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Patterns and processes of wood debris accumulation in the Queets river basin, Washington

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Abstract

Field surveys in the 724-km^2 Queets river basin on the west slope of the Olympic Mountains in NW Washington reveal basin-wide patterns of distinctive wood debris (WD) accumulations that arise from different mechanisms of WD recruitment, hydraulic geometry, and physical characteristics of WD. Individual pieces of WD in an accumulation or jam can be separated into key, racked, and loose members. Ten types of WD accumulations are identified based on the mode of recruitment and the orientation of key, racked, and loose debris relative to the channel axis. Although some types of WD accumulation have few geomorphic effects, others form stable in-stream structures that influence alluvial morphology at both subreach- and reach-length scales ranging from less than 1 to greater than 10 channel widths. In the Queets river, stable accumulations of WD directly influence channel anabranching, planform geometry, flood plain topography, and establishment of long-term riparian refugia for old-growth forest development. The classification of wood debris accumulations in the Queets river basin is based on physical observations that offer a template potentially applicable to other forested mountain regions.

Keywords: Wood debris; Queets river; Log jams

1. Introduction

Wood debris (WD) is a significant component of the matter contributed to stream channels in forested landscapes around the world and observations that wood debris influenced the morphology and dynamics of streams and rivers were common during exploration and settlement of North America (e.g., Lyell, 1830; Shoecraft, 1875; Russell, 1909). Scientific studies of wood debris in fluvial systems have progressed rapidly during the last several decades as it has become increasingly apparent that WD is an important ecological and physical component of channels draining forested landscapes. Patterns and forms of in-stream WD accumulations depend on the physical characteristics of individual pieces of wood and of the channel system, as the characteristics and effects of WD accumulations change, both as a function of channel size and with debris size relative to

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channel dimensions (Zimmerman et al., 1967; Keller and Swanson, 1979; Seno et al., 1984; Swanson and Lienkaemper, 1984; Harmon et al., 1986; Bilby and Ward, 1989). Descriptions of WD accumulations commonly refer to the presence of large "key logs" anchoring debris jams (Gillespie, 1881; Russell, 1909; Keller and Tally, 1979; Nakamura and Swanson, 1993), and the orientation of individual tree boles and jams has been noted to change from relatively random positions in small channels to arrangements parallel to flow in larger channels (Triska and Cromack, 1979; Bisson et al., 1987). Yet few studies have investigated whether physically distinct types of WD accumulations occur within channel networks (Church, 1992; Piégay, 1993; Abbe and Montgomery, 1996; Wallerstein et al., 1997; Gurnell et al., 2001). Here we address the question of whether wood debris accumulates in distinct patterns within a mountain channel network. We approached the problem from a geological perspective analogous to an investigation into bedform development associated with the accumulation of sand and gravel. Based on extensive field surveys and historical sources we identify and describe distinctive WD jam types, factors influencing jam formation and stability, patterns in the distribution of jam types, and some associated geomorphic effects found throughout a channel network of a forested mountain drainage basin.

2. Study area

The Queets river watershed on the Olympic Peninsula of Washington was selected for the study because it has a relatively large channel network with a wide range in the size and shape of riparian trees, a relatively constant climate through the Holocene, and a relatively pristine forest only locally affected by human activities. Olympic National Park, on the west slope of the Olympic Peninsula in NW Washington, preserves one of the largest continuous tracts of undisturbed montane forest in the continental United States. The Queets river flows from Mount Olympus (2430 m) ∼ 86 km to the Pacific Ocean (Fig. 1). The Queets river near its confluence with the Pacific Ocean has an average annual flow of 121 m^3/s and a drainage area of 1163 km^2. The 397-km^2 Clearwater river watershed and the Queets river below its confluence (11 km from the Pacific) were not included as part of this study because these areas have been logged. The Queets river watershed upstream of the confluence with the Clearwater river is 754 km^2 ; most of this lies within Olympic National Park (ONP) where native forest cover has been protected. Based on differences in current and past land management, the study area was separated into the upper and lower Queets at the river's confluence with Sam's river 37 km from the Pacific. The roadless, 414-km^2 upper Queets basin most closely reflects virgin forest conditions, although there was limited forest clearing by homesteaders in the early 1900s in the lower valley downstream of Sam's river (Morgan, 1955).

Although tributaries to the lower Queets are subject to logging, essentially all of the mainstem river valley lies within ONP, and negligible alteration of the channel or riparian forests occurred since 1933. The upper Queets is a rare example of a large, unmanaged, and relatively low-gradient forested alluvial river valley. The western slope of the Olympic mountains is vegetated by temperate rainforest (Franklin and Dryness, 1988) and has one of the highest rates of biomass production per unit area in North America (Franklin and Waring, 1979; Harmon et al., 1986). The Queets watershed offers a wide size range of channel and tree dimensions, as bankfull channel widths range up to 150 m and trees reach 70 m in height with diameters up to 4 m.

The Olympic Mountains rose through gradual convergence of the Juan de Fuca and North American plates, and the Queets basin consists of highly folded marine sandstones and shales accreted to North America in the late Miocene (Tabor and Cady, 1978). The Pacific Northwest experienced several major glaciations during the Pleistocene period, and at least six alpine glaciations affected the west slope of the Olympics (Thackray, 1996). For the last 17,000 years, forest cover on the west side of the Olympic peninsula has been relatively consistent (Florer, 1972; Heusser, 1972, 1974). The region has a humid maritime climate associated with some of the highest levels of precipitation in North America. Annual precipitation ranges from ∼ 2500 mm at the coast to over 6000 mm near the summit of Mount Olympus, with 80% of the annual precipitation falling between October and

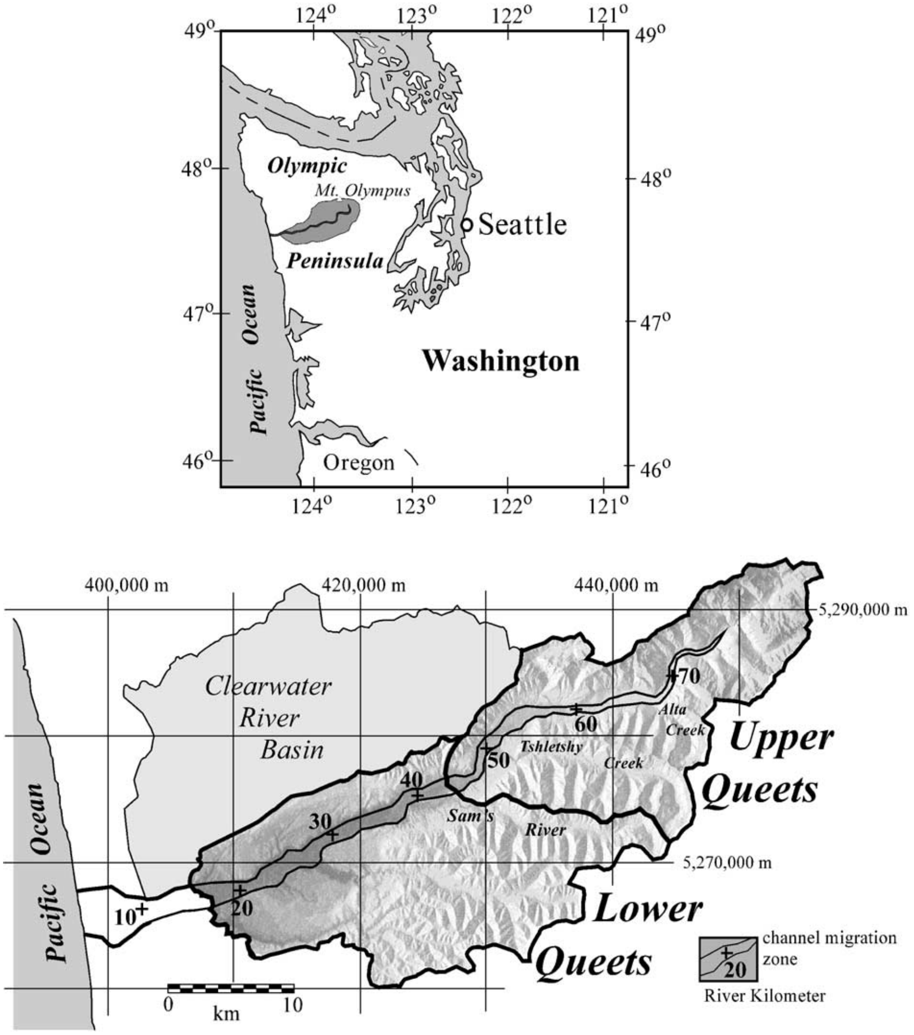

Fig. 1. Shaded relief map of the upper Queets river watershed, Washington.

March (National Oceanic and Atmospheric Administration, 1978).

3. Methods

The general approach of our study was to map WD accumulations in different parts of the Queets river drainage network in order to assess the presence of patterns in WD accumulation relative to channel characteristics (e.g., channel slope, width, and depth). Field observations and literature reviews were used to define different types of WD accumulations and to characterize the processes influencing their formation and geomorphic effects. Interpretation of 1:12,000 color infrared aerial photos taken during low-flow conditions in August 1993, together with field surveys during the summers of 1993–1995, were used to map and measure WD jams in ~ 75 km of the mainstem Queets river and 16 km of tributary channels, whose widths range in size from 2 to over 150 m. Bankfull width, depth and slope were obtained by measuring channel reaches where influence from WD structures was minimal.

During the summer of 1993, patterns of WD accumulations were documented in relation to recruitment processes. Archetypal descriptions of recurring jam types were developed upon recognition of recurring patterns. During three summers of fieldwork (1993–1995), we cataloged the types and sizes of WD jam types and channel characteristics for different portions of the Queets watershed. Channel profiles, cross-sections, and individual pieces of WD were measured at different locations within the channel network. The identification of stable WD was based on interpretation of field observations and historical evidence. For example, a minimum estimate of WD residence time and whether the material had been subjected to a large flood could be made using the age of vegetation growing on top of the WD or the presence of the WD in historical aerial photographs. Pieces of WD that significantly altered flow patterns and channel morphology were assumed to be stable.

Topographic surveys of channel cross-sections, profiles, and flood plain surfaces were made with an optical auto-level and a laser theodolite. Surveyed channel reaches extended from 8 to 20 bankfull widths in length. Bankfull channel widths and depths of the study reaches ranged from 2 to 130 m and 0.3 to 2.2 m, respectively. Reach-averaged channel gradients ranged from 0.001 to 0.26, measured in the field using an autolevel. Geomorphic sketch maps of each study site included the location of WD, bed-material characteristics, bars, and vegetation.

All measured WD was >1 m in length and 0.1 m in diameter. Measurement of WD was done with tapes or laser range-finders and included measuring the rootmass or “rootwad” diameter, the basal diameter of a bole measured 1.4 m from the top side of the rootwad (corresponding to diameter at breast height, dbh), the crown diameter at the end of the bole, the total bole length, and the bole orientation relative to the bankfull channel axis. Measurements of WD dimensions were used to estimate log volume and evaluate the effect of size and shape on WD stability. Individual pieces of debris were classified relative to their inferred function in a jam: *key members* anchor other debris, *racked members* are lodged against a channel obstruction (e.g., boulder, key member, or other debris) and *loose members* fill interstitial space, but add little physical integrity to the jam.

4. Results and interpretations

We start by synthesizing observations of the characteristics of WD accumulations that allow identification of distinct jam types. We then present data on the distribution of these jam types and wood stability in the Queets river system.

4.1. Types of wood debris accumulations

We defined three fundamental categories of WD accumulations, or “jams,” on the basis of whether or not the constituent WD was fluvially transported. In situ or *autochthonous* jams are made of WD that has not moved from the point where it first entered the channel, although it may have rotated, or the channel may have moved. *Transport* or *Allochthonous* jams are made of WD that has moved some distance downstream by fluvial processes. *Combination* jams consist of substantial quantities of both in situ key members and racked and loose members that clearly had been waterborne. Within these three categories, nine basic types of WD accumulation are evident in the Queets basin providing a basis for nomenclature and process-based model representing systematic ways in which jams form and influence alluvial landforms and riparian habitat (Table 1). Additional types of WD accumulations were identified based on observations from managed rivers and from historical observations of other Pacific Northwest rivers. The discriminating characteristics of each of these WD jam types are identified and described in the following sections.

4.1.1. In situ (autochthonous) debris and jams

In situ debris includes those pieces of WD that remain where initially introduced and which subsequently affect flow conditions by influencing flow geometry and roughness. In situ debris generally consists of tree boles with sufficient size and mass to inhibit downstream transport during high flows. In-situ jams may lie partially or completely within the channel. Fallen trees of sufficient size relative to the channel may remain in the place where they entered a channel for many years (Keller and Tally, 1979; Bryant, 1980; Nakamura and Swanson, 1993; Gippel et al., 1996; Hogan et al., 1998). Two distinct varieties of in situ jams (bank input and log steps) were identified based on the orientation, position, and num-

Table 1
Basic wood debris accumulation typology

Types	Distinguishing characteristics
In-situ (autochthonous)	Key member has not moved down channel.
Bank input	Some or all of key member in channel.
Log steps	Key member forming step in channel bed.
Combination	In-situ key members with additional racked WD.
Valley	Jam width exceeds channel width and influences valley bottom.
Flow deflection	Key members may be rotated, jam deflects channel course.
Transport (allochthonous)	Key members moved some distance downstream.
Debris flow/flood	Chaotic WD accumulation, key members uncommon or absent, catastrophically emplaced.
Bench	Key members along channel edge forming bench-like surface.
Bar apex	One or more distinct key members downstream of jam, often associated with development of bar and island.
Meander	Several key members buttressing large accumulation of racked WD upstream. Typically found along outside of meanders.
Raft	Large stable accumulation of WD capable of plugging even large channels and causing significant backwater.
Unstable	Unstable accumulations composed of racked WD upon bar tops or pre-existing banks.

ber of key members forming the jam. Each of these jam types influences channel characteristics in different manners. In situ WD can evolve into several types of combination jams described later.

4.1.1.1. Bank input debris. Bank input debris consists of tree boles that have fallen directly into the channel from their growth locations as a result of bank erosion, windthrow or mass movement. Typically, a small proportion of the volume of bank input debris is situated within the bankfull channel with the remainder lying on banks, adjacent hillslopes or suspended above the channel. In confined channels, this can be due to steep hillslopes adjacent to the channel. Multiple stems, large branches, or a rootwad can elevate a significant portion of the debris mass above the bankfull elevation even though the debris rests on the channel bed, thus promoting stability by reducing buoyant and drag forces. By forming only a partial obstruction to flow, bank input debris typically has only local effects on channel morphology, such as forming small pools and bars immediately adjacent to the debris. Over time, however, the original bank input structure can affect larger portions of the channel cross-sectional area, especially if additional WD accumulates near or on the original piece(s). A channel blockage factor describing the degree of flow obstruction is defined as the ratio of the cross-sectional area of in-stream WD to the channel cross-sectional area. As the blockage coefficient increases, so does the probability of trapping additional WD and sediment, potentially leading to growth of a channel-spanning impoundment or debris dam.

Processes leading to the formation of bank input deposits in the Queets watershed included windthrow, bank erosion, and landslides. Windthrow is an external process independent of channel processes, but bank erosion depends on channel processes that include flows deflected by fallen trees. Windthrow usually results in clusters of trees knocked down parallel to one another and in the direction of the wind gust. Separate windthrow events can result in patches of downed trees with various orientations relative to the channel. As windthrows are not restricted to streamside trees, only some of the affected trees are immediately introduced to the channel, whereas streamside trees recruited through bank erosion usually end up oriented normal to flow because they fall 180° to the direction of principal bank erosion. In either case, once in the channel, the debris can accelerate bank erosion by diverting flows to unobstructed areas that often is toward the base of the recently recruited tree.

4.1.1.2. Log-steps. A log-step forms when a tree bole spans a channel, completely or partially blocking the channel such that water flows over the top. Tree boles that create steps are generally oriented normal to flow, although they can have a wide range of orientations. In tributary streams to the Queets river, channel spanning logs tend to become oriented more parallel to flow with increasing channel gradient. The individual mean diameters of 54 logs which formed channel spanning steps in tributaries less than 10 m in bankfull width ranged from one-half to eight times the bankfull flow depth. Scour pools were observed downstream of all 54 log steps. Accumulations of small detritus and WD (<0.1 m in diameter) were observed to form steps up to 0.3 m in height and 3 m wide (normal to flow) within small aggrading channels, but such accumulations rarely extended across the full width of the channel and are assumed to have negligible geomorphic consequences due to their rapid decay. We found that up to 77% of the low-flow head loss is due to log-steps for channels of the Queets watershed (Table 2), a finding similar to previous reports that log-steps in small channels account for up to 80% of the elevation loss in steep mountain streams (Heede, 1972; Keller and Swanson, 1979; Keller and Tally, 1979; Marston, 1982). Log-steps in moderate- to low-gradient channels tend to occur less frequently than oblique steps found in the steeper channels but can account for a greater proportion of the total elevation drop.

Log-steps can be subdivided based on log orientation relative to the channel axis into two types: oblique and orthogonal. Log orientation, in turn, appears to be influenced by channel gradient. Oblique steps occur most commonly in low-order, steep, semi-confined channels. Log-steps in three study reaches with gradients of 0.40 to 0.69 had orientations of 18–64° from the channel axis. These channels were confined by relatively steep hillslopes, and the majority of log orientations were more parallel than perpendicular to flow. Because WD is more readily transported down steeper hillslopes, the potential source distance for WD recruitment increases with hillslope gradient. In channel reaches with negligible lateral migration, bank input debris and log-step frequency tend to decrease with reduced channel and adjacent hillslope gradients. In unconfined low-gradient channels, the number of steps oriented nearly orthogonal to the channel show a distinct increase and an increased variance in log orientation (29–120°). The higher variance of log-step orientations in low-gradient channels may reflect the diminished influence that adjacent hillslopes have on the direction a tree will fall.

4.1.2. Combination jams

The second basic category of WD accumulations are combination jams that form when deposits of stable in situ debris obstruct a channel and trap waterborne driftwood. The combination of in situ and transported debris can form an effective barrier, deflecting flows around the structure or completely impounding the channel. The presence of significant quantities of transported WD distinguishes combination jams from in situ debris. Combination jams can be subdivided into two types: valley jams and flow-deflection jams.

4.1.2.1. Valley jams. Valley jams are wood accumulations that have widths greater than the bankfull channel, often consisting of fallen trees that extend across a significant portion of the valley bottom. Valley jams form where large trees fall into the channel and constrict much of the channel cross-section. Flow diversion around these obstructions can lead to the recruitment of additional trees and lateral growth of the jam, ultimately creating a structure much larger than the width of the original channel. The key-members in valley jams are typically large boles oriented perpendicular to the channel and inclined less than 30° into the bed. Such jams initiate with either the local recruitment of a single key-member log to the channel or with synchronous inputs of massive debris deposits associated with landsliding or windthrow. Regardless of the recruitment process, one of the distinguishing

Table 2
Log step characteristics in selected channel reaches of the Queets river basin

Channel reach	Reach length (m)	Reach gradient	No. of log steps	Percentage of elevation loss attributed to log steps	Range in log angles (deg)	Mean log angle (deg)
High gradient channels						
1st-Order tributary to Dante Creek	50	0.69	12	27	23–61	41
1st-Order tributary to Queets RK 62.8	60	0.55	17	45	38–71	50
1st-Order tributary to Queets RK 45.9	65	0.33	14	56	37–75	57
Low gradient channels						
Lower Pelton Creek (2nd order stream)	135	0.016	3	68	71–111	93
Lower Bob Creek (3rd order stream)	160	0.015	5	77	79–120	89
Lower Paradise Creek (3rd order stream)	180	0.013	3	74	78–118	87

characteristics of valley jams is autochthonous (i.e., local) recruitment of key members.

Valley jams are stable in-stream structures that obstruct a large portion of the bankfull cross-sectional area, and commonly deflect a substantial portion of the flow. In an alluvial channel, this results in local bed scour, bank erosion, channel widening, as well as recruitment of additional key members. In some instances, additional WD racks up on these key members during high flows, further constricting the channel until it is completely impounded. The valley jam thus forms an effective sediment reservoir that can bury much of the jam-initiating WD. This process further drives channel widening or even avulsion by elevating the riverbed upstream of the jam. Valley jams can form in both confined and unconfined channels, but in our surveys they were limited to channels with gradients between 0.02 and 0.20. Formation of a valley jam depends on the introduction of WD with sufficient size and mass to remain immobile within the channel. These stable key members form the structural foundation of the jam and are therefore a necessary condition for valley jams to form. Bank erosion is the most common mechanism of key-member recruitment for valley jam formation, but landsliding, windfall, and treethrow can contribute key members that initiate valley jams.

In unconfined channels, valley jams form when one or more trees create an obstruction that deflects the channel into adjacent banks. When trees falling into the channel along the eroding bank are large, they extend the width of the jam as they become integrated into the jam structure. Through this process, a jam can expand across the valley floor and grow much wider than the unobstructed bankfull channel width. The progressive age distribution of trees and colonizing seedlings observed on most valley jams indicates a gradual rather than catastrophic formation, such as by a debris flow.

Repeated mapping (1993–1995) of several valley jams in lower Alta Creek illustrate this gradual process of jam growth. Alta Creek has a catchment area of 20 km^2 and enters the Queets about 66 km from the Pacific Ocean. From 1993 to 1995, the channel widened by over 14 m and 16 new key members were recruited to an Alta Creek valley jam (Fig. 2a,b). Widening of a valley jam can proceed for several decades to eventually extend across the entire valley floor. Vertical rates of sedimentation upstream of a structure can be extremely rapid. A large *Thuja plicata* (western red cedar) bole present in Alta Creek surveyed in 1993 initiated a small valley jam, which by 1994 had resulted in up to 4 m of sedimentation and a threefold reduction in channel bed slope (0.062 to 0.019) upstream of the jam (Fig. 2c).

During the lifespan of a valley jam, floods may erode a portion of the structure resulting in local collapse and releasing impounded water and sediment. A dam-break event of this nature occurred during the winter of 1993–1994 at a large valley jam in the east channel of lower Alta Creek, washing out ~ 3.5 ha of 20–30-year-old *Alnus rubra* (red alder) for 230 m downstream of the jam. Yet no perceivable change in the position or condition of the key members was found in the affected valley jam; the failure was limited to racked debris that composed only about 4% of the jam's cross-sectional area. Although headward erosion associated with the failure extended 87 m upstream of the jam, the vast majority of sediment and WD retained by the jam remained in place. Trees growing on surfaces above valley jams buried in fluvial gravel of Alta Creek and the Queets river indicate that these structures can last more than 300 years. A *Pseudotsuga menziesii* (Douglas fir) found growing on a fluvial terrace upstream of a confined valley jam on lower Dante Creek (17 m wide, slope = 0.19) germinated in 1918, indicating that some portion of the valley jam had been present since the early 20th century. Active valley jams were found in mainstem portions of the Queets river with bankfull widths of 50 m and valley widths of 500 m.

4.1.2.2. Flow-deflection jams. In large alluvial channels, the incremental recruitment of streamside trees through bank erosion can result in distinct debris structures that deflect flow nearly orthogonal to the channel axis. Unlike valley jams, flow-deflection jams do not completely span a channel. Flow-deflection jams consist of in situ key members and substantial quantities of racked and loose debris delivered during high flows (Fig. 3).

Flow-deflection jams contribute to channel complexity and local flood plain development in nearly all portions of the Queets channel network except for steep headwater reaches. Formation of a flow-deflection jam typically begins when a key-member tree falls into the channel. Once in the channel, the tree con-

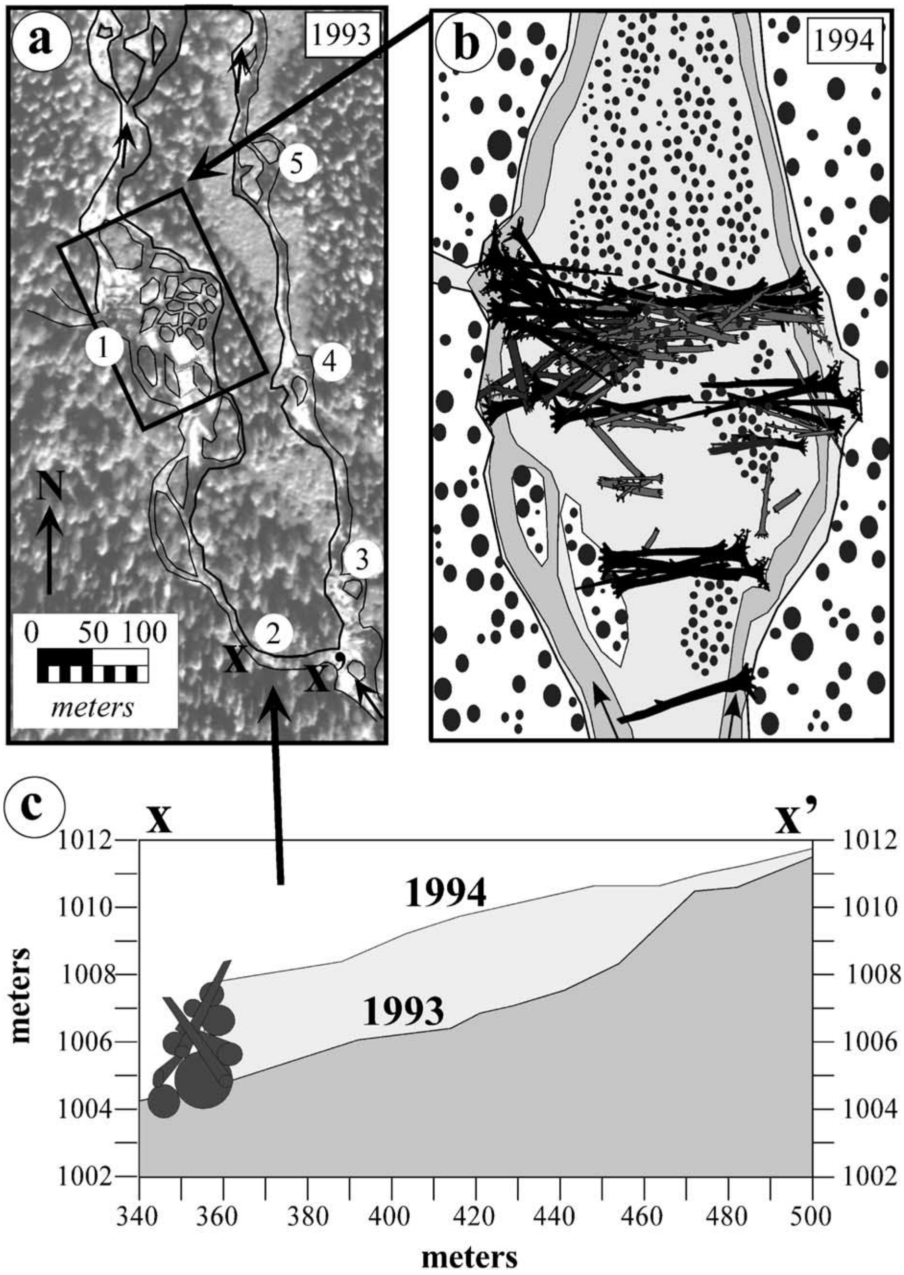

Fig. 2. (a) Location of active valley jams in lower Alta Creek during 1993 and 1994. (b) Schematic planview of the valley jam labeled 1 in (a) illustrating expansion of channel width and development of secondary channels. (c) Channel profile changes from 1993 to 1994 at valley jam 2.

stricts flow around its rootwad and thereby accelerates bank erosion and the recruitment of additional trees, as noted in previous studies (Swanson and Lienkaemper, 1978; Bisson et al., 1987; Nakamura and Swanson, 1993). As this process proceeds, the channel widens; and the jam structure grows by further recruitment of trees from the eroded bank to occupy a larger portion of the bankfull cross-sectional area. Due to their

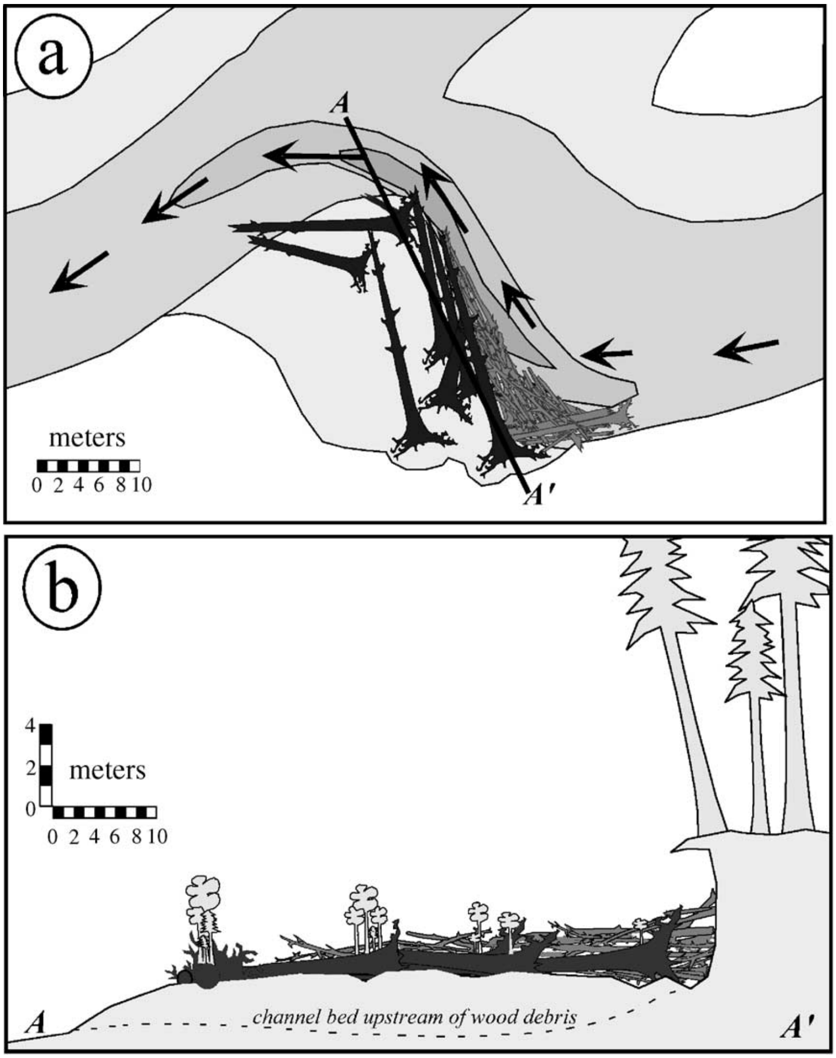

Fig. 3. Flow deflection jam, south bank, Queets river kilometer 70.2: (a) planview map and (b) cross-sectional view looking downstream illustrating jam and age structure of trees colonizing key members.

position in the channel, key members recruited first are subject to the most severe drag during high flows and can rotate downstream to orientations of 20–45°.

The age structure of trees colonizing the key-member boles often records this chronological sequence of jam development and is similar to valley jams except that the flow-deflection jam does not impound the channel. The oldest colonizing trees are found on the key members recruited first and are thus located farthest from the bank (Fig. 3b). Jam development decelerates when a major channel avulsion or cut-off occurs on either side of the jam or when debris racking onto the jam plugs the area between the eroding bank and recently recruited key members. Flow-deflection jams can develop into valley jams if their expansion impounds the channel.

As a flow-deflection jam continues to accumulate debris, it can dramatically alter channel morphology. Large pools form directly upstream of the jam and extend along most or all of the jam's width measured normal to the channel. Slack water or eddies downstream of the jam result in sedimentation and bar development. Much of this sediment can originate from bank erosion associated with key-member recruitment. The area downstream of the jam forms an arcuate wedge in planview that is bounded by the eroding bank on one side and by the jam on its upstream and channel margins. These depositional surfaces tend to resemble flood plain surfaces.

Based on the age of the oldest trees on flow-deflection jams observed in the Queets watershed, flow-deflection jams generally are abandoned after 5–15 years as the active channel migrates away from the jam. The structure may be exposed within a secondary channel or buried and incorporated into the river's flood plain where it remains until re-exposed by channel migration. Because key members are deposited in the channel bed, they lie at relatively low elevations, remain saturated throughout much of the year, and experience extremely low rates of decay. In such situations, a jam can form a hydraulic control and natural revetment for long periods of time, allowing the associated forest patches to mature into large trees that eventually provide a recruitment source for new key members.

4.1.3. Transport (allochthonous) jams

The third basic type of in-stream wood debris is that composed of material that has been fluvially transported. Wood debris can move through a channel as either individual pieces or as congested accumulations (Braudrick et al., 1997). The velocity and mobility of individual pieces of WD depends on their specific gravity, shape, size relative to the depth and width of flow, and channel boundary conditions, as these factors influence the frictional resistance that a piece encounters. Wood debris moving at slower velocities is generally larger, denser, and strongly tapered (i.e., bole with rootwad). This large, slower moving debris obstructs more rapidly moving, smaller WD and can lead to congested accumulations. Debris accumulations are likely to be routed downstream until discharge decreases or the material comes to rest on channel obstructions, on the flood plain, or at the outside of channel bends. When debris accumulations become large enough relative to the channel dimensions, the debris mass will begin to decelerate under its own frictional resistance. At this point, the debris can begin to reduce the flood-wave celerity; thereby causing water upstream of the accumulation to rise, and the flood hydrograph to take on a step-like form atypical of most floods (Costa and Schuster, 1988). Elevated water levels can result in buoyant forces sufficient to dislodge the jam and will continue transporting it downstream.

Observations in the field (Abbe and Montgomery, 1996) and in laboratory flumes (Braudrick et al., 1997) have found that WD transport is greatest along the flow-line of maximum depth and velocity and that deposition is favored at points where this flow-line is obstructed. WD deposits typically occur where this streamline splits upstream of obstructions and bars, where flow depth decreases, or on the outside of bends. Although transport jams usually form the dominant WD structure in the mainstem channel of a large alluvial river, in situ and combination jams can occur in smaller side channels within the same reach. Stable jams that initially formed in the main stem channel are often incorporated into the flood plain and thus, reflect previous positions of the river. Jams that were stable in the mainstem channel will be stable in any secondary flood plain channel, whereas jams that form in a flood plain channel may not remain intact when the mainstem channel reoccupies the site. Transport jams can be divided into distinct types of stable jams: debris flow/flood, bench, bar apex, meander, and log rafts; and three types of unstable accumulations: bar top, bank edge, and bank revetment.

4.1.3.1. Debris-flow/flood jams. Debris-flow jams result from episodic deposition of WD entrained in debris flows initiated by shallow landsliding (Swanson and Lienkaemper, 1978; Swanston, 1991). No studies specifically address the structural characteristics of WD deposited by a debris flow, but several studies describe general characteristics (Swanson and Lienkaemper, 1978; Keller and Swanson, 1979; Johnson, 1991; Swanston, 1991; Coho and Burges, 1994). Ishikawa (1989) presented the most detailed description of WD accumulations associated with debris flows. These descriptions are summarized here because no debris-flow jams were found in the surveyed channels of the Queets watershed. Little doubt exists that debris flows occur within the steep channels of the Queets drainage network, but apparently they are either infrequent and/or do not travel far downstream. Perhaps the abundant, stable WD structures within steep, low-order channels of the Queets watershed retard the downstream propagation of debris flows in the manner described by Swanson and Lienkaemper (1978, p. 6).

Debris-flow jams can grossly resemble valley jams because they commonly span the channel and retain large volumes of sediment upstream. In contrast to valley jams, however, debris-flow jams generally lack key members and have a chaotic assemblage of WD with many different horizontal and vertical orientations. Whereas few of the tree boles that form the key members of a valley jam tend to be oriented such that the bole axis forms an angle >45° with the horizontal, near-vertical orientations of boles and bole fragments are common in debris-flow jams. Debris-flow jams can be very large structures, measuring several meters in height and over a 100 m in length (Swanson and Lienkaemper, 1978; Keller and Swanson, 1979; Swanston, 1991).

Large quantities of WD mobilized during high flows can become congested and form "flood" jams. Such jams initiate under two distinct mechanisms: the gradual hydrograph rise typical of most flood waves or the sharp step-like hydrograph characteristic of dam-break floods. Descriptions of deposits associated with debris flows and dam-break floods are almost entirely from regions that have been logged; the characteristics of these processes and deposits are poorly documented in old-growth forests (Swanson and Lienkaemper, 1978; Coho and Burges, 1994). Our interpretation of factors influencing the formation and attributes of flood jams is based on one structure deposited during the winter of 1994–1995 in Alta Creek, as this jam was the only one found that could be confidently associated with a dam-break flood in the 74 km of surveyed channels of the Queets basin.

When WD in transit during a flood enters a channel bend, angular acceleration and momentum of the flow and debris can drive the WD into adjacent forest stands. Riparian vegetation of sufficient size can form a barrier where debris is deposited and flood waters are dispersed over the flood plain. The flood jam observed along Alta Creek was deposited at the end of a 65-m swath cut through a young stand of *A. rubra* where it encountered a pre-existing valley jam with large conifers (dbh>0.5 m) growing above it (Fig. 4). Observations of similar flood jams associated with dam breaks (Coho and Burges, 1994) suggest that these jams commonly run into adjacent forests where the debris becomes deposited against standing trees. Like debris-flow jams, flood jams have a distinctive "snout" composed of two distinct WD populations differentiated by bole orientation relative to the direction of flow

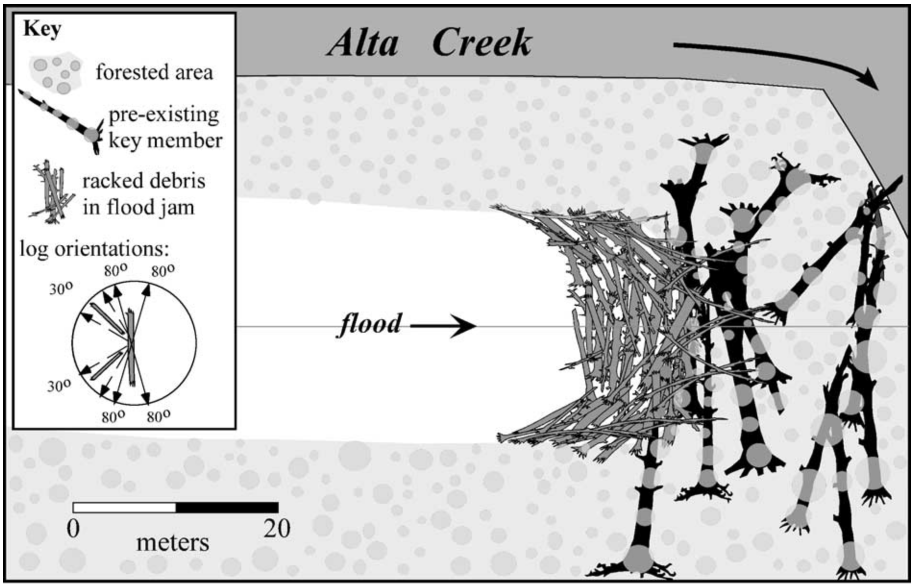

Fig. 4. Planview map of flood jam adjacent to Alta Creek.

when deposited: orthogonal WD is deposited about the centerline of flow and is flanked by deposits of oblique WD.

Flood jams can form channel-spanning structures that remain intact after the flood recedes (Johnson, 1991; Coho and Burges, 1994). The flood jam surveyed in Alta Creek was composed of relatively small debris characterized by stem fragments and small trees with no attached rootwads. Because flood jams are likely to be composed of relatively small debris and lack key members, they are susceptible to catastrophic failure.

4.1.3.2. Bench jams. Bench jams form the dominant WD structure in the steep tributaries of the Queets river and occur most frequently in headwater channels with gradients of 0.06–0.20. Log structures in these accumulations consist of one or more key members oriented oblique or parallel to flow and wedged into irregularities or obstructions in the margins of the channel, such as bedrock outcrops or boulders (Fig. 5). A substantial portion of the cross-sectional area of the channel is left unobstructed because the jams form along the margins of the channel. Deposition of key members creates a structural barrier or natural revetment resulting in low shear stress areas along the channel margin. These hydraulically sheltered areas accumulate fine sediments and WD, leading to development of flood plain-like benches. Smaller WD racks up on the key members, and loose pieces collect on the bench surface. Bench jams were observed in channels with gradients up to 20%, substantially extending the upstream limits of flood plain landforms in the tributaries we examined. In all of the moderately to highly confined study reaches (S>0.06), development of forested flood plains was restricted to locations on bench jams and active or relic valley jams.

4.1.3.3. Bar-apex jams. These distinctive structures typically occur at the upstream end of mid-channel bars and forested islands and play an integral role in the formation of the associated bars and islands. Bar-apex jams can initiate formation of a bar in the thalweg of a channel or accelerate the development of a preexisting bar. Although most of the WD in a bar-apex jam is only visible at the upstream head of the bar, the structure may consist of one or more key members that extend through much of the bar's length. Bar-apex jams can form the principal boundary roughness in a reach, and these jams can also dominate the morphol-

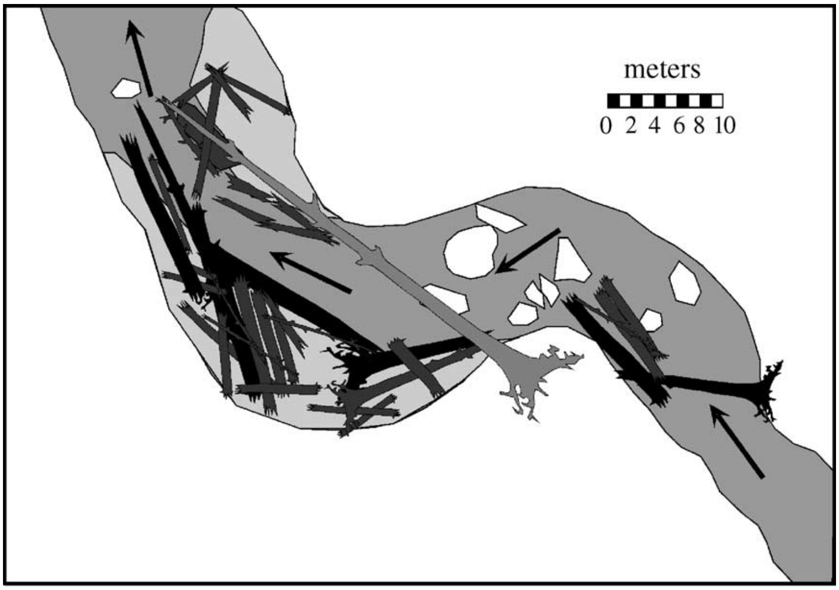

Fig. 5. Bankfull bench jam, Kokopelli Creek, 2nd-order tributary to Harlow Creek: planview map illustrating log orientations (various shades of gray with lightest gray representing log suspended over channel), alluvium trapped by logs (light gray shading), and boulders and bedrock valley walls (white).

ogy and pattern of aquatic and riparian habitat in large channels (Abbe and Montgomery, 1996).

Bar-apex jams consist of three distinct structural members. The jam initiates when a key member deposits in the channel thalweg, on a mid-channel bar, or on the toe of a point bar. This key member is always parallel to flow and usually has an attached rootwad facing upstream (Fig. 6a). The second structural component of the jam consists of racked members that are deposited against the key-member root wad and oriented with their bole axes normal to flow. Wood debris extending into the unobstructed portion of the flow will likely experience considerable torque that will either break or rotate the tree bole. The third structural components are oblique members, debris that has rotated and deposited along the flanks of the key member. These structural components can be distinguished by their orientation. The form of the resulting jam can be likened to an upstream-pointing arrowhead. A more complete description of these jams and their evolution is presented by Abbe and Montgomery (1996).

Three distinct alluvial features are formed by bar-apex jams: flow divergence and deceleration upstream of the jam resulting in deposition of an arcuate bar; flow convergence and acceleration into the bed, vortex flow, and lateral acceleration of flow around the upstream margins of the jam creating a deep crescent-shaped pool; and deceleration within the flow-separation envelope in the lee of the racked members creating a central bar composed of relatively fine sediments along the bole of the key member. In wide pool-riffle reaches of the mainstem Queets river, bar-apex jams are a principal factor in pool formation, accounting for the majority of pools and the largest range of pool depths (Abbe and Montgomery, 1996).

Although vegetation can rapidly obscure WD accumulations, the age structure of riparian forest patches can sometimes be used to recognize bar-apex jams. Vegetation colonization corresponds to the deposition

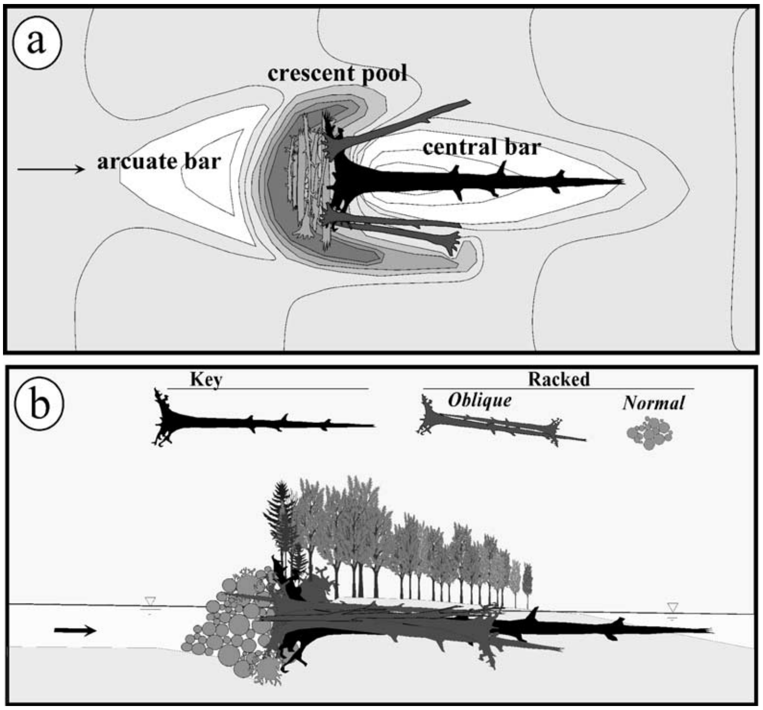

Fig. 6. (a) Planview illustration of basic structure of bar apex jams. Alluvial morphology associated with bar apex jams includes an upstream arcuate bar, a crescent pool adjacent to the jam, and a central bar downstream (Abbe and Montgomery, 1996). (b) Profile illustrating tree colonization along the axis of a bar apex jam commonly exhibiting a distinctive age sequence decreasing downstream from the key-member rootwad.

of substrate sufficiently elevated above the bed (i.e., approaching bankfull or flood plain elevations) and protected from frequent disturbance. Thus, trees initially colonize the protected and elevated areas immediately on and around the basal portion of the key member. Colonization proceeds downstream along the key-member bole as deposition of sediment and WD progressively enlarges the central bar. The resulting age structure of the associated forest patch progressively decreases downstream and normal to the bole axis of the key member (Fig. 6b).

Bar-apex jams are the most common stable jam type and the principal mechanism of island formation within pool-riffle reaches with gradients of less than 3% in the mainstem Queets river: they are associated with 72% of the forested islands surrounded by channels >24 m in width. Within this same 52.6-km section of the Queets river, 98% of the bar-apex jams associated with islands in 1985 remained in the same place in 1993. Island development increases the stability of a bar-apex jam by adding root cohesion and the additional mass of overlying trees to the structure.

4.1.3.4. Meander jams. A variety of WD accumulations occur along the outer margins of meander bends in large alluvial channels. Many of these accumulations are simply unstable debris deposited in shallow portions of a channel, but some are stable structures. Meander jams form a distinct type of stable structure that, unlike flow-deflection jams, are composed of debris that underwent downstream transport (Fig. 7). The name "meander jam" was selected because these structures are commonly found along the outer, downstream bank of channel bends or meanders, although the jams do not necessarily form at bends. Meander jams establish local hard points within alluvial valleys that limit channel migration and influence meander curvature.

Meander jams can initiate in several different parts of an alluvial channel, but once formed these jams deflect flow and define subsequent channel development which can make it difficult to determine the initial conditions at a particular site without detailed geomorphic and historical analysis. Field observations and sequential aerial photographs were used to assemble a conceptual model of meander-jam development. Initial deposition of two or more adjacent key members parallel to flow introduces a local flow deflection that can allow the jam to accumulate additional debris and significantly alter planform development. Early in meander-jam development, flow between the key members adds additional sediment and debris to the jam. Sediment accumulates along the key-member boles and initiates bar formation. Debris accumulates against key-member rootwads; and this racked debris progressively restricts the flow area between the key members, diverting the principle streamline toward the opposite bank along the axis of racked debris. Flow obstruction leads to an increase in water surface elevation upstream of the meander jam, allowing debris to be deposited at higher elevations and increasing the size, mass, and stability of the jam. The resulting hydraulic gradient redirects the principal streamline along the upstream plane of the jam and can also lead to overbank flow across the adjacent flood plain and possibly channel avulsion (Miller, 1995). After a jam has initiated, it remains stable, but the channel can continue to migrate. The outer margin of the meander is held in place at the jam while continuing to migrate upstream of the jam. The result is a progressive decrease in the channel's radius of curvature and increase in meander amplitude, contributing to additional increases in water surface elevation upstream of the jam. Over time, the channel's radius of curvature progressively decreases as the bend tightens up, resulting in a lower radii of curvature for reaches with meander jams than for unobstructed reaches (Fig. 8).

The width of meander jams along the lower Queets river commonly exceeded 200 m, as measured orthogonal to key-member orientation. Meander-jam widths can exceed the bankfull width of the channel and can obstruct 20% or more of the valley floor and, thus, are likely to influence overbank as well as within channel flows. Even though meander jams form entirely within the bankfull channel, only the upstream margin of the jam (consisting of racked WD and part of a key-member rootwad) will usually remain within the active channel. This sometimes gives the impression that WD is piled up against a pre-existing bank. However, meander jams, like bankfull-bench jams, actually create the bank along channel bends.

Large, deep pools are associated with every active meander jam observed in the Queets river. The pools are located along the upstream and lateral margins of

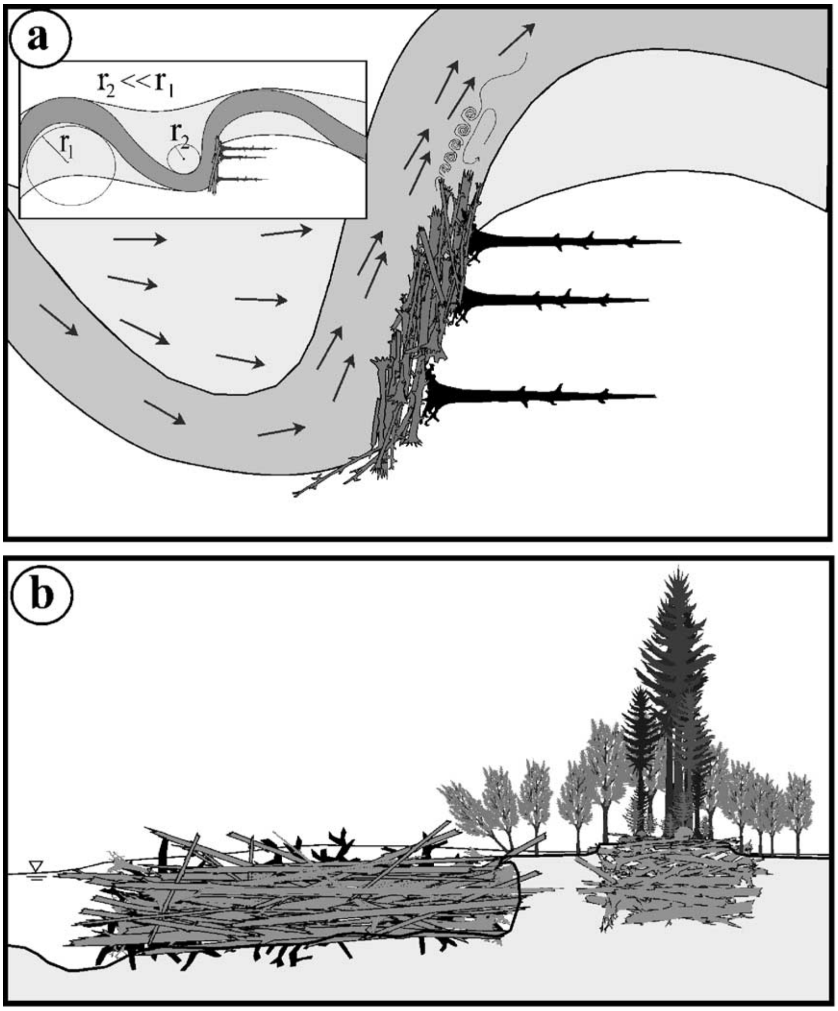

Fig. 7. Schematic sketch showing basic structure of meander jams: (a) planview with inset illustrating reach-scale setting, (b) channel cross-sectional view looking downstream into meander jam.

the jams due to local vortex flow that scours along the upstream margin of the structure, with maximum scour usually observed near the channel edge of racked debris. Surveys of pools in the Queets river found the deepest pools to occur in every case along the margins of meander jams (Abbe and Montgomery, 1996).

4.1.3.5. Log rafts. Historical references from early exploration and land surveys describe the presence of extensive floating accumulations of WD, commonly referred to as "rafts," that completely blocked large lowland rivers in forested regions (Lyell, 1830; Gillespie, 1881; Clay, 1949; Phillips and Holder, 1991). Raft accumulations could have a significant influence on the morphology, planform characteristics, gradient, and sediment-transport capacity of large alluvial river valleys (Triska, 1984; Harvey et al., 1988) and even on the development of coastal deltas (Kanes, 1970). Because no rafts were observed on the mainstem Queets river, we describe log rafts based on historical mapping and descriptions.

Historical accounts of mainstem rafts are primarily from large rivers with much wider valley bottoms and

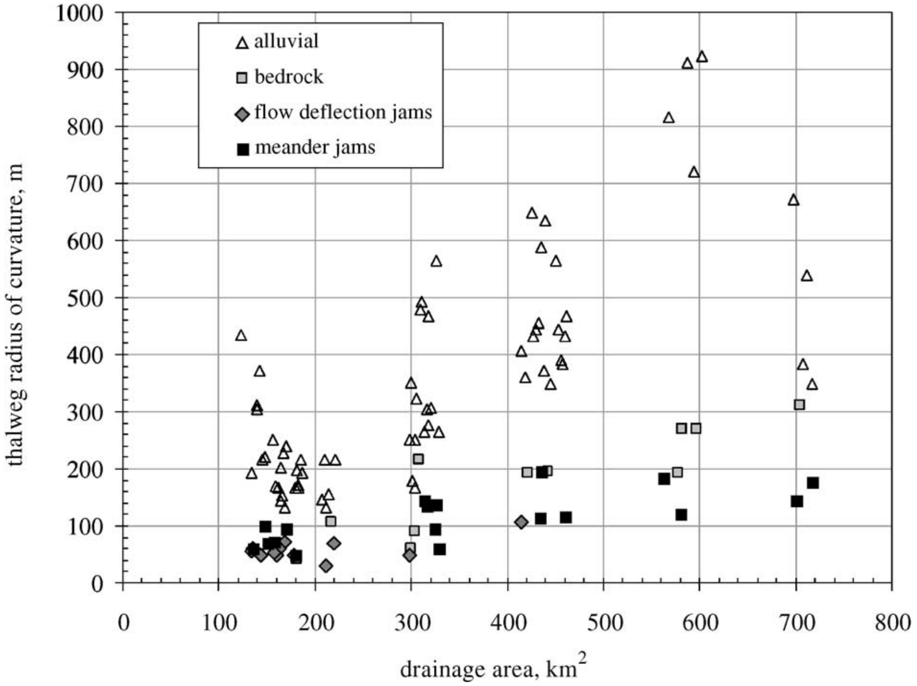

Fig. 8. Radii of curvature for Queets river meanders associated with unobstructed channels ("alluvial"), bedrock outcrops, flow deflection jams, and meander jams as a function of river kilometer.

lower gradients than the Queets river. The first recorded observation of a large channel-spanning wood accumulation or raft in the lower Colorado River, TX (drainage area of 110,190 km^2), was by Spanish explorers in 1690 (Clay, 1949). Prior to removal of this jam by the U.S. Army in 1927, the shoreline at the river's confluence into Matagorda Bay exhibited no protruding delta. Directly after removing the jam, a pronounced delta began to extend into and eventually across the bay (Kanes, 1970). Based on the difference between topographic maps of the site, approximately 14×10^6 m^3 of sediment was introduced to Matagorda Bay over a 29-year period after raft removal. Dramatic geomorphic change after WD raft removal has also been described in the Red river, LA, where a complex of massive WD rafts was documented in the earliest records of European exploration (Triska, 1984). Prior to its removal at the end of the nineteenth century, the Red river raft complex of channel-spanning jams extended 257 km from Shreveport, LA to Fulton, AR, and created a vast mosaic of anastomosing channels and large lakes within the Red River valley.

Removal of these large wood accumulations had dramatic effects on flood routing and the frequency of flood plain inundation. Veatch (1906) reported that a 24-km reach of the Red river upstream from Shreveport incised its channel from 1 to 5 m in the 19 years after the last log jam was removed. Harvey et al. (1988) examined the geomorphic changes experienced by the Red river beginning 13 years after final jam removal and estimated that over the following 92 years the river's sediment-transport capacity increased by a factor of six. The increase in channel width may have been due to the conversion from a system of numerous anastomosing channels to a single channel. Massive WD accumulations and rafts also were recorded in many of the large, low-gradient rivers of Oregon and Washington and often blocked the channel and exhibited similar effects to those in the southern U.S. (Gillespie, 1881; Russell, 1909; Sedell and Froggatt, 1984). A raft jam spanning the width of the Skagit river over a length of 1.21 km caused "the river to overflow its banks annually, flooding 150 mi^2" (Habersham, 1881, p. 2606). The Skagit flood plain was inundated up to 0.3–0.6 m several times a year prior to raft removal; but after removal, even a record spring flood failed to overtop the river banks (Habersham, 1881).

4.1.3.6. Unstable debris: bar top, bank edge, and bank-revetment jams. Stable jams store a vast quantity of organic debris and to some degree regulate the flux of WD in the Queets river system, but large quantities of mobile WD are also deposited along channel banks and on the flood plain during high flows and on bar tops as flood peaks recede. These deposits have negligible impact on channel morphology or bed texture and are likely to continue moving downstream in the next bankfull event. Bar-top jams refer to unstable accumulations found on bars within the bankfull channel and have been described as a significant type of WD accumulation in some systems (Gurnell et al., 2001). These deposits commonly consist of a chaotic assemblage of racked and loose WD with a large variance in orientations (Fig. 9a). They may be slightly more hospitable to colonizing vegetation than areas with no wood because of their nutrients and moisture retention, but they do not offer the structural protection provided by stable jams. From the small size of WD comprising these deposits and their deposition at higher elevations (where debris is unlikely to remain saturated), rapid decay and breakdown are likely in comparison to the larger WD deeply buried near or below the water table.

Loose, mobile debris can accumulate along the bank edge, rack up against streamside vegetation, and form relatively unstable bank-edge jams (Fig. 9c). Note that in the case of stable WD accumulations, the wood debris pre-dates and extends into the bank (Fig. 9d) and not just along the surface of the bank as in the case of unstable WD deposits (Fig. 9c). These deposits tend to consist of WD parallel to channel flow,

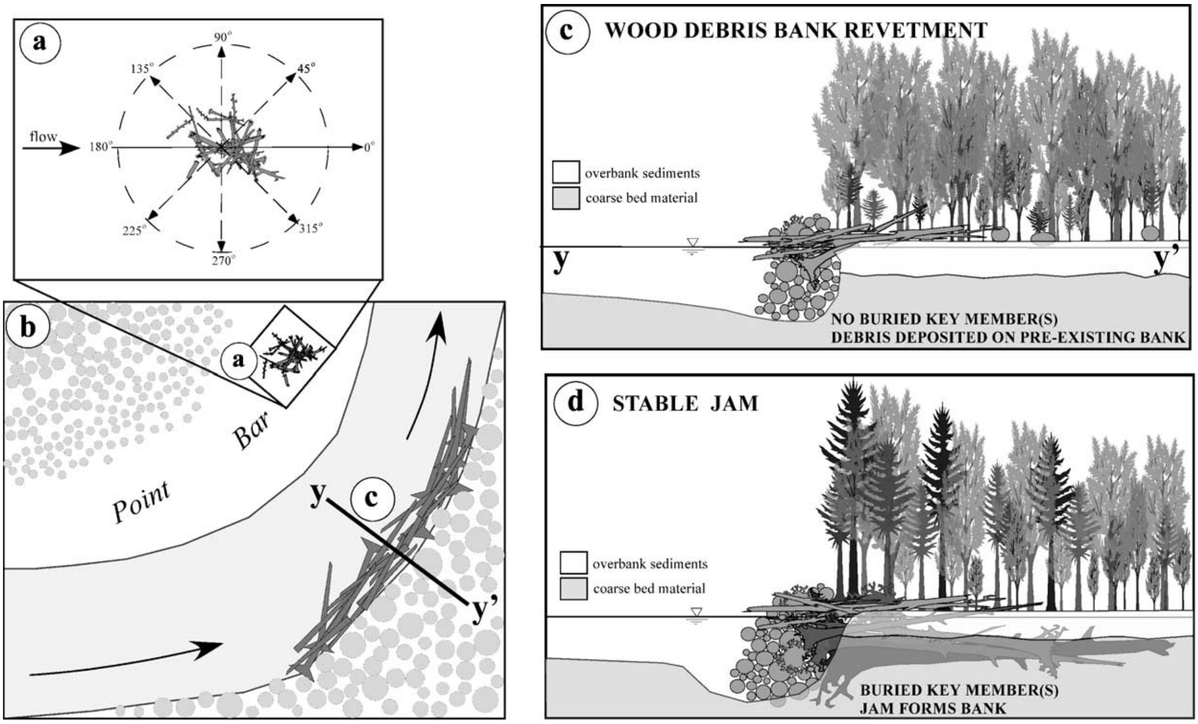

Fig. 9. Unstable wood debris deposits: (a) planview of bar top accumulation (Queets river kilometer 35.1) shows the high variance in log orientations with the mean generally oblique to flow; (b) plan view of bank edge jam exhibits relatively low variance in orientations with mean aligned closely to flow direction/channel margin and debris racked against riparian trees; (c) channel cross-section representation of unstable bank revetment accumulation deposited on pre-existing bank; (d) channel cross-section representation of stable jam buried into bank. Note that in the illustration of stable wood, the key member is situated within the bank itself.

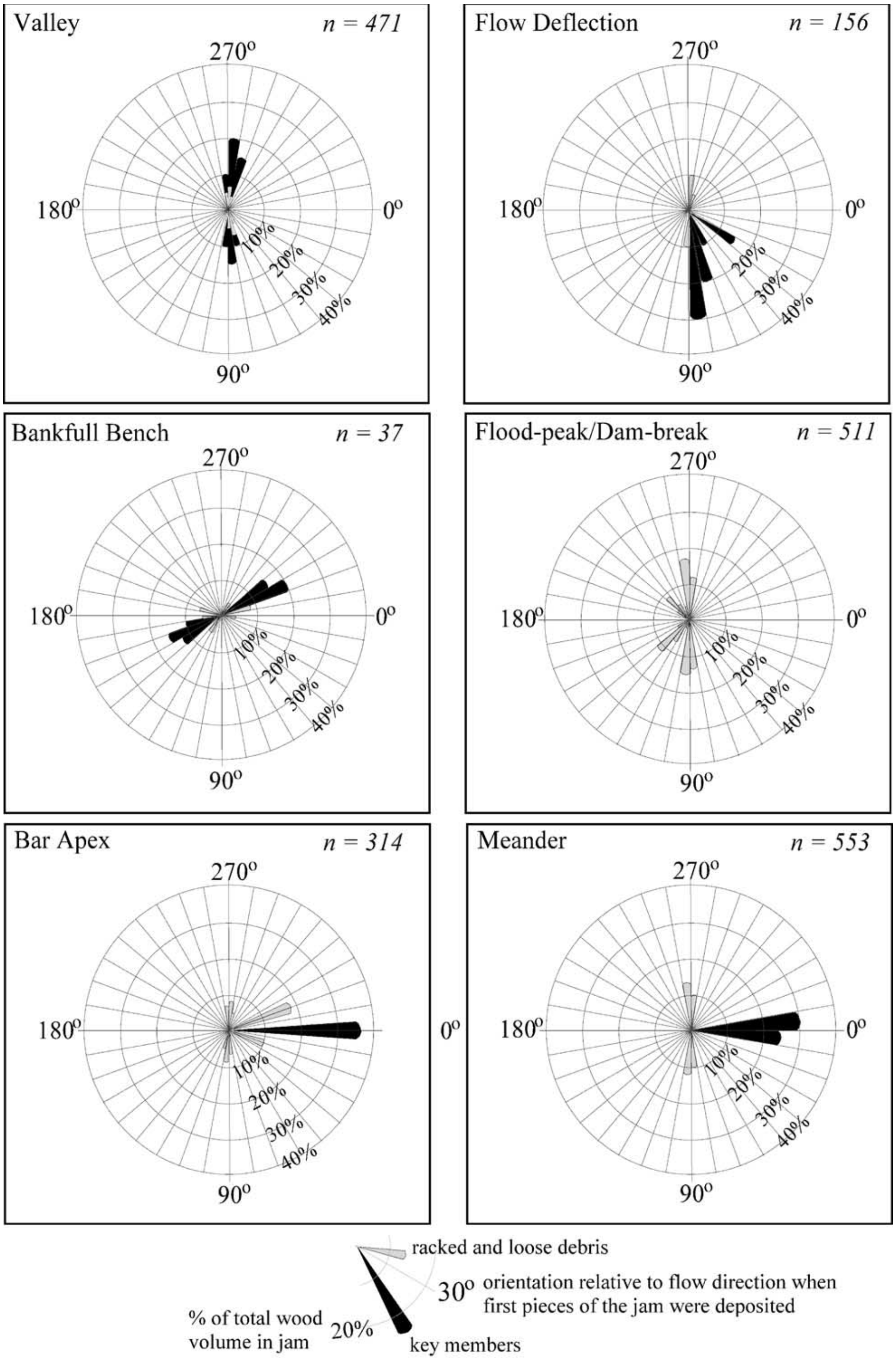

Fig. 10. Rose plot illustrations of wood debris orientation normalized to total volume of wood in individual jams exhibiting differences between jam types, n = number of logs measured in accumulation.

although material racked onto trees can introduce a wide range of orientations. These deposits rarely influence channel or flood plain morphology, although Kochel et al. (1987) documented that log accumulations similar to bank-edge jams locally retained bed material that elevated the channel bed by up to 1.50 m along a small gravel-bed stream in Virginia (similar in size to Alta Creek).

Although unstable WD deposits lack key members, bank-edge or "revetment" jams can become very large. When these deposits attain vertical dimensions exceeding the bankfull depth of the channel, they can form short-term bank revetments that retard bank erosion. Examined from upstream, these "bank-revetment jams" are indistinguishable from meander jams or flow-deflection jams. The critical difference is that downstream of all the racked WD, meander jams and flow-deflection jams have key members. With time, key members become buried under alluvium, WD, and vegetation and can be difficult to find. Because bank-revetment jams have no key members and are simply racked up against a pre-existing bank, a change in the channel's alignment can rip apart the racked WD, destroying a revetment jam and eroding the banks it had protected.

4.1.4. Summary of jam types

Jam types can be distinguished using the orientation and size of individual pieces, particularly when normalized by percent of the jam's total volume (Fig. 10). Key members usually account for a small fraction of individual logs in a jam, but they can compose most of a jam's volume. The total number of pieces will tend to overemphasize the significance of racked and loose debris, as many jams have 1–4 key members and 10–100 times as many racked pieces. Jam types can be difficult to distinguish in the field because the most visible portion of the jam is usually racked debris, which alone cannot distinguish among some jam types. To positively identify jam types, the presence and characteristics of key members, which are often buried and covered by vegetation, must be identified. For example, distinguishing the differences between some flow-deflection, meander, and bank-revetment jams would be difficult by only looking at their racked WD. The first two jam types are distinguished by the orientation of their key members. Bank-revetment jams have no key members, as the racked WD simply piles up along a pre-existing bank. We suggest distinguishing jam types using three basic conditions: (i) where in a drainage basin they tend to be found; (ii) the principal mechanism by which they remain in place; and (iii) unique characteristics of the WD and jam dimensions relative to channel width (Tables 3–5).

4.2. Wood debris jam frequency

The frequency of different types of WD accumulations varies systematically downstream through the Queets watershed (Fig. 11). In general, the frequency of jams increases with drainage area up to about 300 km^2, above which then gradually decreases. Jam occurrence was recorded by walking and floating down the mainstem of the Queets so where there were more than one channel we only recorded jams in the channel we traversed. Thus, our measurements represent jams per unit length of mainstem channel and do not include secondary channels. In situ jams occur most frequently in headwater channels, but our surveys of mainstem channels did not include side channels within the alluvial flood plains of the Queets, where in situ jams were observed to be common. In

Table 3
General characteristics of in-situ (autochthonous) jams

Type	Location in drainage basin	Principal resisting force	Jam/channel characteristics
Bank-input	1–5th order, alluvial, unconfined, ($S<0.06$)	wood debris	$W_{jam}/W>0.5$, $W_{jam}>L_{jam}$
Oblique log steps	1–4th order, bedrock or alluvial channels, $S>0.02$	channel boundary conditions	steps oriented oblique to flow, $W_{jam}/W>1.0$, $W_{jam}>L_{jam}$
Normal log steps	1–4th order, bedrock or alluvial channels, $S<0.02$	channel boundary conditions	steps oriented normal to flow, $W_{jam}/W>1.0$, $W_{jam}>L_{jam}$

WD = wood debris.
W_{jam} = width of jam measured normal to flow.
L_{jam} = length of WD accumulation measured parallel to flow.
W = width of bankfull channel undisturbed by jam.

Table 4
General characteristics of combination jams

Type	Location in drainage basin	Principal resisting force	Jam/channel characteristics
Valley confined	2–4th order, bedrock or alluvial $0.04<S<0.20$	channel boundary conditions	$W_{\mathrm{jam}}/W>1$, $W_{\mathrm{jam}} \le L_{\mathrm{jam}}$
Valley	2–6th order, bedrock or alluvial $0.01<S<0.06$	wood debris	$W_{\mathrm{jam}}/W \gg 1$, $W_{\mathrm{jam}} \gg L_{\mathrm{jam}}$
Flow-deflection	3–7th order bedrock or alluvial $0.01<S<0.03$	wood debris	$W_{\mathrm{jam}}/W>0.2$, $W_{\mathrm{jam}} \ge L_{\mathrm{jam}}$

WD = wood debris.
W_{jam} = width of jam measured normal to flow.
L_{jam} = length of WD accumulation measured parallel to flow.
W = width of bankfull channel undisturbed by jam.

channels where in situ debris forms most of the key members, combination jams form the majority of stable jam types. Transport jams are most common in larger channels where flows are sufficient to move trees entering the channel. Although a general downstream progression from in situ to combination and eventually transport jams, a substantial overlap also exists in the range of specific jam types.

Different types of WD jams occur in different parts of the channel network. Log steps were the most common WD accumulation in drainages less than 10 km^2 and were not observed in channels draining 50 km^2 or more (Fig. 11). Bench jams occurred in channels with gradients of 3% or more and their frequency increased to a maximum in channels draining 10–20 km^2; they were not observed in drainages greater than 30 km^2. Flow deflection jams were not observed in drainage areas of less than 30 km^2, peaked in frequency in drainages of about 80 km^2 and appeared throughout the rest of Queets system with decreasing frequency. Valley jam frequency was greatest at drainage areas of about 20–30 km^2 where the channel gradient is about 0.04 and the channel changes from confined reaches with bedrock exposure to unconfined alluvial reaches. The only flood jam observed was in a channel draining 21 km^2. Bar apex jams were first observed in drainages of about 24 km^2, increased to a maximum frequency at drainage areas of 100–200 km^2, and steadily decreased in frequency in larger channels. Bar apex jams were the most common WD accumulation in channels draining more than 60 km^2. Meander jams were first observed in larger channels with gradients less than 2% and draining 45 km^2, increased to a maximum frequency at a drainage area of about 300 km^2. Hence, there is a

Table 5
General characteristics of transport (allochthonous) jams

Type	Location in drainage basin	Principal source of resistance	Jam/channel characteristics
Debris flow	1–3rd order, $S>0.04$, diffuse rapidly down-stream in channels with abundant obstructions	channel margins, bank, floodplain, and riparian trees	$W_{\mathrm{jam}}/W \approx 1$, $W_{\mathrm{jam}}<L_{\mathrm{jam}}$
Flood peak	>3rd order, $S<0.06$ bedrock or alluvial	channel margins, bank, floodplain, and riparian trees	$0.5<W_{\mathrm{jam}}/W<10$, $W_{\mathrm{jam}} \ge L_{\mathrm{jam}}$
Bankfull-bench	2–4th order, $0.02<S<0.25$, bedrock, cascade, plane-bed	channel boundary and key wood debris	$0.2<W_{\mathrm{jam}}/W<1.0$, $W_{\mathrm{jam}}<L_{\mathrm{jam}}$
Bar apex	>3rd order, $S<0.03$, alluvial pool-riffle, unconfined	key member(s)	$W_{\mathrm{jam}}/W<0.5$, $W_{\mathrm{jam}} \le L_{\mathrm{jam}}$
Meander	>4th order, $S<0.03$, unconfined alluvial pool-riffle, regime	key members	$0.3<W_{\mathrm{jam}}/W<3.0$, $W_{\mathrm{jam}} \ge L_{\mathrm{jam}}$
Unstable debris *bar-top bank-revetments*	>2nd order alluvial channels mantle pre-existing banks	unstable	$W_{\mathrm{jam}}/W<0.5$, $W_{\mathrm{jam}} \approx L_{\mathrm{jam}}$ (a), $W_{\mathrm{jam}} \ll L_{\mathrm{jam}}$ (b)
Rafts	large alluvial regime channels, $S<0.01$, $w>200$ m	key pieces, WD input from upstream	$W_{\mathrm{jam}}/W \approx 1.0$, $W_{\mathrm{jam}} \ll L_{\mathrm{jam}}$

WD = wood debris.
W_{jam} = width of jam measured normal to flow.
L_{jam} = length of WD accumulation measured parallel to flow.
W = width of bankfull channel undisturbed by jam.

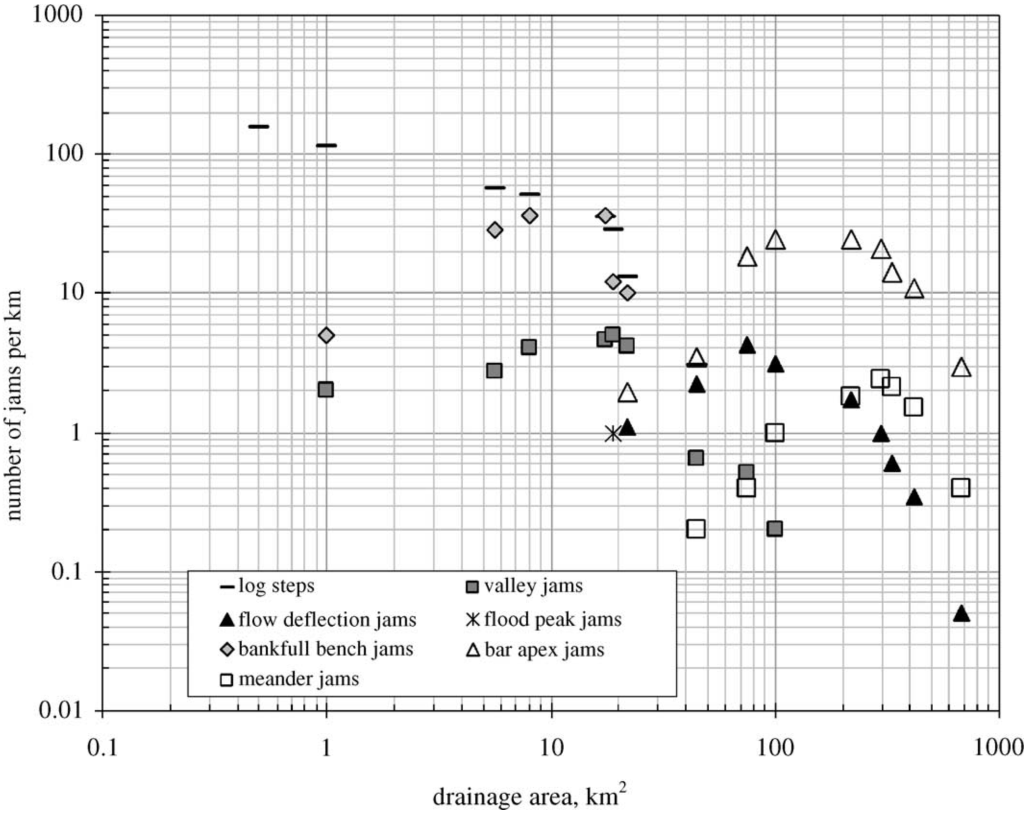

Fig. 11. Downstream variation in the frequency of wood debris accumulation types for the Queets river.

general transition from in-situ to combination to transport jams with increasing distance downstream through the channel network.

4.3. Wood debris stability

We consider "stable" WD pieces to be those that significantly affect channel-bed morphology, trap additional WD, or are unlikely to move downstream during a bed-mobilizing flow. Log size has been repeatedly reported as the principal factor controlling log stability in a given channel (Swanson and Lienkaemper, 1978; Bryant, 1980; Bilby and Ward, 1989; Nakamura and Swanson, 1993). In particular, boles with lengths greater than one-half the channel bankfull width appear to define stable logs in small streams of the Pacific Northwest (Swanson and Lienkaemper, 1984; Bilby and Ward, 1989). The flow depth at which a cylindrical bole will float if situated entirely in an unobstructed channel is controlled by diameter and specific gravity and is independent of the length of the bole. In geometric models more representative of natural WD (e.g., boles with rootwads), such as tapered cones, length can have a secondary effect on the centroid elevation and thereby log stability (Abbe et al., 1997; Braudrick and Grant, 2000).

Observations from the Queets watershed show that stable WD—those pieces capable of forming accumulations of WD that alter the river's morphology—depends on diameter, especially in large channels where bankfull widths tend to exceed the maximum length of in-stream debris. A dimensionless plot of the ratio of basal bole diameter, D_b, to bankfull depth, h, versus the ratio of total tree or log length, L, to bankfull width, w, reveals distinct domains for loose, racked, and stable WD (Fig. 12). For channels <50 m wide, ratios of $D_b/h>0.5$ and $L/w>0.5$ offer a rough approximation for delineating key members. This

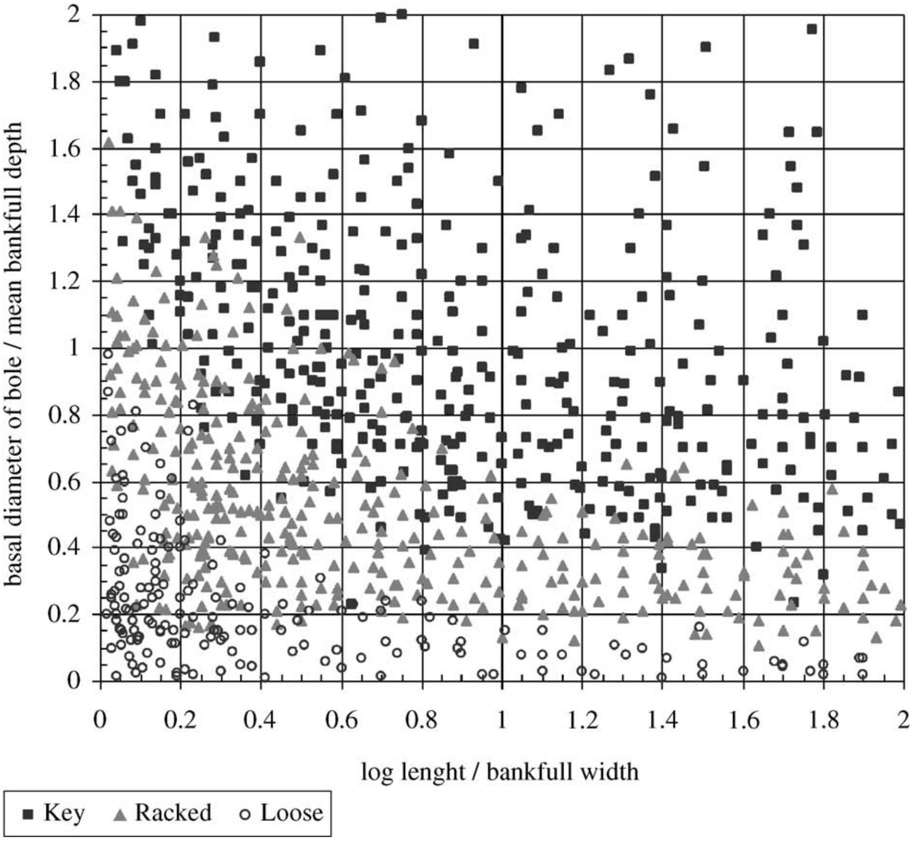

Fig. 12. Dimensionless size plot of log stability thresholds for key, racked, and loose pieces in 32 jams located in five study reaches representing different portions of the Queets channel network. Ratio of log basal diameter to bankfull depth is plotted versus ratio of log length to bankfull width. If log basal diameter is replaced with the rootwad diameter, the domain of key members is further separated from that of racked members.

relationship changes for different locations in the channel network. In small channels, the lower limit of L/w for key members approaches unity while D_b/h remains at 0.5, and in larger channels D_b/h increases toward unity while L/w approaches zero. Rootwads have a dramatic effect on WD stability by effectively increasing D_b/h. Attached rootwads were found in 82% of the 319 key members measured in the Queets watershed and in all but one of the 112 key members in channels >40 m in bankfull width.

5. Discussion

Our observations from the Queets river indicate that WD accumulations can significantly affect the channel and flood plain morphology throughout an old-growth forest mountain–river network. Local effects in the immediate vicinity of a stable log jam include flow redirection, pool scour, sediment impoundment, and bar formation. The associated changes in channel slope can be great enough to change channel type, although this effect is most common in steep channels. Stable WD structures form natural revetments that protect small areas of the flood plain from the catastrophic disturbance normally associated with channel migration across the valley floor. We believe that these "hard-points" provide refugia for conifers to mature within the channel migration zone and thereby provide for a future source of key members. Stable jams prevent local erosion and lead to formation of old-growth forest patches in a sea of young, disturbance-prone, deciduous riparian forest. Vertical changes in both the channel bed and surface water elevations associated with log jam formation can lead to avulsions, and log jams also can block old channels thereby serving to regulate flow into active side channels. This process can lead to formation of a valley bottom with complex local topography characterized by an anastomosing network of unvegetated channels separated by forested islands (Fig. 13).

In summary, large, stable log jams result in fundamental geomorphological effects at the channel-unit, channel-reach, and valley-segment scales. The channel-unit scale effects of WD on, for example, pool formation are well known (e.g., Lisle, 1995; Montgomery et al., 1995). At the channel-reach scale, stable jams increase width, decrease depth and slope, and form major obstructions, creating anastomosing channels where a single-thread channel previously existed. At the valley-segment scale, they create large sediment and debris reservoirs and elevate large sections of the channel bed, inducing flows to inundate older surfaces with greater frequencies and to initiate and carve new channels elsewhere on the valley floor. All in all, processes mediated by stable log jams are a primary influence on fluvial processes and dynamics throughout the Queets river system. The distinct accumulations of WD observed in the Queets river system form the basis for a basic typology to describe patterns of WD accumulation (Fig. 14).

We infer that our observations have trans-regional relevance. We have observed WD accumulations with characteristics similar to those described from the Queets in watersheds throughout the Pacific Northwest, and in Montana, Bolivia, Australia, and New Zealand, suggesting that the patterns and processes of WD accumulation described herein provide generalizable insight into patterns of WD accumulations in forested drainage basins when there is a supply of trees large enough to produce "key-members". In particular, our observations substantiate the importance of tree size on the formation of stable WD accumulations. Regional differences in the spatial distribution of WD accumulations within channel networks would be expected to result from differences in the size and form of trees as well as wood density.

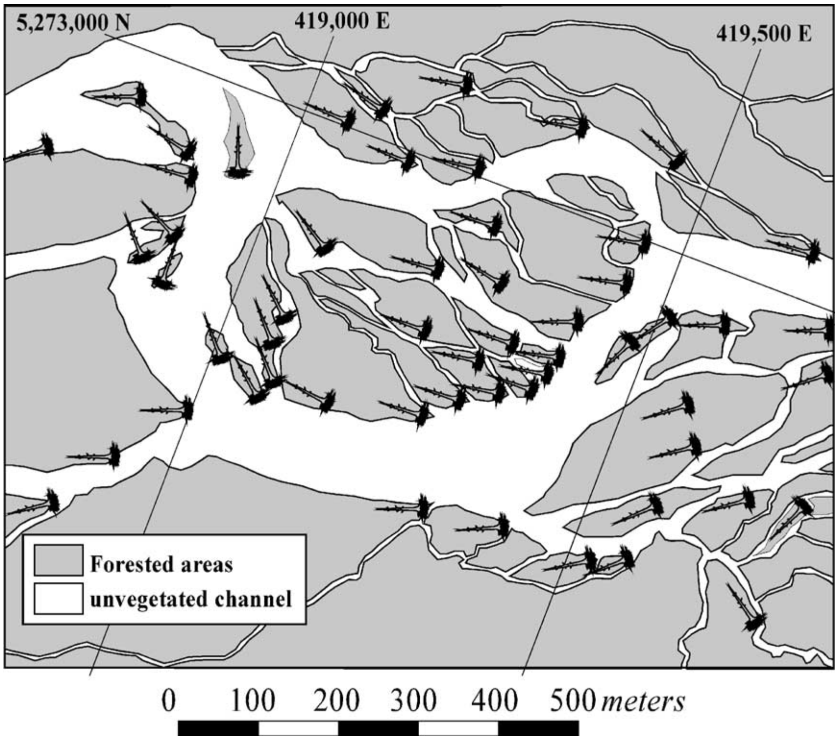

Fig. 13. Map of a section of the Queets river valley showing relationship between the location of logjams and anastomosing channel pattern.

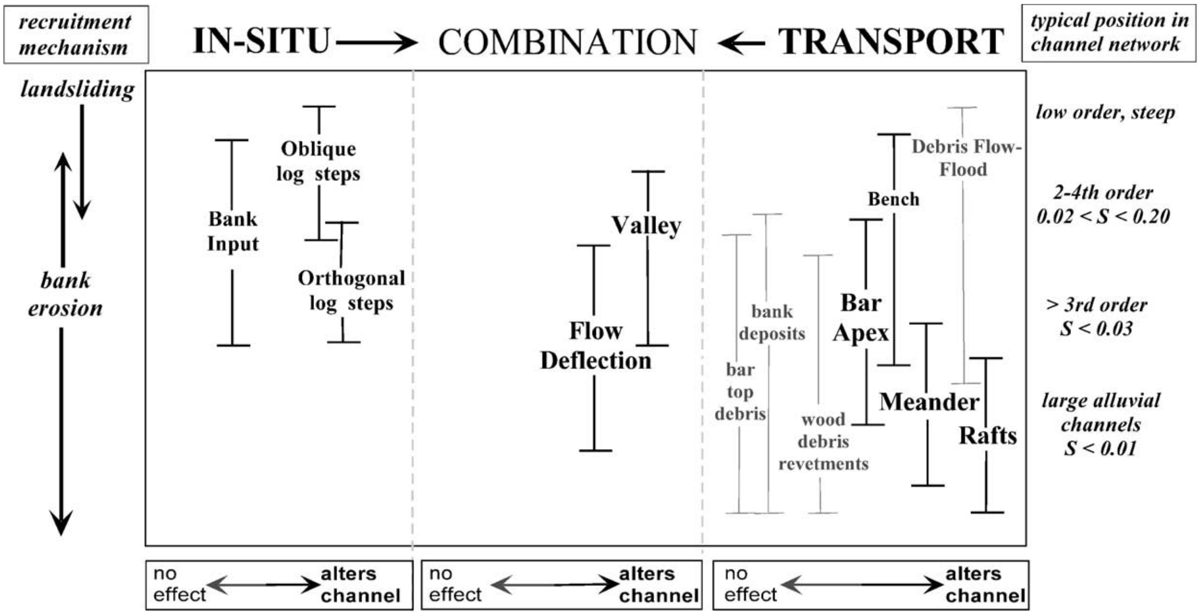

Fig. 14. Summary chart of wood debris accumulation types and their location within a drainage network.

Our extensive surveys in the Queets river show that key members are the principal mechanism forming flow obstructions, stable WD accumulations, and retaining or diffusing mobile WD in large, low-gradient channels. Although large trees typically compose a small percentage of the flood plain tree population, the high rates of channel migration found in these systems provide a means of recruitment and creation of stable WD accumulations. Because the proportion of potentially stable WD entering the channel decreases in larger alluvial channels, these parts of the fluvial system can be quite sensitive to changes in forest-stand characteristics. Once deposited, key members set up channel changes that result in deposition of ''racked'' debris that would otherwise have moved through that section of the channel. The racked debris, in turn, further constricts the channels and collects even finer ''loose'' debris and particulate organic matter. Thus, deposition of key members not only initiates stable WD accumulations but initiates a sequence of changes that significantly affects the physical and biological character and complexity of the aquatic and riparian environment. In particular, river systems with a supply of key-member-size debris would be far more retentive of organic matter than systems lacking key members. Key members comprise a small percentage of the WD recruited to channels, yet they govern the occurrence, construction, and effects of WD jams in the channel network. The supply of key members depends on the extent and characteristics of riparian trees both upstream and adjacent to a site. Hence, the elimination or reduction in the number of large trees in a forest can significantly affect the role of WD on fluvial processes.

We suspect that the dearth of wood debris in rivers in many forested regions today reflects the human legacy of channel alteration driven by expansion of agricultural and industrial development, navigation, and flood control. Historical records of large rivers flowing through pristine forest show that wood debris in the form of individual snags, jams, and rafts were ubiquitous river features. In a description of the abundant snags in the Mississippi river and its tributaries, McCall (1984, p. 181) noted that: ''It is difficult today to picture the size of those underwater trees, for today's forest trees do not compare with the first-growth giants that became snags in rivers, many of them three to six feet (1–2 m) in diameter and imbedded in the channels to a depth of ten to fourteen feet (3–4.3 m).'' Prior to the 1800s, many of the deciduous trees of Vermont commonly reached diameters of 1.2–1.5 m and heights of 60 m; some common pines were even larger (Outwater, 1996). In short, virgin riparian forests contained an abundant supply of trees capable of forming key members in a large range of channels across much of North America (Lyell, 1833; Veatch, 1906; Russell, 1909; Keller and Swanson, 1979; Sedell and Froggatt, 1984; Whitney, 1994). Based on the extensive effects of WD on fluvial processes observed throughout the Queets river system, we suspect that the historical loss of WD and deforestation has resulted in substantial changes to river systems in many forested regions.

6. Summary

Observations and field data for the Queets river watershed allow identification of distinct types of WD accumulation that occur systematically through an old-growth mountain drainage basin. Two additional types of WD accumulation were recognized based on observations from managed watersheds (debris-flow jams) and historical records (rafts). Three basic categories of WD jams are defined by key-member movement: in situ (autochthonous), combination, and transport (allochthonous). Wood debris jam types are distinguished by patterns of WD deposition, morphologic changes to the channel, and characteristics of associated forest patches. The size and type of in-channel WD accumulations vary in frequency as a function of drainage area and channel type; eliminating or reducing the supply of the largest and, therefore, potentially most stable WD can have significant geomorphic consequences.

The behavior of in-stream WD and its influence on channels and aquatic ecosystems depends on processes controlling its recruitment, transport, and deposition. These processes, in turn, depend on WD size and shape, location within the channel network, and channel morphology. Our findings from the Queets river indicate that physically distinct types of WD accumulations reflect local forest conditions, physical processes, and valley-bottom physiography. These factors both influence jam development and also are subsequently affected by jam formation. Prediction of how landscape disturbance and change may affect WD jams and forested river systems can be based on an understanding of factors controlling jam stability, the historical context of WD loading, and the nature of key-member recruitment.

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