Influence of sediment supply, lithology, and wood debris on the distribution of bedrock and alluvial channels

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ABSTRACT

Field surveys in the Willapa River basin, Washington State, indicate that the drainage area–channel slope threshold describing the distribution of bedrock and alluvial channels is influenced by the underlying lithology and that local variations in sediment supply can overwhelm basinwide trends. Field data from 90 short-reach surveys indicate that about one-eighth of the surveyed reaches do not conform to a threshold defined by data from free-formed alluvial and bedrock reaches due to the effects of logjams or local sediment sources or sinks. Mapping of channel type distributions in 18 extended reconnaissance surveys of >100 channel widths in channel length show that ~75% of the channel network was alluvial, but that the proportion of forced alluvial channels varies from 0% to 84%. Using the drainage area–slope thresholds defined by bedrock and alluvial data from the short-reach surveys, only 40% of the total channel length mapped in the longer reconnaissance surveys was correctly classified from a 10 m grid digital elevation model. Of the misclassified reaches, 80% of the alluvial channels predicted to be bedrock had forced alluvial morphologies, while almost half of the bedrock channels predicted to be alluvial were forced by low sediment supply, typically due to their location immediately downstream of large channel-spanning logjams. Poor representation of reach-scale slope in the digital topography and/or a stochastic influence of sediment wave propagation likely account for the remaining misclassified channels, which together compose 7% of the total surveyed channel length. Although variations in sediment supply can locally overwhelm the channel type predicted by the threshold model, the effect of logjams masks any influence of propagating sediment waves on the distribution of bedrock and alluvial channels in the Willapa River basin.

Keywords: alluvial channels, bedrock channels, GIS, logjams, sediment supply, Willapa Bay.

INTRODUCTION

The fundamental distinction between bedrock and alluvial channels can be considered at two different scales. At the scale of entire drainage basins, bedrock channels are mountain channels with at most a thin alluvial cover, whereas alluvial channels are those that occupy broad alluvial valleys. At finer scales within mountain drainage basins, bedrock channels can be considered those reaches that lack an alluvial cover (Howard, 1980; Montgomery and Buffington, 1997). Gilbert (1877, 1914) articulated a conceptual framework for explaining the distribution of bedrock and alluvial channels in mountain drainage basins. In Gilbert's view, bedrock channels reflect an excess of transport capacity over the available sediment supply whereas alluvial channels represent either a balance or an excess of sediment supply over transport capacity. A general model that emphasizes spatial controls on the distribution of bedrock and alluvial reaches uses slope and discharge (or drainage area as a surrogate) to express criteria for an excess of either sediment supply or transport capacity, and thereby channel type (Howard, 1980; Howard and Kerby, 1983; Howard et al., 1994; Montgomery et al., 1996). In contrast, a model based on the propagation of sediment waves through mountain channel networks (Benda and Dunne, 1997) focuses on predicting temporal variations in the distribution of bedrock and alluvial channels due to downstream routing of sediment stochastically introduced into the channel network by hillslope processes. Although these theories propose different, but not mutually exclusive views of Gilbert's criteria, few data exist for distribution of bedrock and alluvial channel reaches in mountain drainage basins.

Recent field studies in western Washington State have shown that a threshold relationship between channel slope and drainage area defines the distribution of bedrock and alluvial channels and that logjams can force an alluvial channel bed in otherwise bedrock reaches (Montgomery et al., 1996; Montgomery and Buffington, 1997). These studies did not assess the influence of lithology, spatial variations in sediment supply, or temporal variability in channel type. Here we report the results of a field study designed to assess the influence of lithology, local variations in sediment supply, and wood loading on the distribution of bedrock and alluvial channels in mountain drainage basins.

THEORY

Gilbert (1877, 1914) argued that bedrock and alluvial channels represent different relationships between sediment transport capacity (q_c) and sediment supply (q_s); bedrock channels occur where $q_c > q_s$, and alluvial channels occur where $q_c < q_s$. The direct measurement of either transport capacity or sediment supply is difficult, and a testable model to formalize this relationship between q_c and q_s needs to be cast in terms of general channel characteristics that can be measured directly.

Gilbert (1914) observed that channel slope (S) and the discharge (Q) during storm events dominantly control bedload transport [i.e., $q_c = \mathrm{f}(Q, S)$]. Recognizing the importance of the combined effects of these two variables, Kirkby (1971) expressed channel transport capacity as a general function that incorporates both channel slope (S) and drainage area (A), a surrogate for discharge:

$$q_c = kA^mS^n, \tag{1}$$

The coefficient k is related to watershed features, such as geology, sediment characteristics,

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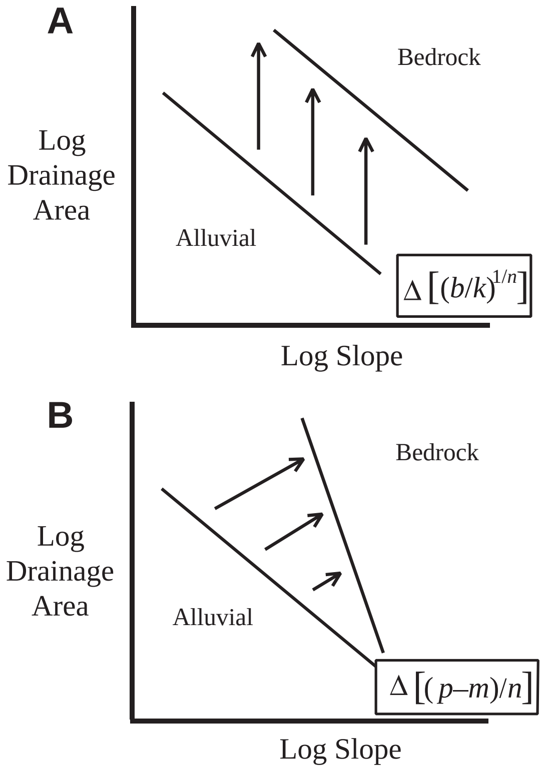

Figure 1. Schematic illustrations displaying effects of changing values for $(b/k)^{1/n}$ and $(p – m)/n$ in equation 4 on the predicted drainage area–slope threshold. (A) The threshold shifts upward as either *b* increases or *k* decreases. (B) A decrease in $(p – m)/n$ changes the slope of the threshold line.

climate, and discharge variability. The exponents *m* and *n* depend on the specific transport processes (Kirkby, 1971) and the appropriate values for these terms are debated.

The amount of bedload moving during a sediment transporting event is difficult to measure, but usually scales with suspended load and is often estimated to be between 10% and 50% of the suspended load (Dunne and Leopold, 1978). Leopold and Maddock (1953) empirically correlated discharge (Q) with measured suspended sediment loads (q_s) from grab samples at a gauging station on the Powder River. They found a relation of the form

$$q_s = \mathrm{d}Q^{\mathrm{j}}, \tag{2}$$

where d and j are empirical constants that depend on regional characteristics such as climate, and estimated j to be <1.0 for downstream variations in discharge. Substituting drainage area for discharge, $Q = cA^y$, into equation 2 yields

$$q_s = bA^p, \tag{3}$$

where $p = \mathrm{j} \cdot y$, and $b = \mathrm{d} \cdot c^{\mathrm{j}}$. As equation 3 relates drainage area to sediment supply independent of individual storm events, we consider it to describe the general sediment regime of a watershed.

In Gilbert's conceptual model, the transition from bedrock to alluvial channels occurs where sediment supply equals transport capacity, or $q_c = q_s$. The threshold slope for this transition can be defined by equating 1 and 3 and rearranging terms:

$$S_c = \left(b/k\right)^{\frac{1}{n}} A^{\left(\frac{p-m}{n}\right)}, \tag{4}$$

where S_c, the critical slope, is the maximum slope of a sediment-covered channel (Montgomery et al., 1996); this model predicts that bedrock channels occur where $S > S_c$, and alluvial channels occur where $S < S_c$. Montgomery et al. (1996) showed that bedrock and alluvial channels of the Satsop River, Washington, define separate regions on a plot of channel slope and drainage area, as predicted by equation 4.

The supply of sediment to a channel, as well as the transport capacity of a network, is often linked with climate and basin geology, and the threshold described by equation 4 should vary within and among drainage basins due to the potential for differences in *b*, *k*, *p*, *m*, and *n*, as a function of climate, sediment loading, landscape characteristics, and sediment-transport processes. The critical-slope threshold plots linearly on a log-log plot of drainage area and slope, and changes in $(b/k)^{1/n}$ would shift the threshold vertically, whereas a change in $(p–m)/n$ would alter the slope of the critical threshold (Fig. 1). In the context of the critical slope theory, channels controlled by local conditions may plot outside of the field defined by basinwide data (Fig. 2). For example, a steep channel that would normally be bedrock but that has a high sediment supply may become an alluvial reach. Conversely, a channel with a gradient low enough to support an alluvial bed may be a bedrock reach if its sediment supply is anomalously low. In addition, passage of a sediment wave could transiently convert a bedrock reach into an alluvial reach that would plot in the bedrock field on a drainage area–slope graph (Fig. 2). Temporal variability in channel types due to the propagation of sediment waves should serve to mask any controls the distribution of bedrock and alluvial channels apparent on an area-slope plot.

STUDY AREA

Geology and Geography

The Willapa River drains 680 km^2 of the coastal hills in southwest Washington State and flows into the Pacific Ocean through Willapa Bay. The drainage basin rises from tidal wetlands to a well-dissected upland that reaches 790 m above sea level. The region has a temperate coastal maritime climate, receiving as much as 3 m of rainfall each year (Owenby and Ezell, 1992). High flows typically occur during winter storms in November through March with the monthly average peak discharges in December and January (Water Resources Data, 1992). Snow accumulates only temporarily in the headwater areas. The Willapa Hills are south of the maximum extent of the Pleistocene glaciation, and the bedrock consists mostly of marine sediments and volcanic rocks uplifted in the Miocene (Lasmanis, 1991). The sedimentary rocks form gentle rolling hills, whereas the slopes underlain by igneous rocks tend to be steeper and more highly dissected.

The two primary bedrock types in the drainage basin of the Willapa River have distinct physical properties (especially hardness). The McIntosh and Lincoln Creek Formations are poorly cemented marine sediments of Tertiary age, while the Crescent Formation is Eocene marine basalt

(Logan, 1987). The sedimentary formations contain some sandstone but consist mostly of siltstone and mudstone. The siltstone is friable upon drying, but strong when wet. The Crescent Formation is predominantly fine-grained basalt with pillows and blocky jointed structures. The basalt is usually much stronger than the sedimentary rocks, and therefore forms clasts more resistant to breakdown in the channel. Hence, there is a sharp contrast in the nature of sediment derived from these formations.

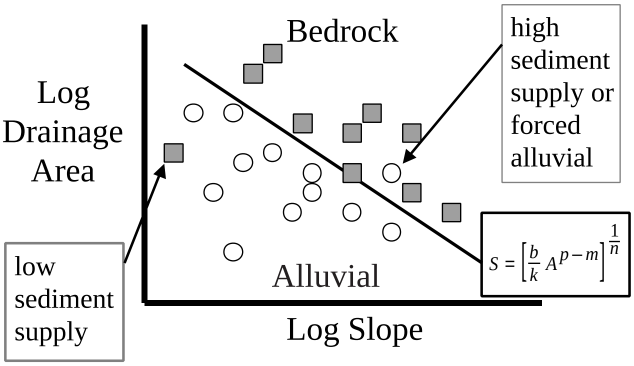

Figure 2. Schematic illustration of the hypothesized influence of local conditions that differ from regional conditions on a slope-area graph.

Land-Use History

Prior to European settlement, the Chehalis and Chenook peoples subsisted on the abundant oysters in Willapa Bay and salmon that spawned in the coastal rivers (Swan, 1857). By the mid-1800s, Europeans had settled in the Willapa Bay area and started exporting these commodities and timber (Swan, 1857). At the turn of the century, riverine log drives and dam releases along major rivers (splash damming) were used extensively to transport logs to the bay (Wendler and Deschamps, 1955). The rivers feeding Willapa Bay were used heavily for these activities until the 1920s, when railroads (Van Syckle, 1980, 1982), and later trucks, became the major transport mechanism for timber. By the 1950s, most of the primary forests had been harvested (Van Syckle, 1980, 1982).

Extensive splash damming in the early 1900s, as well as gravel mining from the main-stem Willapa River, significantly altered the fluvial landscape. Splash dams were released on daily to weekly schedules, mostly depending on the availability of water, which simulated large flood events year round. They were spaced throughout the watershed, in both the main-stem Willapa River and in most major tributaries such as Trap Creek, Forks Creek, and the South Fork Willapa River (Wendler and Deschamps, 1955). Splash damming removed both sediment-storage structures, such as logjams, and the sediment, leaving behind a simplified river channel that was scoured to bedrock in many places. Gravel mining declined after the 1940s, but ongoing wood removal by state agencies and landowners continues to affect channels in the watershed.

METHODS

Field Methods

Field mapping conducted between June 1996 and August 1997 included 90 surveys of reaches 10–20 channel widths in length and 18 extended surveys of reaches 100–400 channel widths in length. These reaches have average slopes from 0.001 to 0.50 and drainage areas from 0.01 to 100 km^2. Data collection occurred throughout the Willapa River watershed, but was concentrated in three main tributaries: Trap Creek, Forks Creek, and the South Fork Willapa River, with a few reaches from Mill Creek (Fig. 3). Observations collected in the shorter surveys consisted of channel type, bedrock type, relative influence of woody debris on channel form, cross sections, longitudinal profiles, and field notes on the local geomorphic context. Longitudinal profiles and cross sections were collected with a hand-held level or a tripod-mounted engineering level, a stadia rod, and a tape. Reach locations were mapped onto U.S. Geological Survey 7.5′ topographic quadrangles, and drainage areas were measured by digitizing watershed boundaries for each reach. Field observations were used to supplement the bedrock lithology determined from geologic maps of the South Bend and Raymond quadrangles (Wagner, 1967a, 1967b).

Reaches from the short surveys were subdivided into four categories: (1) alluvial; (2) bedrock; (3) alluvial channels forced by large wood (forced alluvial); and (4) bedrock channels forced by a locally low sediment supply (forced bedrock). For the bedrock and alluvial channel types, we followed definitions outlined by Montgomery et al. (1996): bedrock reaches contain an alluvial cover

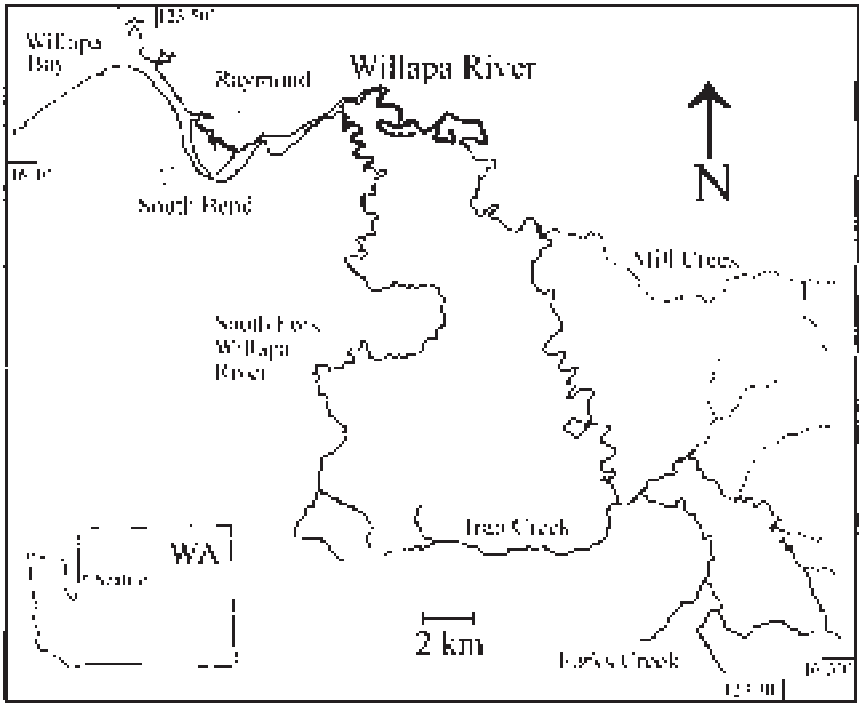

Figure 3. Location map showing the mainstem Willapa River and main tributaries.

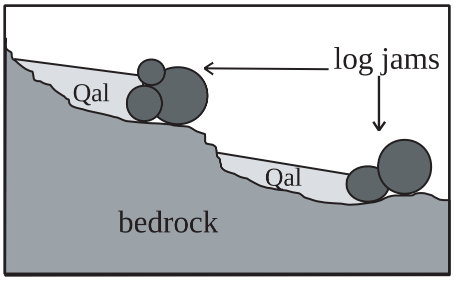

Figure 4. Longitudinal profile of a forced alluvial reach showing the elevation drop and decrease in local slope associated with logjams. Qal—Quaternary alluvium.

over less than one continuous channel width of channel length, whereas alluvial reaches contain less than one continuous channel width of bedrock bed. If a reach did not meet either definition, we considered it as a mixed morphology reach, which we excluded from our analysis. Forced alluvial channel types are those reaches in which large woody debris forces deposition or impounds enough sediment to alter the bed slope (Fig. 4). Forced bedrock reaches with anomalously low sediment supplies typically occurred immediately downstream of a logjam that blocks the supply of sediment from upstream. Our extended surveys involved mapping these four channel types onto U.S. Geological Survey 7.5′ topographic quadrangles.

Channel slopes for the free-formed alluvial and the bedrock reaches were determined using a least-squares linear regression of elevation versus distance from the surveyed longitudinal profiles. We recorded two slope measurements in forced alluvial reaches: the surface slope of the sediment upstream of the jams and a reach average slope based on the total elevation drop across the reach (Fig. 4).

Discriminant analyses were employed to determine the optimal drainage area–slope threshold between the bedrock and alluvial channels. Of the four categories describing the Willapa River data, only the alluvial, bedrock, and forced bedrock categories were employed for determining the threshold location (Fig. 5). Data from forced alluvial reaches were not used in the threshold analysis because the effects of wood debris are not accounted for by the theory. We used 33 surveys for each lithology in the Willapa Basin data. The discriminant analyses were performed using the Statistics Package for the Social Sciences (Norusis, 1994).

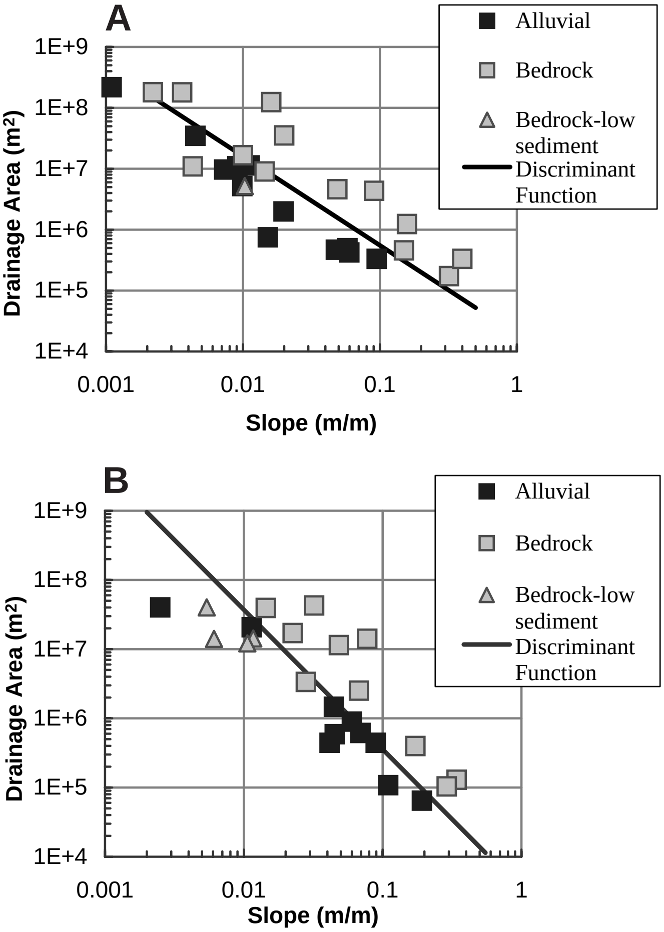

Figure 5. Bedrock and alluvial channel data from the Willapa River watershed. (A) Siltstone. (B) Basalt. All these data were used to define the location of the bedrock–alluvial channel threshold (discriminant function).

Geographic Information Systems (GIS) Methods

We used a 10 m grid size digital elevation model derived from 12 m contours and the empirically determined bedrock-alluvial threshold to predict channel morphology in the entire drainage basin of the Willapa River. The channel network was divided into stream segments based on contour intervals, tributary junctions, and lithologic contacts. Each segment was predicted to be either a bedrock or alluvial channel based on the discriminant function using the segment's slope, drainage area, and lithology (see Massong, 1998, for details).

The channel types predicted from the GIS analysis were then compared to the field data collected during the extended surveys described in the previous section. The total length of correctly and incorrectly classified channels was tabulated for each channel type and for each lithology. For the incorrectly predicted reaches, we reviewed our mapping and field notes to assess whether local processes influenced channel type. On the basis of these observations, we categorized each incorrectly classified reach as (1) alluvial morphology forced by wood, (2) local high sediment supply from proximal sediment sources (e.g., landslides), (3) low sediment supply due to sediment sinks immediately upstream, or (4) reaches with no readily apparent cause for misclassification.

RESULTS

We organize our analysis along three general themes: (1) bedrock-alluvial thresholds, (2) localized controls on channel type, and (3) frequency of bedrock and alluvial channels. After examining the general relationships between bedrock and alluvial channels in each lithology, we estimate values for the $(b/k)^{1/n}$ and $(p–m)/n$ terms using the threshold positions derived from the discriminant analysis. We then explore local mechanisms that contribute to reaches that do not conform to the bedrock-alluvial threshold model and present data on the frequency of bedrock and alluvial channels in the Willapa River system.

Bedrock-Alluvial Thresholds

The bedrock-alluvial data collected in the Willapa River watershed generally conform to the drainage area–slope segregation predicted by equation 4 (Fig. 5), as previously found in the Satsop River (J11. 6). Specifically, data from the Willapa River display distinct bedrock and alluvial fields on drainage area–slope plots, with bedrock channels having steeper slopes for the same drainage area. However, lithology appears to influence specific characteristics of the threshold. The bedrock-alluvial threshold found in the basalt data is not only more steep than that for the siltstone, but also appears to be slightly shifted upward on the drainage area–slope axes (Fig. 5). Of all the thresholds, that in the Satsop River has the steepest slope, even though it has the same underlying lithology (siltstone) as found in the Willapa River basin. Although the form of the area-slope threshold predicted by equation 4 appears generalizable, the specific relation differs between watersheds and lithologies.

The discriminant functions that separate the bedrock and alluvial fields for the Willapa River correctly classified 94% and 82% of the data for the siltstone and basalt lithologies, respectively, while the discriminant function correctly classified 94% of the Satsop River data (Table 1). These results, along with low Wilk's lambda values, indicate a good discrimination was possible between the bedrock and alluvial fields for each data set. The slope of the discriminant function, or the values for the $(p–m)/n$ term from equation 4, ranged from –0.42 for the Satsop River data to –0.69 for siltstone data from the Willapa River. The values for the $(b/k)^{1/n}$ term vary inversely with $(p–m)/n$ values, where the Satsop River data produced the lowest value and the siltstone produced the highest value (Table 1). Hence, the discriminant analysis results also confirm that different thresholds exist between both different lithologies and watersheds with similar underlying lithology.

TABLE 1. SUMMARY OF DISCRIMINANT ANALYSIS RESULTS OF THE WILLAPA RIVER AND SATSOP RIVER DATA

	n	Wilk's lambda*	Discriminant function	Datum correctly classified (%)
Siltstone	33	0.47	$S = 802^* A^{-0.69}$	94
Basalt	33	0.68	$S = 56.4^* A^{-0.49}$	82
Satsop River	60	0.44	$S = 15.4^* A^{-0.42}$	94

Notes: S—slope; *A*—area.
*Lower Lambda values indicate better discrimination possible between data.

Localized Controls on Channel Type

Three local processes not incorporated into this simple model could explain most of the forced bedrock and forced alluvial reaches that did not follow predictions of the discriminant function based on free alluvial and bedrock data: (1) alluvial channels underlain by siltstone, but dominated by basalt clasts (alluvial-basalt); (2) bedrock channels forced by low sediment supply (forced bedrock); and (3) alluvial channels forced by large woody debris (forced alluvial). Of the three subcategories, the siltstone-underlain alluvial channels dominated by basalt clasts segregate the most clearly from the other data (Fig. 7A). Although they cluster systematically on the drainage area–slope figure, they are near or entirely within the bedrock field. A comparison of the discriminant threshold from reaches underlain by basalt shows that most of these siltstone reaches are within the alluvial field for the basalt data. Hence, clast composition influences the maximum attainable slope of an alluvial channel.

The forced bedrock channels with local low sediment supply consistently are below the bedrock-alluvial threshold (Fig. 5), while the wood-forced alluvial channel data plot throughout both bedrock and alluvial fields, and appear somewhat random. The wood steps of the kind described here (Fig. 4) alter the morphology of the channel by both reducing sediment transported downstream (by trapping it) and forcing alluvial morphologies upstream of the jam. The forced alluvial data are in both the bedrock and alluvial fields in Figure 7, while the data for the surface slope of the sediment impounded upstream of logjams are mostly within the alluvial field defined by the discriminant threshold. Although few reaches surveyed in detail were significantly influenced by wood loading in the Willapa River, the effects of logjams are dramatic in the Satsop River data (Fig. 7C).

Frequency of Bedrock and Alluvial Channels

Mapping of channel morphology in our extended reconnaissance surveys found that 73% of the surveyed channel length was covered by alluvium in both basalt and siltstone lithologies. Of the extended reach surveys, 3 had <60% alluvium cover, while 13 had 80% or higher cover (Fig. 8).

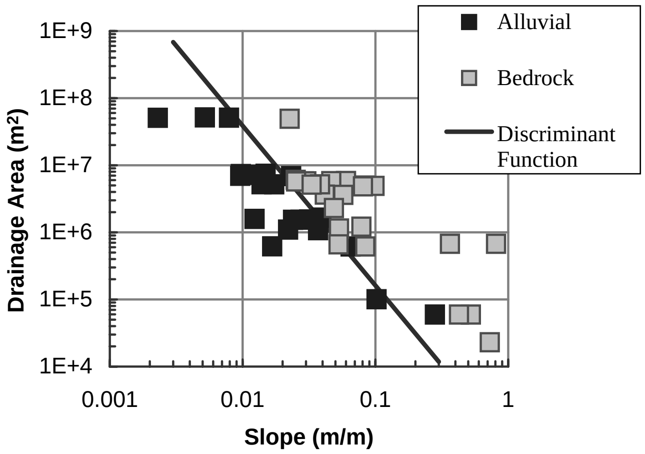

Figure 6. Bedrock and alluvial channel data from the Satsop River watershed (modified from Montgomery et al., 1996).

In these extended surveys, we found that the length of forced alluvial bed varied from 0% to 84% of the survey length. Other than in Trap Creek, individual logs and small logjams were the dominant obstructions in these forced alluvial channels. In contrast, the headwaters of Trap Creek (Fig. 9) and several tributaries to Trap Creek had fully spanning logjams 3 m or more in height. Many of the jams were landslide or debris-flow deposits that formed single steps, forcing the upstream deposition of large sediment wedges. Even though the influence of woody debris on channel morphology is partially dictated by the size of the channel (Abbe and Montgomery, 1996) and the size of wood available, we found no trend between the percentage of forced alluvial channels and their bankfull widths (Fig. 10).

Due to a relatively high frequency of locally controlled reaches found in the extended surveys, we found that predicting channel type from digital topography was not useful without field verification. Of the surveyed channel length, <40% was correctly classified using digital topography (Table 2). The GIS driven classification determined that 46% of the siltstone and 49% of the basalt channels would be alluvial, while the field surveys found that an average of 72% of the channel length was alluvial in both lithologies. In particular, bedrock channels were predicted from the digital topography much more frequently than found in the field surveys.

Using field maps and field observations, we found that logjams and local variations in sediment supply accounted for most of the GIS misclassified reaches. We found that nearly 60% of the alluvial channels that were predicted to be bedrock by the digital topographic data (about 25% of the total surveyed channel length) were alluvial because of wood forcing (Table 3); another 28% of these reaches have high sediment supplies due to readily identifiable local sources. Only 12% of the alluvial channels that were predicted to be bedrock lacked a clear reason in the field for being misclassified by the digital topographic data. For the bedrock channels predicted to be alluvial, nearly 50% were estimated to have an anomalously low sediment supply, while the remaining channels did not appear to be controlled by local features. The historic effects of splash damming and gravel mining, which are not included in the model, may account for the misclassification along the main-stem Willapa River. We speculate that the most likely explanation for the channels that have no apparent reason for misclassification is poor representation of channel slope in the digital topography, but they could also be due to the effect of sediment waves.

Comparison of field-measured slopes with those calculated using the digital topography reveals that the calculated slopes poorly reflected

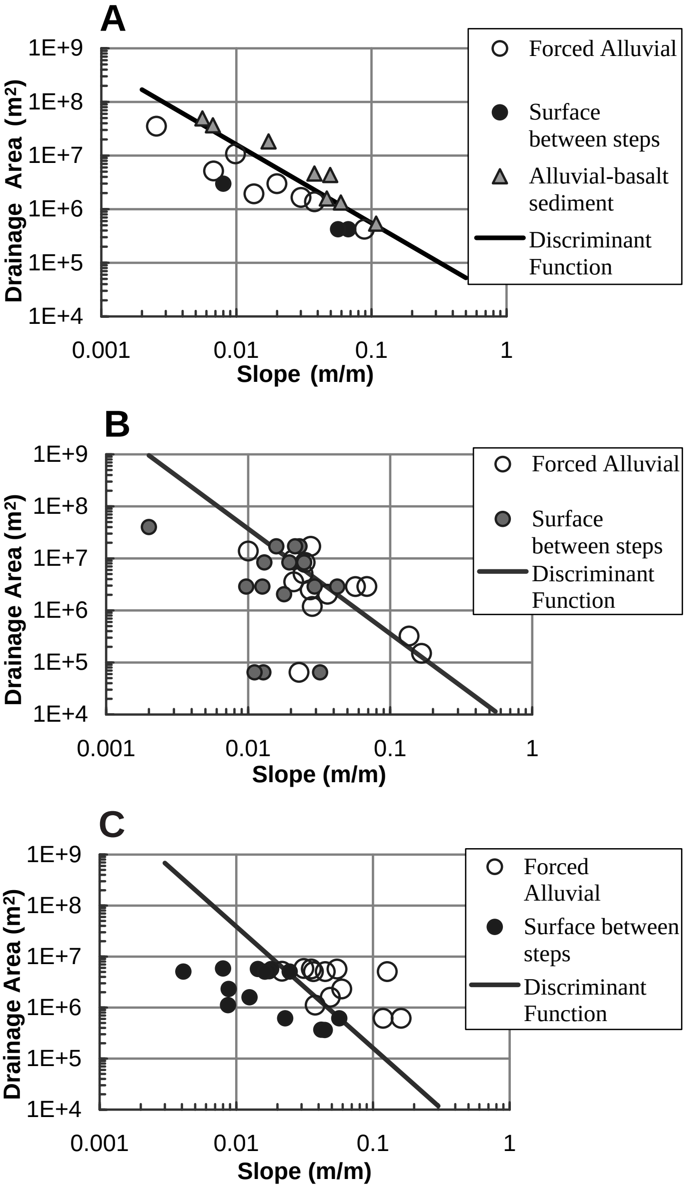

Figure 7. Bedrock and alluvial data for the forced alluvial reaches and reaches with basalt clasts but flowing over siltstone bedrock with the discriminant function for the Willapa River watershed. (A) Siltstone. (B) Basalt. (C) Satsop River data.

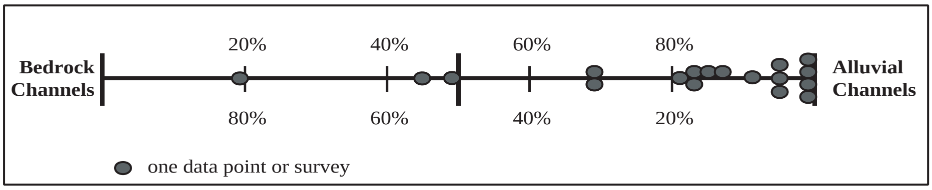

Figure 8. Relative abundance of bedrock and alluvial channels recorded during long surveys.

field measured slopes. Although we found significant scatter for the calculated slope values, almost half of all the GIS-calculated slopes are within ±25% of the field-measured slopes and nearly all were within ±100% (Fig. 11). The potential for large differences between reach-scale channel slope and those calculated from digital topography could easily cause misclassification, and such errors likely account for some, if not all, of the channels misclassified for no apparent reason.

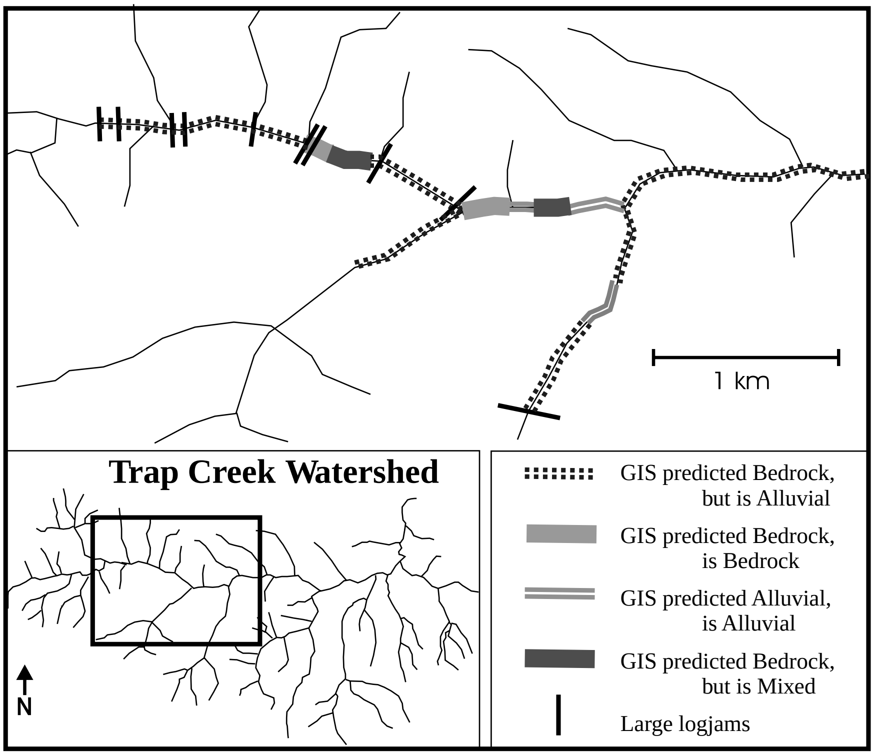

Figure 9. Headwaters of Trap Creek, in the Willapa River watershed, showing locations of logjams, forced sediment wedges, and the GIS predicted channel type.

DISCUSSION

Field data from the Willapa River watershed indicate that the critical slope model and the addition of local channel features predict the channel morphology well. We found that using only channel slope and drainage area, the critical slope model predicted that about half the channel length surveyed would be alluvial, but that field data indicate that almost 80% of the channel length is alluvial. Upon review of field observations for the alluvial channels predicted to be bedrock by the threshold theory, the reaches likely to be influenced by a sediment wave or local perturbation, we found that nearly 90% of these misclassified channels were forced by local sediment sources or by wood. The morphology of the remaining 7% of the total channel length could not easily be explained by our field observations, and could be due to poor representation of channel slopes in the digital elevation model or the propagation of sediment waves. As local features can overrule the expected channel morphology, field verification is advisable for predictions of channel morphology in forest environments.

Influence of Logjams

Our analyses of the Willapa River and the Satsop River data support the view that the addition of flow obstructions, such as fallen trees, can dramatically alter channel morphology. Emplacement of a channel-spanning logjam consumes a portion of the elevation drop for the reach, and therefore the forced alluvial surface created upstream of the obstruction has a gentler slope (Figs. 4 and 7). The height of the logjam dictates the effect on the upstream bed surface slope. In the siltstone lithology, where only small logjams were found, no forced alluvial channels with high-enough slopes to be a bedrock morphology were found. However, in the basalt lithology, where several large jams were surveyed, we found that some of the alluvial channels were likely forced to an alluvial morphology from bedrock (i.e., the reach-average slope was greater than S_c defined by the discriminant function). Most of these channels were in the headwaters of Trap Creek, and were associated with logjams deposited by debris flows. We found that these jams in the Trap Creek headwaters converted about 65% of the channel network to forced alluvial from bedrock (Fig. 9). In this regard, Trap Creek was similar to the Satsop River (Montgomery et al., 1996), where logjams commonly formed by recruitment of key members from the streamside forest forced many bedrock channels to an alluvial morphology (Fig. 7). Although small logjams can convert channels near the bedrock-alluvial threshold to a forced alluvial morphology, we found that even the steep bedrock channels relatively far from the bedrock-alluvial transition can be converted with large-enough logjams. The effects of logjams on sediment waves were not documented in this study, but we hypothesize that a series of logjams could impede the propagation of a sediment pulse such as those simulated by Benda and Dunne (1997).

The small number of large logjams in the Willapa River basin may reflect the small size of wood debris available both in the channel and from the riparian zone, and the systematic removal of the large wood from channels. A recent survey of wood debris in the Willapa River headwaters (Sullivan and Massong, 1994) found that

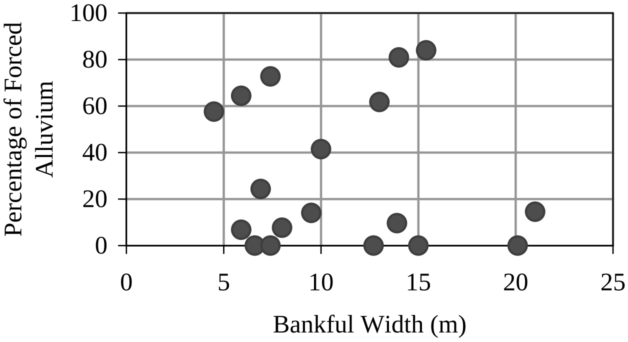

Figure 10. Percentage of alluvial channels with a forced morphology in each long survey vs. the average bankful width of the channel.

TABLE 2. SUMMARY OF GIS RESULTS

	Siltstone*			Basalt*		
	Field alluvial	Field bedrock	Total	Field alluvial	Field bedrock	Total
Predicted alluvial	32.0	14.3	46.3	27.2	21.9	49.1
Predicted bedrock	40.6	13.1	53.7	44.4	6.5	50.9
Total	72.6	27.4	100	71.6	28.4	100

*Results are given in percentage of stream length for each lithology.

TABLE 3. SUMMARY OF MIS-CLASSIFIED GIS DATA

	GIS bedrock—Field alluvial		
	Wood forced	Local high sediment	No apparent reason
Percent based on category	57	28	15
	GIS alluvial—Field bedrock		
	Local low sediment	No apparent reason	
Percent based on category	47	53	

Notes: The category GIS (geographical information system) Bedrock—Field alluvial indicates those channels that were remotely predicted to be bedrock using digital topography, but were field identified as alluvial. The GIS Alluvial—Field bedrock are those channels predicted as alluvial, but field verified as bedrock. By reviewing field notes, we determined three possible mechanisms for the misclassification: wood forcing, anomalously high sediment supply, and anomalously low sediment supply. Those channels that did not fit into these categories are classified as having no apparent reason for misclassification.

>85% of the logs at least partly obstructing flow were <0.5 m in diameter. In contrast, key member sizes in the Satsop River system ranged from 0.7 to >2.0 m (Montgomery et al., 1996); most of the current wood available in the Willapa River system does not appear to be large enough to effectively form logjams capable of altering channel type. The one notable exception, Trap Creek, had logjams with large logs interwoven with sediment and other debris that formed from valley-filling landslides or debris flows.

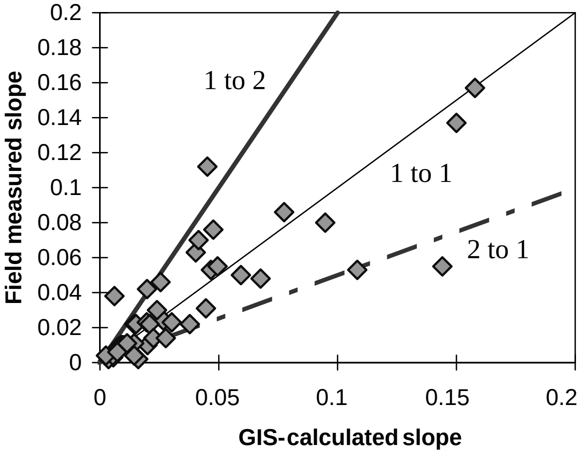

Figure 11. Comparison between field measured reach-average slopes and GIS-computed slopes. The GIS-calculated slopes were determined between topographic contours from a 12 m digital elevation model.

Changes in Sediment Supply

Regional and local variations in sediment supply can affect how data fit into the critical slope threshold model. Channel response to a local point source of sediment, such as a recent landslide, is often easy to recognize and one can map the consequential downstream changes in channel characteristics. A reach influenced by a local change in sediment supply may respond by converting its channel morphology, but a change in regional sediment supply may change the location and/or slope of the bedrock-alluvial threshold for all the channels. In the case of a single reach affected by local changes in sediment supply, we found that both increased and decreased sediment supply can force morphologic change.

In one field-surveyed reach on the South Fork Willapa River (at approximately river mile 17 or 27 km), a series of logjams forced both an alluvial channel upstream and a bedrock channel downstream of the jam. After these channel-spanning jams were removed in 1996 by the Pacific Conservation District (Allen Lebovitz, Willapa Bay Alliance, 1997, personal commun.), the initially alluvial reaches upstream of the jams rapidly converted to bedrock, while the reaches downstream converted from bedrock to a mixed alluvial-bedrock morphology. The morphologic conversion of these reaches after removal of the logjams occurred in less than one year, which highlights both the potential for rapid response to local perturbations, and the influence of woody debris on forcing channel morphology.

About 80% of the alluvial channels predicted to be bedrock, and about 50% of the bedrock channels predicted to be alluvial could be attributed to changes in local sediment supply such as in the South Fork Willapa River example. The channels that had alluvial form but were predicted to be bedrock and that had no apparent reason for the misclassification could be alluvial due to either poor representation of channel slopes in the digital elevation model or to the influence of sediment waves. Even if all those channels could be attributed to sediment wave propagation, it would only encompass 7% of the total network inventoried. Although sediment waves systematically moving through a channel could be an important sediment-transport process in mountain drainage basins, we do not find evidence in our data for a significant influence on the distribution of bedrock and alluvial channels.

Determining the influence of sediment production on a regional scale requires, among other things, a broad understanding of sediment delivery within and among watersheds. Laprade (1994) inventoried the input of sediment to the channels in the Willapa River basin from recent mass-wasting events. He found that hillsides underlain by basalt were steeper and had more landslides than hillsides underlain by siltstone. Although an inventory of other sediment sources, such as bank erosion was not conducted, he concluded that more sediment entered channels flowing through areas underlain by basalt than those channels flowing through areas underlain by siltstone. Laprade's observation of an apparently higher sediment supply for the basalt channels is consistent with our empirically derived bedrock-alluvial threshold position: the threshold for the basalt data has a higher $(b/k)^{1/n}$ value than the siltstone threshold. Hence, a difference in sediment supply, based on underlying lithology of the landscape, may account to some degree for the different thresholds found between the two lithologies in the Willapa River watershed.

Influence of Sediment Characteristics

Grain-size variations between lithologies may also influence the distribution of bedrock and alluvial channels, as the stage required to transport the sediment will increase with increasing grain size (Shields, 1936). Collins and Dunne (1989) noted that sediment derived from glacial sediment in the Satsop River, which were mostly igneous clasts, had larger grain sizes with lower attrition rates than the locally derived sedimentary clasts. Median grain-size measurements in the Willapa River ranged from 33 to 68 mm for channels with basalt clasts, while channels containing only sedimentary clasts ranged from 14 to 34 mm (Sullivan and Massong, 1994). The critical shear stresses required to move the median grain sizes are from two to three times greater for the basalt clasts than for the siltstone clasts. As the larger sediment requires more energy for transport, steeper alluvial channels can be maintained, which may at least partially account for the steep siltstone channels dominated by basalt clasts, and for the differences found between data from the two lithologies in the Willapa River data.

CONCLUSIONS

Our data confirm that a bedrock channel can be forced to an alluvial morphology by woody debris or other flow obstructions, and we can estimate the change in reach average slope needed to make that conversion. Although the distribution of bedrock and alluvial channels is systematic, local features and/or influences complicate predicting their distributions in forested mountain drainage basins. Poor representation of channel slopes and local conditions that force channel conversion not predictable from the topographic data led to <40% of the channels being correctly classified using digital topography. In particular, we found evidence that the bedrock-alluvial threshold varies with sediment lithology, relative sediment supply, and the presence of flow obstructions; most misclassified channels were the result of locally controlled sediment supply and woody debris that require field observations to identify. Our observations show that at present, the widespread occurrence of logjams in the Willapa River watershed exerts a strong influence on the distribution of bedrock and alluvial channel types through the channel network.

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REFERENCES CITED

Abbe, T. B., and Montgomery, D. R., 1996, Large woody debris jams, channel hydraulic and habitat formation in large rivers: Regulated Rivers: Research & Management, v. 12, p. 201–221.

Benda, L., and Dunne, T., 1997, Stochastic forcing of sediment routing and storage in channel networks: Water Resources Research, v. 33, p. 2865–2880.

Collins, B. D., and Dunne, T., 1989, Gravel transport, gravel harvesting, and channel-bed degradation in rivers draining the Southern Olympic Mountains, Washington, U.S.A.: Environmental Geology and Water Science, v. 13, p. 231–224.

Dunne, T., and Leopold, L. B., 1978, Water in environmental planning: New York, W. H. Freeman and Company, 818 p.

Gilbert, G. K., 1877, Geology of the Henry Mountains: Washington, D.C., Geographical and Geological Survey of the Rocky Mountain Region, U.S. Government Printing Office, 160 p.

Gilbert, G. K., 1914, The transport of débris by running water: U.S. Geological Survey Professional Paper 86, 263 p.

Howard, A. D., 1980, Thresholds in river regimes, *in* Coates, D. R., and Vitek, J. D., eds., Thresholds in geomorphology: London, George Allen & Unwin, p. 227–258.

Howard, A., and Kerby, G., 1983, Channel changes in badlands: Geological Society of America Bulletin, v. 94, p. 739–752.

Howard, A. D., Dietrich, W. E., and Seidl, M. A., 1994, Modeling fluvial erosion on regional to continental scales: Journal of Geophysical Research, v. 99, p. 13 971–13 986.

Kirkby, M. J., 1971, Hillslope process-response models based on the continuity equation, *in* Brunsden, D., ed., Slopes: form and process: Institute of British Geographers Special Publication 3, p. 15–30.

Laprade, W. T., 1994, Mass wasting module, appendix A, *in* Willapa headwaters watershed analysis: Olympia, Washington State Department of Natural Resources, 25 p.

Lasmanis, R., 1991, The geology of Washington: Rocks and Minerals, v. 66, p. 262–277.

Leopold, L. B., and Maddock, T., Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geological Survey Professional Paper 252, 57 p.

Logan, R. L., 1987, Geologic map of the Chehalis River and Westport quadrangles, Washington: Olympia, Washington Division of Geology and Earth Resources, OFR-87–8, 1 sheet, scale 1:100 000.

Massong, T. M., 1998, Influence of lithology, sediment supply, and logjams on the distribution of bedrock and alluvial channels [Master's thesis]: Seattle, University of Washington, 62 p.

Montgomery, D. R., and Buffington, J. M., 1997, Channel-reach morphology in mountain drainage basins: Geological Society of America Bulletin, v. 109, p. 596–611.

Montgomery, D. R., Abbe, T. B., Buffington, J. M., Peterson, N. P., Schmidt, K. M., and Stock, J. D., 1996, Distribution of bedrock and alluvial channels in forested mountain drainage basins: Nature, v. 381, p. 587–589.

Norusis, M. J., 1994, SPSS advanced statistics 6.1: Chicago, SPSS Inc., p. 57–106.

Owenby, J. R., and Ezell, D. S., 1992, Monthly station normals of temperature, precipitation, and heating and cooling degree days 1961–1990, Washington: U.S. Department of Commerce, NOAA, National Climatic Data Center, Climatography of the United States no. 81, 28 p.

Shields, A., 1936, Anwendung det Anlichkeitsmechanik und der Turbulenzforschung auf die Geshiebebewegung [translated by W. P. Ott and J. C. van Uchelen]: Pasadena, California Institute of Technology, 26 p.

Sullivan, K., and Massong, T. M., 1994, Stream channel report, appendix E, in Willapa headwaters watershed analysis: Olympia, Washington State Department of Natural Resources, 25 p.

Swan, J. G., 1857, The Northwest coast: New York, Harper, 435 p.

Van Syckle, E., 1980, They tried to cut it all: Grays Harbor . . . Turbulent years of greed and greatness: Seattle, Washington, Pacific Search Press, 308 p.

Van Syckle, E., 1982, The river pioneers: Early days on Grays Harbor: Seattle, Washington, Pacific Search Press, 423 p.

Wagner, H. C., 1967a, Preliminary geologic map of the Raymond quadrangle, Pacific County Washington: U.S. Geological Survey Open-File Report 67-265, 1 sheet, scale 1:62 500.

Wagner, H. C., 1967b, Preliminary geologic map of the South Bend quadrangle, Pacific County Washington: U.S. Geological Survey Open-File Report 67-266, 1 sheet, scale 1:62 500.

Water Resources Data, 1992, Washington water year 1992: U.S. Geological Survey Water-Data Report WA-92-1, 459 p.

Wendler, H. O., and Deschamps, G., 1955, Logging dams on coastal Washington streams: Washington Department of Fisheries, Fisheries Research Papers, v. 1, no. 3, p. 27–38.

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