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LARGE WOODY DEBRIS JAMS, CHANNEL HYDRAULICS AND HABITAT FORMATION IN LARGE RIVERS

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ABSTRACT

Field surveys document the accumulation of large woody debris (LWD) into structurally distinctive jam types in the alluvial channel of the Queets River on the Olympic Peninsula of north west Washington. Calculations, field observations and historical evidence show that these jams can form stable structures controlling local channel hydraulics and providing refugia for riparian forest development over decades and possibly centuries. Distinctive spatial patterns of LWD, pools, bars and forested islands form in association with particular jam types. The deposition of 'key member' logs initiates the formation of stable bar apex and meander jams that alter the local flow hydraulics and thereby the spatial characteristics of scour and deposition leading to pool and bar formation. Historical evidence and the age structure of forest patches documents the temporal development of alluvial topography associated with these jam types. Bar apex jams, for example, are associated with a crescentic pool, an upstream arcuate bar and a downstream central bar that is the focus of forest patch development. Experimental and empirical studies in hydraulic engineering accurately predict channel scour associated with jams. Individual jams can be remarkably stable, providing long-term bank protection that creates local refugia for mature forest patches within a valley floor environment characterized by rapid channel migration and frequent disturbance. Processes controlling the formation, structure and stability of naturally occurring LWD jams are fundamental to the dynamics of forested river ecosystems and provide insights into the design of both habitat restoration structures and ecosystem-based watershed management.

KEY WORDS: large woody debris; debris jams; fluvial geomorphology; forest management

INTRODUCTION

The manner in which large woody debris (LWD) accumulates and influences large alluvial channels is poorly understood, despite its important implications to hydrological, geomorphological and ecological processes in forested watersheds. Forests can contribute prodigious quantities of LWD to a channel network and it exerts a first-order control on channel morphology in small forest channels (e.g. Keller and Swanson, 1979; Lisle, 1986; Sedell *et al.*, 1988; Nakamura and Swanson, 1993). Pool spacing, for example, is strongly correlated with LWD loading in small to moderately sized gravel-bed channels (Montgomery *et al.*, 1995). Historical records reveal that massive accumulations of LWD were a significant channel-altering mechanism in large rivers, directly influencing channel avulsion, lake development and floodplain formation (e.g. Triska, 1984; Lyell, 1990). Jams of LWD sometimes completely filled channels hundreds of metres in width for tens of kilometres. In addition to historical evidence, sedimentological studies recognize an apparent correspondence between LWD deposition and bar formation in larger channels (e.g. Becker and Schirmer, 1977; Nanson, 1981; Green 1982; Hickin, 1984), though it is unclear from such studies whether bar formation triggers LWD deposition or whether the opposite occurs. Aggressive de-snagging efforts for navigation and flood protection during the past two centuries has removed almost all evidence of how LWD jams affected fluvial environments in many regions of the world (e.g. Sedell and Luchessa, 1982; Sedell and Frogatt, 1984; Shields and Nunally, 1984; Triska, 1984; Gippel *et al.*, 1992).

Distinctive structural patterns to LWD accumulations vary systematically through channel networks (e.g. Abbe *et al.*, 1993, Nakamura and Swanson, 1993), even though LWD accumulations in a channel often appear chaotic or even random. This paper discusses the processes governing systematic LWD deposition and accumulation into structurally distinctive 'jams' along the Queets River, Washington.

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Construction of these jams results in distinctive patterns of alluvial channel morphology, which modify the in-stream habitat and influence local riparian forest succession. Jam types referred to as the 'bar apex jam' (BAJ) and 'meander jam' (MJ) provide examples of LWD structures that initiate and accelerate the formation of pools, bars, islands and side-channels that define major in-channel habitat and riparian zones. Field observations and simple models describe the physical characteristics of BAJs and associated channel topography and forest patches. Channel geometry and bed textures provide estimates of the background flow conditions. Models of flow fields and bed scour around a BAJ are compared with field measurements at two BAJs. The persistence of BAJs in the channel and their influence on riparian forest structure is examined and discussed.

STUDY AREA AND METHODS

The 1164 km^2 Queets River basin lies on the west slope of the Olympic Mountains in north-west Washington State (Figure 1). Thirty years of US Geological Survey (USGS) gauging station records at river kilometre (RK) 7·41 define the 1·5 year recurrence flood event as a flow of 1824 m^3/s. Steep glaciated terrain in the headwaters of the basin reaches 2438 m in elevation; heavily forested terrain below 1200 m drains into a broad, low-gradient alluvial valley. The bedrock geology of the basin is characterized by Tertiary marine sandstones and shales that underwent low-grade metamorphism as a fore-arc accretionary prism (Tabor and Cady, 1978; Tabor, 1987). Extensive glacial till records recurrent alpine glaciation in the Queets valley during the Pleistocene (Crandell, 1965). Most of the basin is mantled by temperate rainforest vegetation (e.g. Franklin and Dyrness, 1988, Kirk and Franklin, 1992) associated with extraordinary precipitation averaging about 5 m annually, primarily contributed by rainfall from October to May. Upland forest communities are dominated by sitka spruce (*Picea sitchensis*), Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*). Species commonly associated with floodplain forest communities include red alder (*Alnus rubra*), bigleaf maple (*Acer macrophyllum*) and black cottonwood (*Populus trichocarpa*). In-channel LWD includes each of these tree species, although the individual species abundance primarily depends on the local recruitment population. Potentially recruitable LWD in the Queets River basin includes trees with basal diameters (at breast height) greater than 4 m and lengths in excess of 70 m.

The abundance of large and high quality timber found in the forests of the Olympic Peninsula sustained an intensive resource-based economy over the last century. On touring the region in 1937 and witnessing the

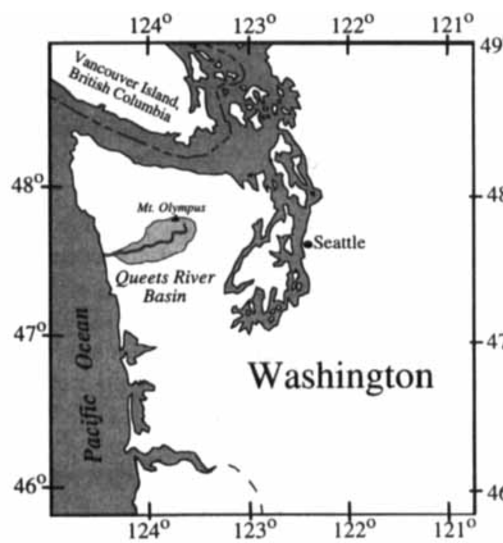


Figure 1. Queets River watershed, Olympic Peninsula

rapidly changing landscape, President Franklin D. Roosevelt resolved to protect a significant portion of the Olympic Peninsula. President Roosevelt signed into law the formation of Olympic National Park in 1938, encompassing the upper 335 km^2 of the Queets River basin, which is now accessible only by foot or pack animal. Of particular interest to river management was Roosevelt's mandate to preserve at least one river valley in its entirety. In 1940 President Roosevelt authorized the federal acquisition of a two mile (3·22 km) wide corridor down the lower 40 km of the Queets River Valley (Morgan, 1955). This unique addition to the park extends to within 11·5 km of the river's confluence with the Pacific Ocean, draining an area of 674 km^2. Field work has been conducted entirely within the park boundaries.

This study was part of a larger investigation in which the mapping of channel reaches representative of different portions of the Queets River documented channel morphology, sediment textures and LWD accumulations. Study reaches extended from low-order ephemeral channels with gradients exceeding 0·25 to large mainstem channels with gradients $<0{\cdot}01$. This paper presents results from pool–riffle reaches (Montgomery and Buffington, 1993) of the mainstem Queets in which the BAJs were observed. Topographic surveys upstream, downstream and proximal to BAJs document associated variations in channel morphology. Surveys were conducted with a tripod-mounted autolevel from July to September 1993 and 1994. Reach surveys recorded floodplain and thalweg elevations, channel and water surface slopes and bankfull widths and depths. Surveys documented both the geometry of obstructed and unobstructed portions of each study reach and pool and bar topography.

A pool survey recording depth and pool type was conducted along a 25 km section of the active Queets River channel between RK 41 to 66 during August 1994. Pools were defined as closed topographic depressions with residual depths (Lisle, 1989) greater than 0·1 m. Pools were divided into those associated with LWD, which were further classified by the LWD jam type, and other pools, which were either free-formed or related to bedrock or boulders. Bed surface grain textures both representative of each study reach and proximal to jams were documented using pebble counts of at least 100 clasts (Wolman, 1954). In-stream flow velocities proximal to a BAJ at RK 59·93 were point-sampled with an electromagnetic velocity probe. Horizontal and vertical velocity components were measured at 0·2, 0·6 and 0·8 of the flow depth. Vertical velocity components were made by attaching a 90° extension to the probe fitting.

Vegetation colonization constrained the minimum age estimates for some jams and provided chronologies of topographic and forest patch development after jam formation. The distribution of BAJs was measured both in the field and form 1 : 12 000 scale colour infra-red aerial photographs shot during field surveys in August 1993. Comparison of 1993 images and 1985 1 : 12 000 scale black and white aerial photographs document jam persistence and illustrate changes in channel planform and forest patch development.

TYPES AND DISTRIBUTION OF WOOD DEBRIS JAMS

The LWD accumulations in large channels display distinctive structural patterns that distinguish jam types formed by different processes (Abbe *et al.*, 1993). The Queets River system exhibits spatial patterns typical of large alluvial rivers in old-growth forest environments: a meandering channel frequently divided by bars and islands, abundant LWD deposition and a complex assemblage of riparian forest patches. These features are illustrated in Figure 2a, a 1985 aerial photograph of the confluence of Tshletshy Creek (flowing north) with the Queets River (flowing north-east to south-west). Examples of three LWD jam types commonly observed along the mainstem Queets River, the bar top jam (BTJ), bar apex jam (BAJ) and meander jam (MJ) are highlighted in Figure 2b. All jams catalogued in the study are recorded by channel name and RK, e.g. the BAJ on the Queets at RK 59·93 is designated as BAJ Q5993. The characteristics of four example study reaches are presented in Table 1.

A random accumulation of logs with little vertical stacking characterize BTJs, which form a loose mat deposited on a bar top during receding flows. Although logs in a BTJ are oriented in all directions relative to the depositing flow, most are oblique. Two of the numerous BTJs visible in Figure 2a are highlighted in Figure 2b. Bar top jams are relatively unstable as they are mobilized at discharges approaching bankfull. Hence they have little appreciable effect on channel morphology.

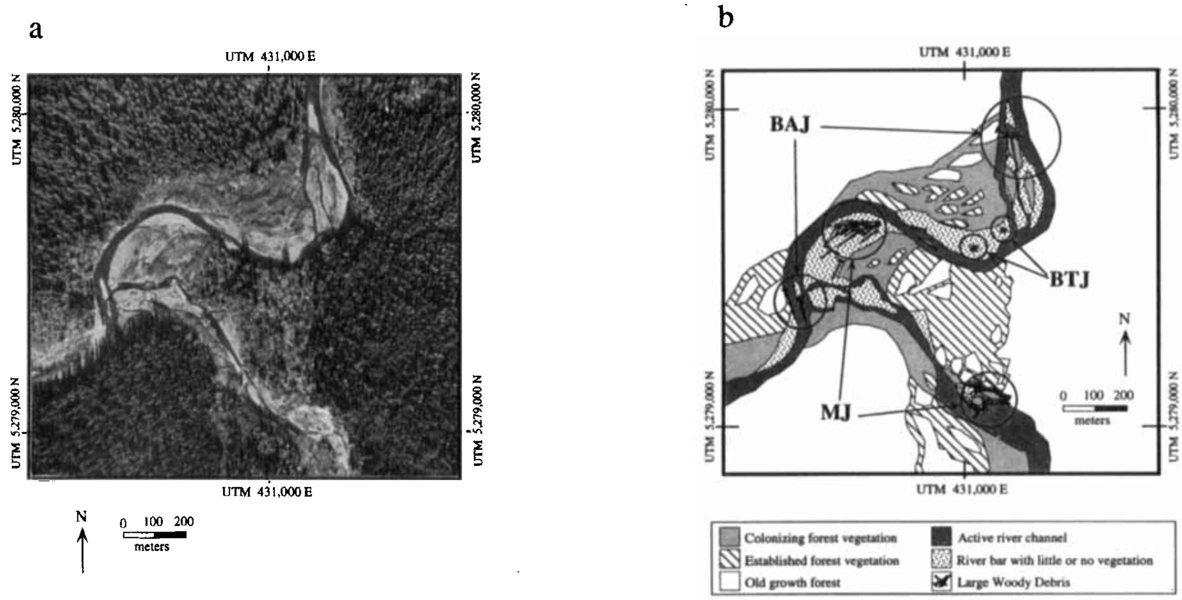


Figure 2. Example of LWD jams in a large alluvial channel, flow is east to west. (a) 7 March 1985 aerial photograph of Queets River Reach km 50·58–km 52·12 and Tshletshy Creek Reach km 0–km 1·12, illustrating complex channel and forest patch patterns of an old-growth river system. (b) Selected examples of three types of LWD jam types observed in the area: unstable bar top james (BTJs); stable bar apex jams (BAJs) and stable meander jams (MJs). General patterns in the forest-patch structure are illustrated.

The more stable BAJ has a distinctive architecture characterized by three primary structural components: a key member nearly parallel to flow, normal members orthogonal to flow and oblique members oriented 10–30° to flow. In the Queets River, the key members appear to be invariably a large log with an attached rootwad facing upstream. The deposition of a key member significantly reduces the effective width of flow within a channel. The LWD that otherwise might be flushed through that portion of the channel is deposited, usually by racking up against the key member and contributing to a further reduction in the effective channel width. Normal members rack up against the key member rootwad orthogonal to flow, whereas oblique members deposit along the flanks of the key member. The sequential deposition of normal and oblique members commonly results in the vertical stacking of five or more interwoven layers. The formation of a jam introduces a local control on channel hydraulics that leads to distinctive changes in channel morphology and riparian forest structure.

Stable LWD structures such as the BAJ provide a barrier to high velocity flows, creating sites of sediment aggradation that can lead to floodplain formation. Stable LWD structures also resist channel migration,

Table I. Channel characteristics of example study reaches

Example study reach	Drainage area (km^2)	Bankfull		Slope (m/m)	D_{50} (m)	D_{84} (m)
		Width (m)	Depth (m)			
T 0·0–1·12*	74·40	30	0·91	0·0112	0·063	0·117
Q 50·58–52·12†	224·72	83	1·42	0·0050	0·022	0·079
Q 59·02–60·31‡	178·97	66	1·29	0·0059	0·047	0·087
Q 65·40–66·49§	154·63	50	1·20	0·0095	0·068	0·161

* Figure 2, Tshletshy Creek at confluence with Queets River.
† Figure 2, Queets River at confluence with Tshletshy Creek.
‡ Figure 7, Queets River RK 59·93.
§ Queets River Pelton Reach.

thereby providing refugia for forest development. Jams buried in the Queets River floodplain are associated with anomalous forest patches significantly older than the stands of floodplain forest surrounding them (Figure 2b). Only two of over 20 BAJs apparent on Figure 2a are identified in Figure 2b. Neither of these jams mobilized during an approximately 20-year flood 23 November 1990. Reaches of the Queets River containing BAJs have slopes, S, ranging from 0·003 to 0·03; widths from 30 to 100 m; and mean bankfull depths, h_b, ranging from approximately 1 to 3 m.

Meander jams become the most common of the stable jams with increasing channel size. Unlike the BAJ, MJs have only two principal structural components: key members and racked members. A MJ has two or more key members that are initially deposited at the upstream head of a point bar and oriented nearly parallel to bankfull flows. Key members usually have rootwads facing upstream and are within approximately one rootwad diameter of one another. Racked members of various sizes accumulate normal to key member rootwads, stacking on top of one another to heights of 6 m or more (several MJs are visible in Figure 2a). As the river migrates laterally, a stable MJ forms a revetment halting local bank erosion, often measurably compressing the river's radius of curvature and changing the orientation of the flow relative to the jam. Meander jams are visible both on the Queets River and Tshletshy Creek in Figure 2a. The MJ identified on the Queets River in Figure 2b was constructed shortly before 1985. Field observations and aerial photographs from 1993 indicate that the Queets channel migrated to the south-west after 1985, except at the MJ, which currently resembles the MJ identified on the north bank of Tshletshy Creek in Figure 2b. These jams eventually armour the concave outer bank of a meander and harbour riparian forest patches proportional in size to the size of the jam.

Alluvial bedforms and riparian forest patches

Field surveys indicate that LWD jams strongly influence the formation of scour pools and bars in large alluvial channels. Our survey of pool depths and probable formative mechanisms along the mainstem Queets channel documents the relative importance of LWD jams for habitat formation in a large alluvial channel. The LWD jams are associated with 70% of all observed pools. Pools associated with jams are on average deeper and exhibit greater variance in depth than free-formed pools (Figure 3). Although these observations illustrate that LWD jams strongly influence pool abundance and morphology in alluvial channels, LWD-associated pools also provide other habitat values (e.g. complex cover and nutrient trapping) not associated with pools formed by other mechanisms.

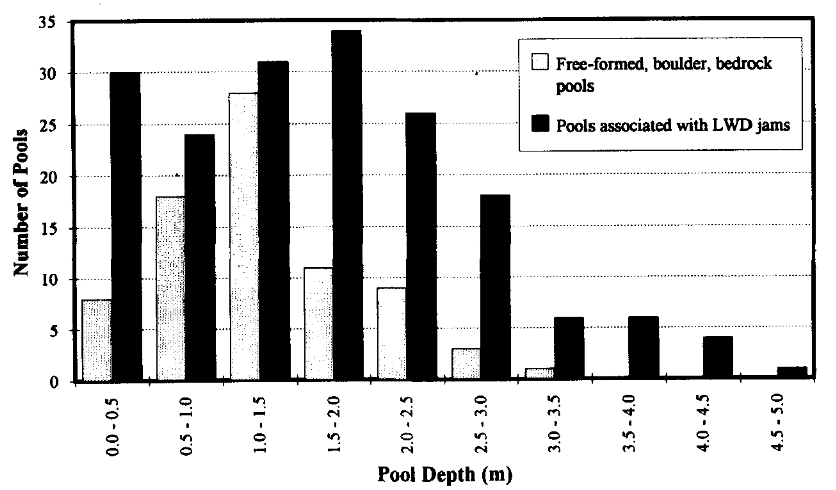
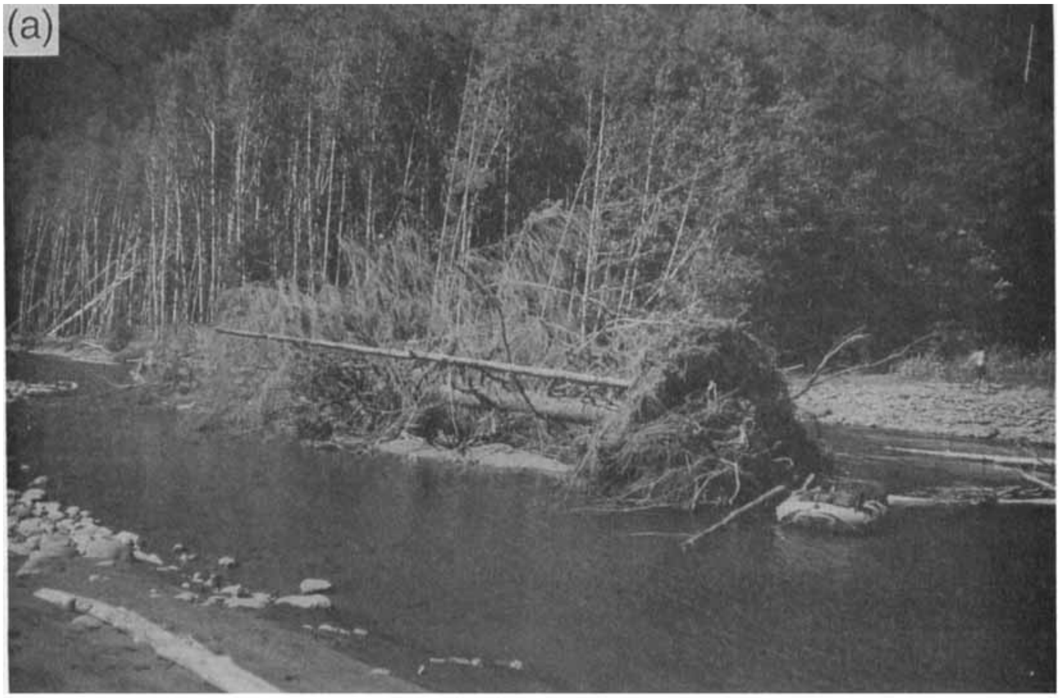


Figure 3. Frequency distribution of the depth of pools associated and not associated with LWD jams between Queets RK 41 and RK 66, surveyed in August 1994



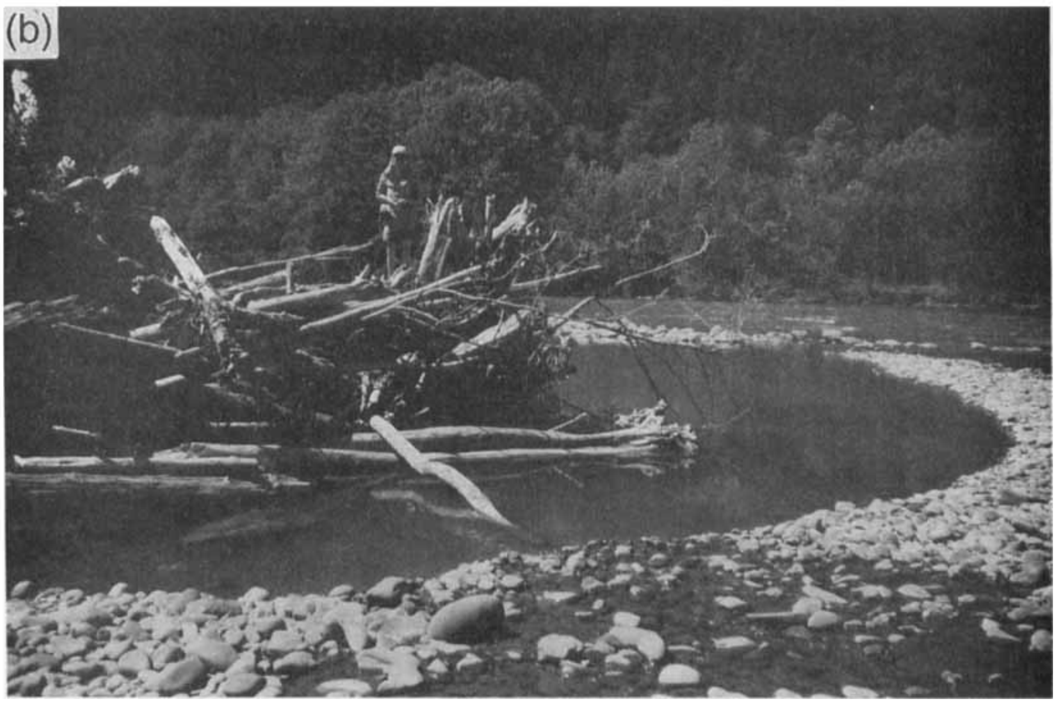


Figure 4. Features associated with BAJs, flow is right to left except in (d). (a) Key member (BAJ Q5993); (b) crescentic pool (BAJ Q5022); (c) arcuate bar (BAJ Q5291); and (d) associated riparian forest patch (BAJ Q6749)

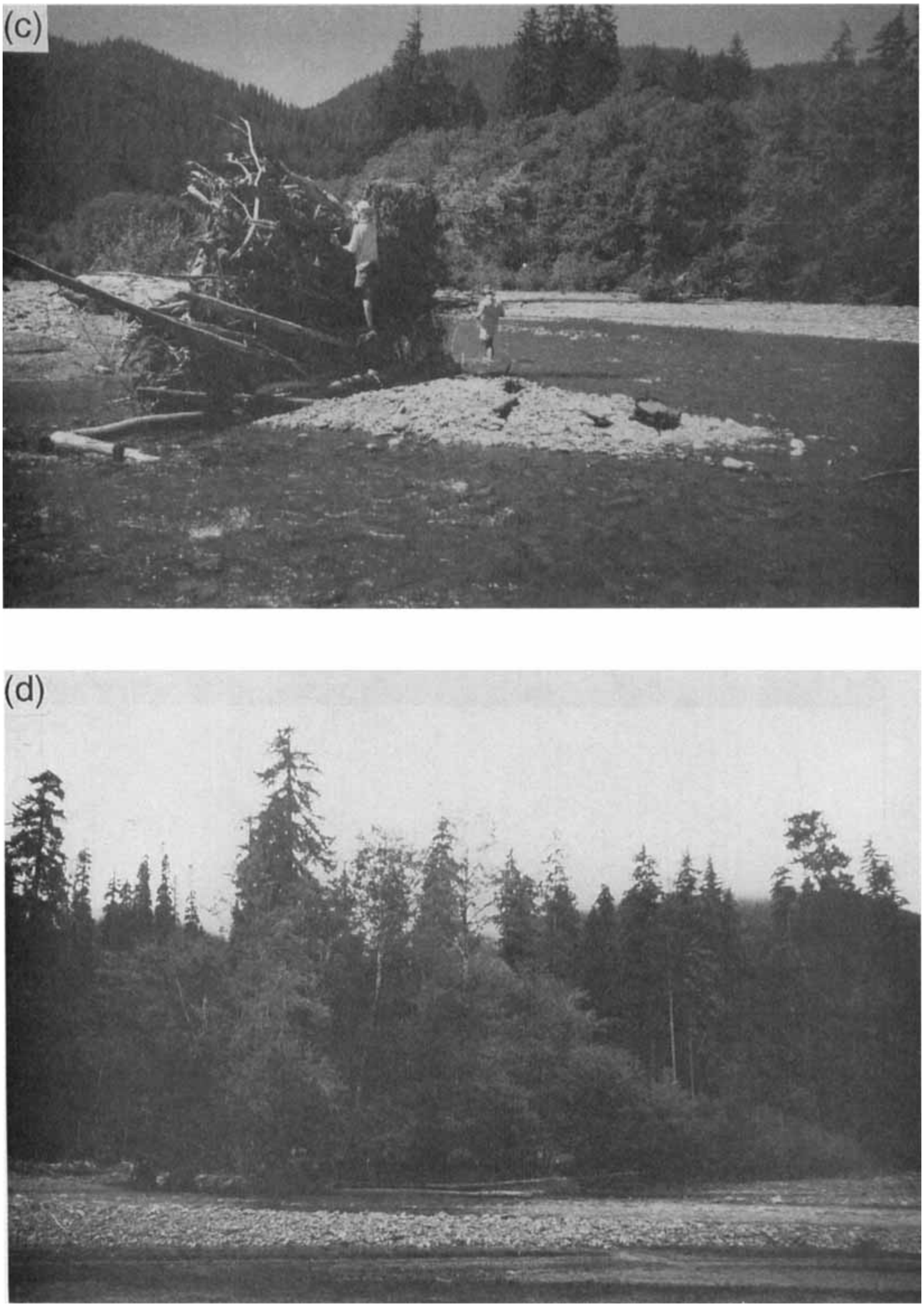


Figure 4(c) & 4(d)

Pool characteristics differ for pools associated with different LWD jam types. The BTJs have little or no influence on pool and bar formation. A BAJ is associated with several alluvial bedforms, each of which appears to form after the deposition of the key member (Figure 4a). A crescentic pool (Figure 4b) forms directly upstream of and adjacent to the jam in an area of vortex development and flow acceleration. A region of flow deceleration upstream of this pool and centred along the axis of the jam results in the deposition of an arcuate bar (Figure 4c). The largest pools associated with LWD jams occur directly upstream of MJs. These pools tend to be long, narrow and curve around the channel side of the MJ. The deepest pools surveyed were also adjacent to MJs.

Distinctive riparian forest patches develop in association with these jam types. Flow separation around the BAJ, for example, results in an elliptical area of low-velocity flow and sediment deposition along the axis of the key member. Progressive downstream colonization of a riparian forest patch occurs on this bar, displaying a distinctive downstream-decreasing profile of tree height (Figure 4d). A composite sketch of the BAJ and the associated alluvial topography and forest patch structure is summarized in Figure 5. The region on the backside of the MJ, anchored by the boles of key members, becomes incorporated into the floodplain and is characterized by spatially coeval tree colonization. Riparian forest patches associated with MJs thus tend to exhibit more uniform age structure and lack the more streamlined patches associated with BAJs. The time over which jams could potentially offer refugia for forest development can be deduced from denchronology, historical data and sedimentological evidence.

Analysis of US Geological Survey maps of the Queets from 1931 and 1985, together with aerial photographs, indicates that large low-gradient alluvial reaches of the Queets actively migrate within the valley floor. Comparison of channel planforms from 1931 and 1985 digitized and referenced to UTM coordinates reveals long-term channel migration rates exceeding 10 m/y. Assuming a simple model of progressive channel migration of 10 m/y across a 1 km floodplain (i.e. ignoring avulsions often associated with

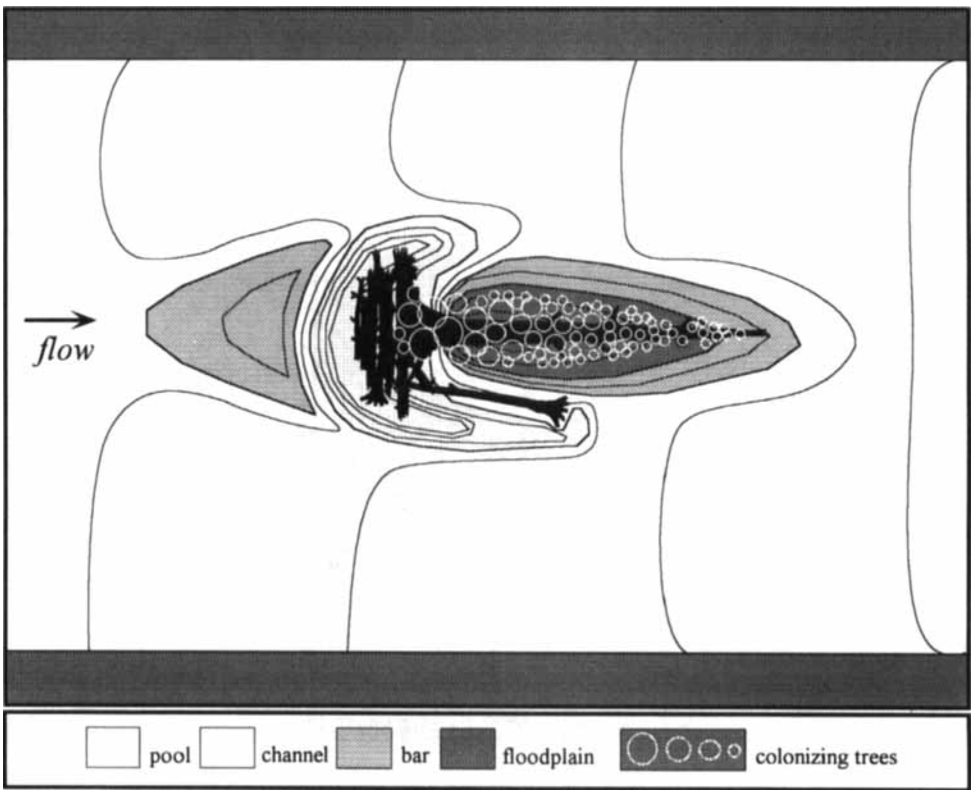


Figure 5. Composite sketch of physical attributes of the BAJ type showing characteristic patterns in channel-bed topography, LWD structure and riparian forest age structure

Table II. Shear stress derivations for Pelton Reach based on bed surface texture

Assumed dimensionless critical shear stress shear stress, τ_c^*	Derivation for estimating critical shear stress at initiation of bedload transport	Computed critical shear stress, τ_c (Pa)	Minimum flow depth† (m)
0·032 (Buffington, 1995)	$\tau_c = \tau_c^*(\rho_s - \rho_w) g D_{50}$	35·0	0·38
0·060 (Pitlick, 1992)	$\tau_c = \tau_c(\rho_s - \rho_w) g D_{50}$	65·6	0·70
0·045 (Komar, 1987)	$\tau_c = \tau_c^*(\rho_s - \rho_w) g D_{50}^{0.6} D_i^{0.4}$	69·5	0·75

† $R = \tau_o/(\rho g S)$, where ρ_w = water density and ρ_s = sediment density.

LWD jams), riparian forest should rarely attain an age over 100 years. Yet anomalous forest patches within the floodplain reach ages in excess of 300 years. Association of these patches with LWD jams indicates that stable LWD jams can provide hydraulic refugia over century time-scales in extremely dynamic forested floodplains.

HYDRAULIC EFFECTS OF DEBRIS JAMS

Analysing the influence of LWD jams on local hydraulics and channel morphology requires modelling jams as simplified flow obstructions. Estimates of channel flow depths and velocities are necessary to determine whether a log is likely to be stable under particular flow conditions. Bed surface textures and topographic surveys allow the back-calculation of channel flow conditions for a range of flows associated with the initiation of active bedload transport.

Grain size distributions on the active channel surface in a section of the study reach lacking other significant roughness elements allow quantitative estimates of the minimum critical shear stress required to initiate motion of the bed material, τ_c, the associated flow depth, h, and the mean channel flow velocity, U. This allows the estimation of the stability and local hydraulic effects of a log through analysis of buoyancy and flow drag. If the channel bed is mobile during bankfull events, then the basal shear stress, τ_o, exceeds τ_c. Estimates of τ_c and τ_o can therefore be used to evaluate a range of possible flow depths and velocities frequently occurring within the study reach.

The bed of most gravel-bed channels mobilizes at near-bankfull flow (see review in Buffington, 1995). The shear stress back-calculated from the size of the bed material depends on a dimensionless shear stress parameter, τ_c^* (Shields, 1936). Pitlick (1992) recommends using $\tau_c^* \approx 0{\cdot}06$ and the median grain size, D_{50}, of the bed surface material to estimate the τ_c necessary to maintain bed material transport on a gravel bed. Buffington (1995) reviewed studies of τ_c^* and concluded that 0·032 provides the most appropriate estimate for τ_c^* in gravel-bed streams with bed material of mixed grain size. Several other studies, however, found that the best estimate of the τ_c necessary to initiate the motion of a gravel bed of mixed grain sizes uses both the D_{50} and the coarsest fraction of the bed surface material (e.g. Parker and Klingeman, 1982; Wiberg and Smith, 1987; Pitlick, 1992). Wiberg and Smith (1987) demonstrate in theory that τ_c increases non-linearly as the bed roughness length, k_s, increases relative to the median grain size. Komar (1987) derived an empirical expression for the transport of a particular size fraction of bed material, d_i, in gravel beds of mixed grain sizes assuming $\tau_c^* = 0{\cdot}045$.

Critical shear stress values derived using these approaches (Table II) allow the estimation of flow depths associated with active bedload transport by assuming $\tau_c = \tau_o = \rho_w g R S$, where $h \approx R$ and $S \approx$ hydraulic gradient. Together with calculated bedform roughness (Nelson and Smith, 1989) values of 0·05–0·10 τ_c for the low-amplitude, long-wave length bar forms in the Pelton reach, this implies significant excess shear stress during bankfull events.

Table III. Estimates of mean horizontal flow velocity for the Pelton Reach

Estimated basal shear stress (Pa)	Shear velocity u^* (m/s)	Mean velocity using law of the wall (m)	Darcy–Weisbach friction factor f	Mean velocity using f (m/s)	Chezy roughness coefficient, C	Mean velocity using C (m/s)
35·0†	0·187	1·41	0·272	1·02	13·59	0·82
65·6‡	0·256	2·32	0·166	1·77	20·11	1·64
69·5†	0·264	2·44	0·158	1·88	20·85	1·76
111·8‡	0·334	2·73	0·110	2·85	25·86	2·76

† Computed critical shear stress, see Table II.
‡ Computed from $\tau_o = \rho_w g R S$, using the bankfull depth.

Background flow velocities are needed to estimate the drag and alterations to the local flow field imposed by a LWD structure. A logarithmic velocity profile as expressed in the Prandtl–von Karman equation (law of the wall) describes velocity profiles in natural channels where the flow depth, h, is much greater than the boundary roughness

$$\frac{u}{u^*} = \frac{1}{\kappa} \ln\left(\frac{z}{z_o}\right) \tag{1}$$

where u is the time-averaged velocity at elevation z above bed, u^* is the shear velocity $[(ghS)^{0 \cdot 5}]$, κ is the von Karman constant ($\approx 0{\cdot}4$) and z_o is the boundary roughness length scale or height above the bed where velocity, u, goes to zero. Assuming the law of the wall adequately describes the velocity profile, integration of Equation (1) over the depth of flow yields the average flow velocity, U

$$U = u^*\left(6{\cdot}00 + 5{\cdot}75 \log \frac{h}{30z_o}\right) \tag{2}$$

where h = flow depth. Nikuradse (1933) demonstrated that $z_o = k_s/30$ in hydraulically rough or high Reynolds number flow, where k_s equals the equivalent sand roughness. Thus the roughness scale measure, either z_o or k_s, becomes the only unknown in solving for U. The Darcy–Weisbach expression provides an additional estimate for the mean flow velocity $[U = (8ghS/f)^{0 \cdot 5}]$, where f = the Darcy–Weisbach friction factor (proxy of roughness scale). Limerinos (1970) found k_s in gravel-bedded rivers to be a function of D_{84}, such that

$$f = \left(1{\cdot}16 + 2{\cdot}03 \log \frac{h}{D_{84}}\right)^{-2} \tag{3}$$

an expression similar to the derivation of Leopold *et al.* (1964). This also yields a Nikuradse's sand roughness, k_s, of $3(D_{84})$, a value corresponding to derivations of $z_o = 0{\cdot}1(D_{84})$ presented by Whiting and Dietrich (1990). This, in turn, allows the calculation of the flow velocity from h and D_{84} (Table III). Flow velocities associated with the initiation of bedload transport also can be derived from Equation (2) using flow depths computed from the three estimated values of τ_c (Table III). Alternatively Ferro and Giordano (1992) also used D_{84} to experimentally derive an expression for the Chezy roughness coefficient, C, in gravel-bed rivers

$$C = g^{0 \cdot 5}\left[7{\cdot}85 \log\left(\frac{h}{D_{84}}\right) + 1{\cdot}41\right] \tag{4}$$

Equation (4) allows the estimation of C for bankfull conditions using estimates of τ_c in the Chezy formula,

$U_b = C(RS)^{0.5}$ (Table III). Estimates of bankfull flow conditions imply that BAJ Q6617 frequently experiences flow velocities of at least 0·8 to 2·9 m/s (Table III).

Buoyancy analyses (Abbe and Montgomery, in preparation) indicate that key members with large rootwads float only at stages well above bankfull and thus the mobility of such logs is principally a function of the drag imposed by the flow. Analytical techniques in open-channel hydraulics for describing flow past bridge piers offer crude analogues to simple LWD models. A model of uniform turbulent flow past a rectangular obstruction attached to a static boundary presents an analogue to flow around a stable rootwad.

Effect of obstructions on flow

Assuming conservation of mass and no energy losses from upstream to downstream of an obstruction, flow will accelerate due to the associated decrease in cross-sectional area. Static pressure increases directly upstream of an obstruction in response to a reduced velocity and dynamic pressure of the approaching fluid mass. In an ideal non-viscous fluid, the energy exchange between dynamic and static pressure upstream of the obstruction occurs downstream and there is no drag. However, the presence of factors such as viscous friction along the boundary, flow separation and a high pressure in front and low pressure behind an obstruction generate a pressure deficit defining a pressure drag force, F_D, empirically described as

$$F_D = \frac{1}{2}\rho_w C_D U_1^2 A_{SW} \tag{5}$$

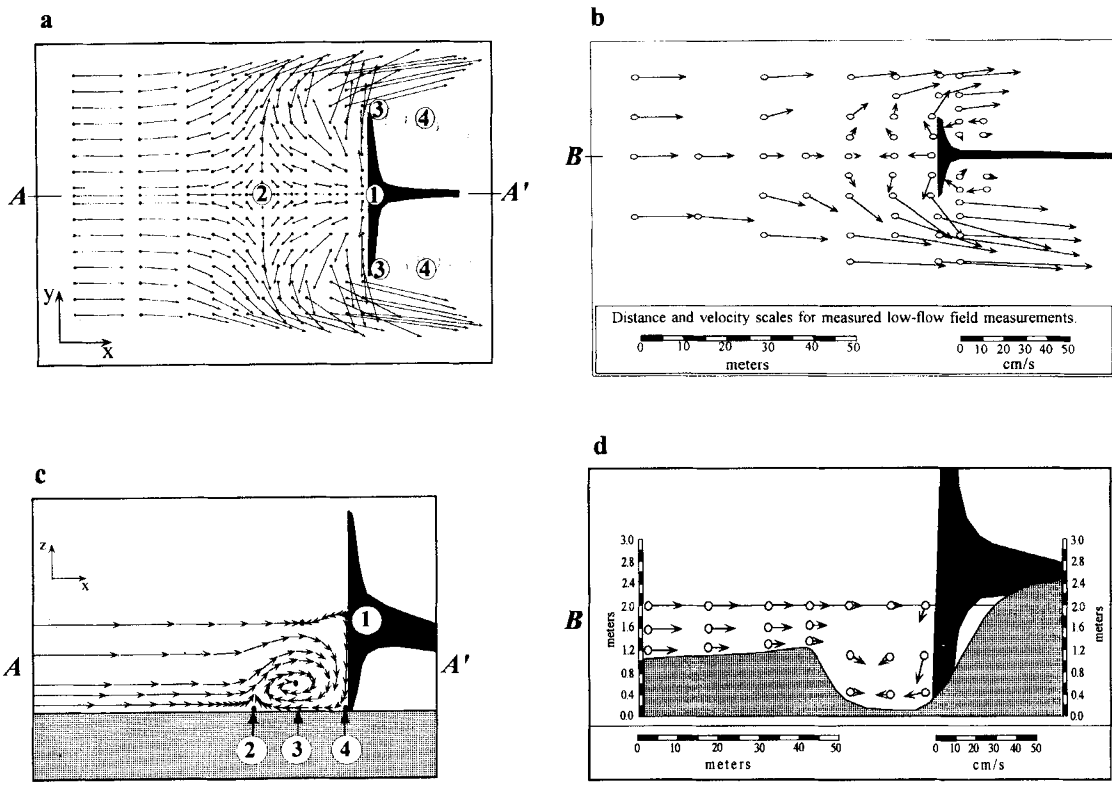


Figure 6. General flow patterns showing relative flow velocity vectors upstream of a BAJ. (a) Plan view of idealized near-bed flow field; point 1 delineates zones of vortex initiation, 2 is the saddle-point where flow goes to zero, 3 is the point of flow separation and 4 is boundary of separation envelope downstream of jam. (b) Plan view of measured near-bed flow velocities at BAJ Q5993 during low flow. (c) Profile of idealized flow field upstream of BAJ, illustrating horizontal and vertical velocity components; point 1 corresponds to the development of a downward acceleration in flow initiating vortex flow, 2 is the saddle point and 3 and 4 delineate the zone of vortex scour. (d) Profile of measured flow field upstream of BAJ Q5993

where A_{SW} is the submerged area of the obstruction normal to the incident flow, U is the mean incident flow velocity and C_D is the drag coefficient of the obstruction.

Mobilization of LWD requires that the drag force must exceed the normal and frictional forces resisting motion. Modelling the rootwad as a solid disc, the key member of BAJQ 6617 would have a submerged area of $4{\cdot}27\,m^2$ normal to flow during bankfull conditions ($h_b = 1{\cdot}2\,m$). Estimating the drag coefficient is less straightforward. Assuming that channel banks impose no boundary effect on the obstruction suggests $C_D \approx 1{\cdot}55$ (Rouse, 1946; Hoerner, 1965). Rootwads, however, are rarely solid, instead consisting of a radial network of roots. Petryk and Bosmajian (1975) recommended setting $C_D = 1{\cdot}0$ for flows through living (standing) vegetation. Boundary conditions influencing flow around the obstruction strongly affect C_D. The magnitude of accelerations around bluff bodies proximal to separation points depends on the blockage ratio, *Br*, defined as the width of the obstruction to the channel width. Ramamurthy and Ng (1973) found that for Reynolds numbers of $10^4 - 10^5$ C_D remains relatively constant when $Br \ll 0{\cdot}10$, but when $Br > 0{\cdot}10$, C_D increases as a function of *Br*. Gippel *et al.* (1992) suggest that the effect on C_D becomes significant with regards to flow conveyance and backwater affects when $Br \gg 0{\cdot}05$. Drag is also affected by the surface boundary of the obstruction itself; the jagged edges of a rootwad, for example, would increase the length scale of the turbulent boundary layer, thereby reducing C_D. Assuming an estimate of $C_D \approx 1{\cdot}55$, the resulting drag force imposed on the key member during a bankfull flow of ≈ 3 m/s is approximately 29·8 kN. For bankfull flow depths the resisting force stabilizing the example key member (Q6617) exceeds 324 kN, an order of magnitude greater than the estimated drag. At the bankfull flow depth of 1·2 m, Equation (5) predicts that the log would become unstable when the flow reached an unrealistic velocity of 42 m/s. Hence, mobilization of this BAJ key member requires flows greatly exceeding the bankfull stage.

INFLUENCE OF DEBRIS JAMS ON CHANNEL MORPHOLOGY

Changes in channel hydraulics due to the presence of stable LWD alter the channel topography and surface textures. A simplified description of LWD jam form, initial channel geometry and particular flow conditions can be used to predict the possible channel response to the jam. Although flow around obstructions in natural channels with deformable boundaries is extremely complex, experimental work provides a range of qualitative and empirical models for predicting channel response around obstructions, especially for bed scour.

Channel topography and bed surface textures provide evidence that LWD jams do affect local hydraulics in ways that appear to reflect the jam structure or type. The development of null points, vortex flow, separation and flow acceleration around a BAJ resembles a conceptual model of flow past a simple obstruction by Raudkivi (1990). Modelling a BAJ as a rectangular plate extending through the water column, we would expect a zone of flow deceleration upstream of the jam, acceleration adjacent to the jam and vortex development due to the translation of predominantly horizontal flow to vertical flow directly upstream of the jam (Figure 5). If a simple rectangular or circular obstruction is introduced orthogonal to a spatially uniform flow, then the flow pattern in the horizontal (x, y) plane (plan view) upstream of the obstruction is assumed to be symmetrical about its central axis. A hypothetical near-bed (x, y) flow field upstream of a BAJ modelled as a simple obstruction on a static bed is presented in Figure 6a. This interpretation was compiled from a conceptual model of vortex flow around a cylindrical pile (Eckerle and Langston, 1986), 3D numerical modelling results of flow upstream of a rectangular obstruction (Lai and Makomaski, 1989), and flow visualization experiments of scour around bridge abutments (Kwan and Melville, 1994). Accumulation of static pressure directly upstream of an obstruction leads to flow reversal near the bed and formation of a 'saddle' or null point at some distance upstream of the obstruction (Figure 6a). For an ideal flow, near-bed horizontal velocity components directly upstream of an obstruction are characterized by two distinct null points (points 1 and 2) and flow reversal. Flow constriction and acceleration occurs adjacent to the obstruction and flow separation occurs downstream (points 3 and 4). Measured flow patterns exhibit similar characteristics around an actual BAJ during low-flow conditions (Figure 6b, photograph of site in Figure 4a). The measured flow field displays a distinct asymmetry mirroring that of the channel; higher flow velocities correspond to the channel thalweg north of BAJ Q5993 and the lower velocities towards the point bar south of the jam.

Null points identified in Figure 6a correspond to areas in which the principal velocity components are transformed from horizontal to vertical, as illustrated along profile A–A′ in Figure 6c. Downward flow acceleration adjacent to the obstruction (between points 1 and 4) and upstream accelerations (between points 4 and 3) are strongly associated with the vortex formation partially responsible for local scour contributing to the formation of the concentric pool upstream of the jam. These flow patterns and resulting scour and deposition are illustrated in profile B–B′ of the measured flow field upstream of BAJ Q5993 (Figure 6d). Flow patterns around BAJ Q5993 illustrated in Figure 6b and 6d are reflected in channel topography and bed surface textures (Figure 7a and 7b). Flow in Figure 7a is right to left and the topography mirrors the asymmetry of flow presented in Figure 6b. Figure 7a also illustrates the formation of the arcuate bar, crescentic pool and downstream bar outlined in Figure 5. In addition to topographic effects, BAJs introduce significant local variations in bed surface textures, most notably coarsening of the bed in the crescentic pool and the

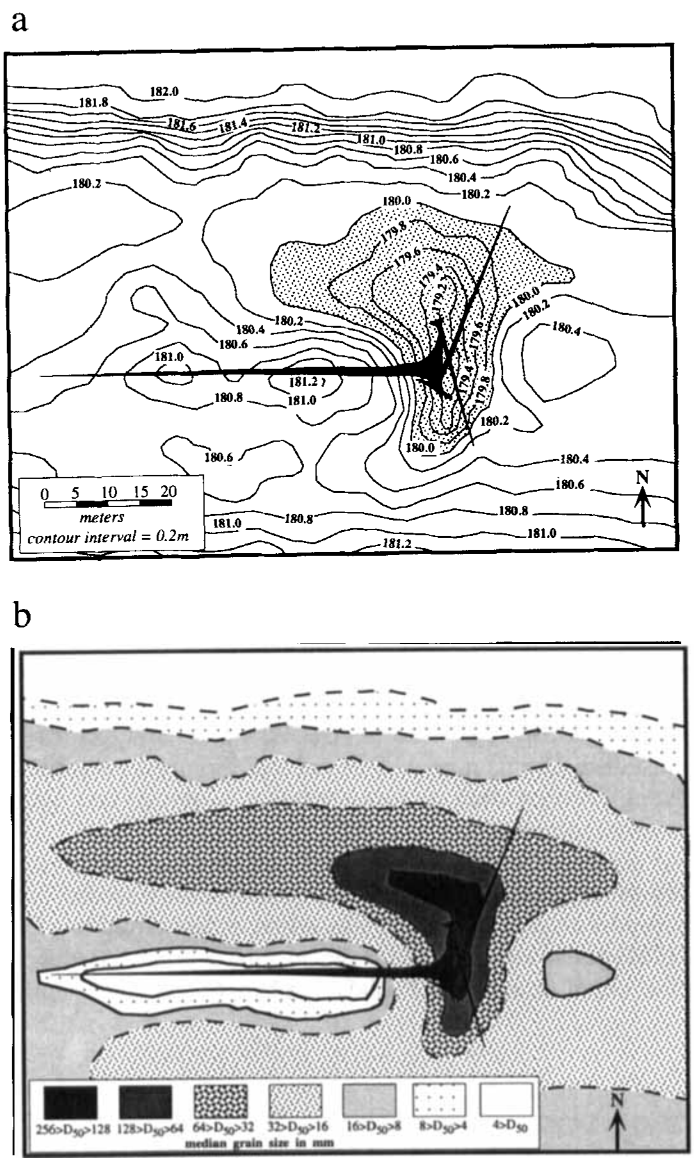


Figure 7. Field survey of BAJ Q5993, flow is right to left. (a) Pool and bar topography, shaded area delineates closed depression defining pool; and (b) median grain size of bed surface

Table IV. Scour predictions for two example BAJs discussed in text

Bed scour predictions	BAJ Q6617	BAJ Q5993
Estimated clean water scour depth, d_{ls} (m) *	4·41	4·18
Estimated constriction scour depth, d_{cs} (m) †	0·62	0·56
Bed grain size standard deviation, $\sigma = (D_{84}/D_{16})^{0.5}$	3·17	3·11
Bed armouring correction factor, k_σ ‡	0·26	0·27
Corrected clean water scour depth (m)	1·15	1·13
Corrected constriction scour depth (m)	0·16	0·15
Total estimated scour depth (m)	1·31	1·28
Observed pool depth (m)	1·35	1·09
Percentage difference	3	17

* Liu *et al.* (1961).
† Laursen (1963).
‡ Raudkivi (1990: 251).

deposition of fines on the downstream bar (Figure 7b). Field observations reveal that sediment deposition forming the downstream bar commonly buries the bole of the key member.

Pool depths

The flow field around a LWD jam not only affects its stability, but also the bedform characteristics around the jam. Pools due to flow scour are commonly associated with channel constrictions or obstructions such as bedrock outcrops, boulders and LWD (e.g. Bisson *et al.*, 1987; Lisle, 1986). Pool frequency is directly correlated with LWD loading in plane bed, pool–riffle and forced pool-riffle channels in Alaska and Washington (Montgomery *et al.*, 1995). Channel obstructions not only introduce constrictions to channel flow, but generate vortex flow which can influence bed scour.

Raudkivi (1990) discusses three general types of bed scour: (i) *general scour* occurs irrespective of an obstruction's presence; (ii) *constriction scour* occurs due to a reduction in channel cross-sectional area; and (iii) *local scour*, which is attributed directly to an obstruction's effect on flow patterns and can be superimposed on either general or constriction scour. Local scour is estimated based on either 'clean water' or 'live bed' active sediment transport conditions. Vortex flow is attributed to the downward acceleration of flow directly upstream of an obstruction (Baker, 1979; Raudkivi, 1990). The envelope of flow separation and re-attachment downstream of an obstruction define the region in which bar formation is probable due to rapid flow deceleration. The point of flow separation is a function of the obstruction's form and surface roughness and the Reynolds number of the flow.The high surface roughness of LWD would tend to reduce the area of separation by increasing the flux of momentum from the outer high-velocity zone into the boundary layer by the transfer of turbulent kinetic energy. This reduces the pressure gradient on either side of the obstruction, thereby reducing pressure drag or forces tending to move the object. It would also reduce the potential scour due to vortex development.

Estimation of bed scour around channel constrictions and obstructions relies primarily on empirical relationships largely based on experimental results from small-scale physical models (Raudkivi, 1990). Models for local scour around an abutment provide a first-order estimate of scour depths around a BAJ structure. Liu *et al.* (1961) derive an equation for dimensionless clean-water scour, (d_{ls}/h), as a function of abutment length, L_A, flow depth, h, and flow Froude number, $Fr = U/(gh)^{0.5}$ using dimensional analysis and laboratory tests

$$\frac{d_{ls}}{h} = 2.15\left[\frac{L_A}{h}\right]^{0.4} Fr^{0.33} \tag{6}$$

Liu *et al.* (1961) and later Tey (1984) found the observed values for maximum scour to be 30% greater than those predicted by Equation (6). Bar apex jam Q6617 in the Pelton reach is about 10 m wide, with scour occurring on either side (e.g. Figure 5). Scour predictions made by modelling the structure as an abutment projecting 5 m into a 25 m wide channel for Q6617 and Q5993 (Figures 4a, 6b, 6d, 7a and 7b) are presented in Table IV. The predicted clean water scour for Q6617 of 4·41 m is significantly greater than the observed pool depth of 1·35 m. This discrepancy may partially reflect bed material characteristics resulting in bed

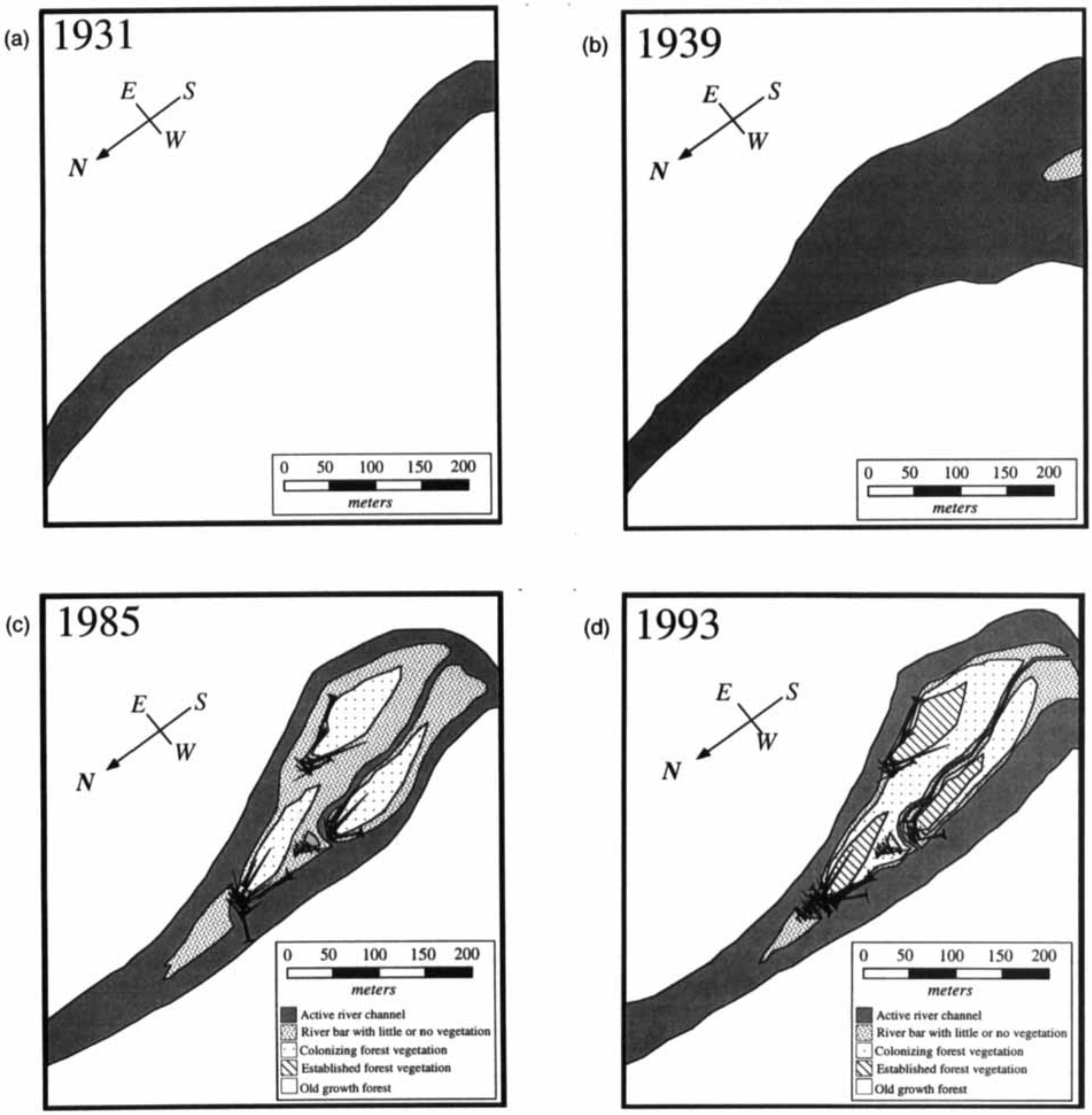


Figure 8. Maps illustrating development of a BAJ and associated alluvial morphology and riparian forest development, Queets RK 51·52–52·3. Flow is from left to right. (a) 1931: active channel boundaries from US Geological Survey plane table map (1 : 32 630, 1·52 m contours). (b) 1939: channel outline from 1 : 62 500 black and white aerial photograph (US Army). (c) 1985: channel, bar and forest boundaries from a 1 : 12 000 black and white aerial photograph shows deposition of several BAJs and colonization of forest vegetation. Based on the present age of trees growing on these BAJs, initial LWD deposition seems to have occurred around 1940. (d) 1993: channel, bar and forest boundaries form a 1 : 12 000 colour infra-red aerial photograph shows that each of the BAJs visible in 1985 are still present and island forest patches have continued to mature

armouring during scour. Raudkivi and Ettema (1977) found that sediment grading is a significant control on the equilibrium clear water scour depth. They found the ratio of d_{ls} in graded sediments to that in uniform sediments to be a function of the geometric standard deviation of the sediment population, $\sigma_g = (D_{84}/D_{16})^{0.5}$. Using the graphical solution presented by Raudkivi (1990: 251) and the Pelton reach $\sigma_g = 4.0$, a correction factor of 0·25 is obtained and the predicted local scour depth is reduced from 4·41 to 1·15 m (Table IV).

Laursen (1963) presented an empirical expression based on experimental results to estimate constriction scour (Raudkivi, 1990: 245)

$$d_{cs} = h\left[\left(\frac{\tau_o}{\tau_c}\right)^{0.429}\left(\frac{w_{b_1}}{w_{b_2}}\right)^{0.857} - 1\right] \tag{7}$$

where h = flow depth, w_{b_1} = unobstructed flow width and w_{b_2} = constricted flow width. The predicted constriction scour depth for Q6617, where $w_{b_1} = 50$ m and $w_{b_2} = 40$ m, is 0·62 m (Table IV). Applying the correction factor of 0·25 due to bed armouring, $d_{cs} = 0.15$ m. Combining constriction scour and local scour from the abutment analysis, the total predicted scour is within 3% of the observed pool depth (Table IV). Similar analysis for the BAJ Q5993 example yields a 17% difference between the predicted and observed scour (Table IV). It therefore seems that in some instances experimentally derived expressions can provide approximate analogues for estimating the size of scour pools associated with natural LWD structures in alluvial channels.

Historical jam stability

Sequential reconstructions based on historical mapping and aerial photographs of the Queets river at RK 52 illustrate the channel characteristics before and after the deposition of several BAJs (Figure 8a–8d). A topographic map of the area completed by a USGS plane-table crew in 1931 shows a single-thread channel (Figure 8a). The reach widened by 1939, developing a bar at the downstream end of the field of view (Figure 8b). A reduction in channel depth probably accompanied this widening, increasing the potential for the deposition of key members. Development of the first bar in the reach may reflect the deposition of a BAJ key member, but cannot be confirmed from the image resolution. Aerial photographs from 1985 and 1993 (Figure 8c and 8d) had the resolution to distinguish general forest cover characteristics not possible from the 1931 map or 1939 photographs. Some time between 1939 and 1985, several key members were deposited in the upstream end of the reach (Figure 8c), well above the initial bar visible in 1939. The BAJ furthest upstream exhibits the distinctive upstream arcuate bar and downstream central island in the process of being colonized by riparian forest vegetation. The same site eight years later in 1993 (Figure 8d) records riparian forest structural development on streamlined islands in the lee of BAJs. By 1993 the islands associated with separate BAJs in 1985 (Figure 8c) coalesced into one large island with a small interior back channel (Figure 8d). Gauge-discharge data for the lower Queets at RK 7·4 indicate that between water years 1985 and 1992 the site was subject to numerous flows above bankfull, including an approximately 20 year flood. Hence the key members forming these BAJs remained stable through several large flow events.

DISCUSSION

The development of BAJs provides a dramatic illustration of the morphological influence of LWD jams in large rivers. The process of BAJ development involves the initial deposition of a key member after hydraulic transport. The deposition of a key member alters the local flow patterns, initiating bar growth and potentially island formation. Changes in channel morphometry due to BAJs can be synthesized into four morphological stages (Figure 9). Stage I consists of the initial recruitment of a key member and the basic flow disturbance it introduces (Figure 9a). Stage II involves the modification of the alluvial landscape into a distinctive set of

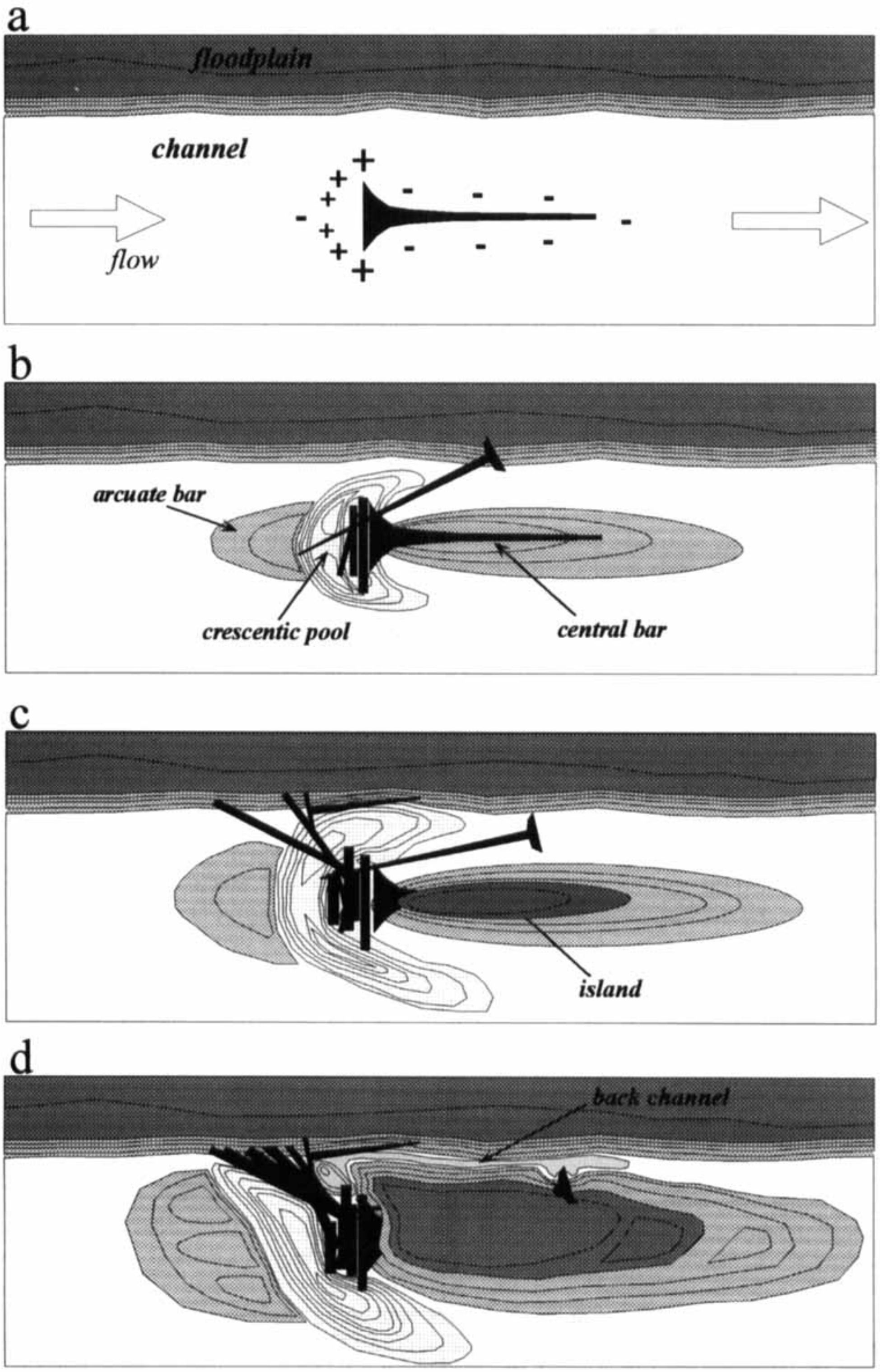


Figure 9. Morphological stages in alluvial topography associated with construction of a BAJ (key to geomorphological surfaces identical to Figure 5). (a) Deposition of the key member; (b) formation of an upstream arcuate bar, a crescentic pool upstream and adjacent to the key member rootwad and/or normal members and a downstream central bar along the axis of the key member bole; (c) island development along central bar; and (d) eventual integration into the floodplain development

bars and pools (Figure 9b). Aggradation on the central bar can eventually lead to island development when the sediment surface reaches or exceeds the bankfull elevation, stage III (Figure 9c). Additional recruitment of racked LWD and/or channel migration unrelated to the original BAJ can close off one of the channels. Subsequent deposition in the abandoned channel can re-attach the island to the floodplain, represented in stage IV (Figure 9d). The entire BAJ site can thus be incorporated into the floodplain, environment; such cases appear to result in anomalous forest patches within more recent riparian forests that colonized the abandoned channels.

Channel habitat structure

Alteration of in-channel flows due to the formation of a BAJ results in three important geomorphological features directly affecting the quality of aquatic and terrestrial riparian habitat: pools, bars and islands. The deepest pools in a 25 km section of the Queets River are associated with LWD jams. Pools are an integral physical component for the life stages of many aquatic organisms, such as providing refugia and rearing habitat to anadromous fish. The rate at which jams and their associated bars grow is likely to be a function of the size and rate of LWD recruitment to the channel upstream of the BAJ and sediment transport through the reach.

Tarzwell (1934) recognized that natural in-channel LWD structures enhance fish habitat and presented designs for constructing hydraulic control structures to restore habitat where natural structures had been eliminated. Despite such early work, natural LWD structures in the Pacific Northwest were aggressively removed from the 1950s to 1980s to 'improve' fish habitat (Sedell *et al.*, 1984). Recognition of the ecological importance of LWD as an in-channel element during the last few decades led many to advocate re-introducing LWD to channels and leaving riparian buffers to provide future LWD recruitment (e.g. Harmon *et al.*, 1986; Gregory and Davis, 1992; National Research Council, 1992). Recognition and modelling of natural LWD structures provide a guide for the design of effective channel restoration schemes.

Riparian forest development and management

Riparian forests along large alluvial channels have generally been characterized as relatively young and homogenous tree communities that reflect frequent disturbance (e.g. Fonda, 1974). Swanson and Lienkaemper (1980), however, noted the presence of isolated forest patches over 250 years in age on relatively low floodplain surfaces dominated by trees only several decades old. Observations along the Queets River (e.g. Figure 2a) show a diverse riparian forest structure and anomalous old-growth patches that attain ages in excess of 300 years within the riparian corridor. Three primary factors facilitate riparian forest colonization downstream of the BAJ: (i) local flow deceleration and decreased basal shear stresses; (ii) sediment deposition; and (iii) an abundant accumulation of organic matter on the surface. The formation of natural LWD structures creates distinctive alluvial topography that can persist for at least as long as the structure remains stable. Observation of old-growth riparian forest patches within the zone of active channel migration suggests that some LWD structures remain stable despite repeated integration into the active channel. The potential for excellent preservation of LWD in fluvial gravels (e.g. Becker and Schmirer, 1977) indicates that a jam buried in floodplain sediments could continue to function as a hydraulic structure even after being re-exposed. Hence these structures may provide long-term refugia for floodplain riparian communities, forming anomalous old-growth riparian forest patches in an alluvial terrain characterized by frequent disturbance.

Our surveys reveal that LWD structures are a principal mechanism for the formation of deep pools and islands in large channels in forested environments. In particular, the formation of BAJs and the associated habitats depends on the recruitment of key members from among the largest trees in channel-margin forests. Moreover, it is the largest trees in a population that are most likely to topple and retain their rootwad instead of snapping above the ground (Putz *et al.*, 1983). Thus if land managers desire the preservation of physical habitat features associated with old-growth riparian systems, management activities must ensure adequate recruitment of the largest LWD from channel-margin forests. Hence selective removal of the largest trees from riparian and floodplain forests will have major impacts on in-channel habitat characteristics.

CONCLUSIONS

Although much is known about the influence of LWD on small channels, substantial effort is necessary to understand the processes influencing the remaining large pristine forest channels of the world. Evidence from the Queets River Watershed of northwest Washington, together with historical studies, documents that distinct types of LWD jams are an integral structural element in large alluvial channels in forested environments. In particular, LWD jams are a principal mechanism controlling reach-level habitat diversity through the formation of scour pools, bars and riparian forest refugia. Jams can act as local hydraulic controls over several decades and possibly centuries. The initiation and development of BAJs illustrates the importance of recruiting the largest components of LWD from channel-margin forests for the formation of aquatic and riparian habitat in large alluvial rivers. The large size of the individual trees necessary to initiate the formation of stable jams has important implications for riparian forest management.

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