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Riparian forest disturbances by a mountain flood — the influence of floated wood

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Abstract:

Large floods can have major impacts on riparian forests. Here we examine the variability and spatial distribution of riparian forest responses along eight third- to fifth-order streams following a large flood (~ 100 year recurrence interval) in the Cascade Mountain Range of Oregon. We categorized disturbance intensity (physical force) exerted on riparian trees during floods into three classes: (i) purely fluvial (high water flow only); (ii) fluvial supplemented by dispersed pieces of floating wood (uncongested wood transport); (iii) fluvial with movement of batches of wood (congested wood transport). These types of material transport and associated classes of disturbance intensity resulted in a gradient of biotic responses of disturbance severity ranging from standing riparian trees inundated by high water, to trees toppled but still partially rooted, to complete removal of trees. High within-stream and among-stream responses were influenced by pre-flood stream and riparian conditions as well as flood dynamics, especially the availability of individual pieces or congested batches of wood.

Fluvial disturbance alone toppled fewer riparian trees than in reaches where floodwaters transported substantial amounts of wood. Debris flows delivered additional wood and sediment to parts of reaches of four of these study streams; riparian trees were removed and toppled for up to 1·5 km downstream of the debris flow tributary channel. Congested wood transport resulted in higher frequency of toppled trees and greater deposition of new wood levees along channel margins. The condition of the landscape at the time of a major flood strongly influenced responses of riparian forests. Recent and historic land-use practices, as well as the time since the previous large flood, influenced not only the structure and age of the riparian forests, but also the availability of agents of disturbance, such as large pieces of floating wood, that contribute to disturbance of riparian forests during floods.

KEY WORDS riparian forests; floods; floating wood; forest disturbance

INTRODUCTION

Floods have long been recognized as primary geomorphological agents shaping the fluvial environment, and have an important role in controlling the pattern of riparian vegetation along channels (Wolman and Miller, 1960; Hupp and Ostercamp, 1996; Hughes, 1997). Floods interact with vegetation in complex ways, both influencing and influenced by the structure and composition of streamside riparian forests. High energy streamflow can erode streambanks and undercut, topple and remove standing vegetation. Entrained woody debris can batter riparian stands, and forests can be buried by sediment deposited by floodwaters. Streamside vegetation physically constrains flood flows, traps floating debris, and its roots increase the erosional resistance of streambanks. The mosaic of riparian vegetation reflects a complex interaction among vegetation, geomorphological processes and time.

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Few studies have comprehensively examined responses of riparian vegetation to floods in mountain streams (Hack and Goodlett, 1960; Decamps, 1996). Hack and Goodlett (1960) described how vegetation along the Little River in the Appalachian Mountains influenced erosion and depositional patterns during a flood and the complex interactions between flood flows and standing and fallen trees. Many flood studies have focused on lateral or floodplain vegetation responses to inundation in low gradient streams (reviewed by Hupp, 1988; also see Hughes, 1997; Piegay and Bravard, 1997; Vadas and Sanger, 1997), where dynamics can be very different than in high gradient streams (Swanson and Sparks, 1990). In mountain streams, physical disturbance processes may dominate riparian forest dynamics, whereas in low gradient streams, riparian forests may be more influenced by physiological responses to protracted inundation. In forested mountain streams, interactions between vegetation and geomorphological processes are heightened by an abundance of wood, high stream power and high sediment transport rates. Studies along western Cascade streams in Oregon have highlighted the ecological and geomorphological importance of large wood delivered to streams during floods (Lamberti *et al.*, 1991; Gregory *et al.*, 1991; Nakamura and Swanson 1993). In landscapes prone to mass movement of soils, such as the Pacific Northwest, USA, landslides can deliver large quantities of wood and sediment to stream channels, accentuating the disturbance potential of floodwaters (Johnson *et al.*, 1997; Swanson *et al.*, 1998; Nakamura *et al.*, 2000, this issue).

A large regional flood in the Pacific Northwest in February, 1996, with a recurrence interval of *c.* 100 years in our study sites, afforded an excellent opportunity to examine interactions between floods and riparian forests along mountain streams and to examine spatial patterns of disturbance to riparian forests. In this paper, we describe flood effects on lateral and longitudinal riparian forest patterns and explore potential flood processes responsible for these patterns. We also examine disturbance to riparian forests by flood waters with and without floating wood, which was influenced by the lasting legacy of previous land-use practices and the present condition of riparian vegetation.

STUDY SITES

Study sites on tributaries of the McKenzie River in the Cascade Mountain Range, Oregon, USA (Figure 1) were selected to examine riparian disturbances over a range of site properties (e.g. stream size and amount of bedrock), forest harvest histories and disturbance regimes within a narrow geographical area with similar geology and elevation. These streams experienced a similar magnitude of high flows (expressed as discharge per unit basin area) during a large regional storm 4–8 February 1996. Four days of excessive rainfall combined with a greater than normal snowpack created one of the highest peak discharges for the years of record for streams and rivers in the McKenzie Basin. Peak discharge at Lookout Creek gauge (64 km^2 drainage area) was 226 m^3/s; the previous maximum of 186 m^3/s occurred in December 1964 (Hubbard *et al.*, 1996).

This portion of the McKenzie River basin is characterized by steep hillslopes that range in elevation from 300 m to over 1600 m. Upland native forests are dominated by several species of large conifers (*Pseudotsuga menziesii* and *Tsuga heterophylla*); some areas of the forest have been harvested commercially and replanted. Riparian areas historically were dominated by large conifers but some have been disturbed and are now dominated by red alder (*Alnus rubra*). Average annual precipitation is 2500 mm, the majority of which occurs during winter as snow at elevations above 1000 m and as rain below 600 m.

METHODS

Field surveys were conducted in eight mid-elevation third- to fifth-order streams (1:24 000 scale maps) during late summer and early autumn low flows following the February 1996 flood (Table I). To examine the spatial variability of disturbance to riparian forests, we collected and recorded data along the longitudinal profile of each 3000 + m section of stream in a spatially explicit manner. Data were referenced to distances along the

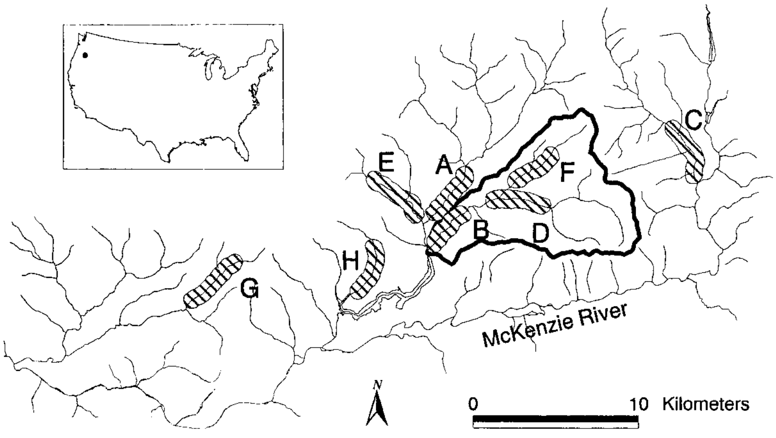

Figure 1. Locations of study sites on tributaries of the McKenzie River, central Oregon, USA. The boundary of the H.J. Andrews Experimental Forest is shown as a bold line. Sites are designated by letters (see Table I for site descriptions)

stream channel, moving downstream from an upstream datum. We used 10-m digital elevation models and stream network maps to calculate basin drainage areas for the study sites.

Because floods have lateral variability of disturbance intensity, from erosional, high energy areas near the channel to backwater, depositional areas at the margins, we identified these zones and examined primarily the dynamics of riparian disturbance within the high energy zone. High energy zones were identified by evidence of scour or erosion, reworking and deposition of large alluvial material or large wood. Low energy zones were primarily areas of backwaters during the flood where there was clear evidence of minor inundation, but soils were not disturbed and floated fine organic matter may have been deposited.

The cross-valley width of the high energy zone was measured at 25 m intervals along the length of the streams. We tallied the number, size and species of standing and toppled riparian vegetation within the high energy zone in 25-m segments. Alder sizes (diameter at 1·4 m above the ground surface) were estimated and grouped: small < 15 cm, medium $= 15$–30 cm, and large > 30 cm. These sizes roughly corresponded to their ages; 10-cm alder were on average 10 years old and 30-cm alder were generally 30 years old (J.A. Jones, Oregon State University, personal communication). To identify the potential pool of riparian trees species, the presence/absence of riparian trees along the flood margins of each bank was recorded every 5 m along

Table I. Summary of site characteristics. Watershed area and elevation were obtained for the most downstream point of the study site from digital elevation models. Valley floor widths are averages from cross-sections measured every 100 m. The category of disturbance intensity is noted; F = fluvial, U = uncongested wood transport, C = congested wood transport

Site	Drainage area (ha)	Elevation (m)	Valley floor width (m)	Reach length (m)	Type of disturbance
A. Blue River	9000	450	30	3000	F
B. Lower Lookout	6250	425	33	3000	U
C. Deer Creek	5900	570	54	3000	F
D. Middle Lookout	5300	520	89	3000	U
E. Tidbits Creek	2680	440	24	3000	F
F. McRae Creek	1550	540	57	3600	U, C, U
G. S.F. Gate Creek	1350	420	26	4300	C, U
H. NF Quartz Creek	1020	430	31	3000	U, C, F

each stream. The number of pieces of fallen large wood (minimum diameter 0·3 m and minimum length 3·0 m) within the high energy zone were counted within each 25 m segment. Volumes of wood accumulations with more than five pieces were estimated from the dimensions of the accumulation. Presence of wood levees (marginal accumulations of wood, oriented parallel to the flow, and serving as a boundary between high and low energy zones) was also noted at 5-m intervals. Channel slope was measured every 25 m using a clinometer. Presence of bedrock was recorded for 5-m intervals if it was exposed in the bed of the stream channel or formed either the right or left bank of the high energy zone. Widths of the low energy zone were measured every 100 m on the left and right floodplain. Maximum heights of flood waters above the thalweg were recorded every 100 m and valley widths were measured using a range finder. Valley floor width indices (VFWI) (Grant and Swanson, 1995) were calculated as the ratio of valley floor width to active channel width (calculated from repeated cross-section measurements of annual bankfull events in reference streams within the H.J. Andrews Experimental Forest for each study stream as a function of drainage area (G.E. Grant, unpublished data)).

Four of the study streams were impacted by multiple debris flows that delivered wood and sediment into the stream channels during the 1996 flood (Table II). The volume of added material was calculated from the volume of the scar of the head scarp of landslides that became debris flows and were delivered into the study streams (F.J. Swanson, unpublished data). The location of the junction of debris flows with the main channel was recorded during the field surveys. Oregon State Department of Forestry provided landslide volumes for S.F. Gate Creek (Vida site, unpublished data).

A comprehensive set of aerial photographs for a 300 m segment of Middle Lookout Creek allowed us to make a detailed examination of riparian vegetation changes during the recent flood history (1959–present). Recent floods of varying magnitude occurred in 1964, 1977, 1986, 1996 and 1997. Flood impacts to the stream channel and riparian vegetation were interpreted from aerial photographs taken in 1959 (1:12 000), 1967 (1:16 000), 1979 (1:12 000) and 1989 (1:2250). Photographs were scanned, enlarged and screen digitized to map the active channel and riparian vegetation. Low-level aerial photographs, using a ‘blimp’ flying at 60 m above the ground surface, were taken in 1996 and 1997 above this section. These photographs were printed at a scale of 1:350 and matched to provide a detailed image, which was then scanned and screen digitized.

For analysis, reaches within sites were assigned to one of three categories of disturbance intensity: fluvial, fluvial plus uncongested wood transport, and fluvial plus congested wood transport (Figure 2). These distinctions were based on: (i) previous knowledge of availability of large wood within the channel (Table II); (ii) its potential for transport during the flood; (iii) amount of wood delivered if a debris flow entered the

Table II. Pre-flood site conditions influencing standing stocks of wood in channels and inputs of debris flows and associated wood during the 1996 flood. Pre-flood conditions are not quantified, but the number of debris flows entering the study streams during the 1996 flood and the relative amounts of wood delivered are indicated: Y = yes; N = no; * = new debris flows did not enter N.F. Quartz but a large debris jam was mobilized

	Pre-flood conditions		During 1996 flood	
Site	Debris flows from tributaries	Wood harvested from channel	Debris flows from tributaries	Wood inputs from debris flows
Blue River	Y — 1964	Y	4	Low
Lower Lookout	Y — 1964	Y	1	Low
Deer Creek	N	Y	0	—
Middle Lookout	N	N	0	—
Tidbits Creek	Y — 1964	Y	0	—
McRae Creek	N	N	1	High
S.F. Gate Creek	Y? — 1964	Y	10	Moderate
N.F. Quartz Creek	Y — 1986	Y	0	*

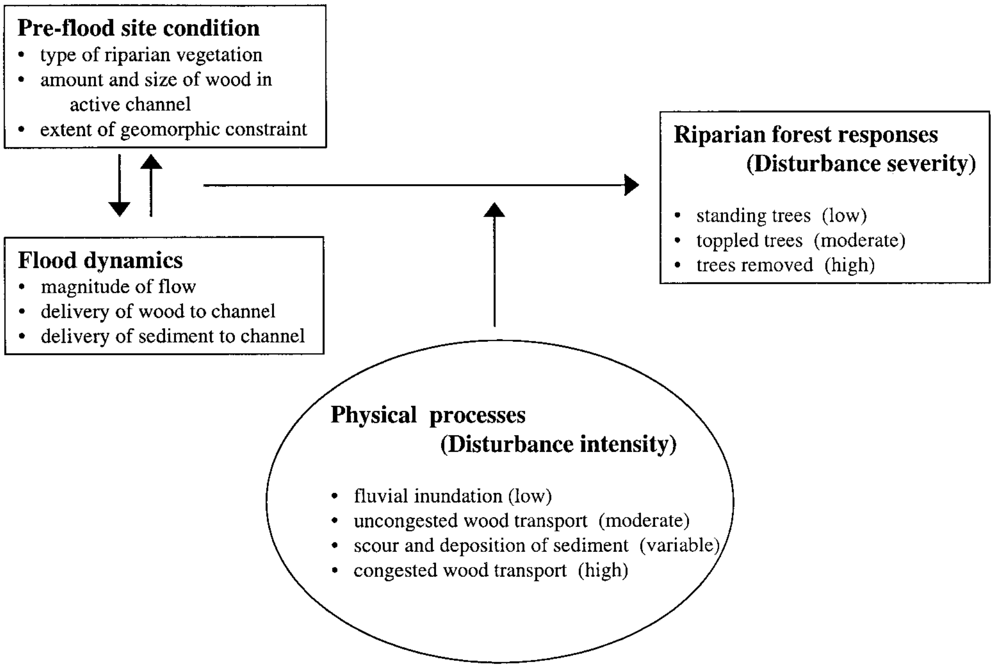

Figure 2. Pre-flood site conditions interact with flood dynamics to determine riparian forest responses to a flood. Physical processes with increasing intensity of disturbance are believed to influence the disturbance severity of riparian forest responses

reach (Table II); (iv) field observations, post-flood, of debris flow transport and depositional patterns. Observations of debris flow path and depositional dynamics post-flood aided in determining whether the wood pieces in debris flows maintained their coherence (congested transport) or became separated and travelled in an uncongested manner. The amount of wood remaining within the high energy zone of reaches after the 1996 flood was not an initial factor of determination of categories owing to multiple factors influencing depositional dynamics.

RESULTS

We observed high variability of flood impacts to riparian forests at three scales; laterally with distance from the channel (plot scale), longitudinally along a stream, and among the eight stream sites (landscape scale). We examined the extent and severity of riparian forest disturbance in relation to the potential of sites for vegetation and geomorphological change to express disturbance patterns. These streams have been the sites of much previous research, which provided a historical and pre-flood perspective to this post-flood study.

Lateral

Average widths of high energy zones were highly variable among streams. The high energy zones from the 1996 flood were wider than the average active channel widths on some streams, but on others were similar in width or even narrower (Figure 3). Small streams into which debris flows delivered tended to have relatively wide high energy zones. The wide high energy zone width in Middle Lookout Creek was the result of the wide valley floor rather than flood effects. Blue River had narrow high energy zone widths, even with small debris flows entering, because the channel is bounded by bedrock and extremely constrained (Figure 4).

The majority of riparian trees standing or toppled within the high energy zone were alder; very few conifers occurred in this zone (Figure 5). Alders ranged in size from 4 to 38 cm diameter. Flood margins had

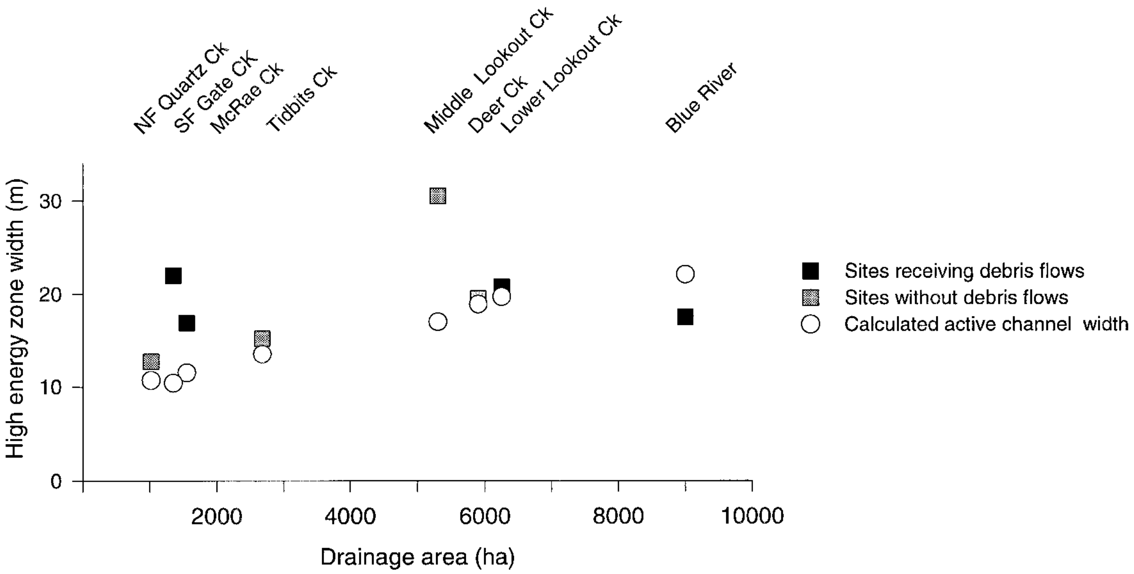

Figure 3. Average high energy zone widths (squares) and calculated active channel (circles) widths for each stream as a function of drainage area

higher richness of tree species and much less toppling, as shown in a representative example from Deer Creek (Figure 6). Average flood depths, measured in the thalweg, ranged from 0·5 to 3·5 m. Flood heights did not appear to be influenced by the entry of debris flows and did not differ as a function of valley floor widths. Valley floor width indices (VFWI) for each stream were not significantly correlated with the widths of low energy zones or with the percentage of riparian trees remaining standing at cross-sections.

Longitudinal

Among streams. The average amount of large wood remaining within high energy zones after the flood generally decreased in streams with larger drainage areas (Figure 5). The percentage of stream high energy zone bordered by wood levees and the average volume of wood jams also decreased. Average wood jam volumes were not higher in streams that had debris flows deliver wood and sediment. Average channel slope decreased with increasing drainage area among sites. Because of local geological outcrops, the amount of the channel flood zone that was constrained by bedrock was greatest in the streams with the largest drainage areas (Figure 4).

Among disturbance categories. Distinguishing stream reaches by categories of availability and mode of transport of wood during the flood indicated that the highest percentage of standing riparian trees occurred in reaches in which there was little wood movement (fluvial) and the lowest in reaches with congested wood transport (Figure 7). The differences among categories were significant (ANOVA, $F = 5{\cdot}96$, P value $= 0{\cdot}02$). The percentage of trees standing, rather than the number of trees standing, was calculated to allow comparison across sites because riparian tree densities varied as a function of pre-flood site characteristics, site potential and flood dynamics. Reaches with uncongested wood transport had more toppled riparian trees than fluvial reaches, but only slightly less than reaches with congested wood transport (Figure 7), due to high scour and therefore low absolute numbers of trees remaining in some reaches in which there had been congested transport. These differences were not significant. The average amount of wood (the sum of number of individual pieces and the number of pieces in wood jams) deposited in the high energy zone reflected the designations of reach categories; differences among categories were significant ($F = 5{\cdot}56$,

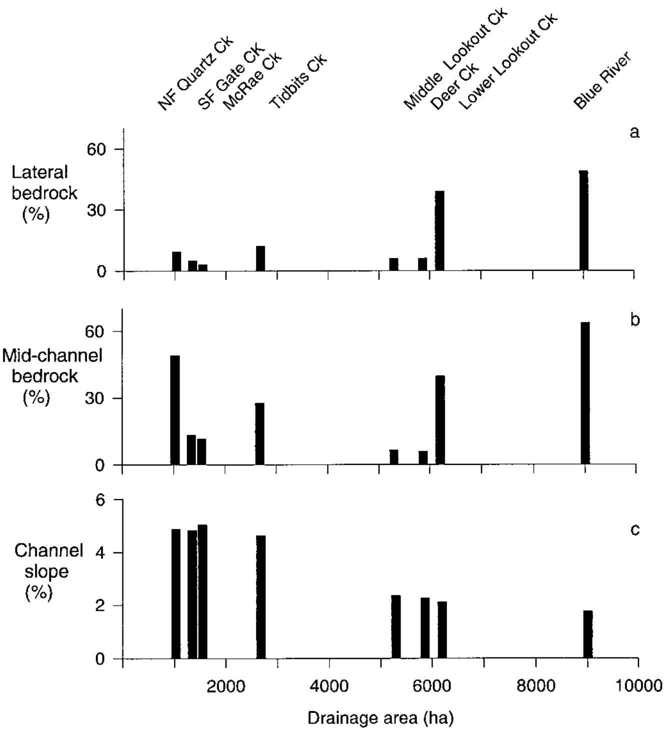

Figure 4. Site characteristics of each study stream arrayed by drainage area: (a) average percentage of total length of channel bordered by bedrock; (b) average percentage of total length of channel with bedrock substrates; (c) average percentage of channel slope. The presence of bedrock was noted for 5 m units for each bank and within the low flow wetted channel. Slopes were measured every 25 m

P value = 0·02). However, amounts in individual reaches varied; for example, Lower Lookout had low amounts of deposited wood and wood jams after the flood, but was categorized as having uncongested wood transport during the flood owing to multiple other factors. The percentage of channel length bounded by wood levees was lowest in fluvial and greatest in uncongested reaches; the differences among categories were significant ($F = 6{\cdot}38$, P value = 0·02).

Within-stream responses — primarily fluvial disturbance. Tidbits Creek had low amounts of wood in the channel (Figure 8), the majority of which did not appear to be mobilized during the 1996 flood. Only two very small debris jams were present following the flood in the study reach. During the 1964 flood, a large debris slide entered Tidbits Creek, delivering wood and sediment to the channel, and triggering a massive debris flow/flood surge down the channel. Since then, wood has been harvested from the stream and floodplain areas. Habitat restoration projects placed wood into the stream channel in 1995 to provide habitat for salmonid fishes (S.V. Gregory, Oregon State University, personal communication). These structures did not wash out during the 1996 flood, nor did they accumulate much additional wood, suggesting that low amounts of wood were transported during the flood. Levees along the flood margins were comprised of old wood, probably dating from the 1964 debris flow. Within the high energy zone, large numbers of alder of mixed sizes remained standing after the 1996 flood and no conifer and very few alder of any age were toppled (Figure 8). Few riparian trees were presumed to have been removed, because a closed-canopy riparian forest extended to the streambank along most of the study reach.

Blue River site had the largest drainage area of the study sites (Figure 4). Very small amounts of wood were present in the high energy zone and wood levees along the margins were few (Figure 5). Wood levels prior to the 1996 flood were low as a result of commercial logging of in-stream and riparian wood following

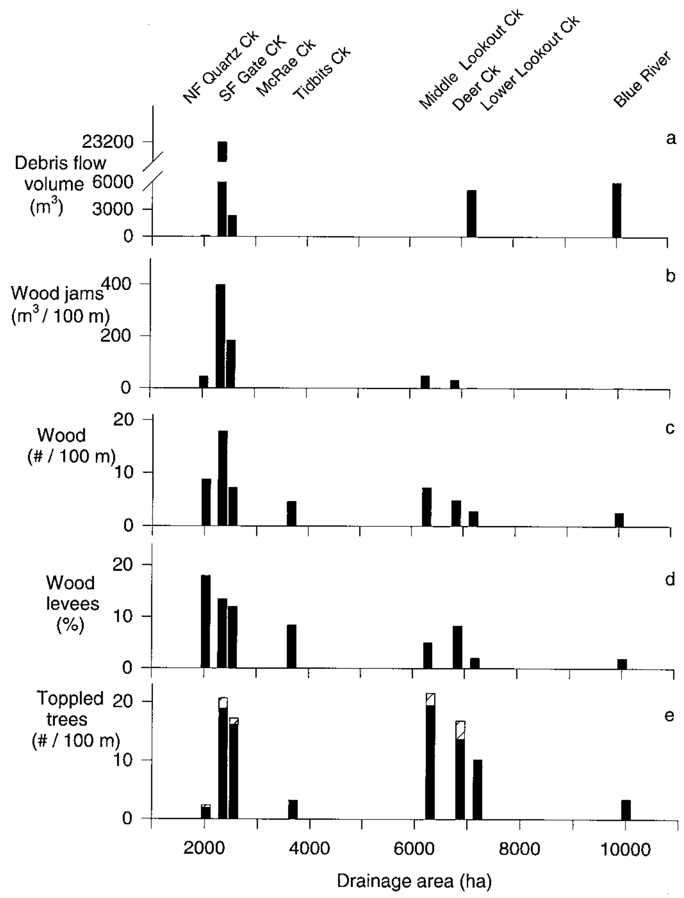

Figure 5. Flood-related inputs and post-flood averages of wood-related materials within the high energy zone: (a) total volume of debris flows delivered to each study site during the 1996 flood; (b) volume of wood debris jams per 100 m of stream length; (c) number of pieces of large wood per 100 m of stream length; (d) the percentage of total channel length with wood levees at the high energy flow margins; (e) number of flood-toppled trees of conifer (hatched fill) and alder (black fill) per 100 m of stream length

the 1964 flood. The presence of riparian trees along the channel before the 1996 flood was limited by bedrock outcrops. After the flood, standing trees were sparsely distributed and clumped, as was the distribution of toppled trees.

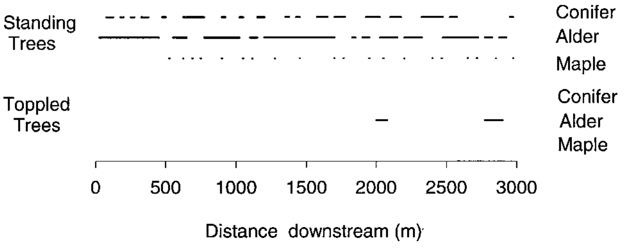

Figure 6. Presence of three tree species bordering the high water margins of the study site at Deer Creek. The locations of standing trees and toppled trees are shown for each species

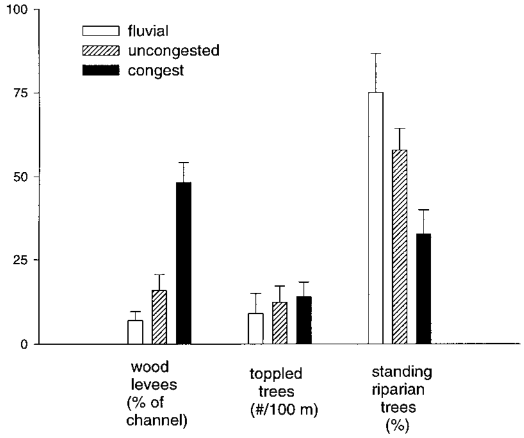

Figure 7. Average (+ SE) percentage of channel bordered by wood levees, number of toppled trees and percentage of riparian forest standing in three categories of flood disturbance

Deer Creek had very limited exposed bedrock (Figure 4). Prior to the flood, high levels of wood had been harvested commercially from the stream and floodplains. Following the 1996 flood, low to moderate amounts of wood in the high energy zone were present and clumped in small debris jams. More trees were toppled than standing and a small portion of the toppled vegetation was large conifer (Figure 5). The percentage of flood margins with wood levees was moderate and may have resulted from previous debris flows.

Within-stream responses — fluvial disturbance plus uncongested wood transport. Middle Lookout Creek also had very low amounts of exposed bedrock (Figure 4). The high energy flood zone was much wider than predicted from drainage area alone, owing to multiple channels that occupy a wide, unconstrained valley floor (Figure 3). Wood was distributed evenly along the length of stream and only a few small debris jams were present (Figure 9). Channel switching and erosion of new channels occurred during this flood as previous main channels were blocked by wood, diverting flow into secondary channels. The high energy zone contained a small number of standing conifers, and some conifers had been toppled by undercutting of stream banks during the flood (Figure 9).

Aerial photographs of Middle Lookout Creek from 1959 show riparian forests that were dominated by a mixture of hardwoods and large conifers (Figure 10), including many old-growth cedar (*Thuja plicata*) and Douglas fir 400 + years old. Stream channels were narrow and often hidden by the forest canopy. By 1967, 3 years after the 1964 flood, the width of the active channel had dramatically increased and the riparian forest had been removed from swaths 40–80 m wide. Aerial photographs since 1967 do not show recolonization of the previous flood zone by conifers. Smaller floods in 1972, 1977 and 1986 resulted in channel avulsion and removal of riparian vegetation.

Lower Lookout Creek had high proportions of lateral and mid-channel bedrock outcrops. A tributary (Watershed 3) delivered multiple debris flows containing wood and inorganic sediments to Lookout Creek at the point 1500 m downstream along the reach studied (Figure 11). This tributary had previously delivered multiple debris flows with abundant large conifers to Lookout Creek during the 1964 flood (Swanson and Dyrness, 1975). During the 1996 flood, it appeared that fewer trees, and primarily alder rather than conifer, were delivered by the debris flow to Lookout Creek. Downstream of the tributary junction for approximately 1 km, very few riparian trees remained standing or toppled in the high energy zone. Pre-flood field observations had recorded alder on alluvial bars, which were now denuded of vegetation following the 1996 flood. Only two small debris jams occurred in this study site and the number of wood pieces present was also

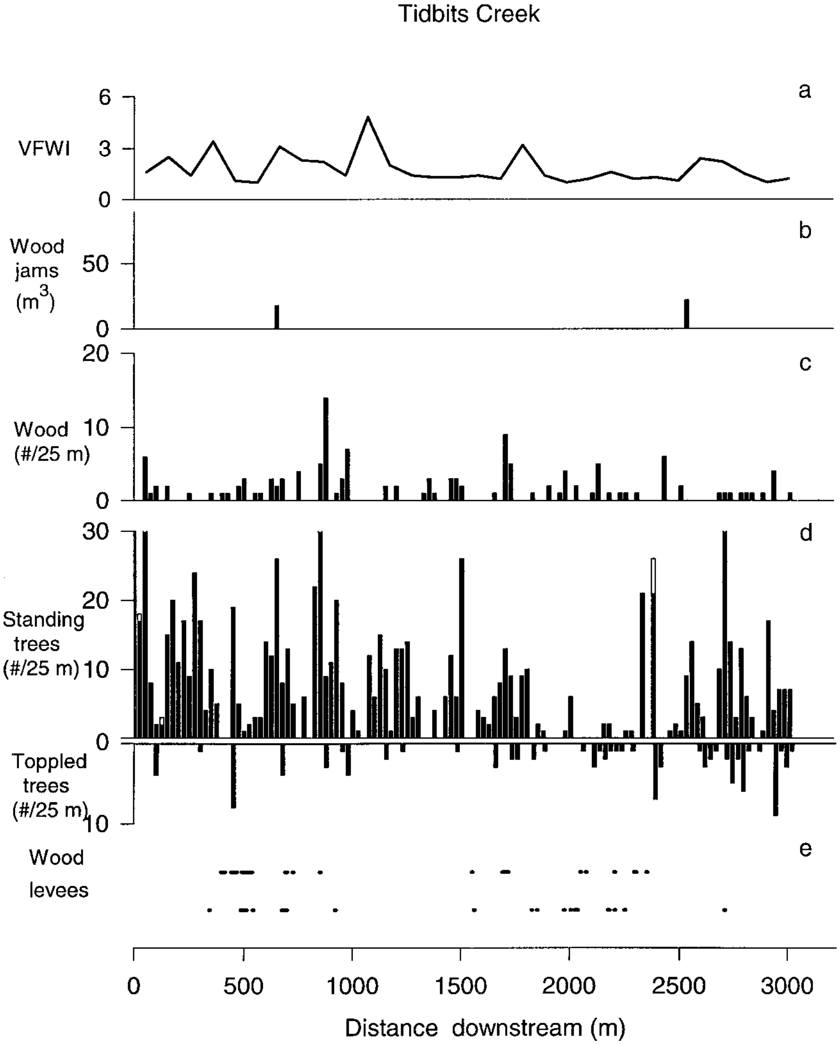

Figure 8. Longitudinal profile of post-flood parameters in the high energy zone of fluvially impacted Tidbits Creek: (a) valley floor width index (VFWI, calculated as valley floor width/active channel width); (b) volume of wood jams; (c) number of pieces of large wood per 25 m of stream length; (d) number of standing and toppled alders (black fill) and conifers (hatched fill) per 25 m of stream length; (e) presence of wood levees along right and left margins of high flow zones

low. Upstream of the junction with the Watershed 3, small and medium alder remained standing, but a larger number were toppled (Figure 11).

Within-stream responses — fluvial disturbance plus congested wood transport. McRae Creek received a debris flow in 1996 from a tributary entering 1100 m downstream of the start of the study reach (Figure 12). The debris flow was comprised of much large wood and sediment; the majority of the wood in this reach appeared to continue to travel down McRae Creek in a congested manner. New wood levees were deposited along the flood margins and constrained the high flows, leading to downcutting of the stream channel into alluvium (Wondzell and Swanson, 1999) and removal or toppling of the majority of riparian trees within the high energy zone for 1·7 km downstream (Figure 12). A large debris jam was deposited at the junction of the debris flow tributary and McRae Creek (1100 m) and a large deposition of transported wood and sediment

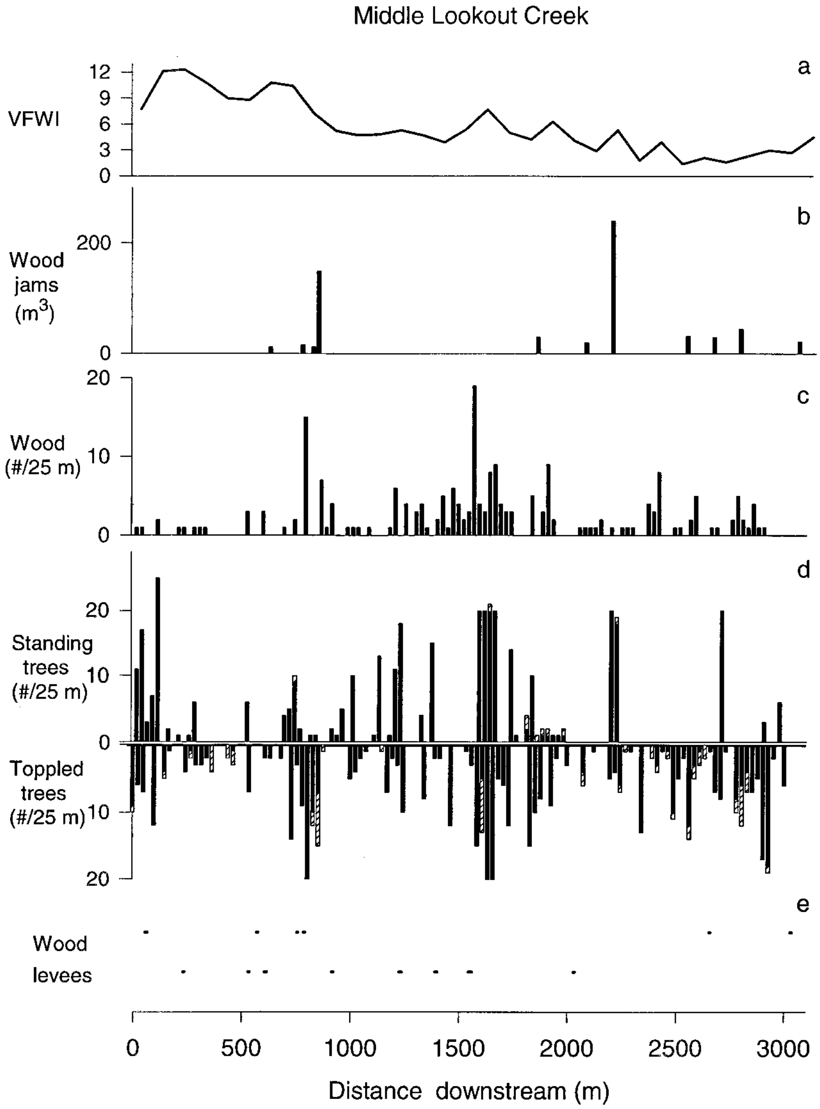

Figure 9. Longitudinal profile of post-flood parameters in the high energy zone of Middle Lookout Creek, in which uncongested wood transport occurred in conjunction with high flows. Graph descriptions are the same as Figure 8

occurred at 2800 m (Figure 12). Downstream of this terminal debris jam and also upstream of the entry of the debris flow, wood transport appeared to have been uncongested. In the downstream reach, large numbers of small and medium sized alders remained standing in the high energy zone and slightly more medium-sized alders than small alders were toppled (Figure 11). Upstream of the entry of the debris flow, very few alders were toppled and many medium-sized alders remained standing. Although wood was distributed along the channel (Figure 12) and available for uncongested transport in the reach above the debris flow, it was primarily large channel-spanning conifer and there was little evidence of much movement of wood in this upstream reach by the flood.

Of the study sites, South Fork Gate Creek (S.F. Gate) had the highest amount of debris flow inputs (Figure 5). It was estimated that over 16 000 m^3 of sediment were mobilized in the headwaters and moved

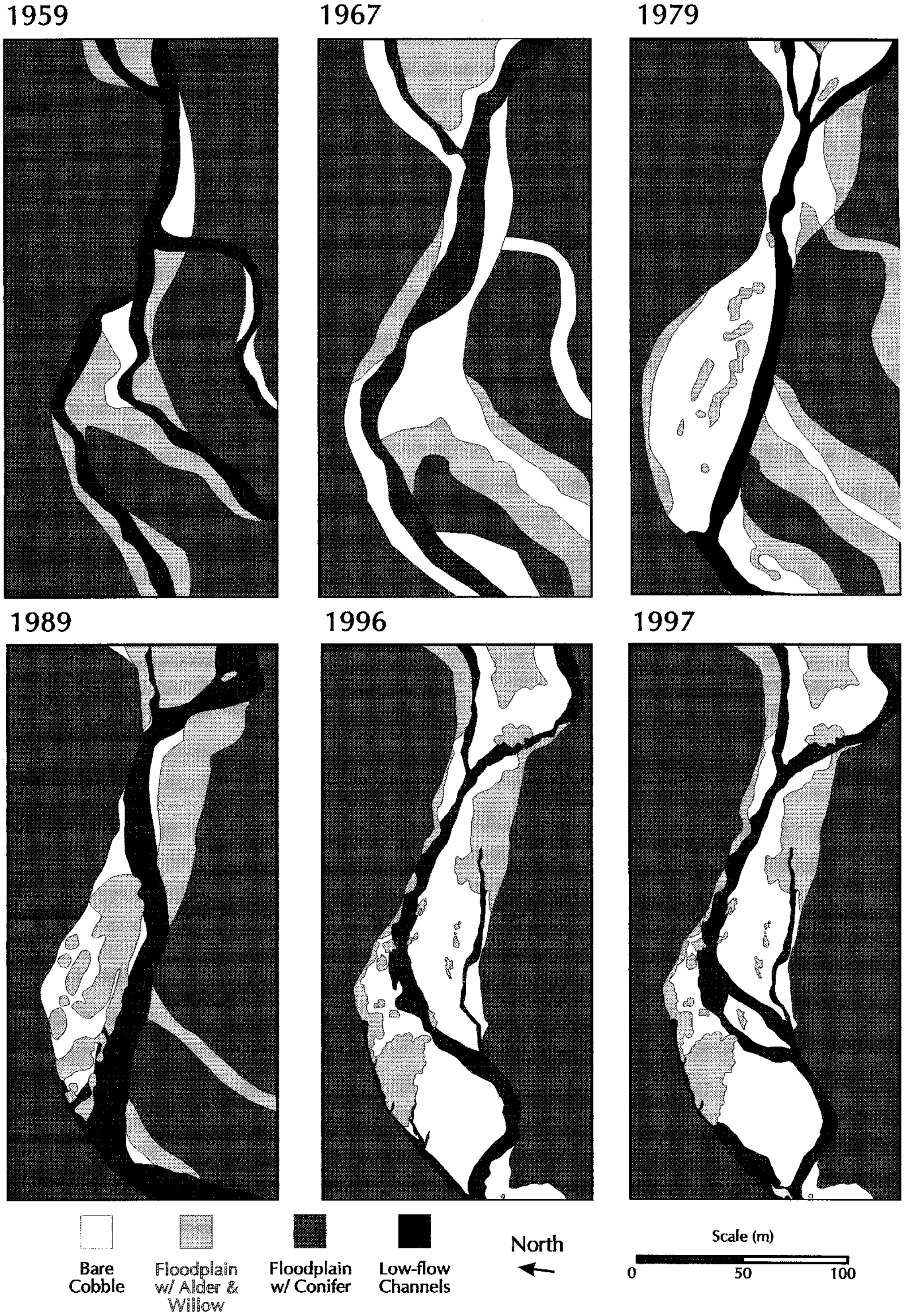

Figure 10. Digitized maps of vegetation types and substrate exposure from aerial photographs of Middle Lookout Creek

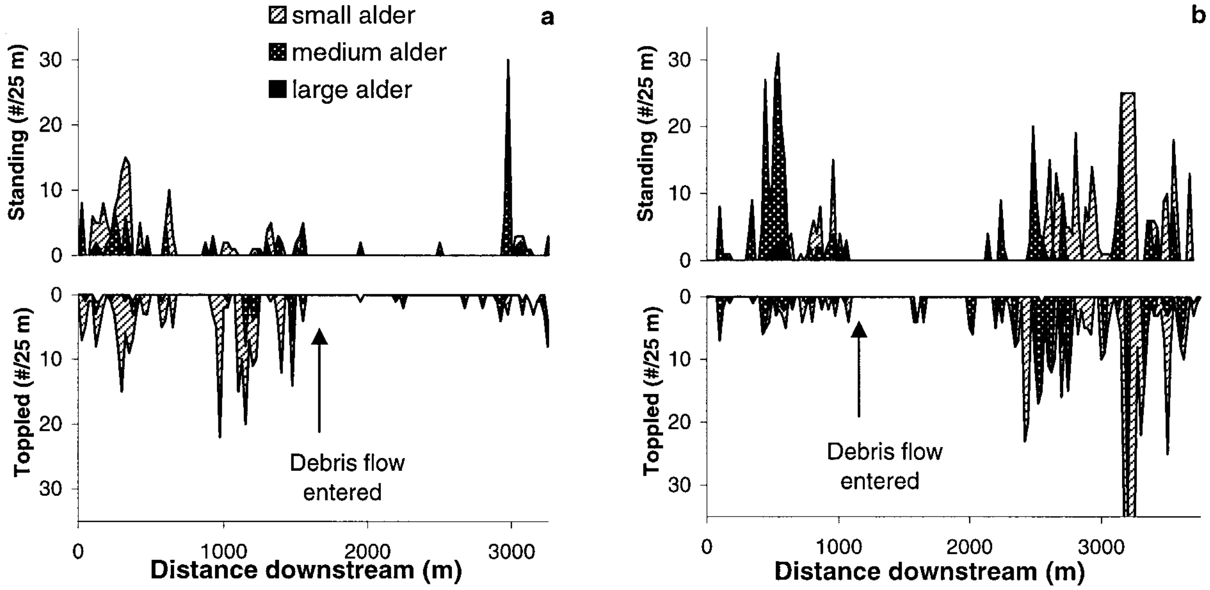

Figure 11. Numbers and sizes of standing and toppled alders within the high energy zone of two streams into which debris flows were delivered: (a) Lower Lookout Creek, in which the wood from the debris flow was transported in an uncongested manner; (b) McRae Creek in which the wood from the debris flow was transported in a congested manner

into the upper reach as bedload transport. Coarse sediment was deposited within the near-channel riparian zone, burying the bases of standing alders to depths of 2 + m in the upper 1500 m, decreasing to 0·5 m in the lower reaches. Large accumulations of wood occurred in the middle reaches and individual pieces of wood were distributed along the length of channel (Figure 13). Much of the wood was slightly decayed, short pieces with cut ends, suggesting that it was logging slash. Few trees remained standing in the high energy zone downstream of the entry of the debris flows and wood levees were numerous (Figure 13). Two debris flows, which entered the channel at 2100 m and 3500 m (Figure 13), appeared to have entered at different flood stages, possibly resulting in dilution and uncongested transport of the most downstream debris flow but more congested, coherent transport of the upstream one.

North Fork Quartz Creek (N.F. Quartz) had the smallest drainage area of the study sites and had a complex history of land-use and debris flow dynamics, which made classification difficult. The basin and riparian zones were heavily harvested in the early 1940s and riparian areas were recolonized by alder (Lamberti *et al.*, 1991); by 1996 these 50-year-old trees were some of the largest alder observed at any site and remained standing post-flood along the upper 1000 m of the channel, a reach designated as having had uncongested wood transport. Previous debris flows had delivered wood and sediment to the stream channel and multiple small debris jams remain. In 1986, a debris flow from a tributary of N.F. Quartz delivered 5000 m^3 of wood and sediment to the channel (Lamberti *et al.*, 1991) and a large debris jam was deposited (at 1300 m downstream in our study). During the 1996 flood, this jam moved and was redistributed over approximately 400 m downstream; this reach was categorized as having had congested wood transport. Numerous wood levees were deposited along the margins (Figure 5), which appeared to have buffered portions of the riparian forest from the high energy flood flows. Low numbers of riparian trees were standing or toppled in this reach after the 1996 flood, but we could not determine the extent to which riparian trees were present before this flood, or had been removed by previous disturbances. The downstream reach, below the terminal lobe of a redistributed debris jam, had uncongested wood transport. Stream habitat enhancement structures remained in place and accumulated small amounts of wood.

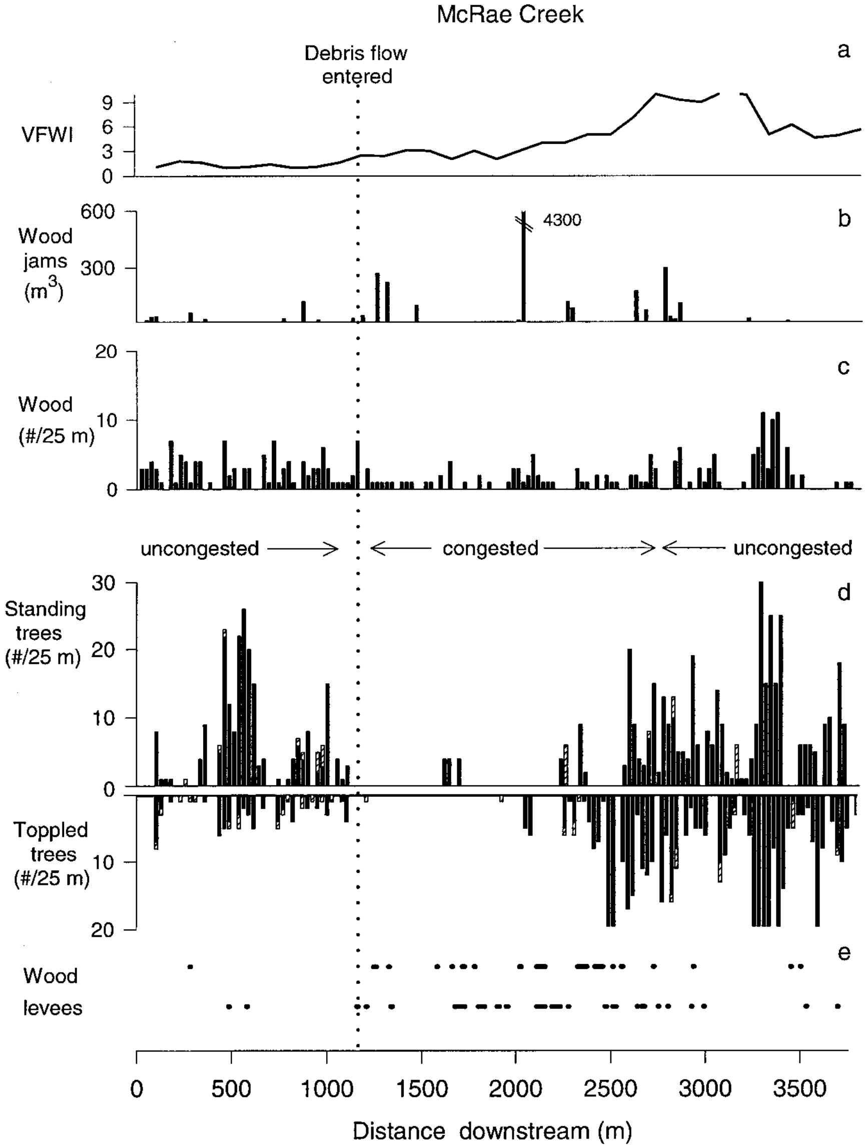

Figure 12. Longitudinal profile of post-flood parameters in the high energy zone of McRae Creek, in which uncongested and congested wood transport occurred. A debris flow, which travelled down a tributary, delivered large wood and sediment to McRae Creek at 1100 m (dotted line) and continued down McRae Creek as congested wood movement for 1700 m. Graph descriptions are the same as Figure 8

DISCUSSION

Floods can result in several types of damage to riparian forests in montane regions. The extent of damage can be indicative of the energy of the flood waters and of physical impact by materials transported by the high flow. Wolman and Miller (1960), Kochel (1988) and others have suggested that the 'geomorphological work', or disturbance potential, of a flood is related to the amount of sediment transported. We suggest that

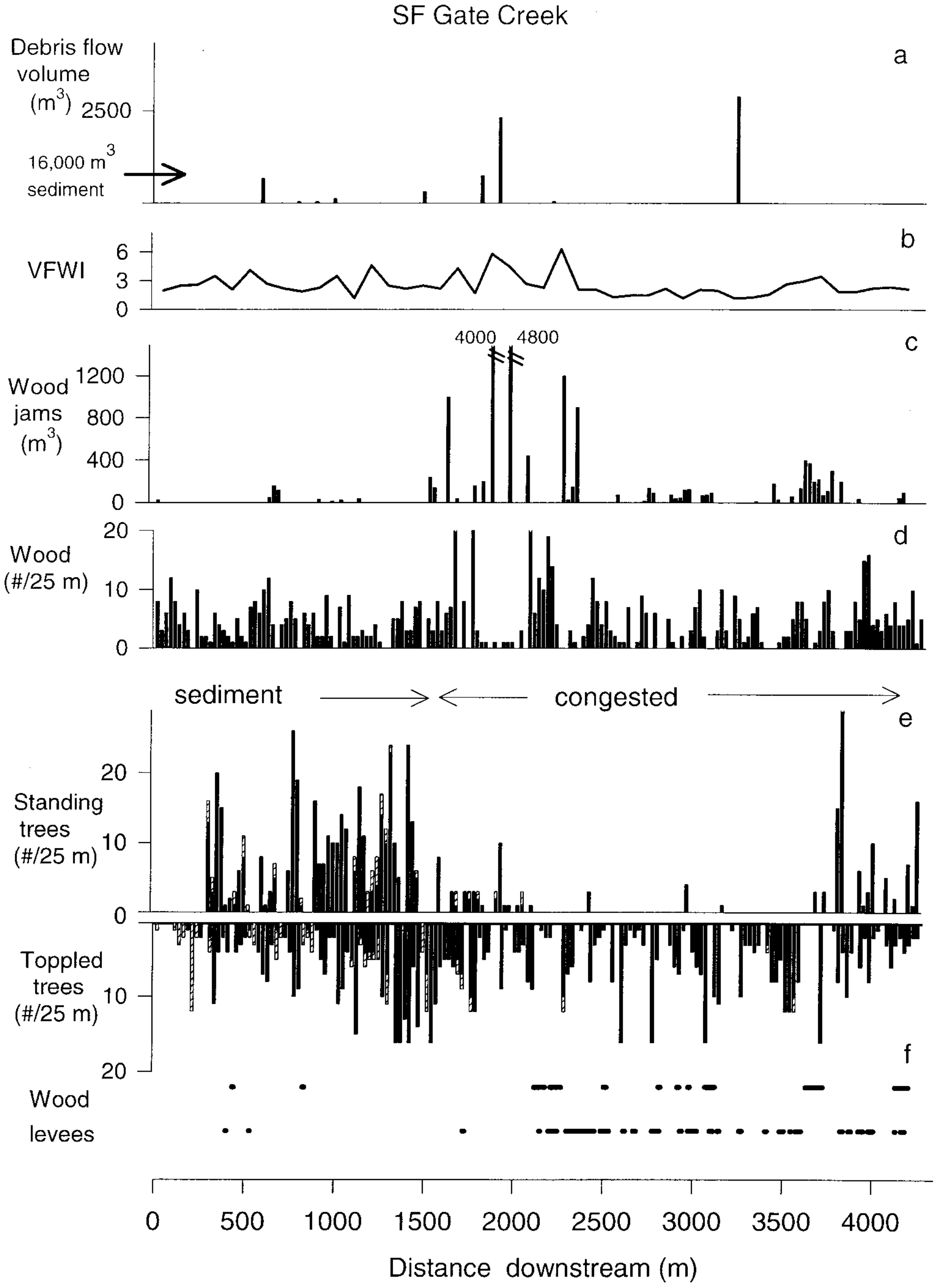

Figure 13. Longitudinal profile of post-flood parameters in the high energy zone of S.F. Gate Creek, in which congested wood transport occurred as well as bedload transport of sediment: (a) volumes of sediment and debris flow inputs to the main channel; (b–e) descriptions are the same as Figure 8

in forested mountain streams and rivers, the agents of disturbance of a flood, especially when examining riparian forest responses, be expanded to include floated wood.

We observed highly variable responses of riparian forests to the February 1996 flood. Zones of severe disturbance, where all riparian vegetation was removed, alternated with zones that appeared to have sustained little disturbance, where small and large riparian trees were standing and undamaged within the high energy zone. The spatial heterogeneity of these riparian responses to disturbance suggests that multiple mechanisms were operating during the flood.

We suggest that a gradient of disturbance intensity (physical force) is exerted on riparian trees during floods that increases from high water alone (fluvial) to high flows supplemented by dispersed pieces of floating wood (uncongested wood transport) to high flows transporting batches of wood (congested wood transport; Braudrick *et al.*, 1997) (Figure 2). These types of material transport and associated classes of disturbance intensity are manifest through increasing disturbance severity, ranging from standing riparian trees inundated by high water, to trees toppled but still partially rooted, to complete removal of trees. We propose that the pre-flood condition of the landscape (Table II) coupled with flood conditions led to variable amounts of wood available for transport, all of which influenced the severity of disturbance to riparian forests (Figure 7).

Riparian interactions with floodwaters: suppression versus augmentation

Riparian forests are not only affected by floods, but interact with the flood flows. The interactions can range from concentrating to dissipating flood energy and are influenced by feedback dynamics of the type of trees, size and location of riparian vegetation. One role that riparian forests often serve during a flood is to dissipate flood energy by providing resistance during high flows (Everitt, 1968; Swanson *et al.*, 1982; Hupp, 1988; Stromberg *et al.*, 1993). Standing vegetation increases the roughness of the channel (increased Manning's n) which dissipates some of the energy of high flows and slows the velocity of water, resulting in deposition of suspended materials. Dense alder riparian forests along these streams might have been expected to have provided increased roughness during the flood and therefore depositional environments. However, stands of alder did not often create low energy zones along these third- to fifth-order streams. In these high gradient, mountain valley streams, upstream dynamics may have dominated over local factors in determining stream power during the flood.

Alternatively, riparian vegetation can constrict high energy flows and narrow the impact zone (Stewart and LaMarche, 1967; Kochel *et al.*, 1987). In our study, riparian forests alone did not constrict the flows but the entrained wood and uprooted trees forcibly deposited against the riparian trees functioned as wood levees, effectively keeping high energy flood water within the stream channel. The constricted flows had higher potential energy, eroding and downcutting channels, as was observed in McRae Creek (Wondzell and Swanson, 1999) and S.F. Gate Creek. On the hillslope side of wood levees, the energy of the water was greatly reduced, creating backwater areas and low energy zones.

Riparian forests can augment flood disturbance in an important additional manner. Existing wood within the channel, trees delivered to channels by debris flows, or riparian trees that have been uprooted and entrained by flood flows can impact against standing trees and provide leverage for the flood waters to topple or uproot them (Stewart and LaMarche, 1967; Keller and Swanson, 1979; Swanson *et al.*, 1998). Reaches with floated wood had lower percentages of standing trees than reaches where less wood was transported by the flood (Figure 7). The type and amount of floated wood and the manner in which it was transported influenced the severity of damage.

Lateral variation in flood impacts on riparian vegetation

Most general hypotheses of flood influences on riparian forests have been derived from studies of lateral impacts of floods (Hupp, 1988; Friedman *et al.*, 1996; Scott *et al.*, 1996), where riparian forests display a gradient of frequency and magnitude of disturbance that decreases with distance from the channel. This disturbance gradient often controls the distribution of riparian vegetation, where either the most floodresistant species (Hupp, 1988; Gregory *et al*., 1991; Friedman *et al*., 1996; Vadas and Sanger, 1997) or the youngest trees (Everitt, 1968; Scott *et al*., 1996; Hughes, 1997) are closest to the channel, and those less tolerant to flooding and older are farther from the channel. We generally observed this pattern in zones at increasing distance from the channel; from high energy zones to low energy zones to hillslopes. The majority of riparian disturbance occurred within alder forests within high energy zones (Figures 8, 9, 12 and 13), while further from the channel, low energy zones sustained only occasional toppling of riparian trees and had higher diversity of tree species (Figure 6). However, within high energy zones, the distribution of impacts was highly variable as a function of distance from the channel.

We had assumed previously that time since disturbance for a surface could be determined by size (or age) of trees on that surface. Surfaces with smaller trees were assumed to have been disturbed in more recent floods (Friedman *et al*., 1996; Scott *et al*., 1996). A very large flood in 1964 in this region removed much riparian vegetation (Stewart and LaMarche, 1967; Lyons and Beschta, 1983) and those surfaces have since been recolonized primarily by red alder. Subsequent smaller floods may have removed patches of the 1964 alder cohort, resulting in riparian stands of multiple ages (Figure 11). A flood should hypothetically disturb all riparian vegetation on the surfaces that were impacted by a previous flood of similar magnitude. Because the 1996 flood was of slightly greater magnitude of discharge than the 1964 flood, it should have potentially disturbed all of the alder recolonizing after the 1964 flood. However, the sizes of standing and toppled alder within the high energy zone were highly variable. Small and large alder remained standing in areas that showed many other signs of high flood energy. Therefore, the median size (or age) of trees may not accurately indicate the time since that surface was disturbed by a flood and the magnitude of previous flood disturbances may be underestimated if erasure is expected. We suggest that floods of equal magnitude may not have an equal impact on all available surfaces, owing to other factors that can influence the intensity and severity of disturbance.

Longitudinal variation in flood impacts to riparian vegetation

We found high variability in riparian flood responses also along the longitudinal gradient of each stream and among streams. Some surfaces within the flood high energy zone were scoured or entirely reworked, but many surfaces were not. The severity of disturbance to these riparian forests was patchy, with reaches where riparian vegetation remained undamaged upstream and downstream of reaches where all the alder trees were removed. We found that distinguishing among reaches, based on the availability of wood for transport, as opposed to examining among streams, provided improved understanding of the distribution and severity of riparian disturbance. Reaches with only fluvial effects had a higher percentage of riparian trees standing after the flood than reaches in which wood was transported (Figure 7).

Congested transport versus uncongested transport. The amount and type of wood mobilized as well as its mode of transport during a flood have important implications for the severity of disturbance to riparian forests (Figure 7). Although wood transport is rarely observed systematically in nature, flume studies have suggested that wood transport occurs in one of two modes (Braudrick *et al*., 1997); uncongested transport, where wood moved as individual pieces, and congested transport, where wood moved *en masse*. The amount and type of material delivered to channels by debris flows (Swanson *et al*., 1998; Nakamura *et al*., 2000, this issue) as well as the size of the receiving channel and the height of flood water at the time of the debris flow have important repercussions on the ability of wood accumulations in debris flows to maintain their coherence and be transported in a congested manner. When a debris flow enters a large stream with high discharge, it tends to be diluted by the large volume of water; the wood can then disperse and move in an uncongested manner. By contrast, in smaller channels, such as third-order or smaller streams, batches of wood delivered by debris flows are more likely to maintain their coherence.

Potential sources of wood vary slightly for the two types of transport. Sources of wood for uncongested transport included mobilization of pre-existing wood within the channel (Middle Lookout Creek), dislodged riparian trees from upstream and within the reach (Lower McRae Creek) and delivery of trees and wood from tributaries by debris flows, which became dissociated upon entering the channel (Lower Lookout

Creek). Wood for congested transport was delivered primarily by debris flows, where the wood accumulation maintained its coherence upon entering the stream channel, resulting in the wood continuing to travel as a unit (McRae Creek and S.F. Gate).

As well as being transported, wood was also deposited as marginal wood levees against standing riparian trees. The wood levees resulting from the 1996 flood were most apparent in streams that had congested wood transport (McRae Creek and S.F. Gate). Many stands of riparian trees were buffered from the floodwaters by the wood levees, increasing the patchy distribution of impacts. Several other studies (Stewart and LaMarche, 1967; Kochel *et al.*, 1987) have noted less extensive levee features and discussed their role as depositional areas in future floods.

The effects of debris flows entering the channels during floods was variable among streams and reach categories. Smaller streams, in which wood delivered by debris flows travelled as congested wood, had widened high energy zones relative to active channel widths (Figure 3). Wood jam volumes were high at some sites that received debris flows, but were very low in others. A trend of decreasing wood availability (jams, individual pieces, levees) with increasing drainage area (Figure 5) may reflect stream-network scale factors associated with larger drainage area and higher stream power that influence the availability of deposited wood in addition to the local scale of inputs from debris flows.

Constrained versus unconstrained. Several authors have suggested that riparian forests are subjected to different flood effects in constrained and unconstrained reaches (Grant and Swanson, 1995; Palik *et al.*, 1998; Nakamura *et al.*, 2000, this issue). Unconstrained reaches, where flood waters can spread out, might sustain less impact to riparian vegetation as a result of the slower, dispersed flows, whereas narrow, constrained reaches might be subjected to more intense disturbances during floods, owing to constricted high energy flows. However, in our study, constrained reaches were not consistently scoured of existing riparian vegetation, but had variable amounts of disturbance to riparian forests and exhibited a range of sizes of standing and toppled alder. In other regions without the abundance of large wood to dominate disturbance dynamics, constraint may be more of a predictor of severity of disturbance to riparian forests.

Legacies and pre-flood site conditions

The condition of a watershed at the time of a major flood has important implications for responses of riparian forests. Legacies of previous floods and land-use practices strongly influence not only the age and type of standing riparian vegetation, but also the availability of disturbance agents, such as large mobile wood within channels that can augment the intensity of disturbance (Figure 2). In our study areas, forest harvest practices that started in the 1940s and 1950s resulted in the construction of numerous logging roads, removal of large conifers from hillslope and riparian areas, and the accumulation of considerable amounts of logging slash in streams (Froehlich, 1973). During floods in the winter of 1964, large volumes of wood and sediment were delivered to stream channels by debris flows and these agents of disturbance in combination with high flows contributed to toppling and uprooting of old-growth riparian conifers (Swanson and Dyrness, 1975; Lyons and Beschta, 1983) (Figure 10). Much of the large wood that was deposited in the channels after the 1964 flood was subsequently harvested, reducing the amounts of wood within the channels. Alder trees became established on sites where old-growth conifers had been removed by the flood.

Although land-use practices accentuated the amount of wood mobilized during the 1964 flood, the net effect of these factors was appreciably lower amounts of wood that were available to be transported by the 1996 flood. Clearcutting 30 years ago along streams and on hillslopes reduced potential sources of new wood to streams. Debris flows from previously harvested areas delivered smaller amounts and sizes of wood. Although a large number of riparian trees were scoured and transported by the 1996 flood, they were smaller alder as opposed to large old-growth conifer. The physical disturbance by flood-transported wood might have been greatly enhanced if large conifers had been the majority of the entrained wood. The disturbance response, however, is also influenced by the rooting structure of riparian tree species; conifers have shallower rooting areas than alder and may be more easily toppled. The 1996 flood encountered a landscape of different structure and composition than previous floods of similar magnitude, highlighting the importance of pre-flood site condition and historical legacies to understanding riparian responses to floods.

In summary, we found high spatial variability of riparian responses to a large flood and suggest that fluvial influences alone had less of an impact on riparian forests than where wood was transported. The type of riparian forest that was present prior to the flood was a result of previous floods and land-use practices and strongly influenced the dynamics of the flood–forest interactions. Ecological and anthropogenic legacies contributed to the complex patterns of disturbance to riparian forests by large floods.

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