambda/k < 3.47$, when a trapped vortex of effectively dead water sheltered in the lee of each roughness element. The vortex was found to be stable when the ratio of roughness spacing to groove length was 2.5 or less. Nowell and Church (1979) extended Morris' (1955) approach by classifying flow types according to the planform density of roughness elements, expressed as the ratio of total plan area of roughness elements to total plan area of channel. Skimming flow occurred at densities of 0.125–0.083, wake-interference flow occurred at densities of 0.063–0.045, and isolated-roughness flow required a density as low as 0.02.

Experiments by Li and Shen (1973) showed that cylinders act as individual roughness elements when their spacing is greater than 200 times their diameter. Nagai and Kurata (1971) measured a significant reduction in the drag force on a cylinder when another in-line cylinder was placed within 15 diameters. Staggered patterns are the most effective in offering resistance to flow (Li and Shen 1973). Nnaji and Wu (1973) considered the importance of roughness variability and found that the standard deviation of roughness height was superior as a roughness index compared with the roughness density.

Single Roughness Elements

The difference in specific force between sections upstream and downstream from an obstruction must equal the drag force exerted by the obstruction (Henderson 1966). Ranga Raju et al. (1983) used this momentum principle to derive an equation for the afflux (increase in water-surface elevation upstream from obstruction) generated by symmetrically placed vertical cylinders. The afflux was found to be a function of the Froude number, the drag coefficient (C_D) of the cylinder, and the blockage ratio. The drag characteristics of a cylinder (and other geometric objects) in flow of infinite extent (no boundary interference) are well known (Hoerner 1958). Over the range of Reynolds number typical of natural streams, C_D for a long, narrow cylinder is 1–1.2 (Hoerner 1958). The drag coefficient for in-channel vegetation, including trees, was assumed to lie between 1.0 and 3.0 (Li and Shen 1973; Klaassen and van der Zwaard 1973; Petryk and Bosmajian 1975; Van Velzen 1992), but few studies have considered the effect of blockage.

Gippel et al. (1992), building on the preliminary work of Young (1991), determined the drag characteristics of model debris [polyvinyl chloride (PVC) cylinders] in a water tunnel and towing carriage. The experiments demonstrated that rotation of a cylinder from a perpendicular alignment to an angle of 10° to 30° to the flow approximately halves the drag coefficient. For more complex shapes resembling debris, C_D showed less variation with orientation angle. For lowland rivers, which typically have debris rotated by the flow, a C_D value of 0.6 is appropriate (Gippel et al. 1992; Shields and Gippel 1995). As expected from the works of Shaw (1971) and Ramamurthy and Ng (1973), blockage increased C_D, such that the drag coefficient of debris occupying 40% of the channel can be as high as five (Gippel et al. 1992). Of course blockage does not alter the inherent drag coefficient of an object. Instead, it is the apparent drag coefficient, defined with respect to the upstream mean velocity, that increases.

COMMENT AND FUTURE RESEARCH NEEDS

Most studies of debris have been conducted in the Pacific Northwest region of the United States, and a few other studies have been conducted in Australia and the United Kingdom. This limited regional diversity suggests the need for research in more diverse hydrological and ecological environments. There are very few data on the distribution of debris in undisturbed lowland rivers. Such information would provide a useful guide for lowland river restoration schemes. Field measurement of debris is problematic (Gippel et al. 1992), and the biologically useful methods of line-intersect transect (Wallace and Benke 1984) and census (Ward and Aumen 1986) are different from those developed for hydraulic investigations (Taylor and Barclay 1985; Shields and Smith 1992). A challenge for research is the development of a hydraulically and biologically meaningful measurement of debris geometry that can be readily used in the field.

The literature contains ample evidence that debris plays a major role in producing hydraulic diversity and preferred habitats, which suggests that debris could be managed to create desirable hydraulic habitats. However, for many species of aquatic fauna there is little knowledge on how hydraulic zones are utilized, what percentage of the flow should be occupied by various hydraulic zones, and how these zones should be distributed spatially throughout the channel. Research in deep, turbid lowland rivers might require the use of innovative techniques such as hydroacoustics (Kubecka et al. 1992; Gippel et al. 1992) and radio tracking. While for some species of fish the preferred, and tolerable, range of hydraulic conditions for spawning, rearing, resting, and migration are known [e.g., Mosley (1985), Sullivan et al. (1987), Davies (1989)], important stream processes necessary for fish survival, such as channel maintenance and provision of food supplies, may involve hydraulic conditions that lie outside these tolerable ranges. Therefore, the optimization of hydraulic habitats is a difficult procedure, even for well-studied species. Not surprisingly, fish biomass is not necessarily well correlated with the amount of useable habitat as defined by hydraulic variables [e.g., Irvine et al. (1987)]. Bisson et al. (1987) noted that although some studies suggest that with respect to fish population densities "more [debris] is better," there is a need for controlled field experiments to determine if an optimum loading exists. Because hydraulic and geomorphic processes in streams are interrelated, debris-management programs also need to consider the possible impact on bed-material transport, development of bedforms, bank erosion, and channel avulsion (Keller and Swanson 1979; Gurnell and Gregory 1981; Mosley 1981; Triska 1984; Taylor and Barclay 1985).

For regulated rivers in which maximization of flow capacity is a priority, the optimum debris loading will be the minimum required to maintain ecological integrity. A pressing research question is to determine the minimum loading of debris required to sustain viable communities of aquatic fauna, especially for threatened species with high conservation value, residing in flow-modified rivers with strong competition for water resources. Borchardt (1993) demonstrated the value of an experimental approach to this question. An idea that deserves more research attention is the possibility of compensating for losses of flow in regulated rivers by the creation of additional habitat, including the introduction of debris (Swales 1989).

Hydraulic models can be used to help plan debris-management programs. The contribution of debris to total-channel roughness depends on many factors, and it is unlikely that the approach of simply measuring changes in roughness coefficients will realize universal relations between debris type and quantity and hydraulic effect. The Shields and Gippel method (1995), which accounts for bed resistance, bend resistance, debris-form drag, and blockage effects is more appropriate but its application will require careful consideration and quantification of local factors. The complexity of wake interference makes quantification of the drag exerted by multiple debris problematic, but there is scope for further laboratory experimentation and field testing of models. Laboratory studies suggest that low flow resistance can be achieved by a high density of roughness elements, spaced around four times their height and occupying about 10% of the channel area. This type of arrangement produces skimming flow with ecologically favorable dead-velocity zones in the lee of obstructions. However, it would be a difficult practical problem to arrange debris in rivers in such a geometrical fashion, and wake interference will nearly always be present. Theoretically, clumps of closely spaced debris on the bed are more hydraulically efficient, per unit volume of debris, than isolated debris. Hydraulic management attention should be directed at the largest few items of debris, because they are responsible for most of the hydraulic impact.

There is some evidence in the literature that large-scale debris removal can improve conveyance within the channel, and this implies that the frequency and duration of flooding could be reduced in some circumstances. Although the claim of reduced frequency or duration of overbank flooding has often been used to justify debris removal, this effect has never been unequivocally demonstrated in the field. Indeed, it is possible that debris removal could increase flood magnitude. This controversial issue presents a difficult, but worthwhile, research problem.

Until better biological information becomes available, placement of debris in streams and rivers should use the distribution present in undisturbed systems as a reference. The few available data indicate that undisturbed lowland rivers have debris loadings of 10–200 m^3/ha, with most of the debris on the bed, lying close to the banks, and oriented about 20° to 40° to the flow in the downstream direction (Gippel et al. 1992). However, natural debris distributions cover a wide range of sizes, positions, and orientations; this diversity could be ecologically important. Research is also required on how best to secure debris that is artificially introduced to channels.

When more is known about the physical and biological significance of debris in rivers, a detailed cost-benefit analysis on its management should be undertaken. For debris-removal programs, the costs of performing the work and habitat loss would need to be balanced against the benefits of protecting land and infrastructure from erosion and flood damage, increased flow, and improved recreational amenity. It may be that, even accepting a degree of habitat loss, the economic value of some agricultural floodplain land may not be high enough to warrant the expense of protection from natural physical processes associated with large woody debris in streams. Such an analysis could help provide a convincing rationale for the ecological rehabilitation of streams.

River rehabilitation is gaining acceptance in countries with long histories of stream regulation, now burdened by the high cost of maintaining heavily engineered channels and suffering ecologically degraded aquatic environments (Fuchs and Statzner 1990; Wagnenaar-Hart 1992; Osborne et al. 1993). A key part of the strategy is protection, or reestablishment, of native riparian forest and woodland communities (Gore 1985; Bisson et al. 1987; Sedell et al. 1991; Higler 1993; Osborne and Kovacic 1993). This will have several benefits, one being the provision of a natural long-term source area for debris recruitment. Research is required on the natural recruitment rates and residence times of debris in channels, so that the costs and time scales involved in the introduction and maintenance of debris can be assessed.

During the historical period when channels were being cleared of debris, in many places floodplains had been, or were concurrently being, cleared of native vegetation (Petts 1990). Although the original woodland or forest vegetation would have offered high resistance to overbank flows, on cleared argicultural land overbank flows can reach erosive velocities. In places where navigation in not a priority, the return of river channels to a near-pristine state with a high debris loading is an admirable goal, but in most cases it would not be currently feasible to reclaim and reafforest large areas of the adjacent floodplain. A moderate loading of debris does not appear to cause serious loss of channel capacity, but heavily congested channels have high flow resistance and can store large quantities of sediment. Thus, more frequent and higher magnitude floodplain inundation should be expected adjacent to channels with high debris loadings. On cleared floodplains, the chance of channel avulsion would be increased by debris dams. Thus, stream management will continue to involve the maintenance of a channel capacity that is appropriate to the hydraulic condition, and intended use, of the floodplain, adjacent and farther downstream. Future research on the hydraulics and hydrology of debris should consider these channel-floodplain interactions.

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