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Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA

Chris J. Brummer [a,b], Tim B. Abbe [a,*], Jennifer R. Sampson [c], David R. Montgomery [b]

[a] *Herrera Environmental Consultants, Inc., 2200 Sixth Ave, Suite 1100, Seattle, WA 98121, USA*
[b] *Department of Earth and Space Sciences, Box 351310, University of Washington, Seattle, WA 98195, USA*
[c] *10,000 Years Institute, P.O. Box 11723, Bainbridge Island, WA 98110, USA*

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Abstract

We combine hydraulic modeling and field investigations of logjams to evaluate linkages between wood-mediated fluctuations in channel-bed-and water-surface elevations and the potential for lateral channel migration in forest rivers of Washington state. In the eleven unconfined rivers we investigated, logjams were associated with reduced channel gradient and bank height. Detailed river gauging and hydraulic modeling document significant increases in the water-surface elevation upstream of channel-spanning wood accumulations. Logjams initiated lateral channel migration by increasing bed-or water-surface elevations above adjacent banks. Because the potential for a channel to avulse and migrate across its floodplain increases with the size and volume of instream wood, the area of the valley bottom potentially occupied by a channel over a specified timeframe — the channel migration zone (CMZ) — is dependent on the state of riparian forests. The return of riparian forests afforded by current land management practices will increase the volume and caliber of wood entering Washington rivers to a degree unprecedented since widespread clearing of wood from forests and rivers nearly 150 years ago. A greater supply of wood from maturing riparian forests will increase the frequency and spatial extent of channel migration relative to observations from wood-poor channels in the period of post-European settlement. We propose conceptual guidelines for the delineation of the CMZs that include allowances for vertical fluctuations in channel elevation caused by accumulations of large woody debris.

Keywords: Channel migration zone (CMZ); Large woody debris (LWD); Logjam; Channel avulsion

1. Introduction

The interaction of large woody debris (LWD) with water and sediment can profoundly affect channel processes and form. Instream wood can change local sediment transport capacity and supply by increasing hydraulic roughness and impounding sediment behind logjams (Keller and Swanson, 1979; Harvey et al., 1987; Shields and Gippel, 1995; Gippel et al., 1996; Montgomery et al., 1996; Buffington and Montgomery, 1999; Manga and Kirchner, 2000). Sediment storage and pool formation associated with logjams can force alluvial morphologies in otherwise bedrock reaches of mountain

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[*] Corresponding author. Herrera Environmental Consultants, Inc., 2200 Sixth Ave, Suite 1100, Seattle, WA 98121, USA. Tel.: +1 206 441 9080.
E-mail address: tabbe@herrerainc.com (T.B. Abbe).

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channels (Montgomery et al., 1996, 2003). The sediment capacitance provided by many small woody debris dams in confined channels can moderate sediment flux from small basins impacted by punctuated sediment inputs (Massong and Montgomery, 2000; Lancaster et al., 2001). Larger, unconfined river systems are capable of organizing LWD into stable structures that can armor banks against erosion or redirect flow into banks (Harmon et al., 1986; Nakamura and Swanson, 1993; Abbe and Montgomery, 1996, 2003). Local aggradation behind stable logjams can raise the bed-surface elevation of channels and increase the potential for floodplain inundation and lateral channel migration (Abbe and Montgomery, 2003). Consequently, changes in the age structure and composition of riparian forests can dramatically influence channel dynamics and the potential for lateral channel migration of unconfined rivers.

Archival and field investigations of floodplain forests in the Puget Lowland of Washington state indicate that wood had a dominant influence on riverine processes and aquatic habitat until late in the mid-nineteenth century, prior to extensive European settlement (Collins et al., 2002). Written accounts by settlers document recurrent flooding and channel avulsion attributed to the chronic clogging of rivers by abundant logjams. In one of the earliest published accounts, Wolff (1916, p. 453) described the formation of logjams as a principal control on the position of the lower White River near Auburn, Washington:

> … the river has deviated greatly from the shortest course, the normal bed and in places has covered considerable areas, cutting away the land and leaving gravel bars below flood level. A close study of conditions shows that in every instance the current was first deflected by an accumulation of drift, the huge timber of this section serving readily in its formation. When one of these catches on an obstruction below, it quickly entangles others, and the mass of drift thus formed is solid enough to deflect the current. Gravel, sand, and silt collect in the dead water, behind the drift piles, strengthening them and preventing the river from returning to its original bed. Evidences of this action are plentiful, and, in the narrow valley of the upper reaches, show that the river has been forced from the hills on one side to those of the other, a distance of ½ mile or more, and the original bed has become overgrown with very heavy timber.

Such inconveniences to navigation and floodplain settlement led to the common practice of clearing snags from Puget Sound rivers throughout the late-nineteenth and early twentieth centuries (Collins et al., 2002). Riparian deforestation and levee construction reduced wood recruitment rates and wood abundance in western Washington rivers (Beechie et al., 2001). But in unconfined rivers retaining mature floodplain forest, large logjams still form and can significantly impact flooding and channel migration (Collins and Montgomery, 2001, 2002; Abbe et al., 2003).

Accumulations of LWD in rivers are likely to become increasingly common with the adoption of regulatory guidelines to protect riparian forests, habitat restoration efforts that re-introduce wood to channels and re-connect floodplains with levee setbacks, and the return of normative flows in the wake of dam-removal projects. The volume of wood entering Washington rivers will be unprecedented since historical forest clearing and instream wood removal by early settlers nearly 150 years ago. In Washington state, guidelines for the delineation of channel migration zones (CMZs) — the area potentially affected by the movement of a channel across its valley bottom over a specified timescale — rely heavily on the historical record of previous channel migration (e.g., WFPB, 2001; Rapp and Abbe, 2003). However, the aerial photographic record in most areas does not begin until the 1930s, well after instream wood removal and widespread harvest of low-elevation riparian forests (Plummer et al., 1902; Collins and Montgomery, 2001). Hence, an increase in the supply and size of wood delivered to rivers will complicate delineation of the CMZs. In particular, guidelines for the delineation of CMZs (e.g., WFPB, 2001) do not account for the causal link between vertical fluctuations in channel-bed elevation and lateral channel migration in rivers where wood obstructions are common.

We quantified the scale of wood-induced vertical fluctuation in channel-bed and water-surface elevations to evaluate the potential for vertical fluctuation from wood obstructions as an additional mechanism for channel migration. Specifically, we investigated the influence of vertical channel change associated with wood accumulations at eleven locations in Washington state (Fig. 1). First, we use hydraulic modeling of historical wood removal from a natural system to suggest a probable magnitude in vertical fluctuation and then question how widespread the mechanism may be in riparian forests. We then compare model results with vertical fluctuations measured at ten field sites impacted by channel avulsions associated with accumulations of LWD. Finally, we discuss the implications of the magnitude of vertical channel fluctuation for the delineation of the CMZs and the impact on lateral

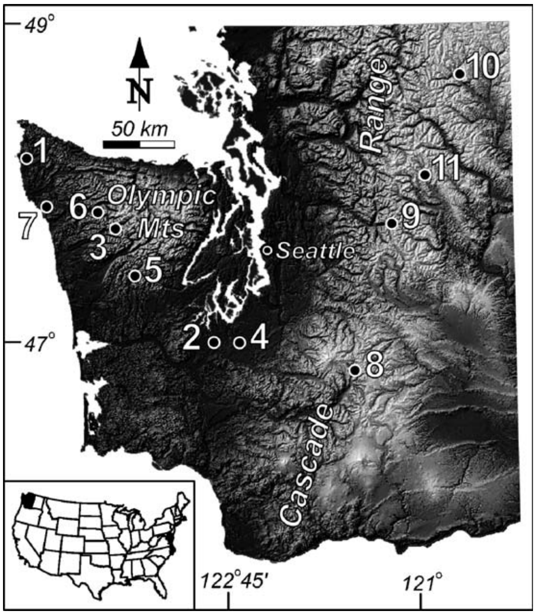

Fig. 1. Shaded relief map of western Washington showing locations of the field sites: Ozette River (1), Deschutes River (2), Queets River (3), Nisqually River (4), West Fork Satsop River (5), South Fork Hoh River (6), Goodman Creek (7), Ohanepacosh River (8), Tye River (9), Methow River (10), and Chiwawa River (11).

channel migration as maturing riparian forests supply increasing wood volume to rivers.

2. Hydraulic model

The influence of wood on the morphologic response of rivers can be evaluated by modeling the effects of flow obstructions on water-surface elevations. Conservation of mass for flow through an open channel dictates that

$$Q = UA \tag{1}$$

where Q is discharge, U is mean velocity, and A is the cross sectional area of flow. Resistance to flow is commonly expressed as an empirical function of U, hydraulic radius (R), and water-surface slope (S) using Manning's equation:

$$n = \frac{R^{2/3}S^{1/2}}{U} \tag{2}$$

where n is Manning's roughness coefficient. Assuming a rectangular cross section allows A to be expressed as the product of channel depth (D) and width (W) and also permits the substitution of D for R. Combining Eqs. (1) and (2) allows the channel width and depth to be cast in terms of discharge, roughness, and slope:

$$D^{5/3}W = Q\left(\frac{n}{S^{1/2}}\right) \tag{3}$$

Eq. (3) provides a conceptual model by which to evaluate the geomorphic response to changes in wood loading. For constant discharge, woody debris that significantly increases hydraulic roughness and reduces channel gradient through sediment accumulation will either increase the depth or width of flow, or both. An increase in flow depth provides a process-based explanation for wood-mediated changes in water-surface elevation and motivates the use of a more sophisticated hydraulic model.

Hydraulic modeling of wood-induced changes in flow depth was conducted to evaluate the hydrogeomorphic effects of historical wood removal from the Ozette River, Washington. The Ozette River drains Lake Ozette on the Olympic Peninsula and flows 8.8 km to the Pacific Ocean (Fig. 2). Inset floodplains, slumping banks, and extensive exposures of bedrock in the channel-bed provide field evidence of recent channel incision along the Ozette River because of wood removal. Encroachment of vegetation along the shoreline of Lake Ozette that began after channel clearing offers additional evidence of a historical drop in lake level of about 1 m. Unfortunately, hydrologic records for the Lake Ozette watershed are sparse, and no historical records of lake levels prior to the removal of logjams from the Ozette River have been identified. However, the Ozette system does provide a unique case study to model the effects of wood removal on vertical changes in water-surface elevation, as the location of a large number of channel-spanning logjams were mapped by Kramer (1953) prior to their removal in the 1950s.

2.1. Model development

The upper 2.2 km of the Ozette River were modeled in HEC-RAS (USACE, 2001) to simulate the effects of historical logjam removal on the water-surface profile of the river and lake (Fig. 2). Twelve cross sections surveyed in the upper 2.2 km of the Ozette River in September 2001 provided the basis for water-surface modeling of wood obstructions. Coefficients for roughness (Manning's n), expansion, and contraction were specified for obstructions at each cross section. A Manning's n of 0.084 was calculated for an unobstructed section of the Ozette River based on cross section and flow measurements taken at a bridge crossing in September 2001. A greater Manning's n of 0.15, which assumes a forested

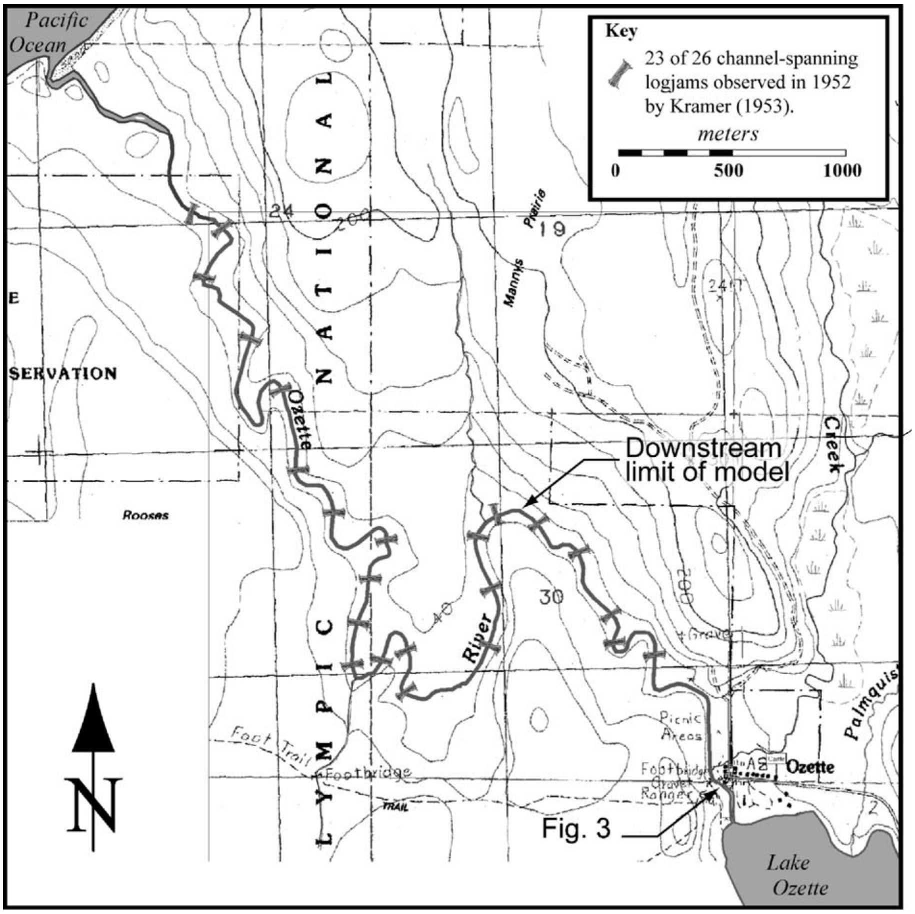

Fig. 2. Topographic map of the Ozette River and extent of the hydraulic model.

floodplain (Chanson, 1999), was used to characterize the riparian corridor outside of the main channel. These values of Manning's *n* were applied consistently to all of the cross sections in the HEC-RAS model (Abbe et al., 2001). Expansion and contraction coefficients of 0.3 and 0.1, respectively, were designated by assuming minor, but abrupt, transitions in bankfull width at each simulated logjam.

The water-surface profile downstream of Lake Ozette was simulated in the HEC-RAS using four different logjam configurations over a range of hydraulic conditions representing summer base flow, bankfull flow, and the greatest historical flood of record. The first simulation modeled baseline conditions without logjam structures (simulation A). In the three remaining simulations (B through D), logjams were modeled in HEC-RAS by designating three rows of channel-spanning structures. The height of each structure was set equal to the bank height, and the longitudinal spacing between them was held constant at 1 m. The number of structures in each row was varied to assess the response of the water-surface elevation to the fraction of the wetted area blocked by wood. The response to wood blockage was evaluated at 50%, 80%, and 100% of the cross sectional areas.

Changes in the water-surface elevation were assessed in terms of the head loss (Δz) calculated from the difference in water-surface elevation between synthetic cross sections, which were constructed 5 m upstream and downstream of each logjam. We converted Δz values to dimensionless quantities for comparison with other field sites by dividing Δz by the bankfull depth (D_{bf}) of 1.03 m measured at the bridge. Because D_{bf} is close to unity, dimensionless discharge ($\Delta z/D_{\mathrm{bf}}$) is a close approximation to Δz. The simulated discharge (Q) was divided by the bankfull discharge (Q_{bf}) of 9.5 m^3/s to derive the dimensionless discharge (Q/Q_{bf}).

2.2. Simulated vertical change

Results from four of the logjam simulations measured at a cross section located ~200 m downstream of

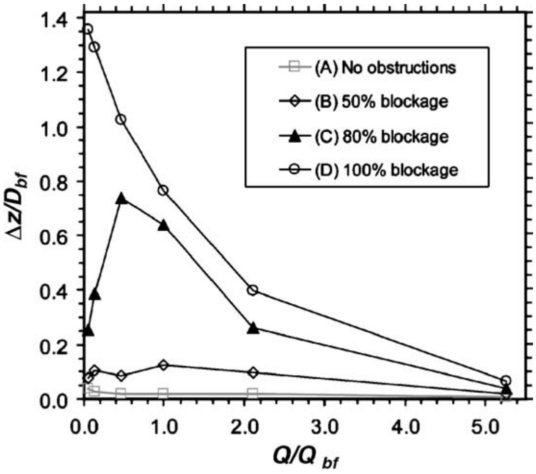

Fig. 3. Plot of dimensionless head loss ($\Delta z/D_{\mathrm{bf}}$) as a function of dimensionless discharge (Q/Q_{bf}) for various HEC-RAS simulations of the upper Ozette River ~200 m below the lake outlet (see Fig. 2). Curves represent model results for logjam simulations, each with three layers and various blockage for the dimensionless discharges shown.

the lake outlet are presented in a plot of $\Delta z/D_{\mathrm{bf}}$ versus Q/Q_{bf} in Fig. 3. A comparison of simulation extrema (A and D) predicts that wood loading, as simulated in the model by an increase in channel blockage, tends to increase $\Delta z/D_{\mathrm{bf}}$, which is manifested in the increase of the upstream water-surface elevation. Simulation B (50% blockage) predicts a modest increase in $\Delta z/D_{\mathrm{bf}}$ with rising river stage until bankfull discharge is reached (i.e., $Q/Q_{\mathrm{bf}}=1$), beyond which head loss declines from a maximum of about 0.1 m as flow spreads over the floodplain. The maximum head loss of 0.74 m calculated from simulation C (80% blockage) is significantly greater than simulation B and occurs when discharge is about half of bankfull. The greatest change in water-surface elevation occurred in simulation D (100% blockage), where the simulated logjam caused a 1.4-m rise in the water-surface elevation. Overall, a comparison of all simulation results shows that maximum values of $\Delta z/D_{\mathrm{bf}}$ occur at progressively lower values of Q/Q_{b} as the amount of blockage increases.

The systematic variation in $\Delta z/D_{\mathrm{bf}}$ predicted by the HEC-RAS model for increasing Q/Q_{bf} and debris loading is consistent with our field observations of the hydraulic effects of wood removal from the Ozette River. Results of the simulation show that flow resistance provided by logjams raises the water-surface elevation until flow is diverted to side channels or the floodplain. Because the model results predict that this effect becomes more pronounced at lower flows through logjams with greater blockage, flow diversion and channel migration should occur more frequently in channels with a greater abundance of LWD. Conversely, results of the HEC-RAS simulations suggest that a decrease in both $\Delta z/D_{\mathrm{bf}}$ and n following wood removal should lead to channel incision and a reduction in the tendency for channel avulsion due to confinement.

Findings from the HEC-RAS simulations suggest that the hydraulic effects of wood removal from the Ozette River could account for local decreases in water-surface elevation on the order of 1 m, roughly the same as the present bankfull channel depth. Because the model does not account for bed scour or sediment deposition, we interpret the predicted drop in elevation from hydraulic effects alone as a minimum estimate of the potential decrease in water-surface elevation caused by wood removal. A reduction in elevation of this magnitude near the outlet of Lake Ozette could have contributed to the suspected drop in lake level and historic encroachment of shoreline vegetation to previously unvegetated beaches around the lake.

3. Field studies

Motivated by results of the hydraulic modeling, we set out to quantify the vertical change in bed-and water-surface elevations caused by channel-spanning logjams and evaluate their influence on channel migration. We investigated ten additional field sites located in unconfined channels congested with large wood accumulations. With the exception of tributaries surveyed along the West Fork Satsop River, field sites were located in channels with a gradient <0.02 and watershed sizes ranging from 20 to 1150 km^2. The study sites represent a range of forest ecotypes and land use practices found throughout Washington state.

Topographic surveys of channel features were used to quantify the vertical change associated with wood accumulations in terms of the change in water-surface elevation (Δz_{w}) and the change in bed-surface elevation (Δz_{b}). In order to provide a robust assessment of Δz_{w} over a range of flow rates, field measurements of Δz_{w} were limited to the Deschutes River field site, where temporary stage-recording gauges were installed. A series of historical aerial photographs was used to qualitatively assess Δz_{w} at a second field site (Nisqually River) through a period of significant woody debris accumulation. Finally, we used the difference in average bank height above the channel-bed surveyed within ~100 m upstream and downstream of logjams to calculate Δz_{b} at the remaining field sites (Fig. 4), with the exception of the Queets and West Fork Satsop rivers, where Δz_{b} was calculated from the difference in bed

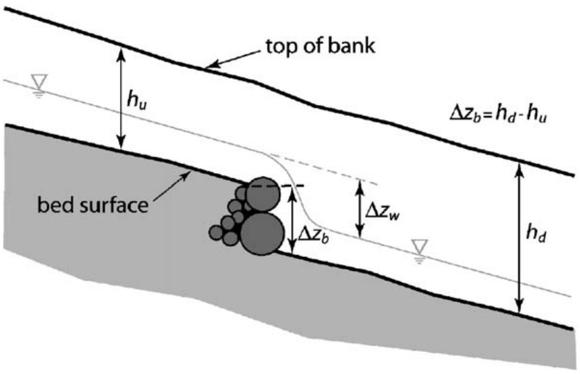

Fig. 4. Schematic profile through a channel-spanning logjam showing methods used to measure relative vertical changes in bed and water-surfaces. Change in water-surface elevation (Δz_w) measured from gauge data. Change in bed-surface elevation (Δz_b) measured from difference between bank height upstream (h_u) and downstream (h_d) of logjams.

elevation immediately upstream and downstream of logjams. Channel gradient was calculated from two points surveyed along the thalweg. In addition to quantifying vertical changes associated with logjams, the field sites illustrate the linkage between wood-mediated changes in bed-and water-surface elevation and lateral channel migration.

3.1. Deschutes River

The Deschutes River originates in private forest land of the Cascade Range and flows into Puget Sound at Olympia. In the early 1990s, a logjam began forming in a large meander bend ~17 km upstream of Olympia. By December 2001, the logjam had grown to completely fill a 400-m reach of the Deschutes River below Waldrick Road (Fig. 5) and flooded adjacent property and residences appeared imminent. Field inspection at that time documented flow diversion and floodplain inundation upstream of the logjam. We investigated relations between discharge and changes in water-surface elevation along the river segment affected by the Deschutes logjam and compared these field observations to the results of the modeling performed for the Ozette River.

Water-surface elevations were measured from stage-recording gauges installed upstream and downstream of the logjam in January 2002 by the Thurston County Department of Public Works. The temporary gauges were installed for purposes of monitoring the logjam and addressing the concerns of riverside property owners. River stage was recorded by both gauges at 30-min intervals between January and March 2002. Head loss (Δz_w) attributed to the logjam was calculated from the difference between gauge data and the elevation loss due to channel gradient (0.033) by using the water-surface profile measured during base flow. The dimensionless head loss ($\Delta z_w / D_{bf}$) was calculated using a bankfull depth of 1.58 m measured upstream of the logjam. Discharge data obtained from the USGS gauge near Olympia were normalized to dimensionless quantities using an estimated bankfull discharge of 60 m^3/s. This bankfull discharge falls between discharges with 1-and 2-year recurrence intervals (54 and 142 m^3/s, respectively) based on a flood frequency analysis of the 46-year hydrologic record for the Deschutes River. Values of $\Delta z_w / D_{bf}$ calculated from

Fig. 5. Oblique aerial photograph of the Deschutes River logjam in 2001 looking downstream. Arrows depict flow direction in the main channel and flow diversion in floodplain channels upstream of the logjam, which grew to over 400 m in length at this location by 2002.

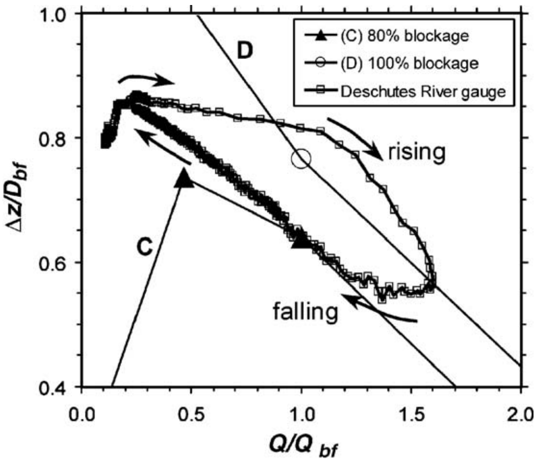

Fig. 6. Dimensionless gauge data for the Deschutes River logjam compared with simulations C and D of the Ozette River. Arrows along the hysteresis indicate rising and falling limbs of the Deschutes hydrograph. Symbols represent 30-min sampling interval.

gauge records are plotted against Q/Q_{bf} to evaluate the effects of the logjam over a range of flows and to compare these results with results of the Ozette simulation (Fig. 6).

Results of the stage and discharge data for the Deschutes River logjam show a distinct hysteresis whereby the logjam has a more pronounced influence on $\Delta z_{\mathrm{w}}/D_{\mathrm{bf}}$ during the rising limb of the flood hydrograph than it does during the receding limb. For instance, $Q/Q_{\mathrm{bf}}=1$, $\Delta z/D_{\mathrm{bf}}$ was measured at 0.82 during the rising limb of the hydrograph but only 0.64 during the falling limb. Thus, the difference in the water-surface elevation caused by logjams can depend on whether discharge is increasing or decreasing.

A comparison of the hysteresis with results of the Ozette River study shows that the rising limb of the stage-discharge hysteresis begins by tracking the trend in simulation C (80% blockage) from the Ozette (albeit translated slightly up and to the left in Fig. 6) and then shifts to track simulation D (100%) as flow approaches bankfull discharge. Stage-discharge relations then shift back to a lower blockage during the falling limb. As in the case of Ozette simulation C, head loss measured across the Deschutes logjam reached a maximum ($\Delta z_{\mathrm{w}}=1.37$ m) at a fraction of bankfull discharge ($Q/Q_{\mathrm{bf}}=0.2$) and then declined with an increasing discharge as flow was diverted to side channels around the logjam. When compared with the Ozette River simulations, the falling curve of the hysteresis suggests a decrease in the relative degree of blockage caused by the logjam. We suggest that the hysteresis reflects the dynamic adjustment of logjam properties in response to the reorganization of individual wood pieces during the rising and falling limbs of the hydrograph. We posit that the logjam porosity increased slowly during the rising limb of the hydrograph as water depth increased. Maximum porosity occurred close to the flood peak and thus allowed more effective flow conveyance during the falling limb of the hydrograph, thereby reducing backwater effects.

3.2. Queets River

The Queets River originates in Olympic National Park and provides a reasonable analog for riverine conditions prior to European settlement. The study site consists of two channel-spanning logjams located above river-km 69 along a 400-m reach surveyed earlier by Abbe and Montgomery (2003) as part of an extensive study of logjam-forming processes. The survey measured the elevation of the thalweg, water-surface, top of active (unvegetated) bars, vegetated floodplain surfaces, and terraces. Floodplain and terrace surfaces were differentiated based on forest stand age and species composition; floodplains were typically (but not always) vegetated with young hardwood species, whereas terraces were forested with late-succession conifers. In addition, we surveyed the top of individual pieces of wood and identified key-member pieces in each logjam. We also report on the investigation of vegetation patterns and alluvial deposits that provide field evidence of prior channel aggradation, incision, and lateral migration.

Results of the Queets study show a complex and discontinuous assemblage of alluvial surfaces along the 400-m longitudinal profile (Fig. 7). Discontinuities in the river profile occur at sites of sediment accumulation upstream of two channel-spanning logjams formed behind key-member logs. Each logjam is associated

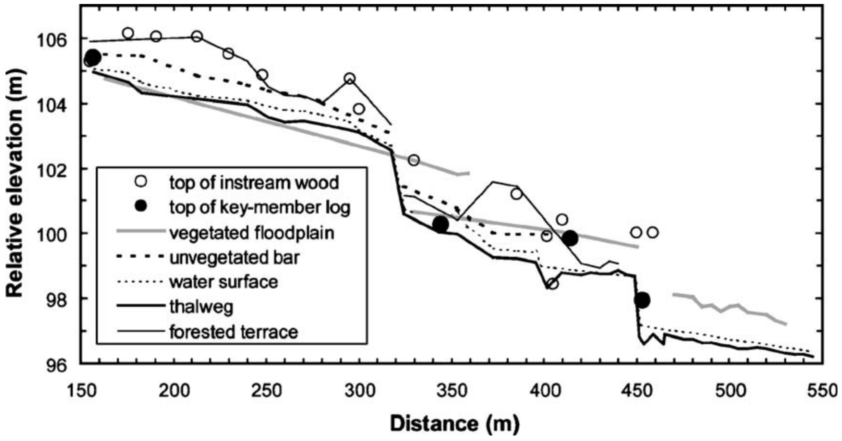

Fig. 7. Profile showing logjams and alluvial surfaces surveyed along the Queets River.

with ~2 m of vertical change in thalweg and water-surface elevations, which account for 44% of the total elevation loss (9 m) over the 400-m longitudinal profile. Upstream of the upper logjam, the active bar surface forms levee-like gravel bars, which allow most of the channel thalweg to lie at a higher elevation than the surrounding floodplain. Likewise, upstream of the lower logjam, the top of the active bar plots either above or <25 cm below the floodplain elevation. The greatest bank height, as measured by the vertical separation between thalweg and levee-like gravel bars upstream of the upper logjam, is ~1 m. Because the elevation change attributed to logjams along this reach is at least twice this height, the potential for lateral migration by logjams on the Queets River is relatively high.

Floodplain deposits and vegetation patterns in the vicinity of nearby logjams provide additional evidence of vertical fluctuations in bed elevation and subsequent lateral channel migration associated with wood. Inundation of a riparian forest during base flow conditions (Fig. 8A) indicates ongoing channel migration upstream of a channel-spanning logjam. Adventitious root development on buried trunks of red alder provides additional evidence of recent channel aggradation above an earlier floodplain surface (Fig. 8B). The inundation of a mature riparian forest and mortality of 200-year-old stand of Sitka spruce (*Picea sitchensis*) upstream of a channel-spanning logjam (Fig. 8C) provides dramatic evidence of a sequence of aggradation, raising of the water-surface elevation, and subsequent incision associated with a large, channel-spanning logjam. A recent alluvial surface colonized by a young stand of red alder (*Alnus rubra*) is located ~2.5 m above the former forest floor occupied by the Sitka spruce. Furthermore, an interbedded sequence of channel-bed gravels and floodplain sands exposed in the banks of the Queets River record a series of fluctuations in bed elevation and channel location. The broad floodplain of the Queets buffers the river from large variations in sediment inputs and rules out episodic debris flows as a potential driver for the observed incision and aggradation. Conditions along the study reach are consistent with field observations throughout the Queets River valley and illustrate the influence of wood on the dynamic forcing of channel planform and patchwork of elevated floodplain landforms (Montgomery and Abbe, 2006).

3.3. Nisqually River

The third case study investigates the sequence of events leading up to the formation of a massive logjam on the Nisqually River to illustrate the influence of large accumulations of woody debris on channel migration. Flow in the Nisqually River originates at the Nisqually Glacier on Mt. Rainier and is regulated by the La Grande and Alder Dams before passing through the study site and into Puget Sound. The study reach occupies a broad, 1-km-wide valley and is unusual because it has not been constrained by bank protection or levees, and it retains a relatively mature riparian forest (Collins and Montgomery, 2002).

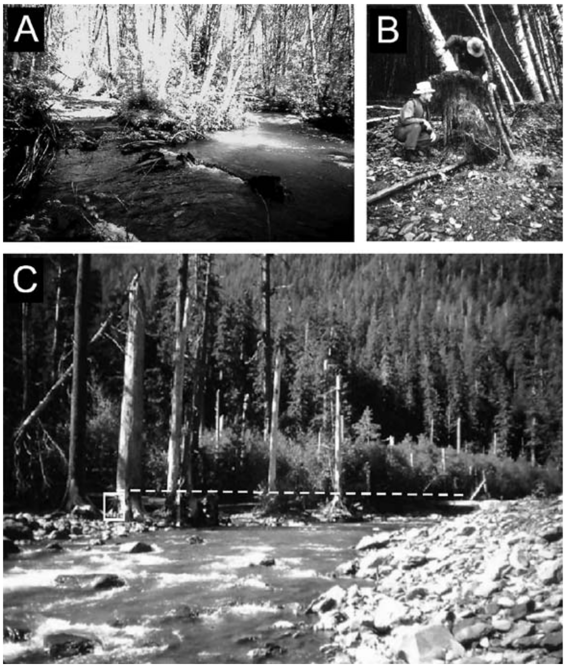

Fig. 8. Field evidence of vertical increase in bed elevation and channel aggradation in the Queets River. (A) Inundation of shallow floodplain channels through riparian forests during summer base flow. (B) Adventitious root development on buried trunk of red alder recently re-exposed by bank erosion and indicating over 1 m of bed aggradation on previous floodplain surface. (C) Burial of riparian forest and formation of an aggradational terrace. Note young stand of red alder on alluvial surface, approximately 2.5 m above buried old growth Sitka spruce on previous floodplain (dashed line, person for scale). Aggradation was followed by re-incision of the channel. Repetitive stratigraphic sequences of channel-bed gravels overlain by floodplain sands mentioned in text are located in opposite bank (not pictured).

We evaluated the geomorphic response of the Nisqually River to the formation of a complex, channel-spanning logjam using a series of aerial photographs taken between 1989 and 1999 (Fig. 9). Prior to 1989, a cutoff channel developed through the large channel meander shown at the bottom of the aerial photograph (Fig. 9A). Although the majority of water appears to be flowing through the cutoff channel, some water is visible flowing in a clockwise direction throughout the abandoned meander. The progressive migration of the river

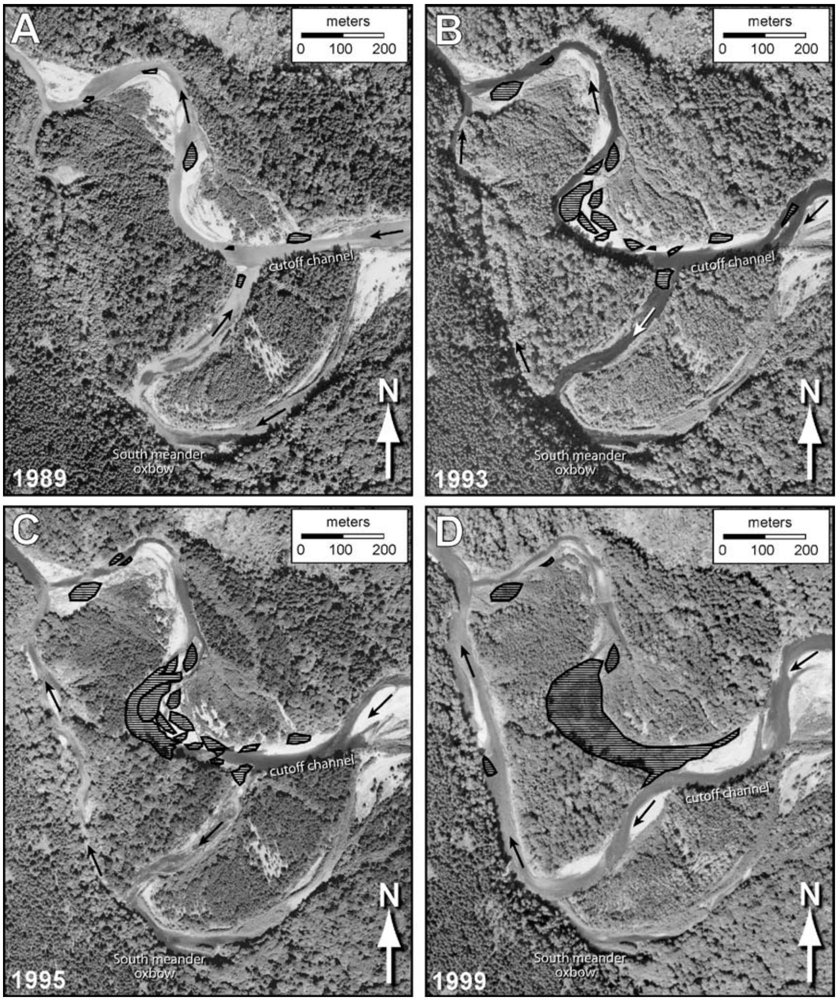

Fig. 9. Sequence of historical aerial photographs, lower Nisqually River, illustrating channel response to the development of large channel-obstructing logjams (hatched areas). Clockwise flow within the south meander shown in 1989 has reversed by 1993 (white arrow) after formation of a large logjam downstream of the cutoff channel. Growth of the logjam by 1995 is concurrent with diversion to the side channel along the western valley margin. Despite two historical floods of record in 1995–96, the logjam continued to expand upstream and divert most of the flow through the south meander.

into the mature forest both upstream and downstream of the meander cutoff in the 1989 and 1993 photographs (Fig. 9A and B) is concurrent with the formation of numerous snags and bar-apex logjams immediately downstream of the cutoff. By 1993, the majority of flow upstream of the logjam had been diverted to the previously abandoned meander, but in a direction opposite to flow observed in the 1989 photograph. The reoccupation of an old side channel along the SW margin of the valley had also occurred by 1993 (Fig. 9B). Continued expansion of the meander, increased congestion with woody debris and sediment, and inundation of the floodplain to the west of the logjam are all evident in the 1995 photograph (Fig. 9C). By this time, the wood and sediment accumulations appear to have diverted the majority of flow to the western limb of the large meander bend and side channel along the valley margin. By 1999, the logjam had expanded farther upstream and the new channel widened considerably along the valley wall (Fig. 9D). Vegetation growing on the surface of the logjam in 1999 attests to the stability of the logjam complex at this time and its isolation from the main channel.

The greatest accumulation of wood and most significant changes in flow patterns occurred between 1989 and 1995, despite close to average annual flows. One of the most profound changes in flow patterns — the reversal of flow direction in the large meander — occurred between 1989 and 1993. In contrast, no major changes in channel planform are evident in the 1999

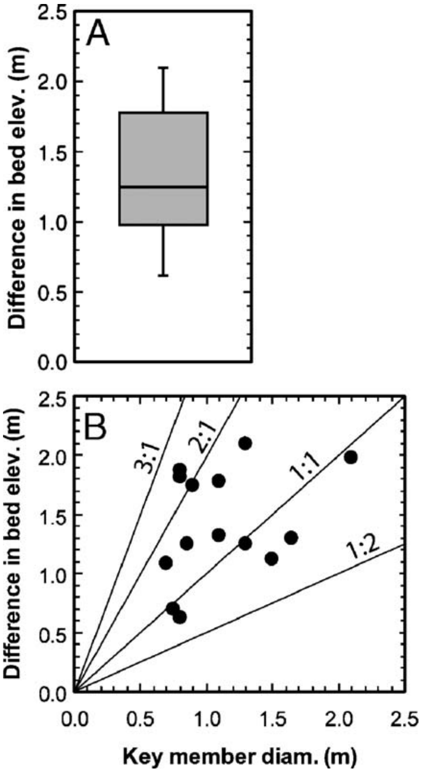

Fig. 10. Elevation difference and key-member size for logjams of the West Fork Satsop River. (A) Box and whisker plot of difference in bed elevation measured between the top and base of 19 logjams. Center bar is sample median, box defines inner and outer quartiles, and whiskers define range of observations. (B) Difference in bed elevation forced by logjams versus the diameter of the largest key-member log. For scaling reference, lines depict ratios between difference in bed elevation and key-member diameter.

photograph, even though the two largest flows of historical record occurred during the winter of 1995–96. Prior to these record events, individual logjams within the active channel coalesced to form a large, channel-spanning complex that became a major impediment to flow. A notable increase in the width of the main-stem channel occurred between 1995 and 1999 as a likely result of record flows, but otherwise discharge did not have any notable effect on channel planform nor were these extreme flows successful in dislodging woody debris and clearing a more direct channel alignment. The logjam complex not only withstood the record flows, but also expanded as a result of wood delivery during the floods. The resilience of the Nisqually logjam through the 1995–96 record flows demonstrates that large wood accumulations — which readily form during average seasonal flows — can dominate the dynamic adjustment and morphology of unconfined forest rivers, thereby damping the effects of extreme hydrologic events.

3.4. West Fork Satsop River

The West Fork Satsop River site is located on the southern Olympic Peninsula on private forest land. Although the basin had been harvested prior to our field work, the tributaries we surveyed were not cleared of debris and therefore retained the instream legacy wood recruited from the old growth forest. Channel-spanning logjams across a range of drainage areas and slopes were surveyed in 1995 as part of the field work to document sediment accumulation and changes in channel morphology forced by logjams (Montgomery et al., 1996). During these surveys we measured the difference in bed elevation and key-member size at each logjam. The difference in thalweg elevation (Δz_b) at the logjams on the West Fork Satsop River ranged from 0.62 to 2.10 m (median of 1.25 m) (Fig. 10A). When compared with the size of the key-member logs for these logjams, the difference in thalweg elevation ranged from 0.75 to 2.35 times the key-member diameter (Fig. 10B).

3.5. Additional field studies

We conducted six additional channel surveys in summer and autumn 2003 specifically for this study to quantify wood-mediated vertical changes in bed elevation (Δz_b). The additional study sites (sites 6 through 11, Fig. 1) were selected from channels where logjams are common in the Olympic Mountains (South Fork Hoh River and Goodman Creek), the western Cascades (Ohanapecosh and Tye Rivers), and the eastern Cascades (Methow and Chiwawa Rivers). The six field sites characterize forest conditions at various stages of recovery from historical forest clearing and provide a minimum estimate of Δz_b that can be expected as riparian forests mature and supply larger trees to rivers. Field

Fig. 11. Photograph of channel-spanning logjam in the Tye River looking upstream. The difference between upstream and downstream bank height at this location is 0.76 m.

Table 1
Field site descriptions

Study area	Upstream slope[a]	Downstream slope[a]	Drainage area (km^2)	Latitude/longitude	Riparian condition	Method	Vertical change (m)
Ozette River[b]	0.002		202	48°09′13″N 124°40′05″W	Harvested	Δz_{w}, HEC-RAS model	0.74–1.4
Deschutes River[c]	0.0033		104	46°55′25″N 122°48′38″W	Harvested	Δz_{w}, Gauge	1.37
Queets River	0.012	0.007	736	47°42′59″N 123°44′18″W	Old growth	Δz_{b}, Field survey	~2
Nisqually River			1882	47°00′26″N 122°39′22″W	Old growth	Δz_{w}, Aerial photos	>0[d]
W.F. Satsop River[e]	0.004–0.065		0.02–52	47°18′53″N 123°33′45″W	Old growth	Δz_{b}, Field survey	0.62–2.10
S.F. Hoh River		0.004	129	47°48′21″N 123°59′22″W	Harvested	Δz_{b}, Field survey	0.41
Goodman Creek	0.008	0.008	72	47°49′58″N 124°28′16″W	Harvested	Δz_{b}, Field survey	0.86
Ohanapecosh River	0.006	0.013	262	46°46′47″N 121°33′10″W	Harvested	Δz_{b}, Field survey	1.83
Tye River	0.005	0.034	21	47°42′42″N 121°17′15″W	Harvested	Δz_{b}, Field survey	0.76
Methow River	0.008	0.014	172	48°37′46″N 120°27′58″W	Harvested	Δz_{b}, Field survey	1.18
Chiwawa River	0.0003	0.002	102	47°56′53″N 120°46′03″W	Harvested	Δz_{b}, Field survey	0.39

[a] Local slope within 100 m upstream and downstream of logjams, as indicated.
[b] Slope is reach-average for model; vertical change reported for 80% and 100% simulated blockage.
[c] Slope is reach average through logjam measured between stage gauges at baseflow.
[d] Vertical change sufficient to reverse flow in meander bend.
[e] Coordinates are for southern extent of study area; vertical change is median difference in bed elevation measured at 19 logjams.

work at Goodman Creek, the South Fork Hoh River, and the Tye River targeted known logjams, whereas logjams at the other three sites were selected based on ease of access and visibility from roads. At each of the six field sites, the main channel was deflected by the dense accumulation of wood (Fig. 11), and an abandoned channel was observed downstream of the logjams.

Results of the additional field surveys show that logjams had a significant influence on Δz_{b}, as measured by the difference in bank height upstream and downstream of channel-spanning logjams (Table 1). The mean bank height measured upstream of each logjam was less than the bank height measured at downstream locations. For instance, the bank height above the Methow River logjam was <0.1 m, whereas 100 m downstream of the logjam, the bank height was 1.26 m. Differences in bank height upstream and downstream of logjams were greatest at the Methow (1.16 m), Tye (0.76 m), and Ohanapecosh Rivers (0.78 m). The thalweg slope measured upstream of logjams was considerably less than the slope measured downstream (Table 1), with the exception of the Goodman Creek site. The ratio of upstream to downstream thalweg slope measured across logjams for the study sites varied by nearly an order of magnitude. The slope ratio was smallest in the Tye and Chiwawa Rivers (i.e., 0.15), whereas the greatest ratios (0.44 and 0.54) were calculated for the Ohanapecosh and Methow logjams, respectively.

4. Discussion

Our case studies show that the potential for lateral channel migration is strongly linked to vertical channel adjustments associated with accumulations of wood. Hydraulic modeling of the Ozette system suggests that logjam removal lowered the water-surface elevation by a minimum of 1 m. The hysteresis between river stage and discharge measured on the Deschutes River suggests logjam properties and hydraulic head mutually adjust through changes in jam porosity and water-surface elevation during rising and falling limbs of the hydrograph. The alternating sequence of channel-bed gravels and floodplain sands preserved along the banks of the Queets River — which record several episodes of bed aggradation, incision, and lateral migration — attest to the dynamic adjustment of unconfined river systems that regularly recruit mature trees from their banks. The disturbance of riparian vegetation, patterns of species composition, and the repetitive sequence of alluvial sediments observed on the Queets River has been attributed to the dynamic cycle of channel aggradation, lateral migration, and subsequent incision associated with the formation of channel-spanning logjams (Abbe and Montgomery, 2003; Montgomery and Abbe, 2006). In a complementary study of the Queets and nearby Quinault rivers, O'Connor et al. (2003) found that bar growth and constant channel shifting caused by logjams reworked half of the floodplain every 300–500 years. In a study of late-Holocene forest disturbance and vegetation change on the Queets floodplain, Greenwald and Brubaker (2001) documented >4 m of vertical fluctuation 300–800 m from the river within the past 500 years. In the case of the Nisqually River, bed aggradation upstream of a large channel-spanning logjam was so severe that it raised the bed to an elevation sufficient to reverse the flow direction in a meander bend. These complementary studies of mature riparian forests illustrate the potential magnitude of vertical change and spatial scale of lateral channel migration forced by accumulations of LWD.

Consistent throughout our field studies is the observation of sediment impoundment behind logjams and initiation of a positive feedback, whereby a reduced transport capacity drives additional sediment deposition and slope reduction until either the top of the logjam is breached or aggradation behind the logjam exceeds the bank height and forces lateral migration. The reduction in mean bank height and channel gradient upstream of logjams relative to the bank height and gradient measured in downstream reaches supports this interpretation. Field surveys show that aggradation and reduced channel gradient upstream of wood obstructions caused more than 2 m of change in bed-surface elevation at some of our field sites and initiated channel migration at all of the field sites.

Luzi (2000) observed wood-induced changes in channel elevation similar to those in our field studies in Carnation Creek, a small (10 km^2) coastal stream on Vancouver Island, British Columbia, where a long-running experimental watershed program investigated the effects of forestry practices on stream ecosystems. Using a series of cross sections, longitudinal profiles, and aerial photographs to monitor the development of a channel-spanning logjam, Luzi (2000) documented that ~1.5 m of aggradation occurred within 4 years of logjam formation, which caused the elevation of some gravel bars to exceed the elevation of the banks. Three years later, continued aggradation forced the channel to migrate around the logjam and inundate side channels. Within 15 year of logjam formation, the logjam began to break up, and the channel migrated back to the pre-jam alignment and grade. The rapid adjustment of bed elevation in response to logjam formation and destruction illustrates the short temporal scale (decade) over which wood-mediated changes in bed elevation and lateral migration can occur at one location.

Although historical wood removal from Washington rivers was widespread (Collins et al., 2002), case studies of channel incision and reduction in migration rates following this practice in Washington state are poorly documented. Studies of wood removal from channels outside of Washington suggest that wood removal leads to channel incision. Wood removal from a Coast Range stream in Oregon caused up to 2 m of bed incision (average of 0.9 m) of previously stored sediment and eroded more than 5000 m^3 of sediment along a 250-m reach the first winter after woody debris removal (Beschta, 1979). Sediment export was greatly increased after removal of wood from a 175-m reach of a New Hampshire stream (Bilby, 1981), and removal of logging debris from several Idaho streams reduced the in-channel sediment storage (Megahan, 1982). Local bed elevation was reduced measurably following wood removal from Black Creek in the southern Olympic Mountains (Montgomery et al., 1996). The effects of wood removal illustrated by these regional studies imply that previously forested rivers will be highly responsive to the re-introduction of woody debris. The geomorphic effects of increasing wood volume from recovering riparian forests described for the American Pacific Northwest have also been observed in European rivers (Boyer et al., 1998; Montgomery and Piégay, 2003) and in southeastern Australia (Brooks et al., 2003). Our regional findings can inform river management and the CMZ delineation in riparian forests throughout the world, where forest recovery is allowing wood to re-enter river systems.

Resource management objectives of restoring fish habitat by encouraging logjam formation will require the growth and recruitment of trees large enough to serve as stable key pieces. Numerous workers have shown that the size of functional wood varies in relation to channel size (Keller and Tally, 1979; Bisson et al., 1987; Bilby and Ward, 1989; Nakamura and Swanson, 1993; Abbe and Montgomery, 1996, 2003; McHenry et al., 1998; Braudick and Grant, 2000). Based on field measurements of logjams from the Queets River system, stable key pieces have a basal diameter of at least one-half the reach-averaged bankfull depth and retain a substantial root mat (Abbe and Montgomery, 2003). Larger diameters are required for the stability of shorter pieces. Data from the West Fork Satsop River show logjams can aggrade a channel to at least the height of twice the key-member diameter. Thus, a comparison of growth rates of riparian species and local bankfull depth can provide a reasonable estimate of the time required to grow a mature riparian forest that can supply key-member trees. Based on a representative bankfull depth of 2 m from our surveys of unconfined rivers in Washington, the minimum diameter of key-member trees necessary to initiate a significant channel response is about 1 m. Smaller rivers will require commensurately smaller-diameter trees. By this standard, few mature riparian forests presently exist in Washington state, although they will likely become more common in the next century if they are allowed to grow.

Results of our case studies, field surveys, and hydraulic modeling provide guidance for the delineation of the CMZs in anticipation of an increased wood loading expected to result from fluvial recruitment of larger diameter trees from floodplain forests. Assuming an unconfined channel can aggrade to at least the elevation of two stacked logs (as indicated by the Queets and West Fork Satsop data), a minimum estimate of the portion of a valley bottom potentially occupied by channels can be determined using an elevation lower than twice the diameter of available trees above the bankfull elevation (Montgomery et al., 2003). Adopting this logic, our results for the larger unconfined channels we investigated indicate that the CMZ delineations should account for no less than 2 m of vertical channel variability above the local bankfull elevation and 1 m in the smallest channels we investigated. Hydraulic modeling of floodplain inundation and the use of detailed topographic mapping offers a practical means of delineating the CMZs. It follows that as riparian forests mature and supply commensurately larger trees to rivers, the frequency and spatial extent of channel avulsions should increase relative to the rates and extent that so far characterized the period of post-European settlement. Therefore, the CMZ can be expected to widen as mature forests reoccupy riparian zones. From a practical perspective, the addition of a wood-induced vertical dynamic to forest channels complicates predictions of channel migration based solely on the migration rates inferred from aerial photographs because the short historical record may not include conditions and dynamics representative of the target riparian condition. The potential ecological and economic consequences of wood re-introduction underscore the need to recognize and understand the influence of wood-mediated changes in channel elevation on the rate and style of lateral channel migration.

5. Conclusions

Stable logjams mediate the water-surface elevation in unconfined alluvial channels by introducing hydraulic resistance and creating sites of sediment impoundment. Field investigations of the effects of logjams in unconfined rivers in Washington State indicate that aggradation behind logjams can result in vertical fluctuations that exceed the bankfull elevation. Resource management goals to restore riverine habitat by increasing the size and supply of wood to rivers currently deficient in stable key logs will likely increase the potential for future lateral channel migration. The response of Washington rivers to increased wood loading documented herein suggests that accounting for the area of the valley bottom within 2 m of the local bankfull elevation provides a reasonable estimate of the minimum area potentially occupied by a channel. A return to wood-mediated fluctuations in bed elevation has implications for forest and river management practices that prescribe forest buffer widths to accommodate flood hazards and protect critical aquatic and riparian habitat. Given the potential ecological gains and economic impacts resulting from increased habitat complexity, floodplain inundation, and lateral channel migration, regulatory guidelines for the delineation of the CMZs (as well as flood hazard areas) that fail to consider the potential for wood-mediated fluctuations in channel elevation will offer little protection of critical forest habitat and the economic resources linked to the health of riparian forests.

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