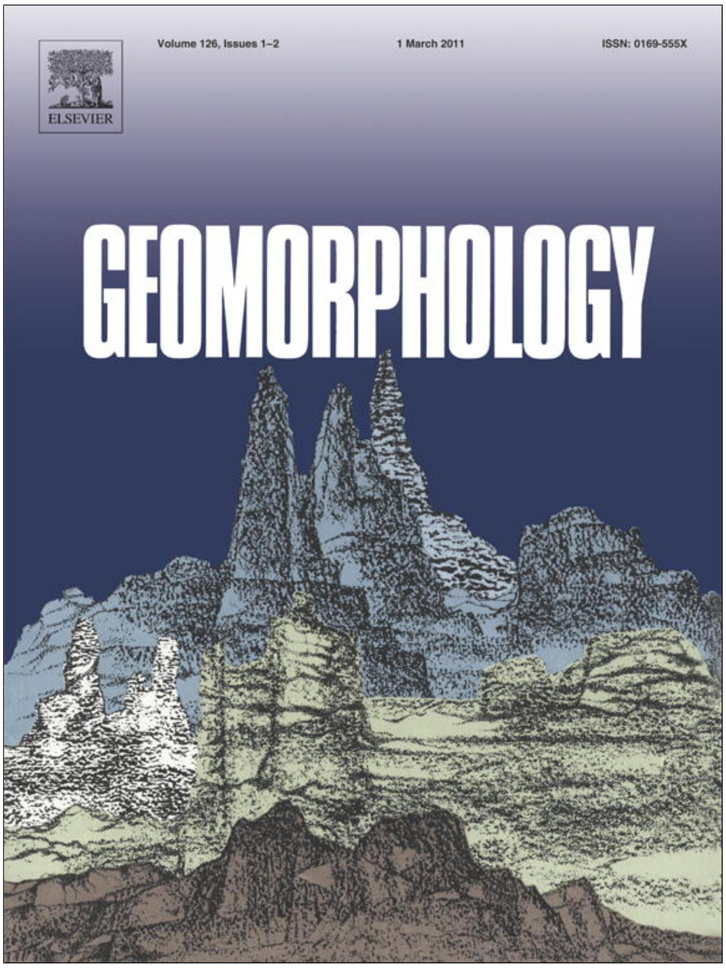
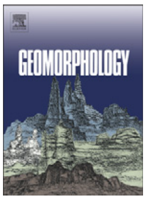

ELSEVIER
Volume 126, Issues 1–2
1 March 2011
ISSN: 0169-555X
GEOMORPHOLOGY

Geomorphology 126 (2011) 174–185

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



The legacy of Pleistocene glaciation and the organization of lowland alluvial process domains in the Puget Sound region

Brian D. Collins *, David R. Montgomery

Quaternary Research Center and Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195-1310, USA

ARTICLE INFO

Article history:
Received 25 August 2010
Received in revised form 3 November 2010
Accepted 8 November 2010
Available online 16 November 2010

Keywords:
Fluvial geomorphology
River longitudinal profile
Disequilibrium
Process domains
River valley morphology
Concavity index

ABSTRACT

Alluvial rivers of the eastern Puget lowland, a landscape shaped by scour and fill from the Cordilleran ice sheet, continue to respond to patterns of deposition and scour by the last-glacial-age ice sheet 18,000 years after deglaciation. Topography revealed by valley cross sections created from high resolution LIDAR digital elevation models shows that rivers are aggrading in valleys eroded by subglacial runoff and degrading in valleys incised by rivers post-glaciation. Slope-area analysis of river profiles shows that profile concavity varies systematically between river segments in the two valley contexts. Concavity indices (θ) in mountain headwaters ($0.3<\theta<0.9$) compare to those of many world rivers ($0.2<\theta<1.0$), but in the lowlands these indices differ between valleys created by subglacial fluvial erosion ($5<\theta<45$) and post-glacially incised river valleys that grade to base levels set by these relict glacial valleys or by post-glacial sea levels ($1<\theta<7$). Dramatic differences in river pattern, landforms, and dynamics occur in valleys having contrasting (aggrading vs. degrading) and incomplete responses to Pleistocene glaciation, creating discrete valley-scale heterogeneities in fluvial process domains along and between rivers. These results point to the importance of valley-scale organization of alluvial process domains along and between rivers having profiles remaining in disequilibrium from Pleistocene glaciation. They also point to the potential usefulness of slope-area analysis of longitudinal profiles in distinguishing among different river valley process domains in lowland alluvial landscapes.

1. Introduction

River landforms and associated habitats are controlled by both the local and systematic downstream spatial organization of geomorphic processes in a drainage network. Understanding the controls on this organization is fundamental to solving problems of river management and restoration for which it is necessary to understand how different process models may apply at different locations along a river, or to different rivers within a region. Knowledge of the controls on the spatial organization of riverine process domains is also fundamental to understanding riverine ecology, research over the past few decades having shown increasingly how landforms can influence ecological systems and structure habitat (Swanson et al., 1988; Naiman et al., 1992). There is a particular need for such understanding of temperate-zone, lowland alluvial rivers, where the transformative and homogenizing effects of historic human activities are often profound and obscure differences in landforms, fluvial processes, and ecosystems along and among rivers (Ward and Tockner, 2001).

Theory in geomorphology is extensive on the systematic downstream variation of processes and landforms, particularly on geomorphic states at the channel or reach scale (Montgomery and Buffington, 1998). Much of this theory on systematic downstream variation is underlain by the equilibrium stream profile concept, in which channel slope adjusts regularly downstream in response to increasing drainage area and discharge and gives rise to regular downstream changes to fluvial processes and landforms. By extension, the equilibrium concept suggests that within a physiographic region similar landforms should develop as an equilibrium response to shared topographic and geologic conditions.

However, research has increasingly shown how the longitudinal profile of alluvial rivers, and their resulting processes and forms, can remain in long-term disequilibrium in response to local factors. Transient conditions common in areas of regional uplift or climate change can strongly influence channel gradient and the along-stream organization of fluvial processes. In glaciated British Columbia, relict glacial topography strongly influences the organization of channel morphologies and river profiles in alpine basins (Brardinoni and Hassan, 2006, 2007). Regionally, persistent response to the sedimentological legacy of Pleistocene glaciations reflects long-term disequilibrium in modern basin erosion (Church and Slaymaker, 1989). Characteristic sets of processes and landforms, or process domains (Montgomery, 1999), thus can vary along rivers systematically in response to equilibrium conditions and locally in response to geologic events or relict landforms to which a river continues to adjust.

* Corresponding author. Tel.: +1 206 616 6584; fax: +1 206 543 0489.
E-mail address: bcollins@u.washington.edu (B.D. Collins).

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doi:10.1016/j.geomorph.2010.11.002

Slope-area analysis is an important tool for understanding the role played by local controls on river profile development and departures from equilibrium conditions. The profile for most rivers is well described by a power law relating local channel slope to upstream drainage area:

$$S = k_s A^{-\theta} \tag{1}$$

where S is local channel slope, A is upstream drainage basin area, and k_s (steepness index) and θ (concavity index) are empirical constants (Flint, 1974). In graded rivers, θ remains constant over the river's length, averaging 0.5 and ranging from 0.2 to 1.0 (Knighton, 1998; Whipple, 2004). Variation in substrates, uplift rates, discharge, and sediment influx can cause profile convexity to vary.

We combine slope-area analysis with examination of valley-bottom landforms and river dynamics to investigate influences on the spatial organization of process domains along and between rivers in the glaciated Puget Sound lowland. We examine the extent to which an ongoing response to the topographic and sedimentologic legacy of Pleistocene glaciation shapes variation in modern river landforms and processes along and between rivers. We evaluate a hypothesis that rivers are undergoing continued, contrasting responses to two distinct river valley forms, created by subglacial fluvial erosion and by post-glacial fluvial response, and that these contrasting responses and the resulting riverine landforms and processes create an important

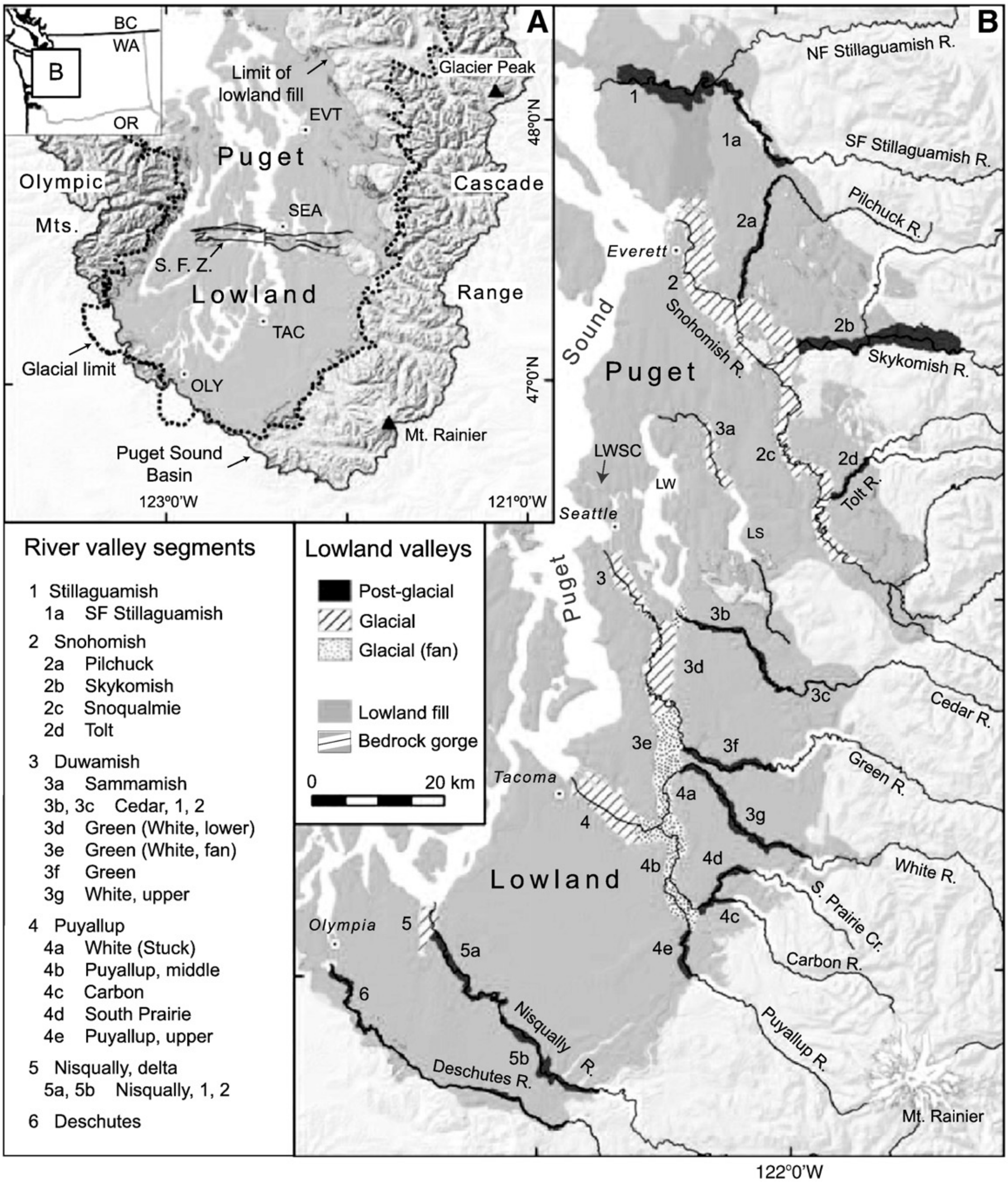


Fig. 1. (A) The Puget lowland, which is defined by the limit of lowland sedimentary fill deposited by Pleistocene continental ice advances. Dashed black line shows generalized ice limit. Map shows the E–W trending Seattle Fault Zone (U.S. Geological Survey, 2006), along which bedrock extends above the fill. (B) Lowland valleys include "glacial valleys" in troughs formed by subglacial fluvial erosion and "post-glacial valleys" incised into the lowland fill. Until the early twentieth century, the Cedar, Sammamish, and upper White Rivers drained to the Duwamish River. The White River was redirected to the Puyallup, and the Sammamish and Cedar Rivers to Puget Sound via Lake Washington ("LW") and the Lake Washington Ship Canal ("LWSC" in panel [B]). For river valley segment names, historic river names are in parentheses.

scale of along- and between-stream organization of river valley process domains.

2. Study area

The Puget Lowland is a glacially-fluted, till-capped outwash plain of the Puget lobe of the Cordilleran ice sheet (Armstrong et al., 1965; Booth, 1994). It averages about 140 m above present sea level. The Quaternary fill reaches thicknesses of 1100 m or more in structural basins near Seattle (Yount et al., 1985) and 600 m near Tacoma (Buchanan-Banks and Collins, 1994), but thins to zero against bedrock hills in the E–W trending Seattle Fault Zone (Fig. 1).

Pleistocene subglacial streams cut a series of prominent, subparallel, N–S trending troughs that bottom out as much as 400 m below the drift surface of the glaciated uplands (Booth and Hallet, 1993; Booth, 1994). Those troughs now contain arms of Puget Sound, large freshwater lakes (Lakes Washington and Sammamish), and rivers that drain the Cascade Range, herein referred to as "glacial valleys" (Fig. 1). After deglaciation, which was about 16.5 cal ka BP in the central lowland (Porter and Swanson, 1998), rivers draining the Cascade Range incised the lowland fill in E–W trending river valleys graded to the base level set by sea level or lakes within the glacial troughs. We refer to these E–W trending, fluvially incised river valleys as "post-glacial" to distinguish them from the N–S trending glacial valleys (Figs. 1 and 2).

Isostatic rebound subsequently lifted the lowland with a S–N tilt of 0.85 m/km (Thorson, 1989) and was nearly complete by the early Holocene (Clague et al., 1982; Dethier et al., 1995). The coincident late-glacial eustatic sea level rise resulted in near-constant sea level relative to landscape features at the approximate latitude of Seattle (Fig. 1), with emergence in the northern lowland and submergence in the southern lowland. Most isostatic rebound occurred within the first 1 ka after deglaciation and initially exceeded eustatic sea level rise, locally. Thus in the northern part of the lowland (where rebound was greatest), the Stillaguamish River incised deeply below the northward extension of the Snoqualmie–Snohomish lowland glacial trough (Fig. 1B), whereas relative submergence in the southern lowland promoted sedimentary filling of the Puyallup and Nisqually River troughs. Relative sea level in the Strait of Juan de Fuca, at the northern margin of Puget Sound and the study area, rose to its approximate present position by 6 cal ka BP (Mosher and Hewitt, 2004). In the north half of Puget Sound, relative sea level has risen about 3–4 m since 5 cal ka BP (Eronen et al., 1987; Beale, 1991).

Fluvial sediment has accumulated since deglaciation at greatly differing rates in different glacial valleys. Numerous lahars (Scott et al., 1995; Dragovich et al., 2000) and alpine glacier erosion (e.g., Mills, 1976) have maintained high Holocene sediment loads in rivers draining Mt. Rainier and Glacier Peak volcanoes. The White, Carbon, and Puyallup Rivers, which drain Mt. Rainier (Fig. 1), have deposited as much as 200 m of fill (Dragovich et al., 1994) in the Duwamish (Fig. 2) and Puyallup troughs, which held early Holocene arms of Puget Sound prior to fluvial and lahar sedimentation. This fill includes alluvial fans built by the three rivers into the two troughs (stippled, Fig. 1B). The White River built an extensive fan that spreads laterally into the lower White and Puyallup valleys; and the Carbon and Puyallup Rivers built an elongate alluvial ramp downvalley 20 km into the Puyallup glacial valley (Fig. 1B) at the southern margin of the system of subglacially eroded troughs (Booth, 1994). Tributaries having smaller sediment loads built smaller fans into the glacial valleys: from the Tolt and Raging Rivers into the Snoqualmie glacial valley, from the Pilchuck River into the Snohomish glacial valley, and from the Cedar River into the White River glacial valley (Fig. 1B). In contrast, rivers entering the Sammamish and Snohomish–Snoqualmie troughs, which do not drain active volcanoes, have only 10–40 m of Holocene valley fill (Thomas et al., 1997).

The modern rivers bear a strong overprint of recent human activity. In the last century, formerly meandering rivers have been straightened, rivers formerly having multiple primary and secondary channels have been simplified to a single channel, and both types of channel have been functionally disconnected from their floodplains. In many rivers, tidal and river flows have shrunk or been obliterated by agriculture and urbanization. Dams and interbasin water transfers have altered the flows of most rivers; some have been wholly redirected, and others no longer run at all. Notably, two early twentieth century interbasin water transfers reduced the Duwamish River watershed to just 30% of its historical area. In the nineteenth century the White River historically flowed north across its fan to join the Green River and on to the Duwamish estuary (Fig. 1), and the Stuck River was a minor distributary stream flowing south to the Puyallup. In 1907 the White River was wholly shunted to the south through the Stuck River valley. The Sammamish River and Cedar River used to drain into Lake Washington and then to the Duwamish River through the Black River (Fig. 1); in 1916, the Lake Washington Ship Canal (Fig. 1) was built, connecting Lake Washington to Puget Sound,

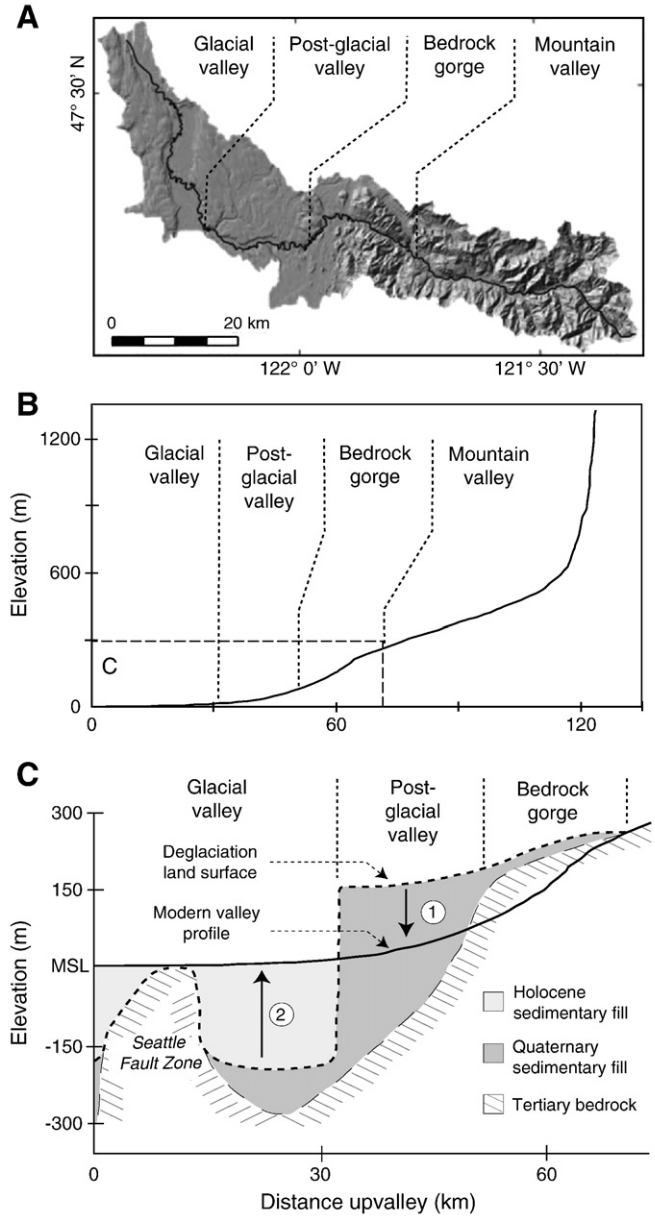


Fig. 2. Schematic longitudinal valley profile of the Duwamish–Green River showing glacial and post-glacial valleys. Schematic shows Pleistocene valley fill above bedrock, original post-glacial surface of glacial trough, and (1) Holocene degradation into lowland fill and (2) Holocene aggradation into glacial trough.

Table 1
Drainage area (average of upper and lower ends of valley segment), length, width, and slope of valley segments and historical slope and sinuosity of river channels in post-glacial valleys, fan-dominated glacial valleys, glacial valleys, and the Nooksack River valley.

Segment		Drainage area (km^2)	Valley dimensions and slope			Historical channel slope and sinuosity	
Number	Name		Length (km)	Width (km)	Slope (m/m)	Slope (m/m)	Sinuosity
Post-glacial valleys							
1	Stillaguamish	1610	16.55	2.38	0.00603	0.00046	1.58
1a	SF Stillaguamish	482	20.64	0.67	0.00207	0.00171	1.24
2a	Pilchuck	257	31.23	0.51	0.00418	0.00341	1.26
2b	Skykomish	1977	25.84	2.21	0.00224	0.00175	1.28
2d	Tolt	283	9.21	0.48	0.00851	0.02250	1.30
3b	Cedar 1	412	23.81	0.55	0.00580	0.00145	1.22
3c	Cedar 2	281	16.76	0.10	0.00663	0.00663	1.05
3f	Green	868	16.21	0.83	0.00318	0.00239	1.29
3g	White	1124	27.02	0.90	0.00791	0.00709	1.10
4c	Carbon	359	6.13	0.69	0.01080	0.01003	1.05
4d	South Prairie Cr	175	8.77	0.68	0.00786	0.00507	1.20
4e	Puyallup, upper	365	8.62	0.81	0.01008	0.00924	1.09
5a	Nisqually 1	1691	10.58	0.99	0.00315	0.00270	1.14
5b	Nisqually 2	1225	20.91	0.75	0.01790	0.00230	1.08
6	Deschutes	250	51.98	0.34	0.00337	0.00310	1.22
Fan-dominated glacial valley							
3e	White, fan	1797	9.10	3.64	0.00158	0.00262	1.28
4a	Stuck[a]		7.59	2.44	0.00116		
4b	Puyallup, middle	1113	20.95	2.53	0.00313	0.00295	1.27
Glacial valley							
2	Snohomish	4415	30.99	4.53	0.00012	0.00014	1.14
2c	Snoqualmie	1335	35.90	1.98	0.00059	0.00035	1.69
3	Duwamish	3995	12.52	1.79	0.00017	0.00006	1.85
3a	Sammamish	341	11.23	1.42	0.00014	0.00008	1.77
3d	White, lower	2419	13.97	3.64	0.00051	0.00035	1.78
4	Puyallup, lower	1318	12.02	4.00	0.00038	0.00018	1.41
5	Nisqually, delta	1931	5.20	3.50	0.00080	0.00050	1.35
7	Nooksack, lower	1835	22.71	2.20	0.00086	0.00060	1.44

[a] The Stuck River historically was a distributary of the White River, small at the time of the PLS surveys, but likely received variable amounts of the river's flow at different times. The channel consisted of numerous small channels in wetlands, and its location is not well defined on historical sources.

and dropped the lake level by 2.7 m (Chrzastowski, 1983), drying up the Black River and rerouting the Sammamish River and Cedar River watersheds through the Ship Canal.

To enlarge the sample of relatively unmodified rivers, we included in this analysis the Nooksack River from the adjacent Fraser lowland region for another example of a glacial valley river. Located to the north of the Puget lowland, the Fraser lowland is within the same broad lowland formed between the Cascade Range and coastal ranges of Washington and British Columbia. Like the Puget lowland, the Fraser has a fill of Quaternary sediment, topped with Everson glaciomarine drift overlain by a Sumas-age outwash plain (Schuster, 2005). The Nooksack River heads in the western Cascade Range and, on entering the Fraser lowland, flows through the reach we studied. The valley is a relict outwash channel, similar in width and slope to the lowland glacial valleys of the Puget lowland (Table 1). At the upstream end of the valley, the Nooksack River has built a Holocene fan. Sedimentary evidence (Cameron, 1989) and relict channels and oxbows, consistent in size and radius with the modern Nooksack River, and alluvial fans truncated by migrating channels (Pittman et al., 2003) together indicate the Nooksack River flowed north on this fan to the Fraser River through much of the Holocene. Radiocarbon dates associated with archaeological sites on the river delta (Hutchings and Campbell, 2005) indicate the Nooksack River may have avulsed to its modern course into Bellingham Bay in the late Holocene.

3. Methods

To evaluate the hypothesis that rivers are responding to the topographic legacy of lowland glacial scour and fill, we delineated river valley segments as one of three types: glacial, alluvial fan-dominated glacial valley, or post-glacial (Fig. 1; Table 1). We used digital elevation models (DEMs) to measure the average gradient of each segment's valley floor.

We made cross valley topographic profiles from LIDAR DEMs having a pixel size of 1.8 m and a vertical resolution of 30 cm or less in flat open terrain (Puget Sound LIDAR Consortium, http://pugetsoundlidar.ess.washington.edu). We sampled DEMs at 0.3-m intervals and then removed obvious cultural artifacts such as road and railroad prisms, building foundations that had not been removed by LIDAR post-processing, and extensive areas of artificial fill. In some intensively developed areas, land grading and cultural features could not be removed.

We created slope-area plots for river profiles by using LIDAR DEM data to derive channel slopes and drainage areas. We digitized the channel thalweg from a DEM having 1.8-m (6-ft) cells, sampled elevations at 1.8-m increments, smoothed the profiles, and resampled profiles at 1.5-m elevation intervals. Where LIDAR coverage was incomplete in the Cascade Range headwaters, we used 10-m DEM data and blue-line channels (from 1:24,000-scale USGS topographic maps) to sample at 12-m elevation intervals. Where LIDAR and 10-m data were both available, we compared results of slope-area regressions using the two data sets. Data derived from LIDAR showed greater scatter and lower correlation coefficients than data from 10-m DEMs [R^2 (LIDAR) mean = 0.42, R^2 (10-m) mean = 0.60], but the regression parameter $-\theta$ agreed generally within 1%.

We measured the sinuosity and characterized the channel pattern of channels in their pre- or early-settlement condition (last half of the nineteenth century) prior to any artificial channel straightening, using maps made by the Public Land Survey or U.S. Geological Survey.

We documented channel migration rates and historical patterns of floodplain occupation in four valley segments least modified by levees or revetments (Table 2). These included (i) a segment of the Nisqually

Table 2
Average channel migration rate and average width of floodplain occupied by river channel for five river segments during the historical map and aerial photo record.

Valley segment		Valley and channel width (m)		Migration rate (m) mean ± SD (n = number of transects)		Historic channel zone[a]	
Number	Name	Flood-plain width	Channel width[b]	1853–1872 to 1933–1937[c]	1933–1937 to 2000–2006[c]	Width (m)	Percent of floodplain width
3g	White	690	104	ND	7.4 ± 6.3 (n = 135)	430	62%
5a	Nisqually	947	70	2.3 ± 1.8 (n = 44)	7.6 ± 5.7 (n = 44)	437	46%
2c	Snoqualmie	1742	66	1.2 ± 1.6 (n = 179)	0.8.± 1.5 (n = 179)	247	15%
7	Nooksack	2230	83	3.8 ± 3.7 (n = 108)	3.4 + 3.9 (n = 108)	290	14%

[a] Bankfull channel (excludes secondary channels).
[b] Channel width from aerial photos: White River 2000; Nisqually 2006; Snoqualmie 2006; Nooksack 1998.
[c] White River: 1867–2000, n = 15; 1931–2000, n = 14. Years = 1867, 1931, 1936, 1940, 1944, 1955, 1959, 1965, 1970, 1974, 1980, 1985, 1989, 1995, 2000. 1867 map data was not reliable enough for use in migration calculations; Nisqually River: 1853–2006, n = 17; 1937–2006, n = 15. Years = 1853, 1873, 1937, 1940, 1948, 1959, 1965, 1968, 1971, 1973, 1978, 1980, 1985, 1990, 1993, 1999, 2006; Snoqualmie River: 1872–2006, n = 5. Years = 1872, 1936/1938, 1953, 1968/1973, 2006. Nooksack River: 1872–2002, n = 14; 1933–2002, n = 12. Years = 1872, 1906, 1933, 1938, 1950, 1955, 1966, 1976, 1980, 1986, 1993, 1995, 1998, 2002.

River [river kilometer (rkm) 6–20] having natural banks; (ii) the White River (rkm 12–45), on which levees were built in the late 1950s in parts of the lower 8 rkm; (iii) the Snoqualmie River (rkm 0–64), where levees were built discontinuously mostly beginning in the 1970s; and (iv) the Nooksack River (rkm 10–39), where levees were built beginning in the 1930s. The Nisqually study segment had limited logging in the late nineteenth and early twentieth centuries (see Collins and Montgomery, 2002, for detail); the White River segment had widespread logging early in the twentieth century but remains forested; the Snoqualmie and Nooksack valleys were converted to agricultural uses in the late nineteenth and early twentieth centuries and have varying widths of remaining streamside forest. We computed average migration rates by measuring the channel centerline position at successive records along transects orthogonal to the valley centerline. To characterize the spatial and temporal history of a channel's occupation of its floodplains, we created grids of 2-m cells that tallied the number of photo or map years in which the channel was present.

4. Results

4.1. Valley topography and landforms

In their widths and slopes, glacial and post-glacial valleys occupy distinct topographic domains (Fig. 3). The glacial valleys (squares), 1.4–4.5 km wide, are on average 3.5 times wider than post-glacial valleys and roughly one-tenth as steep (0.00006–0.003 m/m). Several steeper segments (half-filled squares) of the Puyallup and lower White River valleys are dominated by alluvial fans that tributary rivers have built into the valleys. The post-glacial valleys are steeper (0.002–0.02 m/m) and narrower (0.1–2.4 km wide) than the glacial valleys and generally plot in a cluster in Fig. 3. The Skykomish and Stillaguamish River valleys (points 2b and 1, respectively, in Fig. 3) are wider than the others and have larger drainage areas (Fig. 3A). The Stillaguamish River lost most of its drainage area to the Skagit River drainage in a mid-Holocene drainage capture associated with Glacier Peak lahars (Tabor et al., 2001).

Aggradation in the gently sloping glacial valleys has built alluvial ridges that appear in map view as elongate depositional "tails" that narrow downstream of the alluvial fans rivers have built into glacial valleys (Fig. 4) and typically elevate river banks 3–5 m above the valley floor (Fig. 5A–K). In the Duwamish–White trough, the alluvial ridge narrows downvalley of the White River fan (Figs. 4 and 5A–C). In the Snoqualmie–Snohomish trough, the alluvial ridge narrows downstream of fans at the mouths of two post-glacial valleys, narrowing downstream of the Tolt River fan in the Snoqualmie River valley and downstream of the Skykomish River confluence in the Snohomish River valley (Figs. 4 and 5F–I). The alluvial ridge also narrows downstream of the river's entrance into the lowland glacial valley (Figs. 4 and 5J–K). In each case, flood basins form marginal to the alluvial ridges and widen downvalley of fans as alluvial ridges narrow.

The short glacial valley segment of the Nisqually River (Table 1; Fig. 4) is dominated by the Nisqually River's fan, which grades downvalley into the river's tidal delta. The Sammamish River valley, much smaller than the other glacial troughs (Table 1; Fig. 3), conveys outflow from Lake Sammamish, which limits the river's sediment load. The Sammamish River's artificial levees, resulting from twentieth century river dredging and straightening, obscure the natural

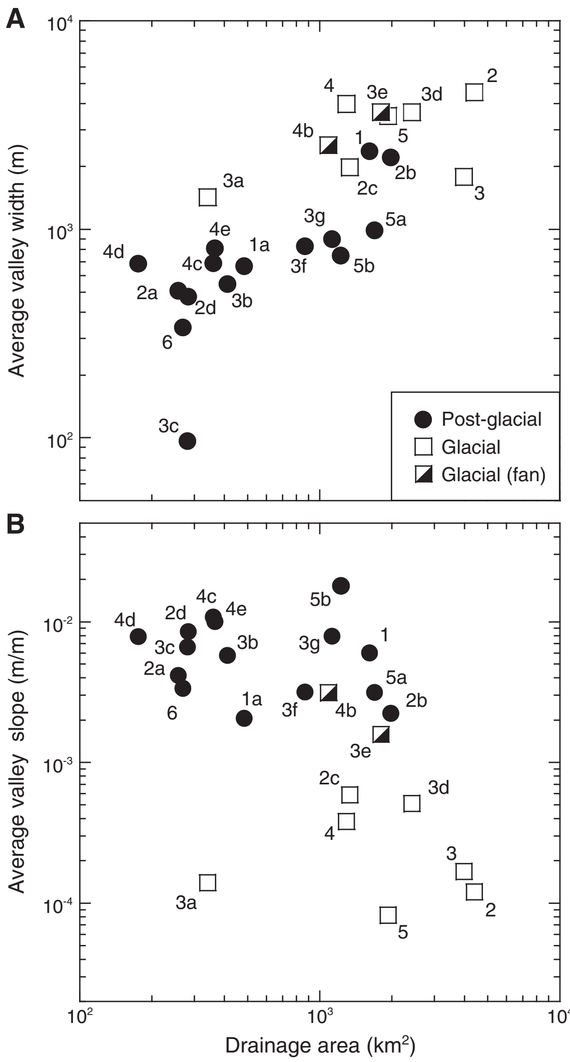


Fig. 3. (A) Average valley width and drainage area in glacial valleys (open square symbols) and post-glacial valleys (solid circle symbols). Black/white squares are segments of Pleistocene glacial valleys dominated by alluvial fans. (B) Average valley slope and drainage area; symbols are as in panel A. Segment numbers are from Fig. 1 and Table 1.

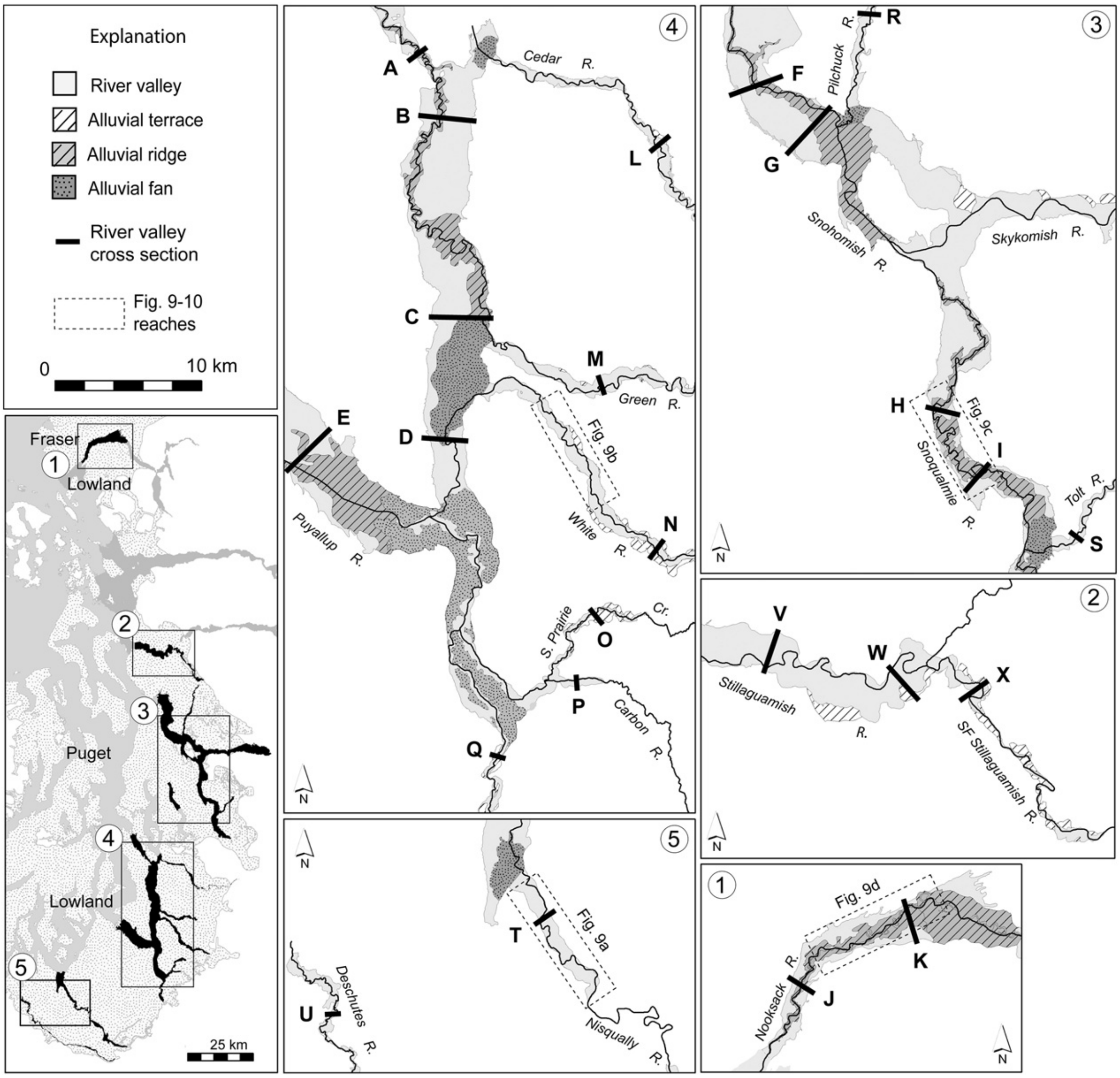


Fig. 4. Alluvial terraces, alluvial ridges, and major alluvial fans or ramps in the study area, and locations of valley cross sections shown in Fig. 5. Also shown are locations for Figs. 9 and 10.

alluvial ridge, which remains only in patches, and had relatively modest relief in comparison to those of the rivers shown in Fig. 5.

Most of the Puyallup River valley (Fig. 4) differs from the other glacial valley segments in having a low terrace, not shown on published geologic maps (Schuster, 2005), standing 2–5 m above the active floodplain. Much of the terrace surface is mapped by Schuster (2005) as deposits of the Electron Mudflow from Mt. Rainier (600 cal YBP; Crandell, 1971). We interpret the Puyallup River valley as an alluvial fan from the Puyallup and Carbon Rivers, which the Puyallup River has trenched, presumably since the Electron Mudflow. In the valley's lowest 10 km, the river has deposited an alluvial ridge that rises 2–3 m higher than the flood basins between the ridge and the valley wall (Fig. 5E).

In contrast to glacial valleys where river banks are at or near the valley bottom's highest elevation, channel banks in post-glacial valleys are near the lowest elevation of their valley bottoms (Fig. 5L–X). The lowest 10 km of the Stillaguamish River valley (Fig. 5V–X) is an exception; here the river has an alluvial ridge similar to that in the glacial valleys. In the Stillaguamish River valley upstream of this lower part and the valley of the river's South Fork, river terraces and floodplain morphology suggest a downcutting regime (Fig. 5W–X). The contrary trend in the lower part of the valley presumably reflects the local effects of rising Holocene sea level.

4.2. Longitudinal profiles

Plots of channel slope and drainage area, created from modern river courses, show two sharp breaks in concavity: one as rivers enter the glacial sediment filled lowland, the other at a transition from post-glacial valleys to glacial valleys, with the concavity index (θ) increasing typically by an order of magnitude (Fig. 6). Profiles for mountain valleys upriver of the lowland fill have concavities in the range 0.3–0.9. In their transition to the lowland, the rivers pass through steep rock gorges and falls, which create knickpoints in their profiles (Fig. 6). Once below the gorges and within the lowland, profiles have concavities of 1–7 in post-glacial valleys and 5–45 in glacial valleys (Fig. 7).

Local geologic factors help explain the range within the clusters of concavity values among lowland glacial, Holocene fluvial, and mountain valleys. Among post-glacial valleys, θ values in the low part of the range in values correspond to rivers at the margins of the lowland, where fill is thin and isolated bedrock crops out in the river

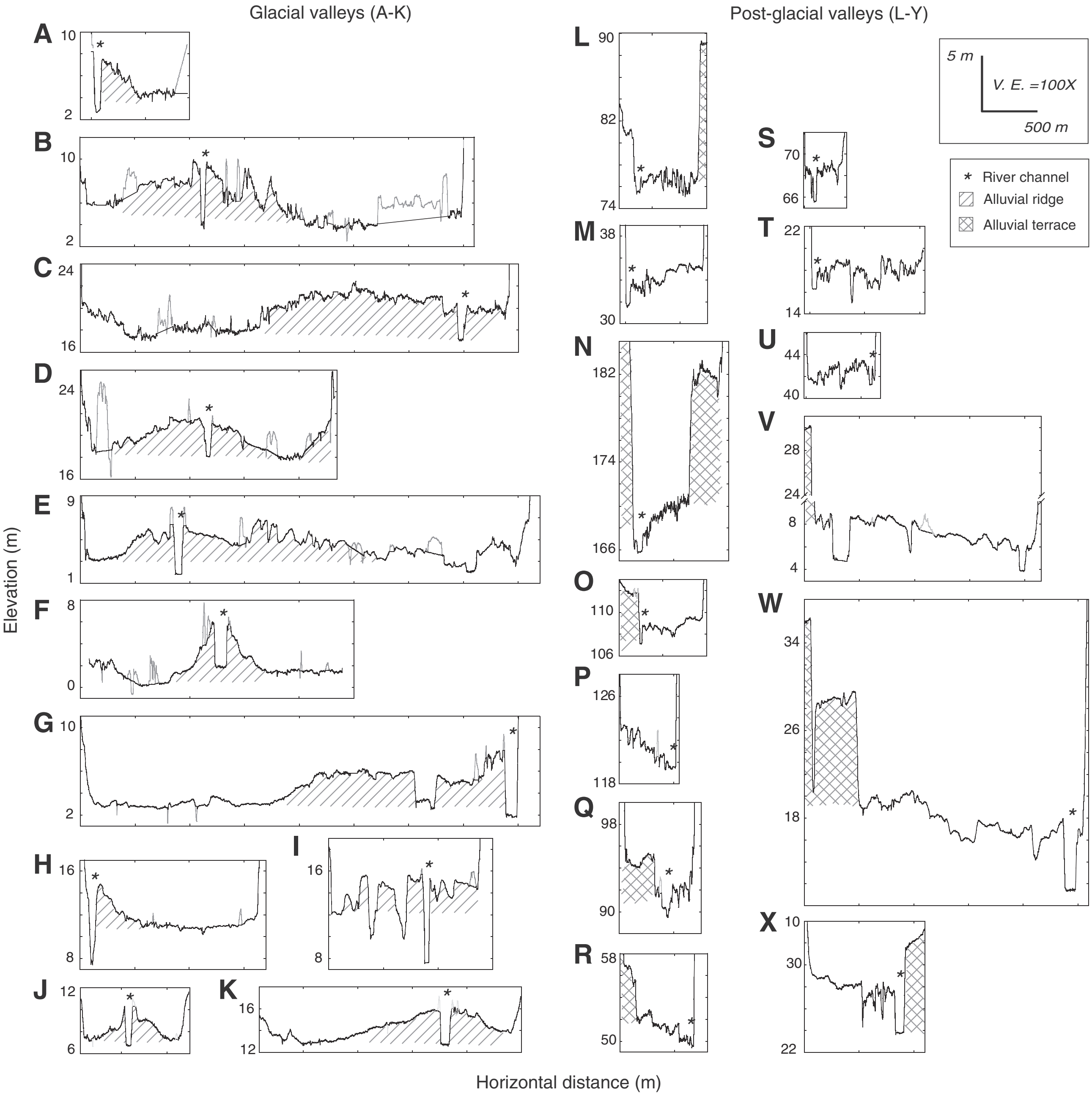
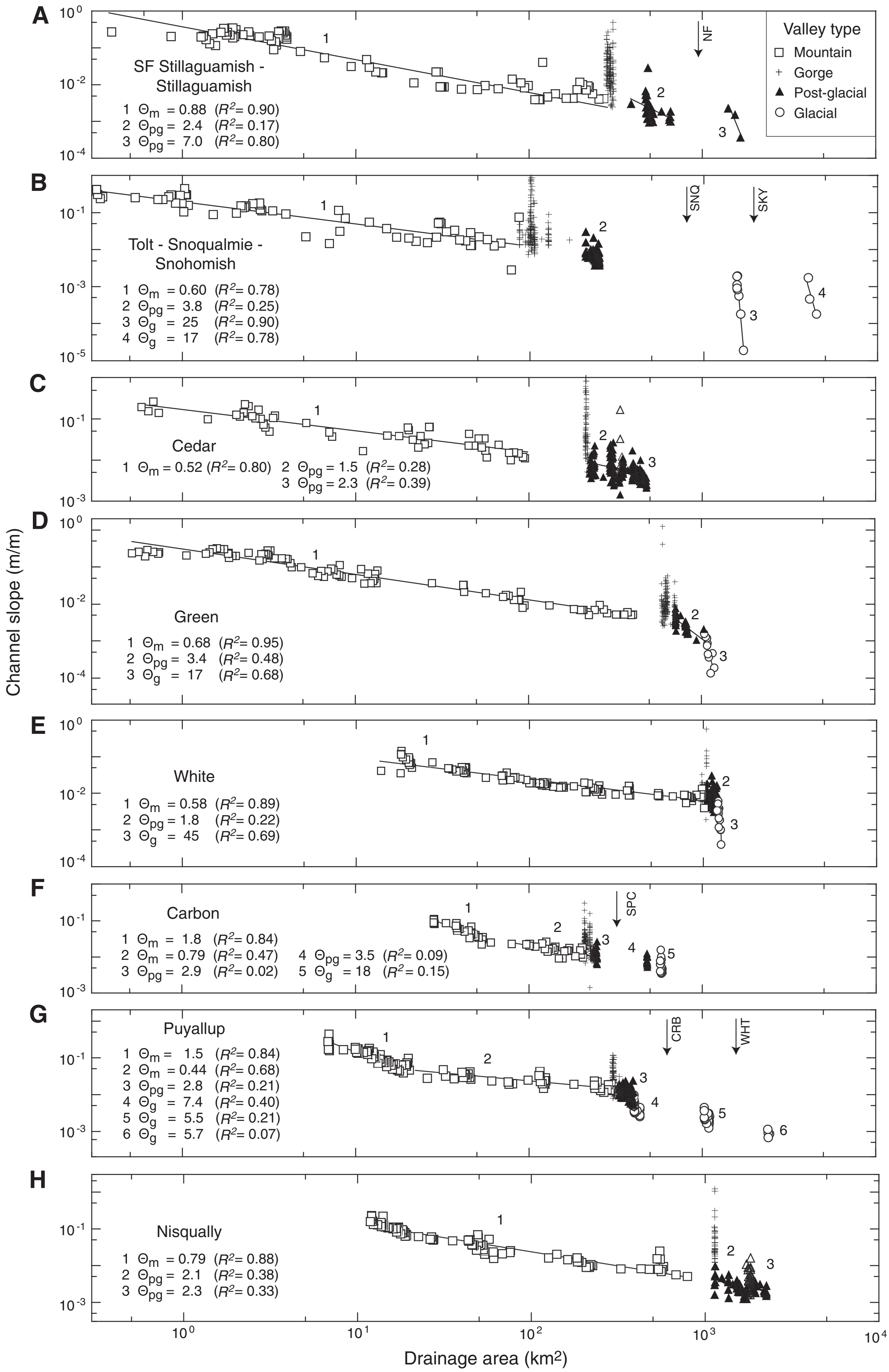


Fig. 5. Representative topographic cross sections, from LIDAR DEMs, showing variation in valley-bottom topography; locations are shown in Fig. 4. Glacial valleys: (A) Duwamish; (B)–(C) lower Green (historical lower White); (D) lower White (historical Stuck); (E) lower Puyallup; (F)–(G) Snohomish; (H)–(I) Snoqualmie; (J)–(K) Nooksack. Post-glacial valleys: (L) Cedar; (M) upper Green; (N) upper White; (O) South Prairie; (P) Carbon; (Q) upper Puyallup; (R) Pilchuck; (S) Tolt; (T) Nisqually; (U) Deschutes; (V)–(W) Stillaguamish; (X) South Fork Stillaguamish. Gray line in profiles indicates cultural features such as artificial fill or levees that have been removed from the profile.

profile (e.g., Deschutes $\theta = 1$; Pilchuck $\theta = 0.8$; upper Cedar $\theta = 1.5$). The Stillaguamish concavity value is higher ($\theta = 7$) than other post-glacial valleys, perhaps because the Stillaguamish River occupies a late-glacial meltwater channel for a much larger drainage (Tabor et al., 2001). The White River value is higher than that for other glacial valleys ($\theta = 45$), probably because historically the valley was occupied by the much smaller Stuck River, a small, anabranching distributary of the historic White River that flowed north to the Duwamish River.

While our analysis focuses on θ and not k_s, the two are correlated; in a power-law regression of $k_s = a\theta^b$, the correlation coefficient is high for mountain valleys ($R^2 = 0.93$ from LIDAR data, 0.49 for profiles derived from 10-m data) and post-glacial valleys ($R^2 = 0.95$ from LIDAR data,

Fig. 6. Channel slope and drainage area data derived from DEMs, as described in text, with power-law regression lines for eight rivers. Data for each river is segmented into one of four valley types: mountain valleys, gorges, post-glacial valleys, and glacial valleys. Separate regression lines are given for each type except for gorges. "Θ_m," "Θ_{pg}," and "Θ_g" refer to power-law regression exponents for segments in mountain, post-glacial, and lowland glacial valleys, respectively. Data is from LIDAR DEMs except for "mountain valley" segments, which are generally from 10-m DEMs. The channel network begins at ~10 km^2 for four rivers (White, Carbon, Puyallup, and Nisqually Rivers) that originate at the terminus of glaciers on Mount Rainier. Hollow gray triangles within "post-glacial valley" segments of the Cedar and Nisqually Rivers correspond to bedrock reaches that were excluded from regressions for those post-glacial valleys.


A
SF Stillaguamish - Stillaguamish
1 Θm = 0.88 (R2= 0.90)
2 Θpg = 2.4 (R2= 0.17)
3 Θpg = 7.0 (R2= 0.80)
NF
Valley type
Mountain
Gorge
Post-glacial
Glacial
B
Tolt - Snoqualmie - Snohomish
1 Θm = 0.60 (R2= 0.78)
2 Θpg = 3.8 (R2= 0.25)
3 Θg = 25 (R2= 0.90)
4 Θg = 17 (R2= 0.78)
SNQ
SKY
C
Cedar
1 Θm = 0.52 (R2= 0.80) 2 Θpg = 1.5 (R2= 0.28)
3 Θpg = 2.3 (R2= 0.39)
D
Green
1 Θm = 0.68 (R2= 0.95)
2 Θpg = 3.4 (R2= 0.48)
3 Θg = 17 (R2= 0.68)
E
White
1 Θm = 0.58 (R2= 0.89)
2 Θpg = 1.8 (R2= 0.22)
3 Θg = 45 (R2= 0.69)
F
Carbon
1 Θm = 1.8 (R2= 0.84)
2 Θm = 0.79 (R2= 0.47)
3 Θpg = 2.9 (R2= 0.02)
4 Θpg = 3.5 (R2= 0.09)
5 Θg = 18 (R2= 0.15)
SPC
G
Puyallup
1 Θm = 1.5 (R2= 0.84)
2 Θm = 0.44 (R2= 0.68)
3 Θpg = 2.8 (R2= 0.21)
4 Θg = 7.4 (R2= 0.40)
5 Θg = 5.5 (R2= 0.21)
6 Θg = 5.7 (R2= 0.07)
CRB
WHT
H
Nisqually
1 Θm = 0.79 (R2= 0.88)
2 Θpg = 2.1 (R2= 0.38)
3 Θpg = 2.3 (R2= 0.33)
Channel slope (m/m)
Drainage area (km2)

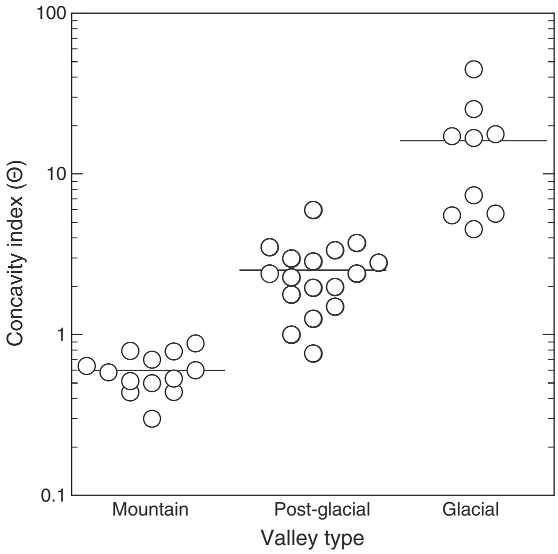


Fig. 7. Distribution of concavity (Θ) values for mountain valleys, lowland post-glacial valleys, and lowland glacial valleys shown in Fig. 6 and from three additional rivers (Skykomish, Pilchuck, and Deschutes Rivers) not included in Fig. 6. For the regression analysis, the Carbon and Skykomish valleys were each subdivided into two sub-segments at major tributaries. Lines indicate mean. Mean and standard error: mountain valleys = 0.59 ± 0.046; post-glacial valleys = 2.52 ± 0.30; glacial valleys = 16.10 ± 4.33.

0.82 from 10-m data) and low ($R^2 = 0.43$ from LIDAR data) for glacial valleys.

4.3. River pattern and dynamics

The contrasting slopes of the two valley types partially determine modern river gradients. (Because rivers have been artificially modified in the last ~150 years, we plotted river planforms reconstructed using late nineteenth and early twentieth century maps and aerial photos.) Pre-settlement gradients of rivers in post-glacial valleys on average are more than 10 times greater than those in lowland glacial valleys of a similar drainage area, excluding the steeper river segments having topography dominated by Holocene fans (Fig. 8A).

The historical channel pattern differs consistently among the three valley types. Rivers in the more gently sloping glacial valleys meandered (Fig. 8B) with a sinuosity averaging 1.6 (Table 1; Fig. 8B). Rivers in post-glacial valleys had an anastomosing pattern (Fig. 8B), with multiple channels divided by forested islands and an average sinuosity of 1.2. Rivers in steeper glacial valley segments dominated by alluvial fans were similar in channel pattern and sinuosity to the post-glacial valleys (Fig. 8B). The Stillaguamish River is an outlier in Fig. 8B; it is the only river with a gradient < 0.001 having an anastomosing pattern, and its sinuosity was significantly greater than the average for post-glacial valleys.

The Nisqually and White Rivers (in post-glacial valleys) clearly contrasted with the Snoqualmie and Nooksack Rivers (in glacial valleys) in their river pattern and occupation characteristics (Fig. 9), migration rate (Fig. 10A–D), and in the proportion of the floodplain the river occupied over the historical record (Fig. 10E–H). In the two post-glacial valleys, the zone of active migration and avulsion includes undisturbed alluvial patches around which rivers avulse without sweeping through (Fig. 9A–B). Average annual channel-migration rates (Table 2) in the Nisqually River averaged 7.7 m (1937–2006; 5.4 m 1853–2006), and in the White River 7.3 m (1931–2000). The two rivers occupied 46% and 65% of the floodplain width, equivalent to 6.2 and 5.2 channel widths, respectively (Table 2; Fig. 10). In contrast, the Snoqualmie River migrated at an annual rate of 1.0 m (1936–2006; 1.0 m 1872–2006) and the Nooksack at 3.4 m (1933–2000; 3.7 m 1872–2000). Rates were

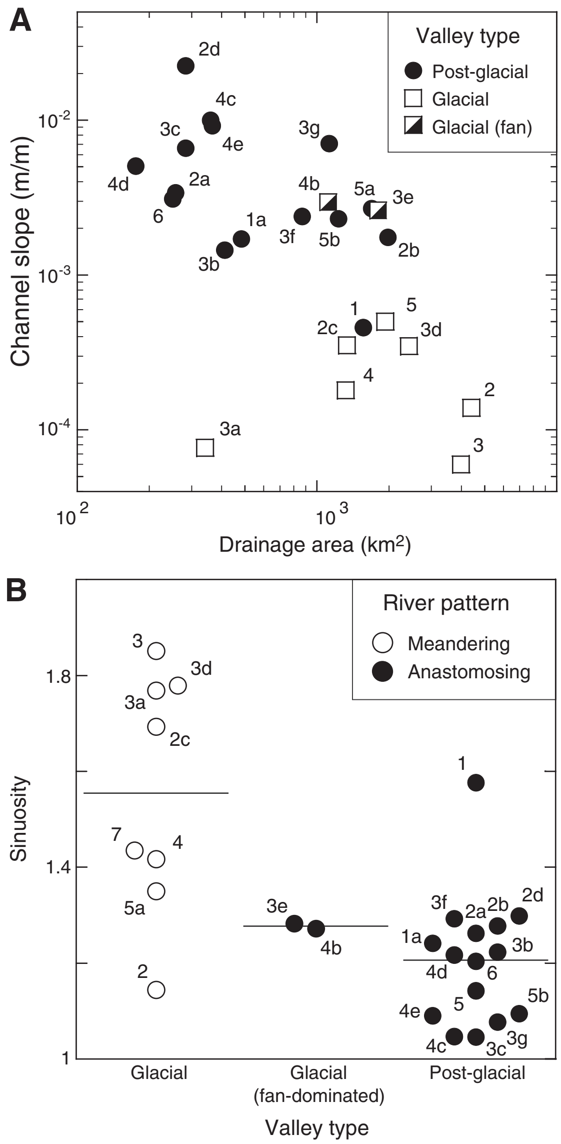


Fig. 8. (A) Drainage area, channel slope, and channel pattern for valley segments identified in Fig. 1 and Table 1. Solid circles are post-glacial valleys; open squares are glacial valleys; half-filled squares are fan-dominated glacial valley segments. (B) Sinuosity measured from reconstructed historical river channels (from Table 1), for glacial, fan-dominated glacial, and post-glacial valleys. Horizontal line is mean for each group. Mean and standard error: glacial valleys = 1.55 ± 0.09; fan-dominated glacial valleys = 1.28 ± 0.005; post-glacial valleys = 1.21 ± 0.04.

higher near Holocene fans (Fig. 10C–D). The channels of the two rivers occupied 14% and 16% of their floodplain width (Fig. 10G–H), equivalent to 3.8 and 3.6 channel widths, respectively (Table 2).

5. Discussion and conclusions

Valley-bottom topography and longitudinal profiles together indicate that Puget Lowland rivers are adjusting their grade to topography imposed by late Pleistocene glaciation, either degrading or aggrading in different parts of their length. These different responses create contrasting landforms, river patterns, and river dynamics that comprise process domains that scale with the different valley types created by glaciation or the post-glacial fluvial response. This creates a strong valley-scale imprint on the organization of landforms and processes along and between rivers.

Although the time required for these rivers to achieve equilibrium conditions undoubtedly varies with such factors as the original late-

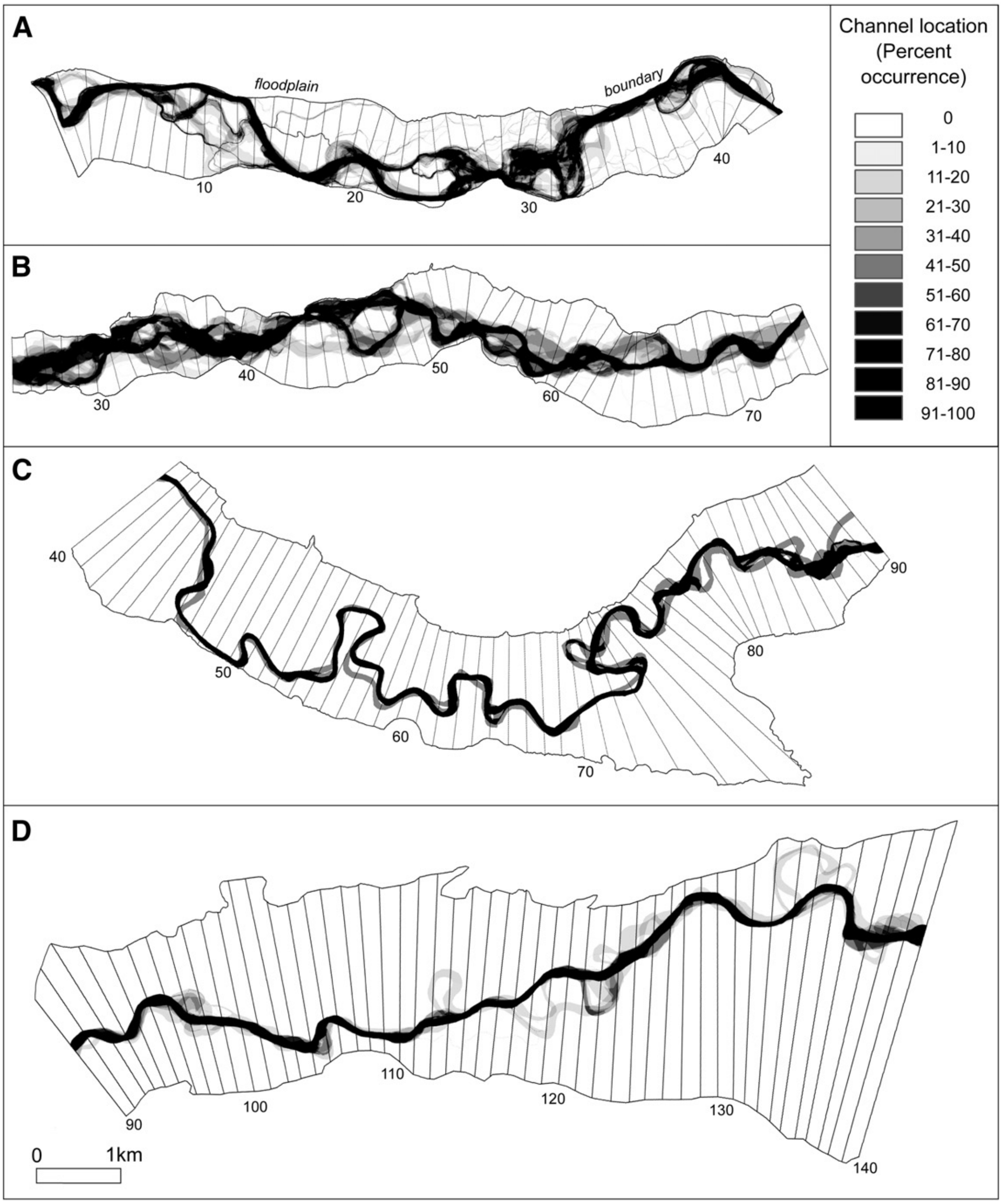


Fig. 9. Channel occupation frequency grids from maps and aerial photographs for 10-km-long representative reaches of four river segments; locations of 10-km reaches are shown in Fig. 4. (A) The Nisqually River from 1853 to 2006; (B) the White River from 1867 to 2000; (C) the Nooksack River from 1872 to 2002; (D) the Snoqualmie River from 1872 to 2006. Number and dates of aerial photos and maps used to create grids are given in Table 2. Numbers are transect numbers used in Fig. 10.

glacial topography of glacial troughs, Holocene sediment supply, and local base level, the required time appears longer than the present interglacial interval (ca. 16,500 years).

Other geologic processes influence the Puget Sound river landscape in addition to glaciation. Several active, E–W trending faults cross the lowland and its river valleys. Fault locations are poorly defined; the Seattle Fault (Fig. 1A) is the only such fault whose location in a river valley is well constrained. The Seattle Fault crosses the lower Duwamish River valley, where the AD 900–930 rupture (Atwater, 1999) created an estimated 5.5 m of uplift (ten Brink et al., 2006); subsequent incision created terraces on the valley floor. However, reconstructions of the pre-settlement land cover combined with valley-bottom topography revealed by LIDAR indicate that the event affected the valley's landforms and land cover for a roughly 5-km length of the valley. Subsidence and uplift of larger crustal areas between the region's faults could have broader, longer term influences on valley-bottom topography. However, available evidence indicates that coseismic uplift and subsidence is local in its influence on rivers and their valleys and secondary to the influence of the glacial legacy.

Along-stream variation in the concavity index of river profiles is commonly used to identify differences in rock uplift rates (Wobus et al., 2006). High concavity indexes (>1) have been associated with knickpoints caused by differences in rock uplift rate and with transitions from incisional to depositional conditions (Whipple, 2004). In this study, discontinuities in concavity correlate with

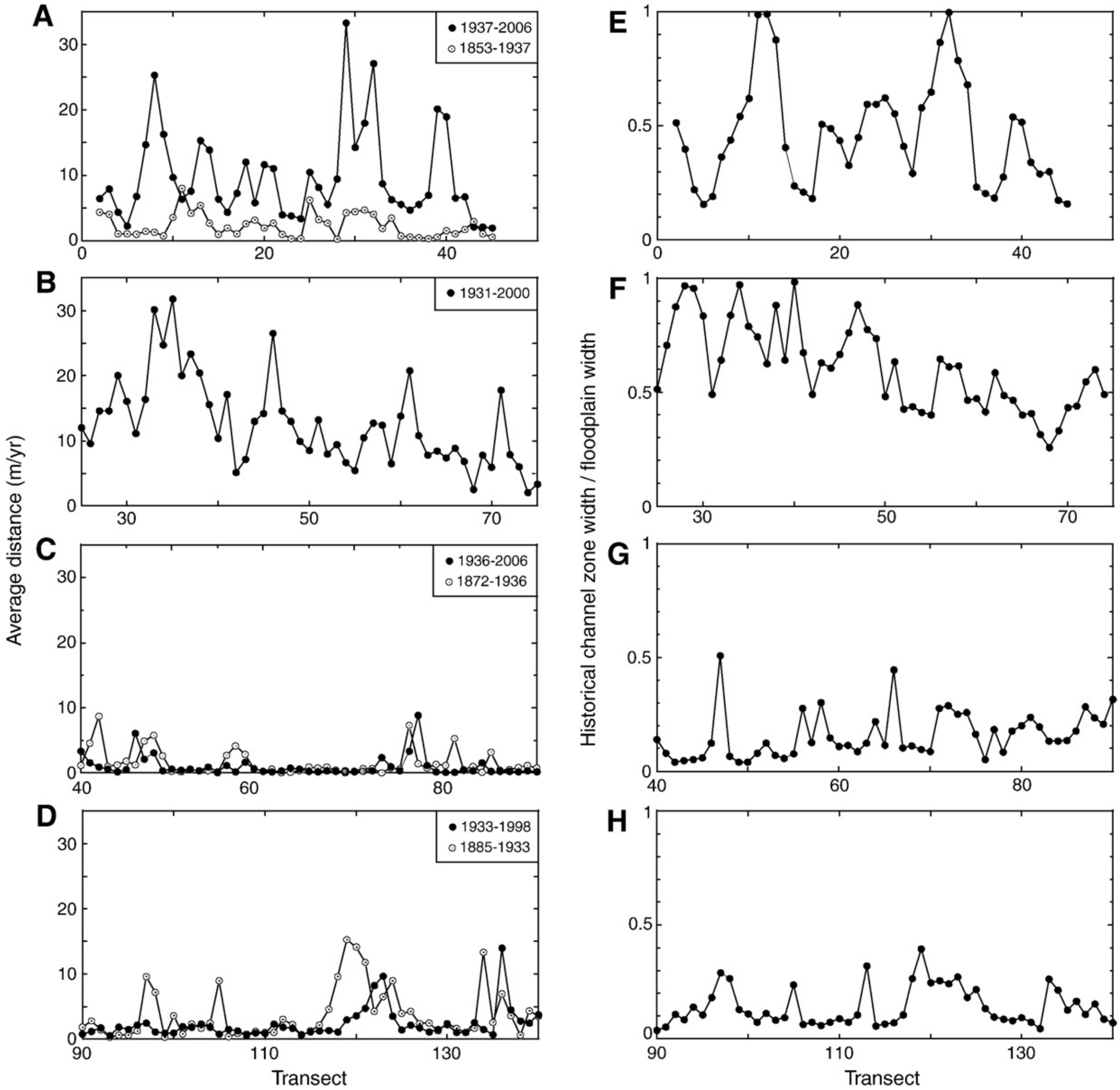


Fig. 10. Average annual migration rates for 10-km-long reaches of the Nisqually River (A), White River (B), Snoqualmie River (C), and Nooksack River (D). Rates are given for the period of the aerial photo record beginning in 1937, 1931, 1936, and 1933, respectively, and for the prior period from maps only. The average width of each transect occupied by the river on one or more maps or photos, expressed as a ratio of the average floodplain width, is given in panels for the Nisqually River (E), White River (F), Snoqualmie River (G), and Nooksack River (H).

different regimes of Holocene fluvial adjustment to topography created by Pleistocene glaciation. Where river profiles are still responding to relict landforms created by glaciation or other histories, slope-area plots may provide a way to delineate and regionally generalize alluvial process domains.

The glacial and post-glacial valleys also functioned as geomorphic templates for contrasting aquatic and terrestrial ecosystems, with considerable differences, for example, in the types and amounts of habitats for salmonids and in the composition and other characteristics of riverine forests (Collins, 2009; unpublished data). A spatial structuring to ecosystems at the river valley scale is consistent with the concept of process domains and hydrogeomorphic patches (Montgomery, 1999; Thorp et al., 2006) and other recent modifications to the river continuum concept (Vannote et al., 1980) that postulates regular downstream change to river ecosystems. Because of the different nature of river and river-floodplain dynamics, river-floodplain connectivity, and aquatic and terrestrial habitats in different river valleys in the Puget Sound lowland, river valley-scale domains provide a way to characterize regional landscapes that is potentially useful for developing appropriate restoration and management plans for rivers and their ecosystems.

River restoration and management programs commonly incorporate assumptions, stated or unstated, about equilibrium conditions prior to Euro-American settlement. Heterogeneous equilibrium conditions in Puget lowland rivers show the importance of understanding rivers in the context of regional landform evolution. Because rivers continue to respond to the glacio-fluvial infill and scour that shaped Puget lowland's late-glacial environment, understanding the erosional and depositional legacy of Pleistocene glacial history (and Holocene fluvial response to it) has direct bearing on modern riverine geomorphology, ecology, restoration, and management. An appreciation for late-glacial history and its ongoing role in the spatial structuring of river domains along and between rivers is thus fundamental to understanding the pre-settlement condition of lowland river environments, which in turn may improve land management and restoration strategies for rivers and riverine ecosystems.

Acknowledgements

We thank the National Science Foundation (SBE/EAR #0648615) for support; the Puget Sound LIDAR Consortium and King County for access to LIDAR data; Harvey Greenberg and Amir Sheikh for GIS assistance; and Brian Atwater, Derek Booth, and Alan Gillespie for their review comments on an earlier version of this manuscript.

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