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Geomorphology 51 (2003) 31–59
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA

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Received 30 June 2001; received in revised form 6 March 2002; accepted 18 October 2002

Abstract

Comparison of historic channel migration rates, modern planform conditions, and overall sediment, wood, and flow conditions and interactions for the Quinault River and Queets River in the western Olympic Peninsula, Washington, reveals decadal- to century-scale interactions between gravel-bed channels and forested flood plains in temperate maritime environments. The downstream alluvial portions of these two rivers can be divided into three reaches of different slope, flow, sediment, and wood regimes: (i) the upper Quinault River is aggrading behind Lake Quinault, a natural lake that traps most sediment and wood transported from the Olympic Mountain headwaters. (ii) The lower Quinault River, downstream of Lake Quinault, transports only sediment and wood derived from reworking of flood-plain deposits and contributed from valley margins. (iii) The Queets River has unimpeded movement of sediment and water from the mountainous headwaters to the Pacific Ocean. Measurements of channel planform characteristics and historic migration rates and patterns show that these three reaches have correspondingly distinct channel and flood-plain morphologies and dynamics. The aggrading and sediment-rich upper Quinault River has the widest flood plain, widest active channel, greatest number of low-flow channels and flanking gravel bars, and an average channel migration rate of 12.7 ± 3.3 m/year between 1900 and 1994. The comparatively sediment-poor lower Quinault River has the narrowest flood plain, narrowest active channel, and lowest channel migration rate (4.0 ± 1.2 m/year); and most flow is through a single channel with few adjacent gravel bars. The Queets River has attributes intermediate between the lower and upper Quinault Rivers, including an average channel migration rate of 7.5 ± 2.9 m/year. Flood-plain turnover rates are similar for all three reaches, with channels eroding the flood plain at the rate of about 0.2% of the flood-plain area per year, and with corresponding flood-plain half-lives of 300 to 500 years.

Observations from this study and previous studies on the Queets River show that channel and flood-plain dynamics and morphology are affected by interactions between flow, sediment, and standing and entrained wood, some of which likely involve time frames similar to 200–500-year flood-plain half-lives. On the upper Quinault River and Queets River, log jams promote bar growth and consequent channel shifting, short-distance avulsions, and meander cutoffs, resulting in mobile and wide active channels. On the lower Quinault River, large portions of the channel are stable and flow within vegetated flood plains. However, locally, channel-spanning log jams have caused channel avulsions within reaches that have been subsequently mobile for several decades. In all three reaches, log jams appear to be areas of conifer germination and growth that may later further influence channel and flood-plain conditions on long time scales by forming flood-plain areas resistant to channel migration and by providing key members of future log jams. Appreciation of these processes and dynamics and associated

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0169-555X/02/$ - see front matter. Published by Elsevier Science B.V.
PII: S0169-555X(02)00324-0

temporal and spatial scales is necessary to formulate effective long-term approaches to managing fluvial ecosystems in forested environments.

Keywords: Channel migration; River pattern; Large woody debris: log jams; Flood plains; Gravel-bed rivers; Olympic Peninsula

1. Introduction

Channel and flood-plain morphology develop from a suite of processes involving sediment and water movement, channel migration, flood-plain erosion and deposition, and wood entrainment and deposition. For alluvial rivers with forested flood plains, feedbacks between channel instability and sediment and wood input and deposition are important factors in controlling channel migration processes and resulting channel and bar morphology at the reach scale (lengths of channel on the order of 10 to 20 channel widths; e.g., Keller and Swanson, 1979; Fetherston et al., 1995; Abbe and Montgomery, 1996; Abbe, 2000). At broader spatial and temporal scales involving several decades and segments of rivers greater than about 20 channel widths, interactions between the channel and forested flood plains have also been hypothesized to control valley-scale patterns of channel instability and flood-plain formation and morphology (e.g., Swanson and Lienkaemper, 1982; Hickin, 1984; Sedell and Froggatt, 1984; Gottesfeld and Gottesfeld, 1990; Church, 1992; Piégay and Gurnell, 1997; Fetherston et al., 1995; Abbe and Montgomery, 1996; Abbe, 2000; Gurnell et al., 2000). While there have been numerous studies that describe such processes and resulting channel and flood-plain morphology, especially at the reach scale, there have been few comparative studies of large alluvial rivers from which to draw conclusions of how these interactions might relate to specific conditions of flow, slope, wood and sediment input, and how these interactions might relate to broader-scale channel and flood-plain conditions.

This paper describes evidence for rates and mechanisms of channel migration on the wood-rich Quinault and Queets Rivers of the western Olympic Peninsula in NW Washington state (Fig. 1). In particular, we describe how differences in channel migration rates and patterns between the two rivers likely relate to differences in interactions among flow, flood-plain forests, sediment flux, and other reach and valley characteristics. Our conclusions draw primarily from analysis of historic channel migration supported by mostly anecdotal historic and field observations of wood, channel, and flood-plain conditions and interactions. Many of our interpretations regarding the specific role of wood in affecting channel and flood-plain dynamics derive in part from studies by Fetherston et al. (1995) and Abbe and Montgomery (1996, 2003) on the Queets River.

2. Setting of the Quinault and Queets Rivers

2.1. Watershed physiography and climate

Both the Quinault River and Queets Rivers drain the rugged core of the Olympic Mountains within Olympic National Park before emptying into the Pacific Ocean along the western coast of the Olympic Peninsula (Fig. 1). The headwaters of each basin are incised into Tertiary marine sedimentary and volcanic rocks that have undergone rapid Cenozoic uplift (Tabor and Cady, 1978a,b; Brandon et al., 1998). Both rivers drain SW from glaciated mountains with peaks higher than 2200 m, exiting the Olympic Mountains and then flowing across a 10- to 30-km wide coastal piedmont underlain by Quaternary glaciofluvial sediment. The Queets River drains a total area of about 1170 km^2 and the Quinault River drains 1134 km^2 (Table 1).

Fig. 1. Location maps of the study reaches. (a) Map of Queets and Quinault River drainage basins and geologic flood plains of the three study reaches. Topographic base from USGS 30-m digital elevation model. (b) Geologic flood plains and 1994 channel of each of the three study reaches. Flood-plain and channel transects shown at 1-km intervals. (c) Section of the Queets River flood plain showing 1994 channels and flood-plain surfaces as mapped from 1994 orthophotos. Channel and flood-plain transects are spaced at 0.2-km intervals.

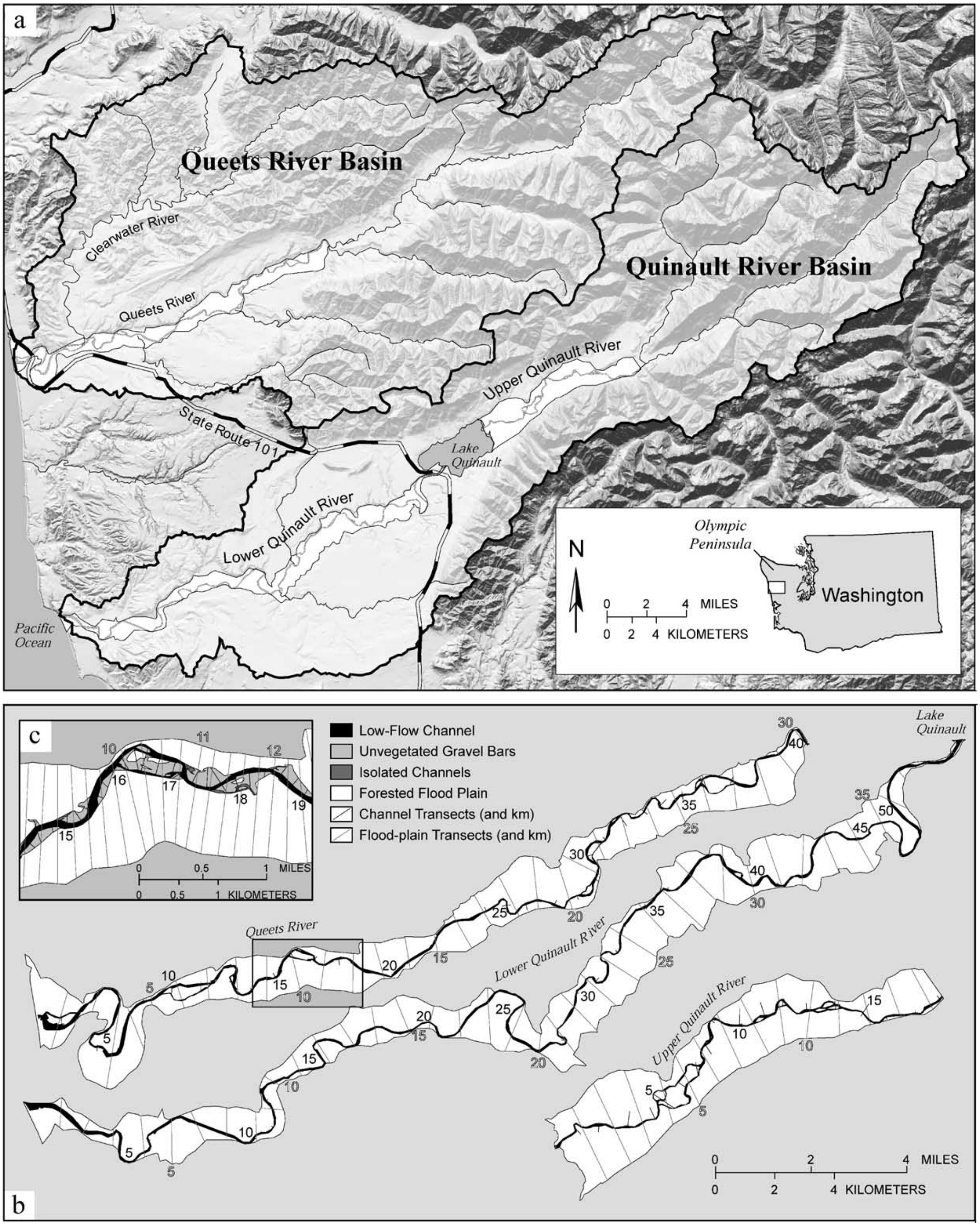

a
Queets River Basin
Quinault River Basin
Clearwater River
Queets River
Upper Quinault River
State Route 101
Lake Quinault
Lower Quinault River
Pacific Ocean
Olympic Peninsula
Washington
N
0 2 4 MILES
0 2 4 KILOMETERS
c
Low-Flow Channel
Unvegetated Gravel Bars
Isolated Channels
Forested Flood Plain
Channel Transects (and km)
Flood-plain Transects (and km)
0 0.5 1 MILES
0 0.5 1 KILOMETERS
Queets River
Lower Quinault River
Upper Quinault River
Lake Quinault
0 2 4 MILES
0 2 4 KILOMETERS
b

Table 1
General study reach characteristics

Reach	Lower Quinault	Upper Quinault	Queets
Location	Lake Quinault outlet (RK 51.6) to Pacific Ocean	North Fork Quinault River confluence (RK 73.9) to Lake Quinault (RK 56.6)	Sams River confluence (RK 39.4) to Pacific Ocean
Length (km)[a]	54.0	18.0	41.2
Drainage area (km^2)	1124 at downstream end[b]; 683 at upstream end[c]	441 at upstream end[b]	1152 at River Mile 4.6[c]
Mean discharge (m^3/s)	81[c]	–	123[c]
Slope (m/m)[d]	0.0011	0.0035	0.0022
Low-flow channel width (m)[a]	65.4–27.7	58.3–24.3	68.9–39.6
Number of channels[a]	1.02–0.14	1.41–0.73	1.30–0.62
Active channel width (m)[a]	95–45	240–104	165–89
Sinuosity (m/m)[a]	1.37	1.24	1.27
Mean flood plain width (m)[e]	1245	1930	1286
Total flood plain area (ha)	4831.8	2728.4	3914.3
Total area historically occupied by channel (ha)[f]	1509.5	675.2	1050.3

[a] Measured from 1994 orthophotoquads.
[b] Geographical Information System analysis (Quinault Indian Nation and USDA Forest Service, 1999).
[c] Information from USGS gage Quinault River at Quinault Lake (12039500), 1912–1997 and Queets River near Clearwater (12040500), 1931–1997 (Wiggins et al., 1998).
[d] Measured from USGS 7.5-min topographic quadrangles.
[e] Measured at 0.20-km increments along flood-plain centerline.
[f] Cumulative area of channels depicted on historic maps and photos (Fig. 2).

Both of these watersheds are strongly influenced by Pacific maritime conditions. During fall, winter, and spring, these watersheds are repeatedly subject to large storms from the SW, delivering substantial rainfall at lower elevations and snow in the higher Olympic Mountains. Summers are relatively dry. Mean annual precipitation is about 3.6 m at Lake Quinault, somewhat less on the coast, and much greater in the mountainous headwaters because of orographic effects. The large precipitation volumes are reflected in high average flows; average annual flow generation is 3.4 m^3/m^2 for the Queets watershed and about 3.7 m^3/m^2 for the Quinault watershed. Particularly large flows, such as the one of March 1997, result during warm and wet storms during which rivers gain substantial flow from melting of low-elevation snowpack.

2.2. Alluvial reaches

As both rivers leave the core of the Olympic Mountains and approach the western foothills and coastal piedmont, valley bottoms broaden and the rivers have established alluvial flood plains up to 3.5 km wide that are flanked by the western ramparts of the Olympic Mountains or, further downstream, by tall bluffs of Pleistocene glacial till and outwash. Overall, channel gradient in the alluvial section of the Queets River between river kilometer (RK) 0 and RK 42.5 is 0.0023; the overall slope for the alluvial section of Quinault River between RK 0 and RK 84.3 is 0.0022. Within their alluvial sections, both rivers have cobble-gravel beds with pool-and-riffle profile morphologies. The planview patterns of these rivers do not neatly fit into standard classes such as "braided" or "meandering" but, at length scales of tens of kilometers, are similar to the "irregular wandering" or "irregular meandering" morphologies as described by Church (1992). Shorter reaches within these wandering river segments have braided (flow around bars within an active channel) and anastomosing (flow around islands excised from the flood plain) planforms as defined by Knighton and Nanson (1993).

Within their alluvial valleys, both of these rivers have shifted back and forth during the Holocene, leaving a suite of fluvial landforms. Valley-bottom surfaces range from unvegetated gravel bars to densely forested alluvial surfaces several meters above the present channel. Aquatic environments include swift flowing main channels, side channels, abandoned channels that are now ponds or wetlands, and abandoned channels that now serve as routes for local tributaries. The native flood-plain trees include hardwoods such as red alder (*Alnus rubra*), vine maple (*Acer circinatum*), bigleaf maple (*Acer macrophyllum*), and black cottonwood (*Populus trichocarpa*) and conifers Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), and smaller amounts of western red cedar (*Thuja plicata*) and Douglas fir (*Pseudotsuga menziesii*). Immense trees grow in the temperate maritime climate, with stem dimensions of some Sitka spruce, Douglas fir, western red cedar exceeding 4 m in basal diameter and 70 m in height.

Despite similarities in the geology, physiography, and channel characteristics between the two watersheds, significant differences result in contrasting channel and flood-plain processes and morphology. The foremost dissimilarity is the continuity of sediment and wood transport. The Queets River flows uninterrupted from its headwaters to the Pacific Ocean, allowing continuous passage of water, sediment, and large woody debris along its entire course. In contrast, the alluvial section of the Quinault River is interrupted between RK 51.6 and RK 56.6 by Lake Quinault, a moraine-dammed lake with a surface area of 15 km^2 (Fig. 1). Lake Quinault forms an intermediate base level for the Quinault River and traps all coarse sediment (sand and coarser) and most large woody debris. Consequently, the Quinault River has two distinct alluvial segments; an upstream segment between RK 56.6 and RK 84.3 that receives sediment and wood from upstream and is aggrading behind the base level set by Lake Quinault, and a segment downstream from the lake (RK 0 to RK 51.6) that receives neither sediment nor wood from upstream. Furthermore, transient flow storage in the lake substantially attenuates peak flows of the Quinault River downstream of Lake Quinault, reducing peak discharges of the five largest flows between 1933 and 1960 by 38%, as determined by comparing normalized discharges for a series of floods on the Queets and Quinault Rivers (Quinault Indian Nation and US Department of Agriculture Forest Service, 1999, pp. 2.4–6).

Ownership and land use history also differ between the Queets River and Quinault River valleys. Most of the Queets River flood plain is now within the Olympic National Park, although early settlers locally cleared and harvested parts of the flood plain prior to acquisition by the Park Service in the 1940s. The lowermost 15 km of the Queets River is within the Quinault Indian Nation Reservation, and the flanking flood plain was mostly unaffected by timber harvest until the 1990s. Upstream of Lake Quinault, the Quinault River flood plain is under a mixture of ownerships, including Olympic National Park, Olympic National Forest, and private landowners. Parts within the National Park are largely undisturbed, but other ownerships have cleared and harvested small areas of the flood plain. The Quinault River flood-plain downstream from Lake Quinault is completely within the Quinault Indian Nation Reservation and has been almost completely harvested one or more times since the late 1920s.

2.3. The study reaches

These differences and the general physiography conveniently lead to the three independently analyzed river segments (Fig. 1; Table 1): (i) the lower Quinault River downstream of Lake Quinault with no upstream-derived sediment or wood and an average gradient of 0.0011, (ii) the alluvial section of upper Quinault River between the North Fork confluence and Lake Quinault that does receive wood and coarse sediment from upstream and has an average gradient of 0.0035, and (iii) the alluvial section of Queets River between RK 41 and RK 0 that also receives sediment and wood from upstream, but has a lower average gradient of 0.0022. The multiple differences among the reaches in what might be considered "independent" or "predictor" variables (sediment and wood supply, slope, flood discharge, land use history) prevent rigorous isolation of the effects of individual variables on channel and flood-plain morphology. Nevertheless, measured and observed differences in channel pattern and dynamics, as discussed in the following sections, can be

Table 2
Summary of sources for mapping of historic channel positions

Channel map source	Scale	Coverage		Dates	Plot date	Comments
General Land Office Surveys (available at the Bureau of Land Management, Portland, OR)	1:31,680	Queets	Sams River confluence to Pacific Ocean	1895–1906	1900	Instrument survey of stream channel (and unvegetated gravel bars?).
		Upper Quinault	Entire study reach	1895–1906	1900	Digitized from 1:31,680
		Lower Quinault	Quinault Indian Reservation	1902	1902	paper copies; georeferenced by section corners.
Office of Indian Affairs (available at Quinault Indian Nation, Taholah, WA)	1:31,680	Lower Quinault	Quinault Indian Reservation	Map dated 1920, notes state surveyed 1915–1917	1915	Transit and stadia for primary control. Digitized from 1:31,680 paper copy; georeferenced by section corners.
US Army Corps of Engineer Tactical Maps "Destruction Island" and "Queets"	1:62,500	Queets	Elk Park to Pacific Ocean	Maps dated 1922, unknown survey date	1922	Surveyed and compiled by US Coastal and Geodetic Survey; methods unknown. Map not used for channel migration analysis because of unsatisfactory registration.
US Geological Survey (USGS) Plan and Profile River Maps (available at University of Washington Map Library, Seattle, WA)	1:31,680	Queets	Paul Creek confluence to Pacific Ocean	Map dated 1935, notes state surveyed 1931–1933	1931	Survey methods unknown but probably by transit and stadia. Digitized from paper copy; georeferenced by
		Upper Quinault	Rustler Creek confluence to Lake Quinault	Map dated 1930, notes state surveyed 1929	1929	section corners. Lower Quinault reach required significant editing due to
		Lower Quinault	Lake Quinault to Pacific Ocean		1929	poor registration.
1939 USGS aerial photographs (available at US Geological Survey, Tacoma, WA)	1:60,000	Most of the Olympic Peninsula		7–39 and 8–39	1939	1939 channel transcribed by eye onto 7.5′ quadrangles and digitized. Spatially referenced by quadrangle corners.
15′ USGS topographic quadrangles	1:62,500	Queets	Entire study reach	Maps dated 1956; on the basis of 1952 source photographs	1952	Digitized from paper copy. Spatially referenced by quadrangle corners.
		Upper Quinault	No 1950s source coverage east of 123°E45°N (RK 67.6)	Maps dated 1953–1955 on the basis of 1953–1954 aerial photography	1953	
		Lower Quinault	Entire study reach		1953	
Duncan and Steinbrenner (1976?) Soil Survey (available at Quinault Indian Nation, Taholah, WA)	1:31,680	Lower Quinault	Quinault Indian Reservation	Map dated 1976(?); on the basis of 1972 aerial photographs	1972	"River" polygons from existing Quinault Indian Nation digital coverage. Date of source photographs provided by Tony Hartrich, Quinault Indian Nation.

Table 2 (*continued*)

Channel map source	Scale	Coverage		Dates	Plot date	Comments
7.5′ USGS topographic quadrangles	1:24,000	Queets	Entire study reach	Map dated 1982–1990; on the basis of 1980, 1981, and 1987 source photographs	1981	Digitized from 1:24,000 paper copy. Spatially referenced by quadrangle corners. Plot dates assigned on the basis of comparisons of mapped channel positions with aerial photographs from time period.
		Upper Quinault	Entire study reach	Maps dated 1990; on the basis of 1981, 1985, and 1987 aerial photography	1981	
		Lower Quinault	Entire study reach	Map dated 1982–1990, on the basis of 1980, 1981, 1985, and 1987 source photographs	1981	
1994 USGS and Washington Department of Natural Resources (DNR) digital orthophotoquads	Derived from 1:12,000 to 1:40,000 aerial photos	Queets	Entire study reach	DNR Sept. 22, 1994	1994	Channel digitized from 1:24,000 paper copy (Queets R.) and on screen from 1:5000) georeferenced digital orthophotoquadrangles (Quinault R.). Queets R. discharge Sept. 22: 25.4 m^3/s. Quinault R. discharge July 11: 35.7 m^3/s, Quinault R. discharge Sept. 16: 54.4 m^3/s, Quinault R. discharge Sept. 22: 24.5 m^3/s
		Upper Quinault	Entire study reach	USGS Sept. 16, 1994		
		Lower Quinault	Entire study reach	USGS July 11 (major;) and DNR Sept. 22 (minor), 1994		
1997 Quinault Indian Nation digital orthophotoquads (available at Quinault Indian Nation, Taholah, WA)	Derived from 1:12,000 aerial photos	Lower Quinault (and lower 15.8 km of the Queets River)	Quinault Indian Reservation	DNR	1997	Channel digitized on screen (1:5000) from georeferenced digital orthophotoquads. Only the lower Quinault coverage used in the channel migration analysis.

qualitatively attributed to differences in flow, slope, and sediment and wood inputs.

3. Methods

For each of the three study reaches, channel characteristics and historic channel migration rates were mapped and measured from historic and current aerial photographs and maps. Inferences regarding interactions between large woody debris, standing forests, the channel, and flood plain were based on historical records and reconnaissance field observations, supplemented by previous work on the Queets River by Fetherston et al. (1995), Abbe (2000), and Abbe and Montgomery (1996, 2003).

3.1. Modern profile and planform characteristics

Channel profiles were obtained from spot water-surface elevations and 6 m (20 ft) contour crossings on USGS 7.5-min topographic quadrangles that were surveyed during the 1980s. Modern channel planform characteristics were measured from digital orthophotos made in the summer of 1994 that covered all three river segments (Table 2). To quantify planform features, measurement transects were placed perpendicular to the centerline of the primary low-flow channel at 0.2-km increments (Fig. 1c). The primary low-flow channel was defined as the widest wetted channel, although in some locations of two or more roughly equal-sized channels, we arbitrarily chose a single channel from which to establish transect locations and orientations. For each of these transects, we measured the number, width, and area of the primary low-flow channel as well as other visible water-filled channels connected at their upstream and downstream termini at the time of the photographs (dates and approximate discharges indicated in Table 2). We also measured the number, width, and area of isolated or partly isolated waterbodies assumed not be flowing, defined as those either not connected to a through-going low-flow channel (i.e., flood-plain lakes and ponds) or a channel only connected at one end to a through-going low-flow channel (i.e., backwater channel). In addition, we also measured the number, width, and area of unvegetated gravel bars. We considered the sum of the widths of the flowing channels and flanking unvegetated gravel bars to represent the "active channel" width as described by Osterkamp and Hedman (1982), which for the Quinault River and Queets Rivers is the part of the flood plain that had sufficient flow during the few years prior to the summer of 1994 to prevent substantial establishment of woody vegetation. The resolution of the 1994 orthophotos is 2 m, but, because of canopy cover, it is likely that many channels and gravel bars less than 10 m wide and bordered by vegetated flood plains were not included in the transect measurements.

More general flood-plain properties were characterized with similar types of measurements using the centerline of the valley bottom (here termed "geologic flood plain") as a frame of reference (Fig. 1c). A flood-plain reference frame allows for systematic measurements of broad-scale attributes such as channel sinuosity and flood-plain width. Furthermore, measurements based on a flood-plain centerline frame of reference are more appropriate for channel and flood-plain features that are widely dispersed across the flood plain and not necessarily causally associated with the present channel.

For both rivers, the geologic flood plain was mapped from aerial photographs, topographic maps, and field observations and consists of the relatively flat areas between flanking valley slopes. For the Queets River, the geologic flood plain closely corresponds to the Holocene alluvium map unit of Thackray (1996). The mapped flood plains of both rivers contain areas of slightly higher elevation that may be due to Neoglacial or earlier Holocene aggradation but are nevertheless inundated during large flows. The delineated flood plains for all three river segments exclude tributary fans.

3.2. Channel migration

Patterns and rates of channel change for each of the three study reaches were determined from maps, aerial photos, and orthophotos showing channel position between 1895 and 1997 (Table 2, Fig. 2). Channel boundaries as shown on each source were digitized into a geographic information system. Channel positions derived from maps and orthophotos were georeferenced by quadrangle corners and public land survey township corners. Channel positions from aerial photograph sources were first transcribed onto topographic quadrangles and then digitized.

Several sources of uncertainty affect quantitative assessments of channel position with time from these types of historical data. A key uncertainty associated with the turn-of-the-century General Land Office (GLO) surveys is that they do not necessarily show the actual channel boundary but the inferred channel extent at "mean high-water elevation," which "is found at the margin of the area occupied by the water for the greater portion of each average year" (Bureau of Land Management, 1973, pp. 93–97). In practice, this definition probably results in local inclusion of gravel bars and overflow channels outside the low-flow channel, whereas most other sources portray only the low-flow channel. This was clearly the case for the GLO surveys of the upper Quinault River (Fig. 2b), but the GLO maps for the lower Quinault River and Queets River distinguish between channel and unvegetated gravel bars. Other uncertainties arise from differences in flow stage, errors in transcription, and errors in registration and digitizing. From consideration of the degree of overlay of relatively stable reaches and the scale of the source documents, our estimate of the maximum error in placement of channel boundaries from the older sources (1900–1902 GLO maps, 1921–1931 USGS Plan and Profile Maps, and 1939 aerial photos) is about 50 m, but the error is probably much

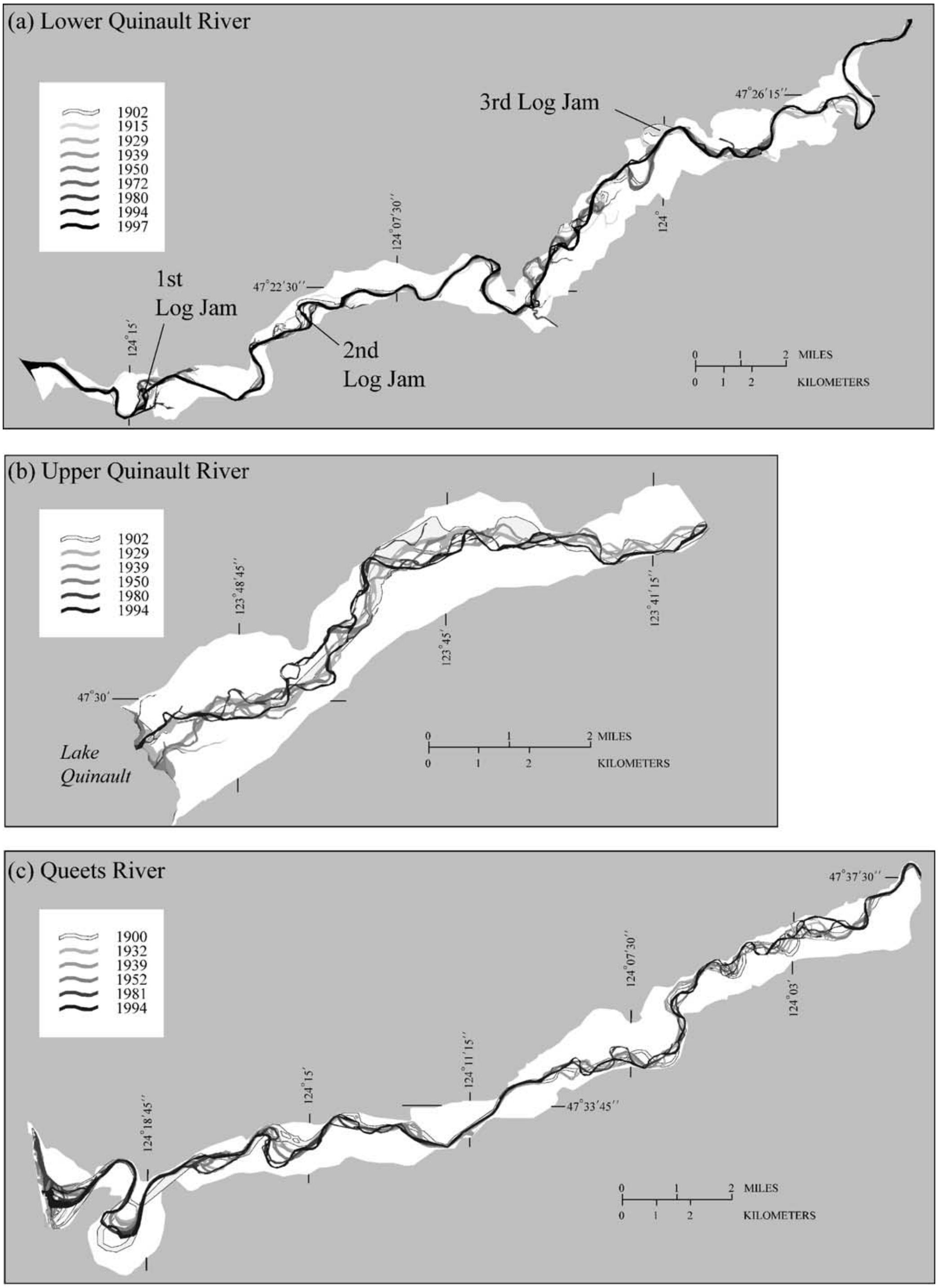


Fig. 2. Maps of historic channel positions as digitized from sources described in Table 2. Geologic flood plain indicated by unshaded area. For the upper Quinault River study reach, there is no 1950 coverage east of longitude 123°45′.

less (< 20 m) for the more recent topographic maps and orthophotos. In the worst case, an uncertainty of 50 m over a 10-years time interval between channel position sources results in errors of about 50% to 100% of the mean distance of channel movement for the three reaches. However, for longer time intervals and higher accuracy source maps, the errors are probably much smaller.

For this study, we quantified channel migration across the flood plain in two manners. The first approach is similar to a variety of methods for obtaining lineal measurements of lateral channel movement (e.g., Leopold, 1973; Hickin and Nanson, 1975; Hooke, 1980; Pizzuto, 1994; Gurnell et al., 1994; Gillespie and Giardino, 1996; Gurnell, 1997; Elliot and Gyetvai, 1999; Shields et al., 2000). For each of the three study reaches, we measured changes in the position of the intersection of channel centerline of the primary low-flow channel with flood-plain transects spaced at 0.2-km increments, thus providing 70 (upper Quinault), 150 (Queets), and 196 (lower Quinault) closely spaced measurements of lateral channel movement (orthogonal to the flood-plain axis) for each photo and map interval. This method is similar to that of Gurnell et al. (1994), Piégay et al. (1996), and Gurnell (1997), and allows for systematic temporal and spatial analysis of channel movement within a flood-plain frame of reference without the bias typically introduced by trying to make measurements at specific channel geometric features, such as channel bends or straight reaches.

The second approach to evaluating channel movement was to define each mapped channel and the geologic flood plain as polygons in a geographic information system and evaluate the temporal sequence of channel positions. This approach has been the basis of studies such as Piégay et al. (1996), Jacobson and Pugh (1997), and Ham and Church (2000). For each record of channel position, we calculated (i) the total area of the low-flow channel, (ii) the area of channel outside the area of the previous record, and (iii) the area of channel outside any previous map or photo record of previous channel positions. These results allow assessment of how total channel area has changed with time and the proportion of new channel area at each map date that represents erosion of historically uneroded flood plain (in contrast to reoccupying channel locations shown in previous maps and photos). Thus providing a basis for determining flood-plain turnover rates—that is, a measure of time required for the channel to occupy the entire flood plain.

3.3. Large woody debris and forested flood-plain interactions

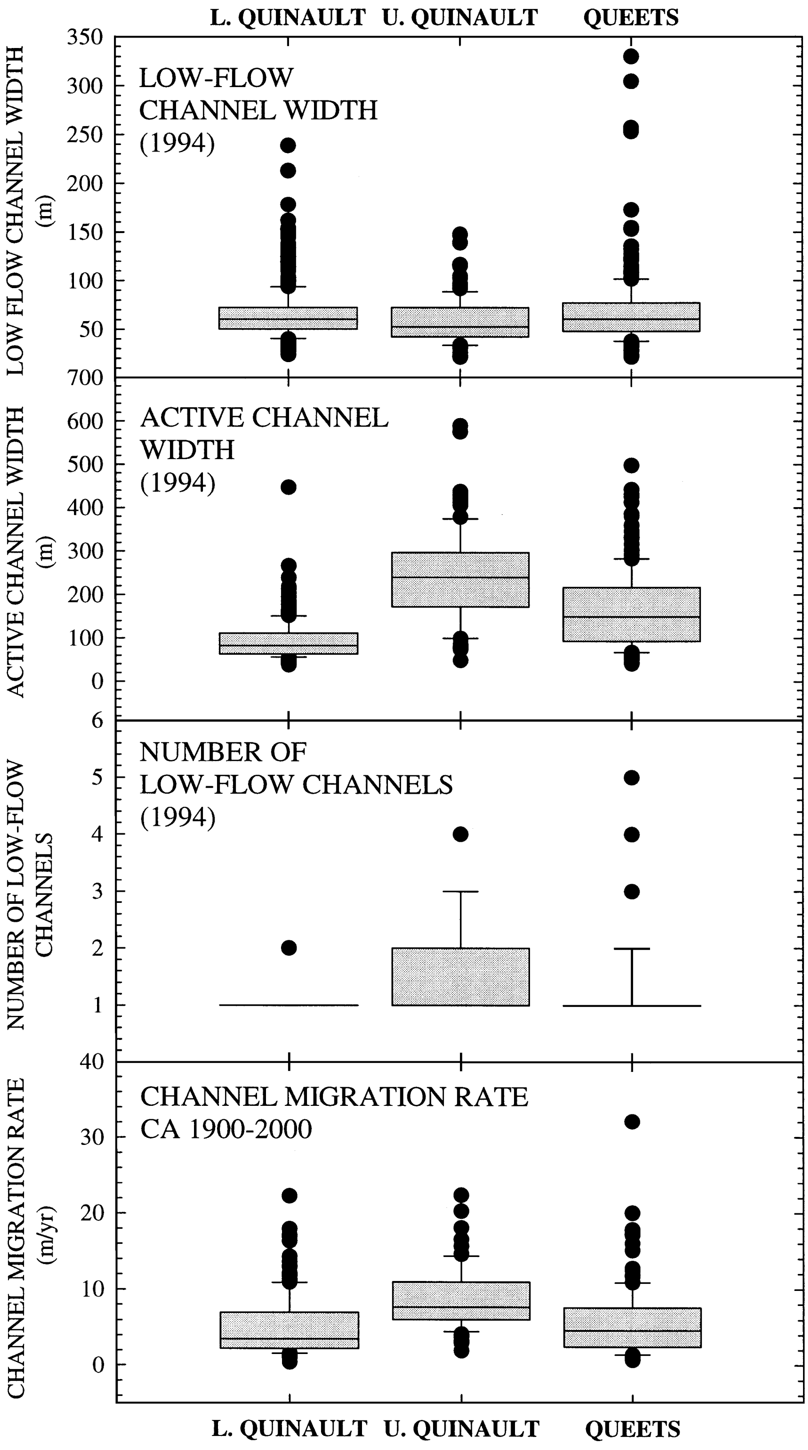
The role of in-channel large woody debris and flood-plain vegetation in affecting channel migration was evaluated from historical accounts of locations and positions of large wood jams, including records of early settlers, notes accompanying late 1800s and early 1900s General Land Office Surveys, and maps and aerial photographs showing locations of wood jams. Reconnaissance field mapping of channel conditions, wood accumulations, bank stratigraphy and vegetation conditions supplemented these historical sources. Included in these field observations were site visits before and after the flood of March 19, 1997 (1315 m^3/s, Quinault River; 3115 m^3/s Queets River), which was the largest (Quinault River) or second largest (Queets River) flood since 1955. Additionally, we relied heavily on the findings of Fetherston et al. (1995), Abbe and Montgomery (1996, 2003), and Abbe (2000) regarding the role of channel and flood-plain wood in affecting channel morphology and migration processes on the Queets River.

4. Results

4.1. Modern profile and planform characteristics

Measurements of 1994 flood-plain and channel planform characteristics (Figs. 2 and 3) show distinct differences among the three river segments, many of

Fig. 3. Box plots summarizing major study reach characteristics as measured from the channel and flood-plain transects. Boxes show 75th, 50th, and 25th percentiles; vertical lines depict the 90th and 10th percentiles; individual symbols are points outside the 10th and 90th percentiles. Low-flow channel width, active channel width, and number of low-flow channels are from measurements from 1994 orthophotos at 0.2-km increments along the 1994 channel axis. Channel migration rate is from analysis of historic lateral movement of the primary channel measured on transects orthogonal to the flood-plain axis spaced at 0.2-km increments.


L. QUINAULT
U. QUINAULT
QUEETS
LOW-FLOW CHANNEL WIDTH (1994)
LOW FLOW CHANNEL WIDTH (m)
ACTIVE CHANNEL WIDTH (1994)
ACTIVE CHANNEL WIDTH (m)
NUMBER OF LOW-FLOW CHANNELS (1994)
NUMBER OF LOW-FLOW CHANNELS
CHANNEL MIGRATION RATE CA 1900-2000
CHANNEL MIGRATION RATE (m/yr)

which that would be difficult to describe using typical channel classification schemes (e.g., Leopold and Wolman, 1957; Kellerhals et al., 1976; Schumm, 1985; Church, 1992; Knighton and Nanson, 1993). The average flood-plain width for the lower Quinault and Queets segments is about 1250 m, but the upper Quinault River flood plain is substantially wider with a mean width of 2470 m. Channel sinuosity is similar for the upper Quinault River (1.24) and Queets River (1.27) segments but is higher for the lower Quinault River (1.37). All of these values are within the < 1.5 "sinuous" (as opposed to >1.5 "meandering") category of Leopold et al. (1964, p. 281).

Although resolution is coarse, all three reaches have longitudinal profiles of generally decreasing gradient downstream (Fig. 4a). Channel slopes for both the upper Quinault and Queets segments decrease almost monotonically, resulting in smooth profiles at this scale of analysis. In contrast, the profile of the lower Quinault River is more varied; gradients range between 0.0001 and 0.0025, with less systematic change in the downstream direction.

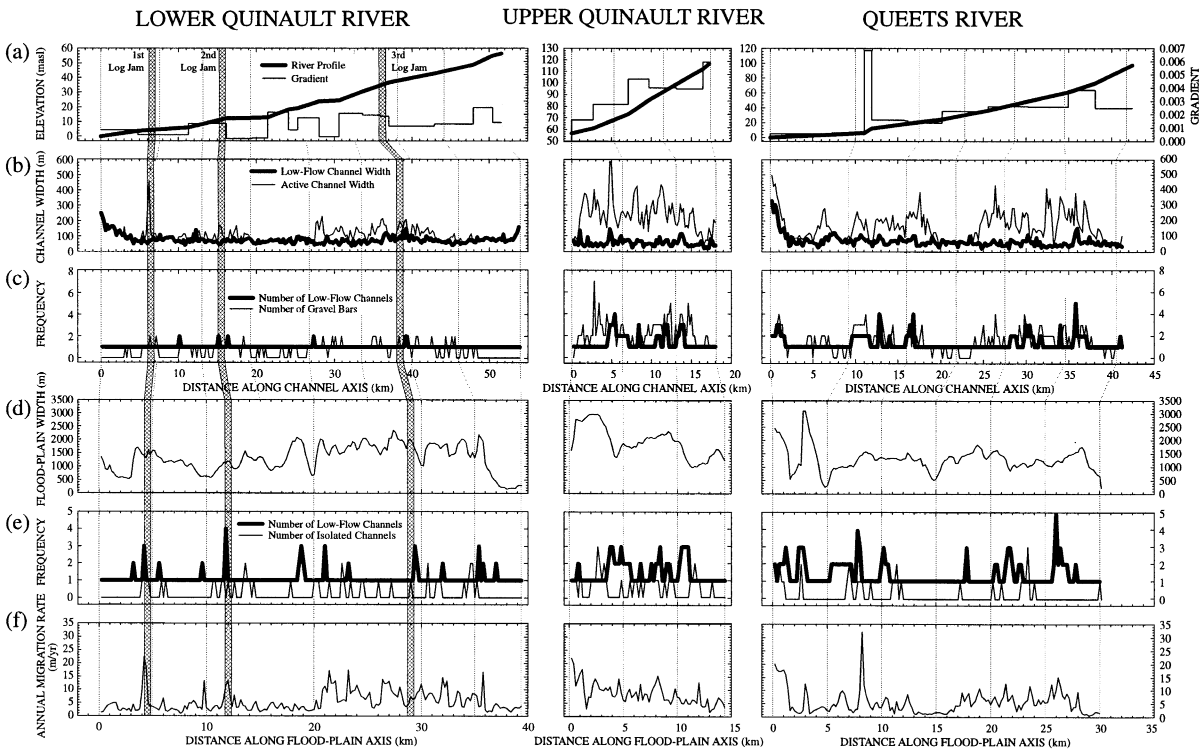


Fig. 4. Plots of channel and flood-plain features for each of the three study reaches. The thin vertical lines relate the flood-plain axis used for plots d–f to the 1994 channel axis used for plots b and c, and the 1980s channel axis used for plot a. Wide patterned vertical lines on the lower Quinault River plots show relative locations of the three channel-spanning log jams shown on the 1915 timber survey map of the Quinault Indian Reservation (Table 2). (a) Channel profile and reach gradients, from information on USGS 7.5′ topographic quadrangles. (b) Low-flow and active channel width, as measured from 1994 orthophotos (Table 1) at 0.2-km increments along the axis of the primary low-flow channel. Low-flow channels were defined as water-filled channels visibly connected at both their upstream and downstream ends on the 1994 orthophotos. The "active channel" was operationally defined to include the low-flow channels and flanking unvegetated sand and gravel bars. (c) The number of low-flow channels and unvegetated gravel bars intersected by transects orthogonal to the 1994 low-flow channel at 0.2-km increments. (d) Width of the Holocene flood plain as portrayed in Fig. 1, measured at 0.2-km increments along the flood-plain centerline. (e) Number of low-flow and isolated channels, measured at 0.2-km increments along the flood-plain centerline. Isolated channels included all flood-plain waterbodies visible on the 1994 orthophotos that were not low-flow channels. (f) Mean annual channel migration rate for the entire period of historical channel information for each flood-plain transect.

The low-flow channel widths of each of the three river segments are similar, but the active channel widths are significantly different (Figs. 3 and 4b). The upper Quinault River has by far the widest active channel, averaging 240 m wide compared to 165 m for the Queets River and 95 m for the lower Quinault. The active channel of upper Quinault River is almost everywhere at least twice as wide as the low-flow channel. However, for both for the Queets and lower Quinault segments, several reaches more than a kilometer long consist of a single channel flowing entirely within vegetated flood-plain surfaces, with no flanking exposed and unvegetated gravel bars. For both the Queets and lower Quinault segments, the low-flow channels widen as they approach within 1 to 2 km of the Pacific Ocean.

Although all three river segments have reaches containing multiple channels at low flow, the upper Quinault and Queets segments have more low-flow channels than the lower Quinault River, averaging 1.41 and 1.30 channels per flood-plain transect, respectively, compared to 1.02 for the lower Quinault River (Table 1; Figs. 3 and 4c,e). For both the upper Quinault River and Queets River, there are several reaches as long as a kilometer with two or three low-flow channels. Some reaches have four or five visible low-flow channels. The lower Quinault River has only five multichannel reaches, all of which are shorter than 400 m.

4.2. Patterns of channel movement, channel migration rates, and flood-plain turnover

The historic map and photo sequences show that the styles and spatial patterns of channel migration vary between the three study reaches (Fig. 2). The channels of the upper Quinault River and the Queets River upstream of RK 20 are mobile, with no stable reaches and most migration accomplished by lateral bank erosion and short avulsions (generally < 0.5 km) involving low-amplitude meander curves with wavelengths of 2 to 3 km (Figs. 2 and 5). Downstream of RK 20 on the Queets River, most of the historic channel migration has been associated with progressive enlargement and subsequent cutoff of five large meander loops. Three of these meander loops have migrated over more than a kilometer of flood-plain width during the last 100 years and have undergone

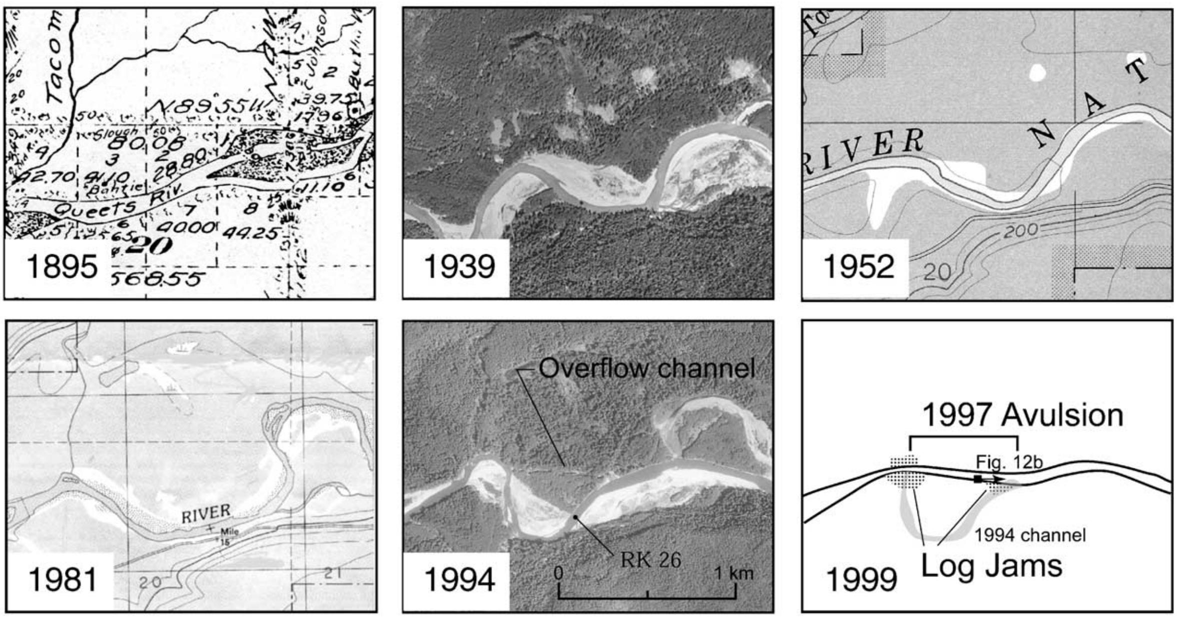


Fig. 5. Sequence of channel maps of a portion of the Queets River near RK 26. Maps from 1895–1994 from sources listed in Table 2. The 1999 map from a field sketch.

complete cycles of growth and cutoff (Fig. 6). Reaches between individual meander loops have remained generally stable.

The lower Quinault River has a planview channel pattern similar to the downstream portion of the Queets River study reach, flowing through meanders with wavelengths of up to 4 km and amplitudes as great as 2 km (Fig. 1b). In contrast with the Queets River, few of these meander loops have migrated substantially during the last 100 years (Fig. 2a). Most channel migration on the lower Quinault River has been associated with (i) channel avulsions across previously stable meander loops and (ii) adjacent short stretches of more fully dynamic reaches similar to the upper Quinault and upper Queets Rivers. Three reaches have been particularly active historically: (i) a short reach within RK 6–8; (ii) between RK 10 and 17; and (iii) a long reach between RK 27 and 40, where, since 1902, the channel has avulsed across two meander bends (Fig. 7).

Channel migration rates vary within and among the three study segments (Figs. 3 and 4f). Calculated on the basis of changes in channel centerline position relative to flood-plain transects spaced at 0.2-km increments, the mean channel migration rate for the lower Quinault River between 1902 and 1997 was 5.0 ± 3.9 m/year. The Queets River had a similarly calculated mean migration rate of 5.6 ± 4.5 m/year between 1900 and 1994. The upper Quinault River has had a channel migration rate of 8.8 ± 4.1 m/year between 1902 and 1994, significantly higher than those measured for the lower Quinault and Queets segments ($p \ll 0.01$; two-tailed *t*-test). Error terms are the standard deviation of the spatial variation in mean migration rate, as averaged for each flood-plain transect for the entire period of record.

Owing to substantial back-and-forth channel movement between times of known channel position, the calculated migration rates will likely be less than the actual migration rates by some factor that depends on the length of time between sequential maps. Consequently, the calculated migration rates for each of the study reaches is likely biased by the different number of historic sources and uneven interval lengths between known channel positions. For each of the three study segments, significant inverse correlations ($p < 0.1$; two-tailed *t*-test) between measured reach-average migration rates and the number of years between map dates (Fig. 8) indicate that this bias is indeed present for all three reaches and that a significant amount of channel migration is "missed" between times of known channel positions. To account for this, we have normalized migration rates to a 17-year interval period, representing the mean interval between all pairs of channel position information used in the study, using the linear regressions

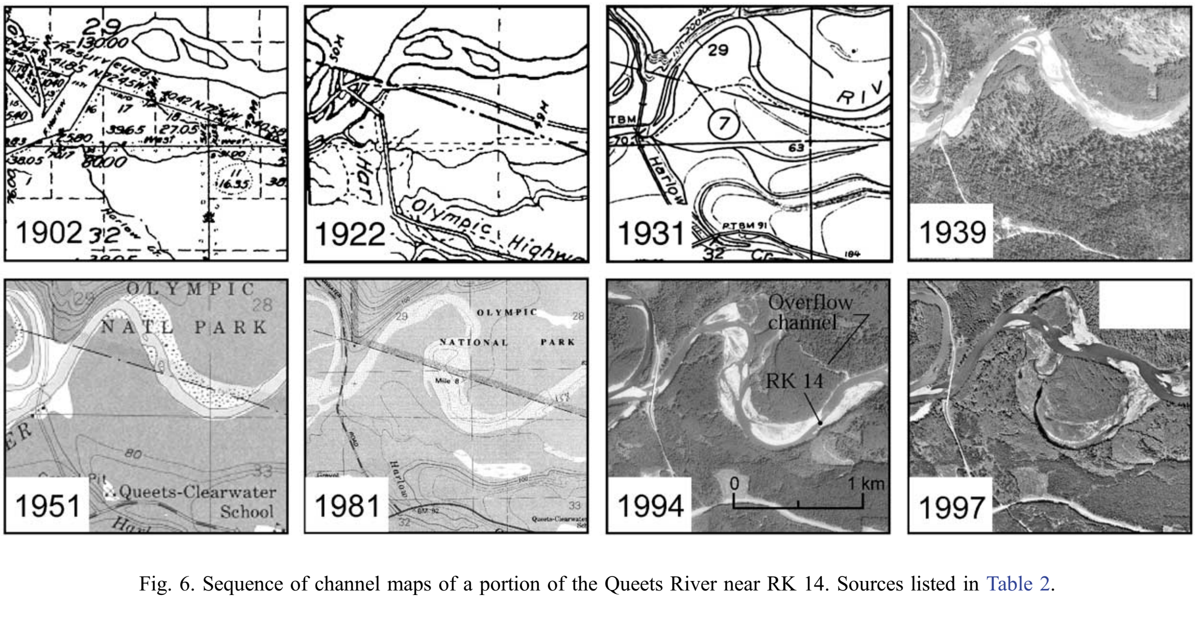


Fig. 6. Sequence of channel maps of a portion of the Queets River near RK 14. Sources listed in Table 2.

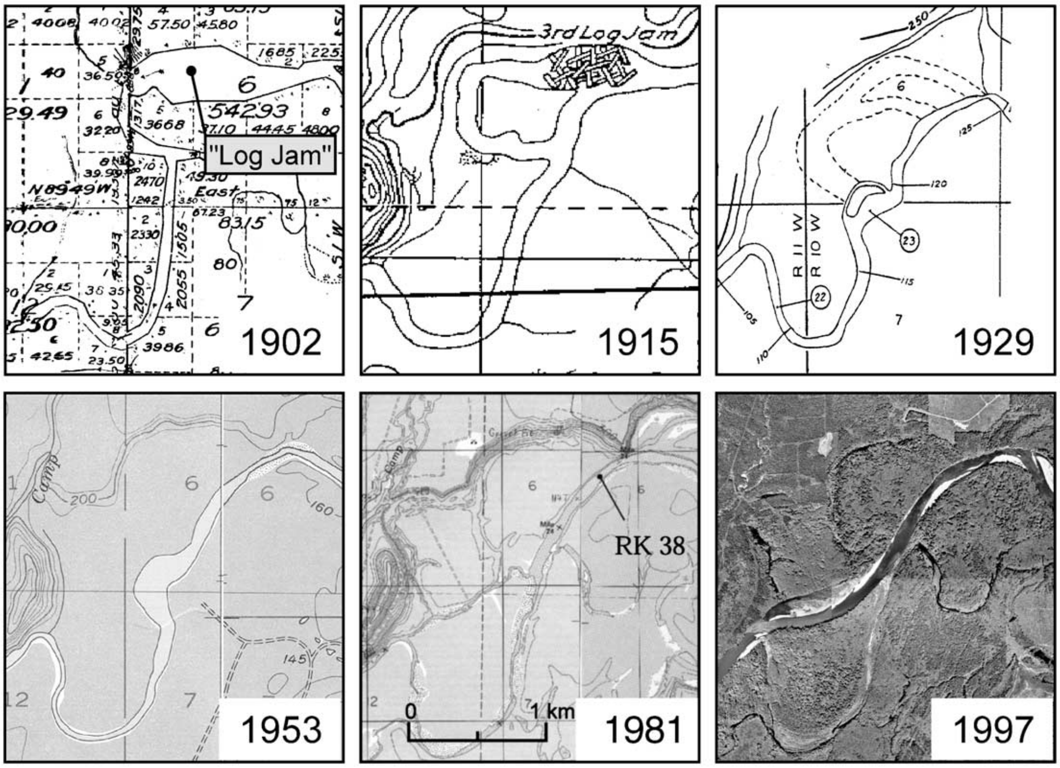


Fig. 7. Sequence of channel maps of a portion of the lower Quinault River at the site of the 3rd log jam near RK 38. Sources listed in Table 2.

shown in Fig. 8. This adjustment results in normalized migration rates of 4.0 ± 1.2 m/year for the lower Quinault River, 7.5 ± 2.9 m/year for the Queets River, and 12.7 ± 3.3 m/year for the upper Quinault River (the error terms are the estimated standard error for a sampling interval of 17 years resulting from the regression of the mean cross-section migration rate against the sampling period, calculated using Eq. 1.4.7 of Draper and Smith, 1966).

The other approach to analyzing channel change, the overlay of channel polygons, shows that for all three reaches, the apparent channel areas were greatest at the time of the turn-of-the-century General Land Office mapping (Fig. 9). These earliest maps, however, undoubtedly include large active channel areas outside the low-flow channels—especially for the upper Quinault River and perhaps for the Queets River. For the 1939 and later sources, which were all based on aerial photographs made during summer low-flow periods, channel area for each of the three study reaches has varied by less than $\pm$ 20%. For almost all time periods on the upper Quinault and Queets segments, more than 50% of the channel area at a specific map date was outside of the channel area of the previous record. For the upper Quinault River, channel movement between times of mapping typically involved more than 75% of the channel area (Fig. 9b). For the lower Quinault River, the area of new channel between map dates has generally been less than 50% of the total channel area (Fig. 9a). Similarly, the proportion of channel movement that was into previously unoccupied flood plain (as opposed to previous channel locations) has remained relatively constant for the last 50 to 60 years. (The results from the first part of the historical record are skewed by the shortness of the record.) For the Queets and upper Quinault segments, 40% to 50% of the channel erosion between photo and map sets is into historically unoccupied flood plain; whereas for the lower Quinault River, only 18% to 30% of new channel areas are outside of historical channel positions.

Over the 94 to 97 years covered by the channel maps, the channel has at some time occupied 25% to

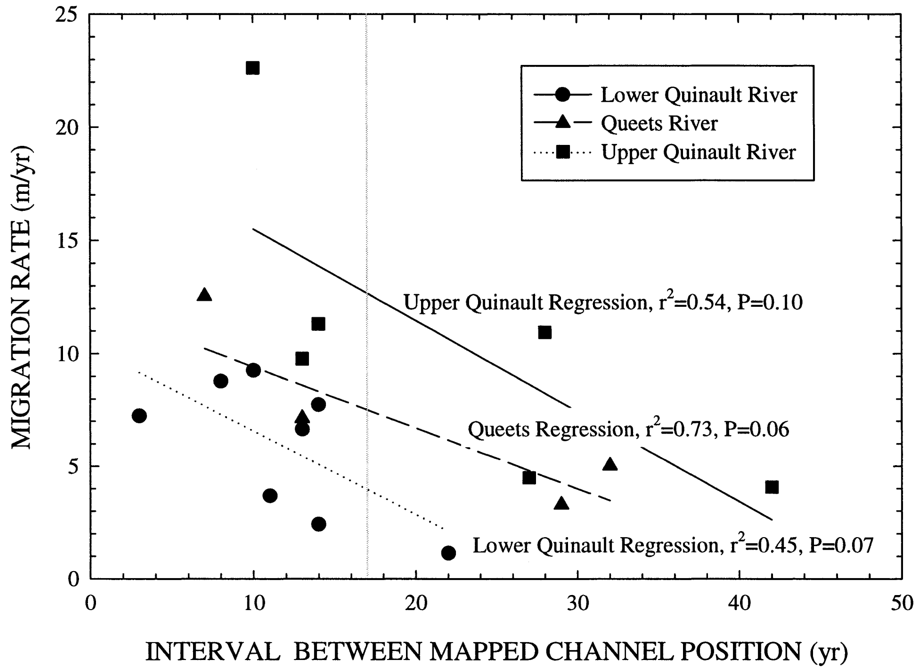


Fig. 8. Scatter plots and linear regressions showing relations between the interval between successive channel maps used in the analysis and the calculated annual channel migration rate for the corresponding periods. Vertical gray line represents the mean interval (17 years) between successive channel maps used in this analysis and is the basis for marmalizing the calculated channel migration rates.

29% of the geologic flood plains (Fig. 2). The annual rate with which the channels moved into flood-plain areas not occupied previously within the record of maps and photos has generally varied between about 0.05% and 0.5% per year (Fig. 10). Extrapolated forward, these rates imply 200- to 2000-year flood-plain "turnover" periods in which, on average, the channel occupies all of the geologic flood plain.

However, mobile channels typically form and erode relatively young flood-plain surfaces near to recent and present channel positions, allowing surfaces farther away to become much older (Everitt, 1968). This is the case for both the Queets River and Quinault River, where 18% to 50% of channel migration reworks flood plain or gravel bars < 100 years old (Fig. 9). Therefore, the age distribution of flood-plain surfaces is likely to be logarithmic, leading Everitt (1968) and Gottesfeld and Gottesfeld (1990) to discuss the time scale of flood-plain turnover in terms of flood-plain half-lives, defined as the length of time in which the channel occupies half of the total flood-plain area.

We have calculated flood-plain half-lives for each of the three study reaches by fitting exponential decay curves to the cumulative erosion of 1900–1902 flood plains (areas outside the 1900–1902 mapped channel, but within the geologic flood plain) over the subsequent 94 to 97 years (Fig. 11). For the Queets River segment, the calculated flood-plain half-life is 385 + 48/ − 39 years (the stated error represents the standard error about the exponential regression), whereas the half-life is somewhat longer at 495 + 38/ − 32 years for the upper Quinault River flood plain and somewhat shorter at 277 + 53/ − 38 years for the lower Quinault River segment, although this latter result is heavily influenced by the measured channel differences between the 1902 and 1915 maps for which errors due to poor registration may be large. Because of the likelihood that there were areas of the flood plains occupied by the channels over the last 94 to 97 years that were not recorded at the isolated instances portrayed on the channel maps, these calculated half-lives likely overestimate the actual flood-plain half-lives, al-

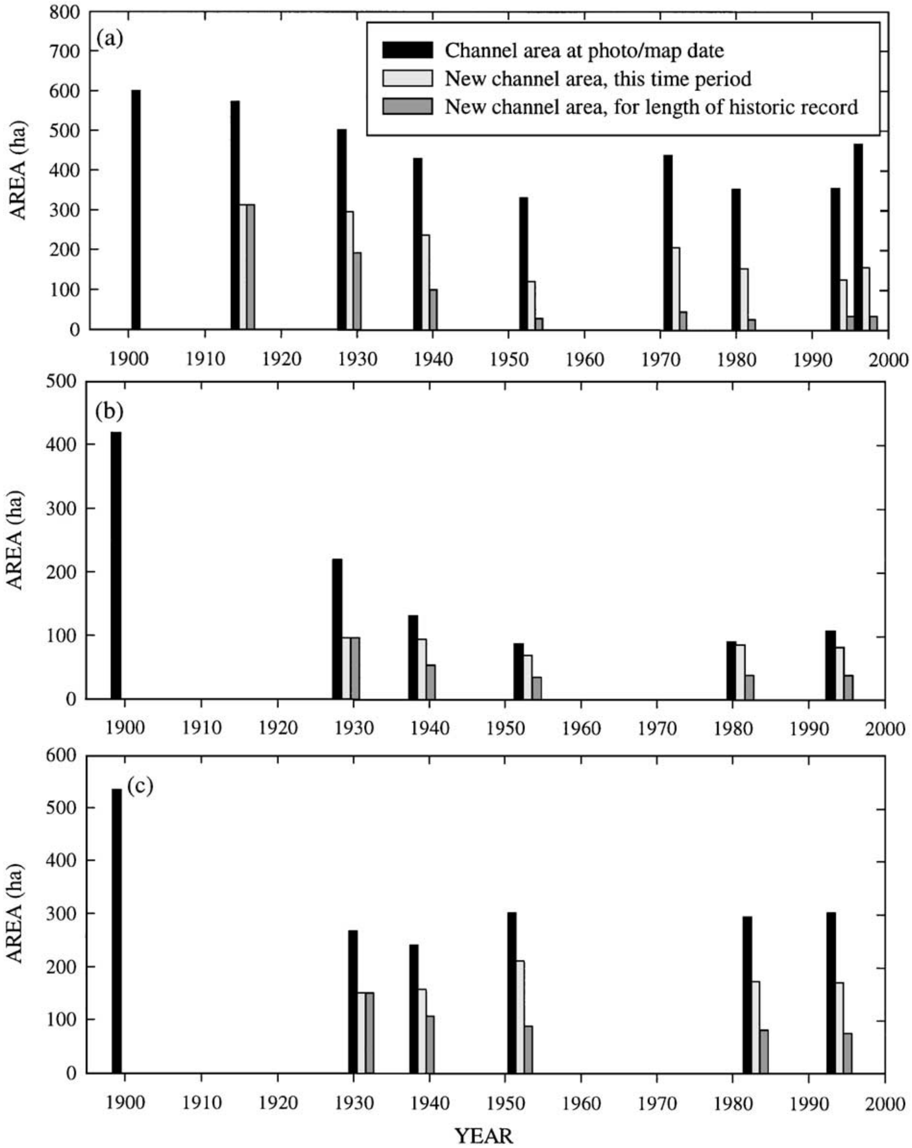


Fig. 9. Results of GIS analysis of sequential channel positions for the (a) lower Quinault, (b) upper Quinault, and (c) Queets River segments showing, for each map/photo record, (i) the area of channel, (ii) the area of channel that is different than the previous record of channel positions, and (iii) the area of channel that is different than any previous map/photo record.

though this error is probably partly compensated for by registration errors associated with the individual maps and photos (which would most likely lead to erroneously high calculated migration rates). This approach to calculating flood-plain half-life differs from the more direct approach adopted by Everitt (1968) in which the age distribution of the flood-plain surface was determined by mapping tree ages. Such an approach could be undertaken on the Queets and Quinault Rivers to test the results determined from analysis of channel movement, as well as provide information on flood-plain turnover rates prior to human land use effects, but this has not yet been done.

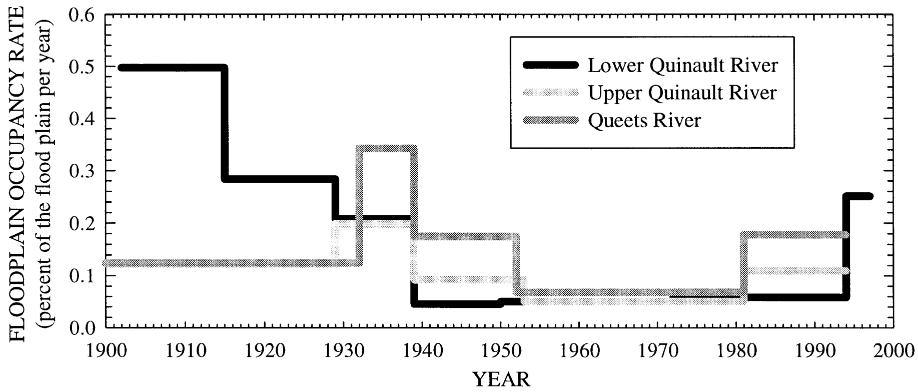


Fig. 10. Temporal variation in mean annual erosion of the geologic flood plain by the channel. Calculated on the basis of annual percent area of channel movement into areas of the flood plain, which have not been historically occupied by the channel. Results are partly a function of the length of record, especially for the first 40 to 50 years (when the historical record is relatively short).

4.3. Large woody debris

On the lower Quinault River, despite little wood entering from upstream, large in-channel log jams were common. Early settlers reported that wood accumulations grew large enough to completely span the channel, including jams that were nearly 0.5 km long and completely impassable to navigation (Cleland, 1959, pp. 177–178). Prior to the historic record, such jams required the Quinault Indians to build flat-bottomed canoes to ease portage over these jams when navigating the Quinault River (Capoeman, 1991, p.

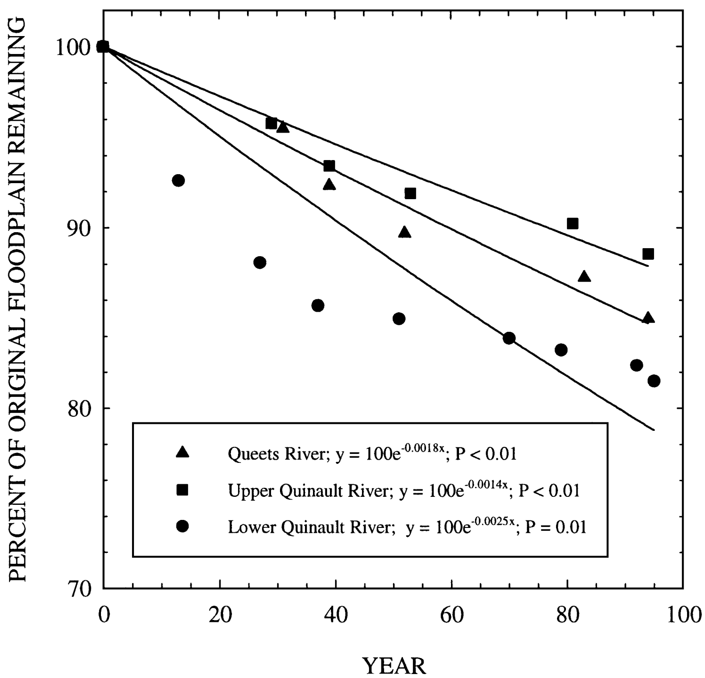


Fig. 11. Exponential decay curves fit to the cumulative erosion (as indicated by subsequent channel positions shown in Fig. 2) of the portions of the geologic flood plains that were outside the channels portrayed on the 1900–1902 General Land Office maps.

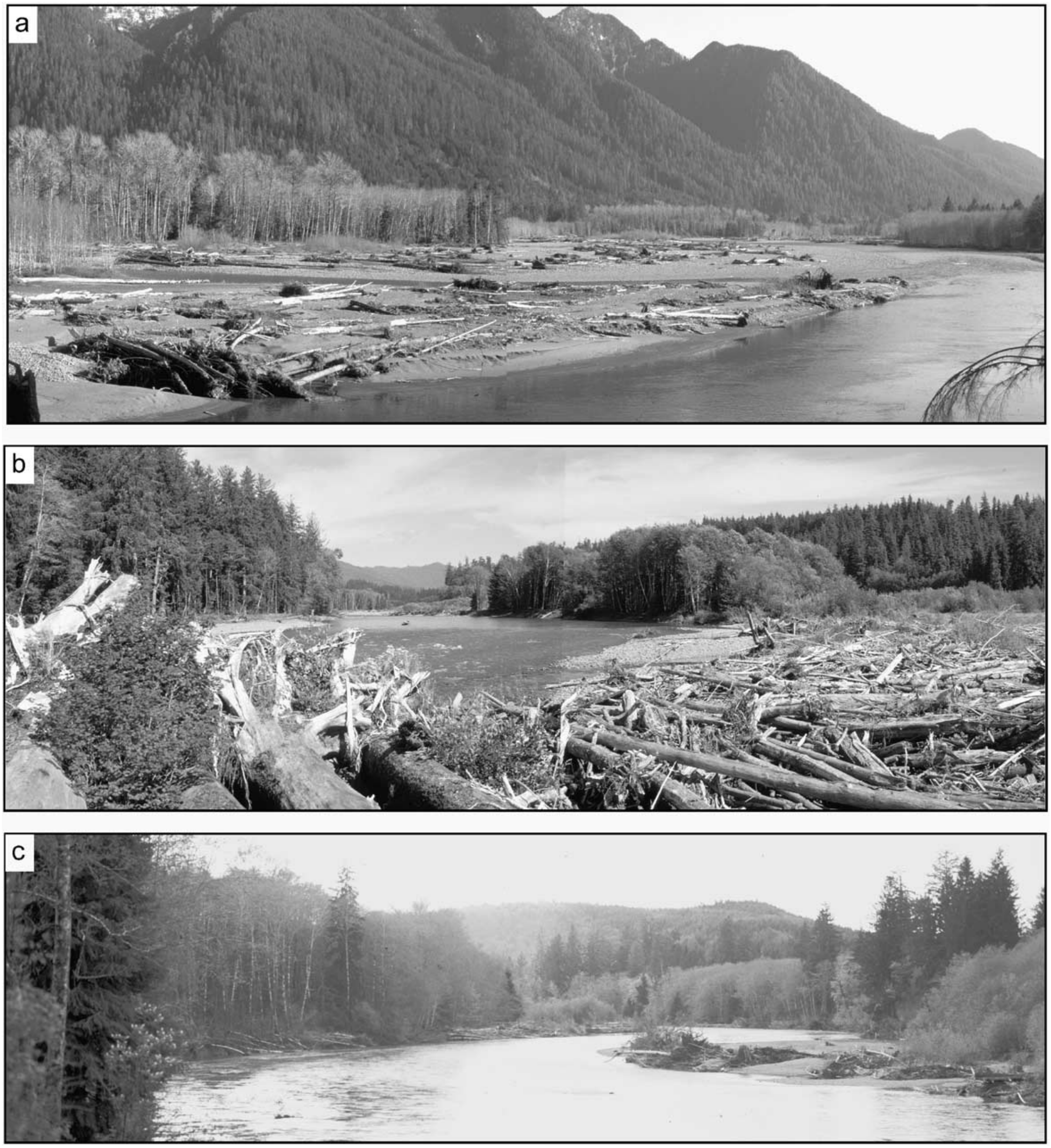


Fig. 12. Typical settings of in-channel wood, sediment, and flood-plain vegetation on the three river segments. (a) April 2, 1997, view downstream from the right bank of the upper Quinault River at RK 67.6, showing single pieces and small groups of wood that have accumulated on gravel bars between low-flow channels (analogous to the ''bar-top'' jams of Abbe and Montgomery, 1996). Channel is flanked by stands of red alder. (b) Aug. 7, 1999, view upstream of the Queets River at RK 26. Location and orientation of the view shown in Fig. 5. This log jam and associated aggradation of the former channel (off to the right in this perspective) resulted in a 700-m avulsion of the channel during the March 1997 flood along a route marked by a small overflow channel on 1994 aerial photos (Fig. 5). (c) April 29, 1997, view downstream of the lower Quinault River from left bank at RK 16.6. This has been a reach of historic channel migration near the ''2nd log jam'' depicted on the 1915–1916 timber surveys (Table 2). The March 1997 flood resulted in formation of a point bar of gravel and wood, forcing flow to erode laterally into the adjacent flood plain. Flood-plain vegetation, consisting primarily of even-aged stands of red alder and groves of spruce has been entrained and deposited on the downstream bar.

107). A map constructed during a 1915–1916 timber survey (Table 2) of the reservation shows three large log jams (Fig. 2a), one of which covered about 15 ha (Fig. 7). Presently, no channel log jams span the lower Quinault River, in part due to active removal to aid navigation (Philip Martin Jr., Quinault Indian Nation, oral communication, 1997) and, perhaps, less large wood in the river because of substantial flood-plain timber harvest during the last 80 years.

The sequence of events at what was mapped as "3rd log jam" on the 1915–1916 timber survey (Fig. 7) may be representative of channel and flood-plain conditions associated with channel-spanning log jams on the lower Quinault River prior to significant human channel clearing and flood-plain timber harvest. The location of this jam is consistent with early 1890s accounts of a "big jam of trees and rubbish completely blocking the channel" (Cleland, 1959, pp. 177–178). This large jam completely spanned the channel in 1902, according to notes accompanying the General Land Office survey of the channel (cadastral survey notes for T. 22 N., R. 10 E., housed at the Bureau of Land Management office in Portland, Oregon). The 1902 General Land Office survey depicts a wide and ponded channel at the area of the jam but no note or portrayal of a bypass channel. The 1915–1916 timber survey also shows the log jam completely blocking the main channel but by that time, a small bypass channel had formed. A 1929 survey of the channel shows that the bypass channel had become the main channel, with the former route dashed in, indicating as much as 500 m of lateral avulsion of nearly a kilometer of channel. A similar sequence of events apparently caused another avulsion in the next meander downstream between 1953 and 1997 (Fig. 7), partly resulting from a log jam most likely formed of wood eroded from the flood-plain forest during the 1902–1929 avulsion. The locations of other two log jams portrayed on the 1915–1916 timber survey have also had similar but smaller avulsions and have been reaches of persistent channel instability (Figs. 2 and 4).

In contrast to the large, channel-spanning jams and consequent channel avulsions that have affected at least three reaches of the lower Quinault River during the early 20th century, the Queets River and upper Quinault River (and, to a more local extent, the lower Quinault River) have mostly been affected by individual pieces of wood and wood jams that flank or only partially block the channel (Fig. 12). These wood accumulations have been associated with rapid bar growth, bank erosion, and short-length channel avulsions as described for the Queets River by Fetherston et al. (1995), Abbe and Montgomery (1996, 2003), and Abbe (2000). In these reaches of frequent wood and sediment transport, large woody debris is commonly deposited on bar tops, at bar apices, and in meander bends, commonly promoting mid-channel and point bar growth which then redirects flow against channel margins, causing bank erosion and channel migration (Abbe and Montgomery, 1996). An example on the Queets River is shown in Figs. 5 and 12b, where about 500 m of new channel formed as a result of partial channel blockage by wood and sediment, resulting in a meander cutoff during the high flow of March 1997. Two similar avulsions, both involving channel lengths less than 400 m, occurred during the same flood on the lower Quinault River at RK 32.5 and 27.2. Judging from the abundant in-channel wood, our field observations of channel change between 1996 and 1999, and high lateral migration rates, such channel shifting and lateral migration is common, perhaps occurring most years on the upper Quinault River and Queets River above RK 20.

Downstream of RK 20 on the Queets River, the channel has a lower gradient and more sinuous planform and there has been more systematic growth and cutoff of large meander loops (e.g., Fig. 6). Inspection of aerial photographs and observations from site visits indicate that these meanders grow as a result of point

Fig. 13. Photographs illustrating evidence for role of log jams in promoting flood-plain conifer growth. (a) Sitka spruce trees growing from partly decomposed nurse logs at the site of the 1902–1915 3rd log jam on the lower Quinault River near RK 38. Shovel (0.5 m) is leaning against a spruce stem. (b) Conifer seedlings growing on spruce stem deposited near the margin of the 1952 channel of the Queets River near RK 26. The largest is a 5-m tall spruce growing from the root wad of the nurse log. (c) Recently deposited spruce bole on the right margin of the lower Quinault River at about RK 26. A 1.5-m tall spruce is growing from the root wad. (d) Grove of mature spruce growing at western margin of the 1902–1915 3rd log jam on the lower Quinault River near RK 38. Shovel (0.5 m) is leaning against a spruce stem. (e) Exposure of the right bank of the Quinault River near RK 21.8 where three Sitka spruce, including the 1.5-m diameter spruce on the left edge of the photograph, apparently grew from a partially decomposed conifer log now emerging from the eroding bank (upon which the person is standing).


a
b
spruce
spruce
cedar
c
spruce
seedling
spruce bole
d
e
partly exhumed
nurse log

bars forming on the insides of meander bends, facilitated by deposition in the lee of wood accumulations. The resulting aggradation, as indicated by buried wood accumulations and wide active channels within the meander bends, probably facilitates overbank flow across the meander bend and eventual cutoff.

Longer-term feedbacks between fluvially transported wood and flood-plain vegetation are evident at sites of historic wood accumulation and channel change. At the location of the channel-spanning 3rd log jam on the lower Quinault River segment, which is now as far as 500 m away from the channel, numerous spruce are now growing from higher logs within this jam (Fig. 13a). Many of these spruce have diameters of 30 to 40 cm within vegetation otherwise dominated by maple and alder, indicating that these log jams may facilitate flood-plain conifer establishment by providing elevated and nourishing sites for seedling establishment. Consistent with this, large conifers recently deposited along both the Quinault River and Queets River have young spruce and western red cedar growing from their stems and rootwads (Fig. 13a,b). In addition, the unharvested flood plain within the cutoff meander loop adjacent to the area of the 3rd log jam is vegetated primarily by hardwoods, but locally interspersed are groves of large spruce, some with basal diameters exceeding 2 m (Fig. 13d). These spruce grow in clusters of about 400 m^2 or less on surfaces that stand 1 to 2 m above the surrounding flood plain. No direct evidence of nurse logs was found at these groves, but commonly three or more of the spruce would be aligned, supporting the inference that these spruce groves have formed on long-rotted or buried nurse logs. The grouping of these spruce, in combination with the higher terrain which they are found, leads us to conclude that these groves of mature spruce occupy sites of old log jams, although it cannot be ruled out that windthrow may have formed the downed logs upon which the present spruce have grown. A bank exposure downstream along the lower Quinault River shows that similar arrangements of large spruce are indeed rooted in logs now buried by overbank sediment and forest soils (Fig. 13e).

Similar interactions between channel shifting, wood deposition and recruitment, and flood-plain morphology and vegetation are also evident in conjunction with wood accumulations that do not completely span the channel. In particular for the Queets River, Fetherston et al. (1995) described feedbacks between riparian forest conditions and large woody debris accumulations, and Abbe and Montgomery (1996) conducted detailed studies between RK 41 and 46 where they have related wood accumulations to hydraulic, depositional, and aquatic habitat conditions. These earlier studies on the Queets River and our observations on all three river segments indicate that deposited large woody debris commonly promotes mid-channel and point bar growth (Fig. 12a). Additionally, bar formation in the lee of wood accumulations can lead to establishment of riparian vegetation on the resulting higher and finer-grained deposits, and ultimately, stands of even-age riparian vegetation. Bank erosion and the consequent entrainment of flood-plain trees can foster further channel instability as the downed wood steers flow into banks (the "auto diversion" process of Keller and Swanson, 1979).

5. Discussion

Despite the overall similar physiographic settings of the Queets River and Quinault River basins, the three study reaches have distinct planform characteristics as well as patterns and rates of channel migration and flood-plain erosion. These differences can be logically attributed to the different sediment, water, and wood inputs to the basin, and interactions among these factors, although rigorous identification of cause and effect is hampered by the multiple differences between the reaches and the long time scales of interactions. These inferences regarding effects of sediment, wood, and flow on channel morphology, coupled with observations of flood-plain morphology and vegetation that may represent even longer time frames, serve as a basis for speculation on interactions among channel migration, in-channel wood, and flood-plain forests at time scales ranging from decades to centuries (Fig. 14).

5.1. Flood-plain and channel planform characteristics

Variation in flood-plain width primarily reflects Quaternary geologic controls on valley morphology.

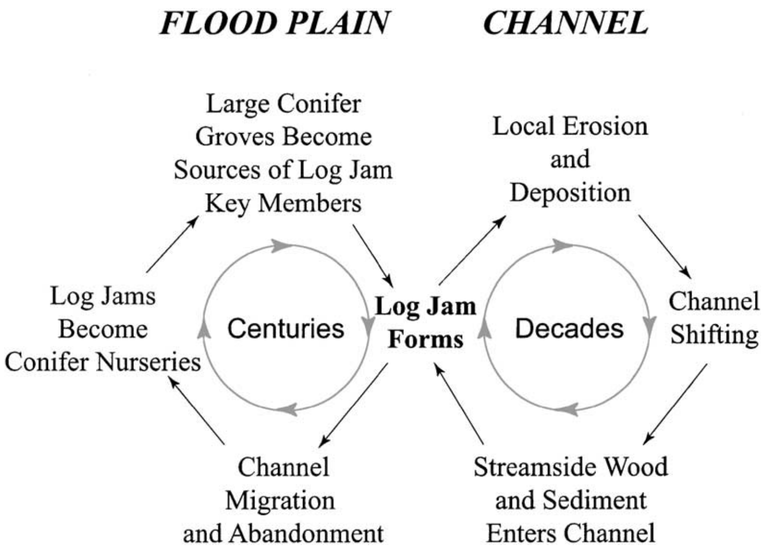


Fig. 14. Feedbacks hypothesized between large wood and flood-plain and channel evolution, at time scales of decades to centuries, for the Queets River and Quinault River. Partly derived from findings described by Fetherston et al. (1995), Abbe and Montgomery (1996) and Abbe (2000).

For both the lower Quinault River and Queets River segments, there is pronounced narrowing of the flood plains where they pass through Quaternary terminal moraine complexes (Thackray, 1996). Within the upper Quinault River segment, the flood-plain narrows where bedrock ridges encroach from the north, but widens where it is aggrading behind moraine-dammed Lake Quinault. Flood-plain width does not correlate with channel planform characteristics such as low-flow width, active channel width, or the frequency of low-flow channels ($p>0.1$ in all cases; two-tailed t-test). Thus, we infer that most aspects of channel and flood-plain morphology are independent of the local geologic controls that affect flood-plain width.

Channel planform characteristics appear to be more directly related to overall sediment, wood, and flow regimes. For example, similar low-flow widths for all three study reaches are likely due to similar low-flow discharges. The greater active channel width, greater channel slopes, higher migration rates, and greater frequency of multiple and unconnected channels of the upper Quinault River, and to a lesser extent the Queets River, probably owe to the greater sediment supply and higher peak discharges of these two reaches compared to the lower Quinault River. The lower Quinault River has an overall narrower active channel width, lower channel gradient, and greater sinuosity, likely reflecting the combined influence of upstream sediment and wood trapping and flow attenuation provided by Lake Quinault. These differences are consistent with Schumm's (1985) qualitative observations of the relationships among channel slope, sediment load, channel stability, and channel form.

Different base-level conditions may also be an important factor in controlling planform channel and flood-plain morphology. The Queets and upper Quinault Rivers have overall similar sediment and flow regimes; however, the upper Quinault River, which has been aggrading behind Lake Quinault during the Holocene, has a significantly wider flood plain, wider active channel, more low-flow and high-flow channels, and greater migration rates. Valley aggradation of the upper Quinault River has apparently primarily affected the downstream 5 km of valley bottom, resulting in lower channel gradient and higher channel migration rate compared to the upstream part of the upper Quinault study segment (Fig. 4).

In contrast, the Queets River and lower Quinault Rivers have similar base-level conditions, but different sediment, wood, and peak discharge conditions because of the presence of Lake Quinault upstream of the lower Quinault River. The relatively greater sediment and wood supply of the Queets River in conjunction with greater peak flows is probably responsible for its greater active channel width and perhaps gradient as well. The greater sediment supply and steeper channel of the Queets River also likely result in the slightly greater channel migration rates and, in conjunction with the wider active channel, more numerous low-flow channels (which generally occupy recently abandoned channels). In general, though, the overall morphologic differences between the Queets and lower Quinault segments are less pronounced than are the differences between the aggrading upper Quinault River and the other two study reaches (Fig. 3).

5.2. Channel migration patterns and dynamics

Parts of all three study reaches have distinctive styles and rates of channel migration (Figs. 2–4). The upper Quinault River has been multi-channeled with high migration rates, with most migration accomplished by lateral bank erosion and short avulsions. Similarly, the channel of Queets River upstream of RK 20 has been everywhere active, but changes downstream to a series of stationary meander loops that have grown and cutoff over time scales of about 100 years. Channel migration on the lower Quinault River during the last 94 years has been focused in three distinct reaches of channel avulsions across meander loops and adjacent reaches of lateral channel migration and short avulsions. Between these dynamic reaches, the lower Quinault River has been mostly stable.

On all three river segments, rates of channel migration over the last 100 years correspond with modern channel and flood-plain planform characteristics (Fig. 4). This is especially evident for the Queets River and lower Quinault River, where discrete reaches of distinctly higher historic migration rates have wider active channel widths, greater numbers of low-flow and unconnected channels, and more unvegetated gravel bars compared to reaches that have been historically stable or less active. This correspondence supports the importance of channel migration as a process responsible for many ecologically important channel and flood-plain characteristics.

Despite different channel migration rates, the flood-plain occupancy rates for all three reaches are broadly similar, indicating that flood-plain turnover occurs over 200 to 2000 years with flood-plain half-lives of 200 to 500 years. These half-lives are close to those determined for a variety of other alluvial rivers (e.g., Nanson and Beach, 1977; Hughes, 1997), but somewhat longer than the 30–50 years estimated by Gottesfeld and Gottesfeld (1990) for the Morice River in British Columbia, which has a similar physiographic setting as the three study segments analyzed here. Three factors apparently control flood-plain turnover rates the Queets and Quinault study segments: (i) the width of the flood plain; (ii) the channel migration rate; (iii) the propensity of channel migration to erode into the flood plain rather than to occupy previous channel locations. These factors apparently counterbalance each other in the Queets and Quinault Rivers to produce broadly similar flood-plain turnover rates. The high migration rate of the upper Quinault River is offset by its wider flood plain. In contrast, the Queets and lower Quinault segments have lower migration rates but narrower flood plains.

5.3. Interactions among wood, sediment, flow and resulting channel and flood-plain morphology

At length scales of individual channel bends and time scales of individual flow events to decades, many of the channel migration and flood-plain growth and erosion processes on all study reaches are controlled by interactions between flow, sediment, and wood (Fig. 12). As described for the Queets River by Fetherston et al. (1995) and Abbe and Montgomery (1996, 2003), and Abbe (2000), these processes involve many forms of wood, including standing trees, entrained wood, and previously deposited accumulations of large woody debris. In places, wood deposition triggers sedimentation, such as in the "bar apex jams," and in other locations, sediment deposits trap woody debris, such as the "bar top jams" (Abbe and Montgomery, 1996). In both cases, the resulting accumulations of wood and sediment can promote flood-plain generation by providing sites and substrate suitable for establishment of flood-plain vegetation (Gottesfeld and Gottesfeld, 1990; Abbe and Montgomery, 1996; Fetherston et al., 1995). Additionally, sediment and wood accumulations locally cause flood-plain erosion by directing flow toward banks, thus introducing additional sediment and wood in the river (e.g., Keller and Swanson, 1979). These interactions are evident along most of the lengths of the Queets and upper Quinault Rivers, which both receive substantial sediment and wood from upstream as well as from bank erosion, although the style of migration apparently corresponds to channel slope on the Queets River. All of these and similar processes have been described for rivers with forested flood plains (e.g., Hack and Goodlet, 1960; Nanson and Beach, 1977; Keller and Swanson, 1979; Swanson and Lienkaemper, 1982; Sedell and Froggatt, 1984; Gottesfeld and Gottesfeld, 1990; Church, 1992; Piégay, 1993; Maser and Sedell, 1994, pp. 44–50; Piégay and Gurnell, 1997; Piégay and Marston, 1998; Jacobson et al., 1999; Gurnell et al., 2000).

On the lower Quinault River, however, these types of short reach- and time-scale interactions have been primarily restricted to the parts of the river that have been historically active between RK 6 and 8, RK 10 and 17, and RK 27 and 40 (Fig. 2). This condition of dynamic reaches within otherwise more stable channels has been observed in other rivers with forested flood plains where they have been called "sedimentation zones" (Church, 1983) or "disturbance reaches" (Jacobson and Pugh, 1997). Higher channel mobility within such sedimentation zones has been attributed to external controls such as Neoglacial sediment production, tributary fan locations (Church, 1983), and valley geometry (Jacobson and Pugh, 1997), as well as internal mechanisms involving feedbacks between large woody debris accumulations, sedimentation, and lateral channel shifting (Keller and Swanson, 1979; Gottesfeld and Gottesfeld, 1990). On the lower Quinault River, where external controls such as tributary fans and upper basin sediment and wood production have little influence on the channel or flood plain, internal mechanisms involving wood, sediment, and channel migrations must be the primary factors controlling channel and flood-plain dynamics.

The correspondence of the three large log jams mapped in the 1915–1916 timber survey with these dynamic reaches on the lower Quinault River points to the likely role of large log jams in creating persistent zones of unstable channels (Fig. 4). In particular, the long reach of high channel migration since 1902 between RK 27 and 40 is mostly downstream of the large channel-spanning log jam at the time of the 1902 cadastral survey (Fig. 7). Ponding behind this log jam likely triggered the channel avulsion between 1915 and 1929, and indirectly caused the 1953–1981 avulsion downstream (Fig. 7) as erosion of the new channel brought additional wood from the flood-plain forest into the channel, leading to formation of another jam downstream. Wood and sediment brought into the channel by these two jam-related avulsions has probably been the source of the continued downstream instability in a river system where the only sources of wood and sediment are the flood plains and valley margins. For the lower Quinault River, such feedbacks between flood-plain sediment and wood erosion and deposition must be primary mechanisms promoting channel instability.

The absence of large, channel-spanning log jams on the upper Quinault River or Queets River may be due to their greater sediment supply, peak discharge, and gradient. Although there is no direct evidence for this, we speculate that the higher sediment flux on the upper Quinault and Queets River segments results in more rapid sediment deposition at sites of wood accumulation compared to the lower Quinault River, thus forcing flow to erode laterally prior to complete blockage of the channel by wood. The greater slopes and peak discharges of the upper Quinault River and Queets River would also promote such lateral erosion as well as erosion of alternate flow routes prior to complete blockage. In contrast, the lower Quinault River, with low sediment flux and lower peak discharges, may allow substantial wood accumulation—to the point of completely blocking the channel—before the ponded river completely overtops the flood plain and erodes another course.

Channel-spanning log jams and consequent avulsions similar to those of the lower Quinault River have been reported for other large, low-gradient rivers with forested flood plains. Examples include the Willamette River of western Oregon, where historic accounts describe extensive rafts of wood blocking channels and consequent formation of new channels (Sedell and Froggatt, 1984); the Morice River of British Columbia (Gottesfeld and Gottesfeld, 1990); the Skagit and Stillaquamish Rivers of western Washington (Maser and Sedell, 1994, p. 134); and the Red River of Louisiana, where a complex series of channel-spanning log jams formed between the mid-17th century and 1873, obstructing the channel for more than 250 km and diverting the lower Red River to another route to the Gulf of Mexico (Veatch, 1906).

Feedbacks among log jams, channel migration, and flood-plain vegetation also involve longer time scales (e.g., Naiman et al., 2000). Bars composed of relatively fine-grained sediment form in the lee of large woody debris accumulations (Fig. 12a; Swanson and Lienkaemper, 1982; Gottesfeld and Gottesfeld, 1990; Church, 1992; Maser and Sedell, 1994, pp. 47–50; Fetherston et al., 1995; Abbe and Montgomery, 1996, 2003; Jacobson et al., 1999). Woody debris accumulations, especially large and stable bar-apex and meander jams (Fig. 12b; Abbe and Montgomery, 1996, 2003), and their associated downstream pendant bars commonly stand several meters above adjacent channel and bar areas and provide advantageous substrate and topographic conditions for flood-plain vegetation establishment and growth. For the Queets and Quinault Rivers, red alder typically colonizes these bars within a few years of emplacement and, if the log jam remains in place, will survive to further stabilize the bar and promote soil and flood-plain forest development, resulting in forest patches older than surrounding vegetation growing in subsequently abandoned channels (Fetherston et al., 1995; Abbe and Montgomery, 1996; Abbe, 2000).

Furthermore, the log jams themselves may become important in controlling future in-channel wood and flood-plain forest conditions. Log jams are a rich source of organic material and provide habitats and energy sources for a variety of terrestrial plant and animal species (Maser and Sedell, 1994, pp. 47–50; Fetherston et al., 1995; Jacobson et al., 1999). Moreover, log jams become germination sites for conifers, especially spruce that grow directly on logs or from soil clinging to rootwads on less-traveled tree stems incorporated into the log jam (Fig. 13; Gottesfeld and Gottesfeld, 1990). In the Queets and Quinault River valley bottoms, it appears that large log jams provide germination sites, stability, and organic-rich substrate to allow conifers to successfully compete and coexist with rapid hardwood colonization of the more barren gravel bars (Fig. 13). This is shown by the young spruce growing from members of the 1902 log jam on the Quinault River, and perhaps by the groves of large and aligned spruce at the margins of the 1902 jam. Analogously, spruce forests advance into salt marshes in coastal environments by colonizing stable piles of driftwood (Maser and Sedell, 1994, p. 84).

We further speculate that for the Quinault River and Queets River, such spruce groves may have effects on channel migration on time scales of centuries to millennia (Fig. 14) by (i) providing a source of large trees that may eventually fall into the channel and become key members of future log jams (Abbe and Montgomery, 1996; Abbe, 2000) and (ii) forming patches of flood-plain vegetation resistant to erosion, thus affecting locations of future log jams and channel migration. This may have been the case for the 1902 log jam on the lower Quinault River, for which the downstream logs are racked up against one of these mature spruce groves.

5.4. Management implications

These results and inferences have implications for management of large, gravel-bed rivers flowing through forested flood plains. Foremost, flood-plain morphology and channel conditions at any one time are the product of several hundred to thousands of years of channel migration and flood-plain forest development. Consequently, time scales of this order are the necessary perspective from which to consider the full suite of channel and flood-plain processes for these types of rivers. River management strategies that do not fully consider the entire flood plain over time scales of centuries are likely to lead to eventual changes in channel and flood-plain processes and morphology (Naiman et al., 2000), although such effects may require several decades or centuries to become evident. In contrast, most present strategies for actively managed forested flood plains implicitly operate in consideration of time frames of at most several decades, corresponding to timber cutting schedules and areas of sediment and wood input associated with the present channel location. Secondly, channel and flood-plain processes and morphologies can be very different, even within broadly similar physiographic settings such as the western Olympic Peninsula. For example, the distribution and extent of various flood-plain environments (channels, unvegetated gravel bars, flood-plain forests of various composition and age structure) were likely to have been different for each of the three study reaches under natural conditions because of differences in the natural sediment, flow, and wood regimes. Specification of realistic goals and optimizing actions to meet habitat or harvest objectives must account for these differences and the processes that underlie them.

6. Conclusions

The gravel-bed channels and forested flood plains of the lower Quinault River, upper Quinault River, and Queets River have distinctive physical morphologies and dynamics that reflect different flow, sediment, and wood regimes within an overall similar physiographic environment. These are the major observations:

(i) Local channel migration rates, active channel width, and number of channels are highly correlated to one another (Fig. 4). The sediment-and-wood-rich upper Quinault River, aggrading behind Lake Quinault, has the greatest migration rate, widest active channel, most multi-channel reaches, and greatest overall channel slope of the three river segments. The lower Quinault River, with no upstream sediment source, has the lowest migration rate, narrowest active channel, fewest multi-channel reaches, and the lowest overall gradient. The Queets River, with a sediment supply that is likely similar to the upper Quinault River but in a nonaggradational setting, has attributes intermediate between the upper Quinault and lower Quinault segments.

(ii) Overall, rates of encroachment of the channel across the flood plain are broadly similar for each of the three study reaches, resulting in flood-plain half-lives of 200 to 500 years. The higher channel migration rate of the upper Quinault River relative to the Queets and lower Quinault Rivers is compensated by a wider flood plain. For the lower Quinault River segment, the lower overall channel migration rate and the relatively low proportion of channel movement into historically unoccupied flood plain are likely responsible for the overall narrower Holocene flood plain.

(iii) Historic patterns and processes of channel migration are different among the three reaches, and these differences influence channel and flood-plain morphology as well as spatial variations in channel migration and flood-plain occupancy rates. Channel change on the upper Quinault River and the upstream portion of the Queets River study reach is primarily due to short-wavelength, low-amplitude meander formation and cutoffs, largely spurred by bar formation in the lee of large woody debris accumulations and by partial blockage of the channel by log jams. These reaches are dynamic and multichanneled, and channels commonly shift back and forth between previously occupied channels on an annual to decadal time frame. For the lower portion of the Queets River study reach, most channel migration is due to progressive enlargement and cutoff of large meander bends, with complete cycles of meander growth and cutoff occurring over several decades to centuries. For the lower Quinault River, avulsions are apparently triggered by channel-spanning log jams, which then set up reaches of channel instability separated by long reaches of relatively stable channels.

(iv) Channel migration, sediment transport, large woody debris, and flood-plain vegetation and morphology involve several feedbacks, some encompassing several century durations of the same order as flood-plain turnover rates. Channel shifting introduces large woody debris and flood-plain sediment into the channel system, which then triggers further channel shifting. For the lower Quinault River, this is probably the primary process maintaining input of wood and sediment into the channel. Log jams and sediment accumulations become unique terrestrial environments for flood-plain forest formation. The log jams are preferred sites of conifer germination and thus become areas resistant to future flood-plain erosion as well as areas that may eventually provide source wood for future log jams.

Acknowledgements

Phillip Martin Jr. of the Quinault Indian Nation, Department of Natural Resources, provided logistical support and boat access to the lower Quinault River. Mark Mobbs, Justine Turner, Antonio Hartrich, and

John Sims of the Quinault Indian Nation provided historic documents and maps. Tina Marie and Danial Polette, US Geological Survey, provided cartographic and GIS assistance. Discussions with Mark Mobbs, Dave Lasorda, Gordon Grant, Tim Abbe, Jonathan Friedman, and Fred Swanson helped to clarify many of the ideas presented here. Reviews of earlier versions by John Parker, Ed Prych, Jonathan Friedman, and Fred Swanson improved the paper. Kevin Fetherston and an anonymous referee provided helpful reviews for *Geomorphology*, as did journal editors David Montgomery and Herve Piégay. Partial funding was provided by the Quinault Indian Nation.

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