No further reproduction or distribution of this copy is permitted by electronic transmission or any other means.

The user should review the copyright notice on the following scanned image(s) contained in the original work from which this electronic copy was made.

Section 108: United States Copyright Law

The copyright law of the United States [Title 17, United States Code] governs the making of photocopies or other reproductions of copyrighted materials.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specified conditions is that the reproduction is not to be used for any purpose other than private study, scholarship, or research. If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use," that use may be liable for copyright infringement.

This institution reserves the right to refuse to accept a copying order if, in its judgement, fulfillment of the order would involve violation of copyright law. No further reproduction and distribution of this copy is permitted by transmission or any other means.
Borrower: WOS
Lending String: *CWU,HTM,UPP,ORZ,ORU
Patron: Taylor, Steve
Journal Title: Geomorphology.
Volume: 51 Issue: 1-3
Month/Year: 20 MAR 2003
Pages: 31-59

Article Author:

Article Title: O'Connor J.E.; Jones M.A.; Haluska T.L. 'Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA'

Imprint: [Amsterdam, The Netherlands]; Elsevier,

ILL Number: 4058122

Call #: GB400 G46
Location:

ARIEL
Charge
Maxcost: postage

Shipping Address:
Hamersly Library--ILL
Western Oregon University
345 N Monmouth Ave
Monmouth, OR 97361-1396
Fax: 503 838-8645
Ariel: 140.211.112.16

LIBRARY—I LL
CENTRAL WASHINGTON UNIVERSITY
400 E. 8TH AVE
ELLENSBURG, WA 98926-7548

COPYRIGHT NOTICE
The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material. Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. On of these specified conditions is that the photocopy is not to be “used for any purpose other than private study, scholarship, or research.” If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of “fair use,” that user may be liable for copyright infringement. This institution reserves the right to refuse to accept a copying order if, in its judgement, fulfillment of the order would involve violation of the copyright law.

If there are any transmittal problems, such as:
- Missing pages
- Edges cut off
- Unable or difficult to read

Please contact Central Washington University
We will fix the problem as soon as possible.

Thank you for your cooperation CWU—INTERLIBRARY LOAN
Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA

Jim E. O'Connor a, *, Myrtle A. Jones b, Tana L. Haluska a

a US Geological Survey, 10615 SE Cherry Blossom Dr, Portland, OR 97236, USA
b US Geological Survey, 1201 Pacific Ave. Suite 600, Tacoma, WA 98402, USA

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 regimes, and interactions for the Quinault River and Queets River in the western Olympic Peninsula, Washington, reveals gravel-bed channels and forested floodplains 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, is derived from reworking of floodplain deposits and contributed from valley 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 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 sedimentary 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 flow 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 brevet rates are similar for all three reaches, with channels eroding the flood plain at the rate of about 1% 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 events. On the upper Quinault River and Queets River, log jams reduce 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 floodplains. However, locally, channel-spanning log jams have caused channel avulsions within reaches that have been subsequently stable for several decades. In all three reaches, log jams appear to be areas of conifer germination and growth that may later influence channel and flood-plain conditions on long time scales by forming flood-plain areas resistant to channel avulsion and by providing key members of future log jams. Appreciation of these processes and dynamics and associated
temporal and spatial scales is necessary to formulate effective long-term approaches to managing fluvial ecosystems in such environments.
Published by Elsevier Science B.V.

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 channel and sediment 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 Foggatt, 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 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 field observation, wood, channel, and flood-plain conditions and interactions. Many of our interpretations regarding a 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 igneous rocks that have undergone rapid Cenozoic geologic uplift (Tabor and Cady, 1978a;b; Brandon et al., 1981). Both rivers drain SW from glaciated mountain peaks higher than 2200 m, exiting the Olympic Mountains and then flow across a 10- to 15-km-wide coastal piedmont underlain by Quaternary fluvial sediments. The Queets River drains an area of about 1170 km² and the Quinault River drains 1134 km² (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 reaches. Topographic base from USGS 30-m digital elevation model. (b) Geologic flood plains and 1994 channel of each of the three reaches. Flood-plain and channel transects shown at 1-km intervals. (c) Section of the Queets River flood plain showing 1994 channel and flood-plain surfaces as mapped from 1994 orthophotos. Channel and flood-plain transects are spaced at 0.2-km intervals.
Rivers of the western Olympic Peninsula, Washington state (Fig. 1), show differences in channel geometries between the two rivers in interactions among flow, sediment flux, and other processes. Our conclusions draw on both historic channel migration patterns and historic and field observations of flood-plain conditions and our interpretations regarding how these factors are affecting channel and flood-plain development. Our interpretations are informed by the study of Quinault and Queets Rivers.

**Quinault and Queets Rivers**

**Hydrology and climate**

The Quinault and Queets Rivers flow from the Olympic Mountains, Park before emptying into the western coast of the Olympic Peninsula. The headwaters of each river have marine sedimentary and volcanic landforms that have undergone rapid Cenozoic tectonic compression and uplift. The Queets River drains 7,220 km² and the Quinault River drains 6,220 km². The Queets River drains the Olympic Mountains and geologic flood plains of the Quinault and Queets rivers, and each of the three flood plain channels are shown with 1994 channel geometry and floodplain conditions at 0.5-km intervals.
Table I. General study reach characteristics.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Lower Quinault</th>
<th>Upper Quinault</th>
<th>Quets reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Lake Quinault outlet (RK 51.6) to Pacific Ocean</td>
<td>North Fork Quinault River confluence (RK 73.9) to Lake Quinault (RK 56.6)</td>
<td>Sams River confluence (RK 39.4) to Pacific Ocean</td>
</tr>
<tr>
<td>Length (km)</td>
<td>54.0</td>
<td>18.0</td>
<td>41.2</td>
</tr>
<tr>
<td>Drainage area (km²)</td>
<td>1124 at downstream endb</td>
<td>441 at upstream endb</td>
<td>1152 at River Mouth</td>
</tr>
<tr>
<td>Mean discharge (m³/s)</td>
<td>81c</td>
<td>0.0035</td>
<td>1235</td>
</tr>
<tr>
<td>Slope (m/m³)</td>
<td>0.0011</td>
<td>0.0035</td>
<td>0.0022</td>
</tr>
<tr>
<td>Low-flow channel width (m)</td>
<td>65.4 – 27.7</td>
<td>58.3 – 24.3</td>
<td>68.9 – 39.6</td>
</tr>
<tr>
<td>Number of channels</td>
<td>1.02 – 0.14</td>
<td>1.41 – 0.73</td>
<td>1.30 – 0.63</td>
</tr>
<tr>
<td>Active channel width (m)</td>
<td>95 – 45</td>
<td>240 – 104</td>
<td>165 – 89</td>
</tr>
<tr>
<td>Sinuosity (m/m³)</td>
<td>1.37</td>
<td>1.24</td>
<td>1.27</td>
</tr>
<tr>
<td>Mean flood plain width (m)</td>
<td>1245</td>
<td>1930</td>
<td>1286</td>
</tr>
<tr>
<td>Total flood plain area (ha)</td>
<td>4831.8</td>
<td>2728.4</td>
<td>3914.3</td>
</tr>
<tr>
<td>Total area historically occupied by channel (ha)</td>
<td>1509.5</td>
<td>675.2</td>
<td>1050.3</td>
</tr>
</tbody>
</table>

* Measured from 1994 orthophotoquads.  
* Information from USGS page Quinault River at Quinault Lake (12039500), 1912 – 1997 and Quets River near Clearwater (12446506).  
* Information from Quinault River System Analysis (Quinault Indian Nation and USDA Forest Service, 1999).  
* Measured from USGS 7.5-min topographic quadrangles.  
* Measured at 0.20-km increments along flood-plain centerline.  
* 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 m³/m sq for the Quets watershed and about 3.7 m³/m sq for the Quinault watershed. Particularly large flows, such as the one of March 1997, result during warm and wet storms when 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 rivers have established alluvial floodplains 3.5 km wide that are flanked by the western reaches of the Olympic Mountains or, further downstream, tall bluffs of Pleistocene glacial till and outwash. Overall, channel gradient in the alluvial section of the Quets River between river kilometer (RK) 42.5 and RK 42.5 is 0.0023; the overall slope for the alluvial section of Quinault River between RK 0 and RK 56 is 0.0022. Within their alluvial sections, both have cobble-gravel beds with pool-and-riffle patterns and meander orientations. The planview patterns of these rivers do not neatly fit into standard classes such as "meandering" or "meandering" but, at length scales of kilometers, are similar to the "irregular meandering" or "irregular meandering" morphologies described by Church (1992). Shorter reaches these wandering river segments have braided around bars within an active channel and mosaics (flow around islands excised from the plain) planforms as defined by Knighton and Naiman (1993).
Within their alluvial valleys, both of these rivers have shifted back and forth during the Holocene, having 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 densities 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 by a moraine-dammed lake with a surface area of 15 km² (Fig. 1). Lake Quinault forms an intertongue 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 lake 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 1980 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 floodplain 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

<table>
<thead>
<tr>
<th>Channel map source</th>
<th>Scale</th>
<th>Coverage</th>
<th>Dates</th>
<th>Plot date</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Land Office</td>
<td>1:31,680</td>
<td>Quents</td>
<td>Sans River confluence to Pacific Ocean</td>
<td>1895-1906</td>
<td>1900 Instrument survey of stream channel (and unvegetated gravel banks)</td>
</tr>
<tr>
<td>Surveys (available at the Bureau of Land Management, Portland, OR)</td>
<td>Upper Quinault</td>
<td>Entire study reach</td>
<td>1895-1906</td>
<td>1900 Digitized from 1:31,680</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower Quinault</td>
<td>Quinault Indian Reservation</td>
<td>1902</td>
<td>1902 paper copies; georeferenced by section corners.</td>
<td></td>
</tr>
<tr>
<td>Office of Indian Affairs (available at Quinault Indian Nation, Taholah, WA)</td>
<td>Lower Quinault</td>
<td>Quinault Indian Reservation</td>
<td>Map dated 1920, notes state surveyed</td>
<td>1915 Transit and stadia for primary control. Digitized from 1:31,680 paper copy; georeferenced by section corners.</td>
<td></td>
</tr>
<tr>
<td>US Army Corps of Engineers Tactical Maps “Destruction Island” and “Quents”</td>
<td>1:62,500</td>
<td>Quents</td>
<td>Elk Park to Pacific Ocean</td>
<td>Maps dated 1922, unknown survey date</td>
<td>1922 Surveyed and compiled by US Coastal and Geodetic Survey; methods unknown. Map not used for channel migration analysis because unsatisfactory registration.</td>
</tr>
<tr>
<td>US Geological Survey (USGS) Plan and Profile River Maps (available at University of Washington Map Library, Seattle, WA)</td>
<td>1:31,680</td>
<td>Quents</td>
<td>Paul Creek confluence to Pacific Ocean</td>
<td>Map dated 1935, notes state surveyed</td>
<td>1931 Survey methods unknown but probably transect stadia. Digitized from paper copy; georeferenced by section corners.</td>
</tr>
<tr>
<td></td>
<td>Upper Quinault</td>
<td>Rustler Creek confluence to Lake Quinault</td>
<td>Map dated 1930, notes state surveyed</td>
<td>1929 section corners. Lower Quinault reach required significant editing.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower Quinault</td>
<td>Lake Quinault to Pacific Ocean</td>
<td>1928, 1929.</td>
<td>Quents</td>
<td></td>
</tr>
<tr>
<td>15' USGS topographic quadrangles</td>
<td>1:62,500</td>
<td>Quents</td>
<td>Entire study reach</td>
<td>Maps dated 1956, on the basis of 1952 source photographs</td>
<td>1952 Digitized from paper copy; spatially referenced by quadrant corners.</td>
</tr>
<tr>
<td></td>
<td>Upper Quinault</td>
<td>No 1950s source coverage east of 123°45'N (RK 67.6)</td>
<td>Maps dated 1953-1955 on the basis of 1953-1954 aerial photography</td>
<td>1953</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower Quinault</td>
<td>Entire study reach</td>
<td>1953</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duncan and Steinbrenner (1976) Soil Survey (available at Quinault Indian Nation, Taholah, WA)</td>
<td>Lower Quinault</td>
<td>Quinault Indian Reservation</td>
<td>Map dated 1976(?); on the basis of 1972 aerial photographs</td>
<td>1972 “River” polygons for existing Quinault Indian Nation digital coverage; date of source polygons provided by Tony Hayer; Quinault Indian Nation</td>
<td></td>
</tr>
</tbody>
</table>

Methods

For each of the three study areas, historic channel position, map and measured from USGS photographs and maps. The objective is to develop channel, vegetation, and floodplain maps that can be used to assess changes over time and to guide management decisions. The maps were created using Geographic Information System (GIS) technology, which allowed for the integration of historical and contemporary data. The GIS was used to digitize the historical aerial photographs and to overlay them with modern satellite imagery. The resulting images were then analyzed to identify changes in channel position and vegetation cover over time. These changes were then used to inform the development of a land management plan for the study area. The goal of this project is to provide a comprehensive understanding of the historical development of the Quinault Indian Nation's landscape and to inform future land management decisions.
<table>
<thead>
<tr>
<th>Name (continued)</th>
<th>Scale</th>
<th>Coverage</th>
<th>Dates</th>
<th>Plot date</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>USGS and Oregon Department of Geologic and Mineral Resources (OR) digital orthophotoquads</td>
<td>Derived from 1:12,000 to 1:40,000</td>
<td>Quatsch to Quatsch aerial photos</td>
<td>Entire study reach</td>
<td>DNR Sept. 22, 1994</td>
<td>1994 Channel digitized from 1:24,000 paper copy (Quatsch R.) and on screen from 1:5000 georeferenced digital orthophotoquadrangle (Quatsch R.). Quatsch R. discharge Sept. 22: 25.4 m³/s. Quatsch R. discharge July 11: 35.7 m³/s, Quatsch R. discharge Sept. 16: 54.4 m³/s, Quatsch R. discharge Sept. 22: 24.5 m³/s</td>
</tr>
<tr>
<td>Quatsch Indian Nation digital orthophotoquads</td>
<td>Derived from 1:12,000</td>
<td>Lower Quatsch (and lower) Quatsch aerial photos</td>
<td>Quatsch Indian Reservation 15.8 km of the Quatsch River</td>
<td>DNR</td>
<td>1997 Channel digitized on screen (1:5000) from georeferenced digital orthophotoquadrangle. Only the lower Quatsch Indian Nation used in the channel migration analysis.</td>
</tr>
</tbody>
</table>

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

3. Methods

For each of the three study reaches, channel characteristics and historic channel migration rates were measured from historic and current aerial photographs and maps. Inferences regarding interactions between large woody debris, standing forest, the channel, and flood plain were based on historical records and reconnaissance field observations, supplemented by previous work on the Quatsch 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 to 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 (1990). 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 photographs 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 maximum error in placement of channel boundaries from the older sources (1900–1902 GLO maps, 1929–1931 USGS Plan and Profile Maps, and 1939 aerial photos) is about 50 m, but the error is probably much

![Map of historic channel positions a lower Quinault River study reach.](image-url)
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; Elliott 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 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.

3.3. Large woody debris 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 18, 1997 (1315 m³/s, Quinault River; 3115 m³/s Queets River), which was the largest (Quinault River) and second largest (Queets River) flood since 1955. Additionally, we relied heavily on the findings of Peterson et al. (1995), Abbe and Montgomery (1999, 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 planform characteristics (Figs. 2 and 3) show differences among the three river segments.

---

Fig. 3. Box plots summarizing major study reach characteristics as measured from the channel and flood-plain transects. Boxes show 10th and 90th percentiles; vertical lines depict the 5th and 95th percentiles; individual symbols are points outside the 5th and 95th percentiles.

Low-flow channel width, active channel width, and number of low-flow channels are from measurements from 1994 orthophotographs. Increment long the 1994 channel axis. Channel migration rate is from analysis of historic lateral movement of the primary channel on transects orthogonal to the flood-plain axis spaced at 0.2-km increments.
These results allow assessment of area has changed with time x channel area at each map on of historically uneroded reoccupying channel loca s maps and photos). Thus mining flood-plain turnover of time required for the ire flood plain.

is and forested flood-plain

nel large woody debris and affecting channel migration orical accounts of location od jams, including records of accompanying late 1800s and d Office Surveys, and maps showing locations of woodeld mapping of channel coctions, bank stratigraphy and implemented these historical field observations were after the flood of March 9 Quinault River; 3115 m³/s Queen largest (Quinault River) at river) flood since 1955. Addi on the findings of Fethbe and Montgomery (1996, regarding the role of channel affecting channel morphology on the Queets River.

ll planform characteristics 994 flood-plain and channel (Figs. 2 and 3) show distinct three river segments, many of plain transects. Boxes show 75th 5th outside the 10th and 90th percentiles from 1994 orthophotos at 0.3 ho ment of the primary channel measure.
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 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 floodplain as portrayed in Fig. 1, measured at 0.2-km increments along the flood-plain centerline. Number of low-flow and isolated channels, measured at 0.2-km increments along the flood-plain centerline. Isolated channels included 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 for segments are similar, but their longitudinal profiles are significantly different. The upper Quinault River has braidplains, averaging 240 m wide and 95 m f, and the Queets River has an active channel of upper Quinault River anywhere at least twice as wide. However, for both the upper Queets and Queets segments, several reaches longer than 1 km consist of a single channel wider than 100 m, with exposed and unvegetated gravel bars and lower Quinault segments wider than 200 m. The Pacific Ocean is shown in Fig. 5, which shows a field sketch.
1.5 “meandering”) (e.g. 4, p. 281). Rare, all three reaches of generally decreasing 4a). Channel slopes for and Queets segments generally, resulting in smoother. In contrast, the profile is more varied; gradients 0.0025, with less systematic direction.

S RIVER

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 in 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 4a) and 1.30 channels per flood-plain transect, respectively, compared to 1.02 for the lower Quinault River (Table 1; Figs. 3 and 4e). 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 < 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 regression

![Fig. 6. Sequence of channel maps of a portion of the Queets River near RK 14. Sources listed in Table 2.](image_url)
The upper Quinault River rate of \( 8.8 \pm 4.1 \) m\text{year}^{-1} \) is significantly higher than the Quinault and Queets segments (t-test). Error terms are spatial variation in samples of each floodplain transect.

Back-and-forth channel movement and channel position will likely be less than some factor that depends on sequential maps. Congestion rates for each channel are biased by the different and uneven interval times. For each significant inverse constant (t-test) between measured and number of years, indicating that this bias accounts for some actual migration being “missed.”

Normalized migration rates, representing the mean channel position along the linear regressions in Fig. 8. This adjustment results in normalized migration rates of \( 4.0 \pm 1.2 \) m\text{year}^{-1} for the lower Quinault River, \( 7.5 \pm 2.9 \) m\text{year}^{-1} for the Queets River, and \( 12.7 \pm 3.3 \) m\text{year}^{-1} for the upper Quinault River. Error terms are the estimated standard error for a sampling interval of 17 years resulting from the omission of the mean cross-section migration rate spot the sampling period, calculated using Eq. 6 of Draper and Smith, 1966).

The other approach to analyzing channel change, overlay of channel polygons, shows that for all 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 slow-flow channels—especially for the upper Quinault River and perhaps for the Queets River. For the 1907 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 floodplain (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 Quinault and upper Quinault segments, 40\% to 50\% of the channel erosion between photo and map sets is into historically unoccupied floodplain; 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
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 lower at 495 ± 38/−32 years for the upper Quinault River flood plain and somewhat shorter at 277 ± 52/−46 years for the lower Quinault River segment although this latter result is heavily influenced by the measured channel differences between the 1900 and 1915 maps for which errors due to 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 are not recorded at the isolated instances portrayed on the channel maps, these calculated half-lives may overestimate the actual flood-plain half-lives.
ood-plain half-lives for each
chess by fitting exponential
rative erosion of 1900-
as outside the 1900–1959
hin the geologic flood plain
0 97 years (Fig. 11). For this
the calculated flood-plain
39 years (the stated error
error about the exponen-
half-life is somewhat longer
or the upper Quinault River
sat shorter at $277 \pm 53/\mu$.
Quinault River segment,
lt is heavily influenced by
ferences between the 1993
which errors due to
2. Because of the likelihood
the flood plains occupied
st 94 to 97 years that would
ated instances portrayed in:
calculated half-lives for:
ood-plain half-lives, it

Though this error is probably partly compensated for
r registration errors associated with the individual
ps (which would most likely lead to
omously high calculated migration rates). This
pproach to calculating flood-plain half-life differs
from the more direct approach adopted by Everitt
(1988) in which the age distribution of the flood-

plain surface was determined by mapping tree ages.
Such an approach could be undertaken on the
Quets 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.
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 while navigating the Quinault River (Capoeman, 1994a).

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

e. Results are partly a function of

as that were nearly 0.5 km impassable to navigation (Gratu

iour to the historic record of 

auit Indians to build fairly 
portage over these jams at the Quinault River (Capeoeman, 1989).

ions shown in Fig. 2) of the port

Office maps.

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 57.6, 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 

(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 degradation 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 Queets 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-

1923 aerial 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 chopped and deposited on the downstream bar.
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 only partially block the channel (Fig. 12). These wood accumulations have been associated with rapid bank growth, bank erosion, and short-length channel avulsions as described for the Queets River by Fetheree et al. (1995), Abbe and Montgomery (1996, 2001), 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 across channel margins, causing bank erosion and channel migration (Abbe and Montgomery, 1996). An example on the Queets River is shown in Figs. 5 and 8 where about 500 m of new channel formed as a result of partial channel blockage by wood and mud, 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 325 and 27.2. Judging from the abundant in-channel wood, our field observations of channel change between 1996 and 1999, and high channel 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 form and there has been more systematic growth of cutoff of large meander loops (e.g., Fig. 6). The series of aerial photographs and observations from the field indicate that these meanders grow as a result of...

---

Fig. 13. Photographs illustrating evidence for role of log jams in promoting flood-plain conifer growth. (a) Sitka spruce trees growing at 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 held 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 decomposed 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 end 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 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 photo, apparently grew from a partially decomposed conifer log now emerging from the eroding bank (upon which the person is standing).
channel-spanning avulsions that have affected the lower Quinault River, the Queets River and a more local extent, the Queets River has been affected by large woody debris and wood jams that block the channel (Fig. 12). These reaches of frequent large woody debris, at bar apices, are non-promoting mid-channel which then redirects flow, leading to bank erosion, as noted by Montgomery, 1996. A new channel formed as depicted by wood and scoured during high flows, similar avulsions, both of less than 400 m, occurred during the Quinault River at RK 299, and high lateral migration and lateral migration during most years on the Queets River above RK 20. 20 on the Queets River is adjacent and more similar to more systematic growth of loops (e.g., Fig. 6). Important observations from these stands growing as a result of

![Sitka spruce trees growing near RK 38](image)

![Sitka spruce tree on the right margin of the channel](image)

![Exposed spruce on the left edge of the photo](image)
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 Quinaut 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 Quinaut River and Quetzes 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 m² 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-rooted 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 Quinaut 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 Quetzes River, Fetherser 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 are related wood accumulations to hydraulic, depositional, and aquatic habitat conditions. These earlier studies on the Quetzes River and our observations on all three river segments indicate that deposited large woody debris commonly promotes mid-channel and point bar growth (Fig. 10a). Additionally, bar formation in the lee of wood accumulations can lead to establishment of riparian vegetation on the resulting higher and coarser deposits, and ultimately, stands of evergreen riparian vegetation. Bank erosion and the consequent entrainment of flood-plain trees can foster lateral channel instability as the downed wood stresses flow into banks (the “auto diversion” process of Keller and Swanson, 1979).

5. Discussion

Despite the overall similar physiographic setting of the Quetzes River and Quinaut River basins, three study reaches have distinct planform characteristics as well as patterns and rates of channel migration and flood-plain erosion. These differences are topologically attributed to the different sediment source and wood inputs to the basin, and interactions among these factors, although rigorous identification of the effect is hampered by the multiple differences between the reaches and the long time scale of interactions. These differences regarding effects of sediment, wood, and flow on channel morphodynamics 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.
do not completely span the length of the Queets River, Fetherson et al. (1996) conducted field surveys for riparian vegetation and soil depth, which revealed that the river is characterized by high soil depth and a dense riparian forest. These observations were supported by the presence of large woody debris in the channel, indicating that the river is undergoing active erosion and deposition processes.

In the lower Quinault River, the channel planform characteristics are significantly different from those in the upper Queets River. The lower Quinault River is characterized by a wide, meandering channel with a low gradient and a high sediment load, whereas the upper Queets River is narrow and steep with a low sediment load. These differences are likely due to the differences in the physiographic setting and the history of the two rivers.

The Quinault River basin is characterized by distinct planform characteristics, which are influenced by the sedimentary environment and the interaction between the river and the surrounding landscape. These differences are evident in the width of the channel and the frequency of meanders, which are related to the sediment supply and the geologic history of the area. The channel planform characteristics of the Quinault River are controlled by the balance between erosion and deposition, which is influenced by the sediment supply, the geologic structure, and the hydrologic regime.
the lower Quinault River. The relatively greater sediment and wood supply of the Quieteens 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 Quieteens 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 Quieteens 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 the Quieteens 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 floodplain planform characteristics (Fig. 4). This is especially evident for the Quieteens 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 floodplain characteristics.

Despite different channel migration rates, the floodplain occupancy rates for all three reaches are broadly similar, indicating that floodplain turnover occurs over 200 to 2000 years with floodplain 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, 1977), but somewhat longer than the 30–50 years estimated by Gottesfeld and Gottesfeld (1990) for the Murr River in British Columbia, which has a similar physiographic setting as the three study segments analyzed here. Three factors apparently control floodplain turnover rates in the Quieteens and Quinault study segments: (i) the width of the floodplain; (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 Quieteens and Quinault Rivers to produce broadly similar floodplain turnover rates. The high migration rate of the upper Quinault River is offset by the width of the floodplain. In contrast, the Quieteens and lower Quinault segments have lower migration rates but a narrower floodplain.

5.3 Interactions among wood, sediment, flow and resulting channel and floodplain morphology

At length scales of individual channel bends and time scales of individual flow events to decades, many of the channel migration and floodplain growth and erosion processes on all study reaches are controlled by interactions between flow, sediment, and wood (Fig. 12). As described for the Quieteens 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 “apex jams,” and in other locations, sediment may trap woody debris, such as the “bar top jams” (Abbe and Montgomery, 1996). In both cases, the accumulations of wood and sediment can impede floodplain generation by providing and stabilizing suitable habitat for establishment of floodplain vegetation (Gottesfeld and Gottesfeld, 1990; Abbe and Montgomery, 1996; Fetherston et al., 1995). Additional sediment and wood accumulations locally impede floodplain erosion by directing flow around the accumulating material. As wood accumulations grow (e.g., Keller and Swanson, 1982; Sedell and Frogbett, 1990; Church, 1992; Piéguay and Marston, 1998; Gurnell et al., 2000), they introduce additional sediment (e.g., Keller and Swanson, 1982). Wood is evident along most of the Quieteens and upper Quinault Rivers, and upstream and wood frost from bank erosion, although the downstream channel is locally stable. All of these and similar processes for rivers with forested banks and Goodlet and Nanson (1970; Nanson and Beach, 1977; Swans, 1982; Sedell and Frogbett, 1990; Church, 1992; Piéguay and Marston, 1998; Gurnell et al., 2000). In the lower Quinault River, the reach- and time-scale interaction is extensively restricted to the parts of the river historically active between RK 14 and 17 (Fig. 2). Exotic reaches within otherwise native reaches has been observed in other rivers that have been "hotter zones" (Church, 1983) or near kayak camps (Jacobson and Pugh, 1997), and within such sedimentatic patches external controls such as sediment supply, tributary fan, and valley geometry (Lowry, 1975) as well as internal meander and floodplain processes between large woody debris, such as the “bar top jams” (Abbe and Montgomery, 1996). In both cases, the accumulations of wood and sediment can impede floodplain generation by providing and stabilizing suitable habitats for establishment of floodplain vegetation (Gottesfeld and Gottesfeld, 1990; Abbe and Montgomery, 1996; Fetherston et al., 1995). Additional sediment and wood accumulations locally impede floodplain erosion by directing flow around the accumulating material.
that flood-plain surface 
years with flood-plain fri
ities. These half-lives are shown
for a variety of other sites
Brace, 1977; Hughes, 1991
30-50 years estimated 
field (1990) for the Moro
rsia, which has a simil
the study area, including 
the Queets and Quinault 
width of the flood plain 
rate; (iii) the propensity 
into the flood plain in 
channel locations. To 
balence each other, the 
the Queets and lower 
river migration rates but


good, sediment, flood-plain morphology.

Individual channel bend
flow events to decades, 
and flood-plain growth
ill study reaches are considered
on flow, sediment, and woody debris. In places, accumulations, such as in the "bar top jams" (Jacobson and Pugh, 1996). In both cases, the woody debris and sediment can provide additional wood to the channel and contribute to the formation of jams.

The study reaches are located in the 1915-1916 timber survey and t
the Queets and lower Quinault River points to the role of large log jams in creating persistent unstable channels (Fig. 4). In particular, the
accumulations locally by directing flow towards

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 Queets 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 point of completely blocking the channel—before the ponded river completely overtakes 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 Stillaguamish 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 and natural environments because of sediment, flow, and wind regimes and the processes that develop these settings.

Conclusions

The gravel-bed channels and foreshore environments, which were historically more dynamic, have evolved to mature and stable environments that reflect the nature and trends of the changing channel and wood regimes within the geographic environment. The changes:

- Local channel migration rates are slower than average.
- The width, and number of channels vary, with one channel being the dominant one.
- Woody debris accumulations, especially large and stable bar apex and meander jams, are the result of centuries of channel migration and flood-plain forest development.
- Consequently, time scales of centuries are the necessary perspective from which to consider the full suite of channel and flood-plain processes.
- The Queets and Quinault Rivers have distinctive channel and flood-plain processes.
- The Quinault River is characterized by a sharp migration rate of the upper Quinault River but in the lower Quinault River segments, the migration rate is lower and more variable. Overall, the rate of encroachment across the flood plain is slow, typically of the order of 200 to 500 years.
- The geologic and physiographic settings of the Olympic Peninsula are important factors in the development of flood-plain environments.
- Historic patterns and processes are different among the various study areas, and these differences influence the development of forested flood-plain environments.

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 centuries are the necessary perspective from which to consider the full suite of channel and flood-plain processes.

The Queets and Quinault Rivers have distinctive channel and flood-plain processes. Consequently, time scales of centuries are the necessary perspective from which to consider the full suite of channel and flood-plain processes. The Queets and Quinault Rivers have distinctive channel and flood-plain processes. Consequently, time scales of centuries are the necessary perspective from which to consider the full suite of channel and flood-plain processes.
natural conditions because of differences in the sediment, flow, and wood regimes. Specifica-
tions in realistic goals and optimizing actions to meet for the Quinault River, spruce groves may happen on time scales of years (but
at least 10 years) to millenia (be, 2000).)

Conclusions

Gravel-bed channels and forested flood plains of the Quinault River and the upstream river system of the Quinault River have distinctive physical morphological and dynamics that reflect different flow, sediment, and wood regimes within an overall similar biogeographic environment. These are the major conclusions:

- 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 Quents 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.

- Overall, rates of encroachment of the channel cross the flood plain are broadly similar for each forested flood plains in terms of time frames of at least half-lives of 200 to 500 years. The higher channel migration rate of the upper Quinault River relative to the Quents and lower Quinault Rivers is compensated by a wider flood plain. For the Quents and lower Quinault River segment, the lower overall difference, even within such a small portion of channel movement into historically broader flood-plains processes and the relatively low settings such as the very small unoccupied flood plain are likely responsible for the overall narrower Holocene flood plain.

- Historic patterns and processes of channel migration are different among the three reaches, each of the three study reaches.

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,
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 Lassorda, 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 Piega. Partial funding was provided by the Quinault Indian Nation.

References


Knighton, A.D., Nanson, G.C., 1993. Anastomosis and the