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Key Points:
- Channel beds at 49 gages on Washington State mountain streams range from remarkably stable to remarkably unstable over 30–90-year records
- Channels do not respond consistently to peak flows, suggesting that sediment supply fluctuations are more responsible for channel bed variability
- Channels with highly variable bed elevations tend to be downstream from glaciers

Supporting Information:
- Supporting Information S1
- Data Set S1
- Table S1

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River Bed Elevation Variability Reflects Sediment Supply, Rather Than Peak Flows, in the Uplands of Washington State

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Abstract River channel beds aggrade and incise through time in response to temporal variation in the upstream supply of water and sediment. However, we lack a thorough understanding of which of these is the dominant driver of channel bed elevation change. This lack hampers flood hazard prediction, as changes to the bed elevation can either augment or reduce flood heights. Here, we explore the drivers of channel change using multidecadal time series of river bed elevation at 49 United States Geological Survey (USGS) gage sites in the uplands of Washington State, USA. We find that channel bed elevations at many of the gages change remarkably little over >80 years, while others are highly unstable. Despite regionally synchronous decadal fluctuations in flood intensity, there is a lack of regional synchrony of channel response at the decadal scale. At the monthly scale, the magnitude of antecedent high flow events between gage measurements does not predict either the direction or magnitude of shift in channel bed elevation. That variations in flood magnitude are insufficient to explain changes in bed elevation suggests that fluctuations in sediment supply, rather than variation in peak flows, are the primary driver of change to river bed elevation. In this region, channels downstream from glaciers have statistically significantly greater variability in bed elevation compared to those lacking upstream glaciers. Together, these findings suggest that aggradation and incision signals in this region predominately reflect fluctuations in sediment supply, commonly associated with glaciogenic sources, rather than response to high flow events.

1. Introduction

River channels change through time by incising and aggrading and by changing in width and roughness. Causes ascribed to river channel change vary widely and include individual floods (e.g., Nelson & Dubé, 2016), mass wasting events (e.g., Yanites et al., 2018), and shifts in climate (e.g., Anderson & Konrad, 2019) and land use (Liébault et al., 2005). Morphologic adjustments may have different temporal and spatial characteristics that can point to their cause. For example, channel changes can occur as abrupt shifts (e.g., Yanites et al., 2018) or more gradually, over successive hydrologic events (e.g., Stover & Montgomery, 2001); they can be regionally synchronous (e.g., Rumsby & Macklin, 1994) or singular (e.g., Stover & Montgomery, 2001).

Understanding the drivers of river channel change is important for flood hazard management. Channels with steady morphology represent a simpler situation for assessing and managing flood hazards (Lane et al., 2007). But in channels having a frequently changing geometry, a high flow event of the same discharge may cause different degrees of flooding from year to year. Slater et al. (2015) demonstrated that in nearly half of the 401 U.S. stream gage sites analyzed, geomorphic change has caused statistically significant trends in overbank flood frequency over the past half century. Thus, there is a practical need to understand the drivers of channel change over engineering timescales.

Fundamentally, all changes in bed surface elevation stem from divergences in the local sediment flux. While there are also secondary channel responses such as bed armoring or fining, if the transport capacity of the flow exceeds the incoming supply of sediment, the bed will erode, whereas if the incoming supply exceeds the capacity, sediment will deposit and the bed will aggrade. Thus, changes in the channel bed elevation can be viewed as primarily caused by either unsteadiness in the supply of sediment, relative to the flow, or unsteadiness in the hydrograph, relative to the supply of sediment.

Channel bed aggradation or incision could potentially be driven by either short-term or long-term hydrologic shifts. At large spatial and temporal scales, Mol et al. (2000) showed that the planform and vertical dimensions of midlatitude European rivers responded synchronously to global climatic change over 100-kyr timescales. On a shorter time scale, Rumsby and Macklin (1994) connected decadal-scale trends in incision to periods of wetter climate and an increase in the frequency of large floods in England. However, it remains unclear how common these regionally consistent, synchronous channel responses to hydrologic shifts might be.

Although increases in channel width after individual large floods are common (e.g., Rathburn et al., 2017), there is, to our knowledge, little documentation of whether channel bed elevations respond consistently to floods of a given magnitude. Physical experiments and 1-D numerical models have been used to explore the effects of cyclic hydrographs on channel bed elevation change in the case of steady sediment supply (An et al., 2017; Wong & Parker, 2006). These experiments suggest that downstream from the fluctuating upstream boundary (referred to as the *hydrograph boundary layer*), gravel river beds adjust such that they maintain a steady elevation throughout the cycled hydrograph. However, natural hydrographs are neither rhythmic nor consistent in magnitude between events or years. In a river prone to channel bed elevation change, do peak flows have predictable, consistent effects on bed elevation? To our knowledge, no work has directly addressed this question.

Channels also respond to changes in upstream sediment supply. The channel response to a given supply perturbation will depend on how that supply signal propagates downstream, which can vary as a function of the magnitude and frequency of the supply signal (Jerolmack & Paola, 2010), the grain size of the delivered material (Cui & Parker, 2005), and the geometry of the watershed, which dictates whether spatially distributed stochastic sediment inputs may aggregate as a coherent downstream signal (Gran & Czuba, 2017). Bed elevation response to point source pulses of sediment, such as dam removals (e.g., East et al., 2015) or large landslides (e.g., Sutherland et al., 2002), are well studied. In many cases, channel response to such punctuated increases in supply tends to attenuate downstream, as initially coherent pulses of material disperse as they move downstream (e.g., Lisle et al., 2001), muting their impact on downstream flood hazards. However, large increases in coarse sediment, such as those associated with widespread land use impacts (Gilbert, 1917; Madej et al., 2009) or exceptional large storms (Czuba et al., 2012; Yanites et al., 2018), have been shown to result in vertical channel change that may have significant downstream impacts that propagate downstream many kilometers and over periods of decades.

In case studies of river channel response to disturbance, the disturbance in question is often singular and large, and there is little ambiguity about cause and effect (e.g., East et al., 2015). However, linking geomorphic cause and effect becomes more difficult over long periods of time or across regional scales, where it is typically not possible or practical to assess the specific events responsible for individual periods of channel change. Instead, long-term or regional assessments of controls on sediment supply or changes in channel condition typically rely on correlations with upstream basin characteristics, such as mean basin slope (Slater & Singer, 2013) or the relative abundance of weak lithologies O'Connor et al., 2014).

Here, we aim to elucidate the primary drivers of river bed elevation change in the mountainous regions of Washington State, encompassing a range of steep forested watersheds and glaciated terrain. To accomplish this, we use high temporal resolution (15 min), multidecadal (30–80-year) time series of channel geometry, quantified via analysis of changes in the stage-discharge relationship at USGS gage sites. Stage-discharge trends, interpreted as indications of changing channel bed elevation, combined with daily discharge and basin-scale topographic and lithologic data, enable us to disentangle the relative importance of

1. variable hydrology, both decade-scale climatic variations and individual peak flows, and
2. variable sediment supply, from both pulses of sediment from distributed sources (e.g., small landslides) and from more persistent, localized sources (e.g., glaciogenic sediment supply) in shaping the vertical stability of rivers in the region.

1.1. Site Description

The mountainous regions of Washington State are a geologic patchwork of metasedimentary and metavolcanic rocks and exhumed plutons, Pleistocene glacial deposits, and active stratovolcanoes. The Puget Sound lowland is dominated by unconsolidated deposits associated with the advance and retreat of the Cordilleran Ice Sheet. The Coast Range and Olympic Mountains, with peak elevations ~1,000 and ~2,500 m, respectively, comprise the accretionary wedge of the Cascadia subduction zone. To the east, the crest of the Cascade Range, an inland volcanic arc, is ~2,000 m, punctuated by large glaciated stratovolcanoes up to 4,392 m in elevation. Alpine cirque glaciers are common across both the Cascade and Olympic ranges. Nearly all of the glaciers in the region are receding (Frans et al., 2018; Menounos et al., 2018), though the rate of response to fluctuations in regional climate varies among glaciers depending on their geometry and local climate (Roe et al., 2017). In Olympic Mountain and Cascade Range basins lacking glaciers, long-term erosion rates, estimated from cosmogenic ^{10}Be, are in the range of 0.1–0.3 mm/year (Belmont et al., 2007; Pazzaglia & Brandon, 2001) and 0.1–0.6 mm/year (Moon et al., 2011), respectively.

Major precipitation events in this region often result from large synoptic storms known as atmospheric rivers, which occur from November to March (Neiman et al., 2008). During many of these events, precipitation generally falls as rain in the lowlands and snow at the crest of the mountains, with upland basins receiving a combination of the two. Climate projections indicate that peak flows will increase in the future as mountain precipitation continues to shift from snow to rain (Hamlet et al., 2013). Across western Washington, peak flows tend to occur during wet-season rainfall and rain-on-snow events. This is the case even in basins that drain Mt. Rainier (elevation 4,392 m), where peak flows generally coincide with precipitation events, rather than spring snowmelt. In contrast, spring snowmelt drives the highest flows in basins in mountainous eastern Washington. The West Coast of the U.S. has experienced approximately decadal-scale fluctuations in climate, associated with the Pacific Decadal Oscillation (Mantua & Hare, 2009), shifting from periods of wet and cold climate to periods of warm and dry.

The 49 sites in our compilation (Figure 1 and supporting information Table S1) range in drainage area from 105 to 3,981 km^2 (median = 399 km^2). Channel slopes in the kilometer upstream from a gage, measured from a 10-m digital elevation model, range from 0.015% to 4.6% (median = 0.49%), with one outlier of 8%, resulting from a large waterfall 800 m upstream. We focused our analysis on upland and foothill rivers, excluding basins with reservoirs or other major flow regulation. Furthermore, we have excluded sites with levees or sites in which channel bed dredging or extensive in-channel gravel mining is known to have occurred. Human impacts (i.e., logging roads, timber harvesting, and settlements) are prevalent in nearly all of the basins included in this analysis. Because our methods rest on the use of the most recent rating curves, we selected only active sites with readily available rating curves. For 27 of the 49 sites in our compilation, we augmented the digitally available record, accessed via the USGS National Water Information System online system, with newly digitized historical records.

2. Methods

Rating curves that relate stage (water height above an arbitrary datum) to stream discharge are constructed using field measurements of channel cross sectional area and velocity at a stream gage site (e.g., James, 1991). The USGS stream gage network includes thousands of stream gages, many of which have been continuously operated for decades or, in some cases, over a century. Because channel geometry and roughness can change through time, frequent field measurements are made to update and maintain an accurate stage-discharge rating curve. The time series of changes in the stage-discharge relationship for a single stream gage yields a quantitative measure of channel geometry change through time. This approach, termed *specific gage analysis* (Blench, 1969), was used by G. K. Gilbert at the turn of the last century to track the downstream progression of sediment pulses from hydraulic mining (Gilbert, 1917). More recently, the availability of online stream gage datasets (Juracek & Fitzpatrick, 2009) has facilitated more widespread use of this method (Anderson & Konrad, 2019; O'Connor et al., 2009; Pinter et al., 2006; Slater et al., 2015; Stover & Montgomery, 2001).

Stage-discharge rating curve residuals (hereafter *stage residuals*) measure the difference between a paired measurement of stage and discharge made in the field and the stage predicted for that discharge based on the rating curve (Figure 2). Here, we have calculated stage residuals relative to the most recent rating curve on record for each site. In a time series of stage residuals, an increase indicates that the flow stage associated

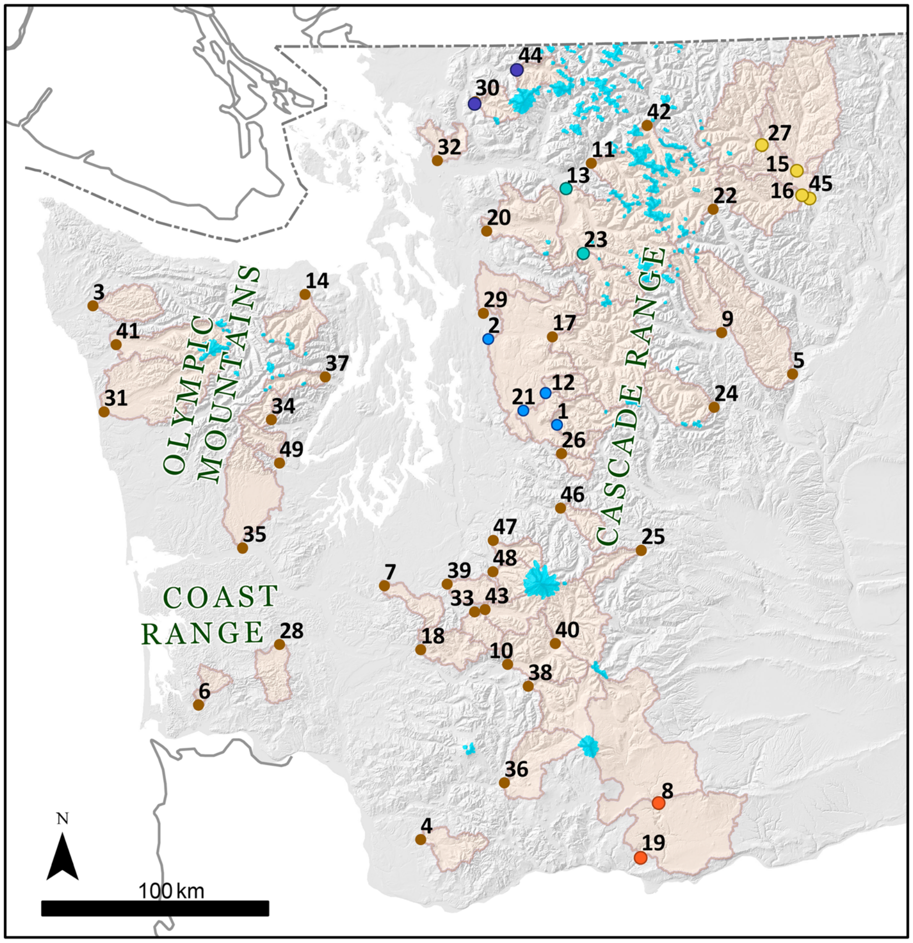

Figure 1. Location of stream gages used in this study, Washington State, USA. Sites are marked by brown points, with their respective contributing areas shaded in tan. Select colored points correspond to the sites shown in Figure 3. Glaciated areas are colored in blue. Site numbers correspond to those in Table S1 and Figure 3, below.

with a given discharge has increased. Increases can result from aggradation, narrowing, increased roughness, or some combination of the three, while decreasing stage residuals result from incision, widening, and/or decreased roughness.

Changes in the stage for a given discharge have typically been assumed to reflect changes in mean channel bed elevation (Anderson & Konrad, 2019; O'Connor et al., 2009; Weatherly & Jakob, 2014). That assumption was verified here by assessing variations in average flow depth for a given discharge and comparing those data to the variations in stage for a given discharge. Depth-discharge residuals are sensitive to changes in channel roughness and width but are independent of changes in mean bed elevation. We find that depth-discharge residuals generally do not show significant trends and do not change synchronously with stage-discharge residuals (supporting information Figure S1). This supports the assumption that changes in stage-discharge relations at our sites primarily reflect changes in mean elevation, and not roughness or width.

Stage is measured above a (often arbitrary) local datum. That datum may be changed over time, typically associated with updates to equipment or replacements to equipment if the site and associated benchmarks are destroyed in floods (Wilby et al., 2017). Stations may also be moved upstream or downstream over time, which results in an apparent change in the stage for a given discharge simply due to the slope of the river bed. These changes in datum location are summarized in the USGS annual water reports. In this analysis, we excluded all stage residual data that precede station moves greater than 150 m. Only five sites had datum shifts associated with station moves greater than 50 m. In simple situations where datum shifts were known, and the station was not moved more than 150 m, the published datum shifts were used to correct all measurements to a common effective datum. In situations where the magnitude of datum shifts was not known, typically because the site was destroyed in a flood or reactivated after a long period of inactivity, records before and after the datum shift were combined using the assumption that no change occurred between the measurements immediately preceding and following the datum shift. This *zeroing* process was used on six gages.

In cases with a defined datum shift, the nominal published date of that shift often differed modestly from the actual date at which measurements begin to reflect the new datum. This is typically because stage records from measurements made immediately before the datum transition may be converted to the new datum in the database or because of a period of overlap between two recording devices when both stages are recorded on paper, but only one is retained in digital records. To identify the true timing of the transition between datums, the largest single shift in the 10 measurements centered around the nominal date of the datum shift was assumed to represent the transition between datums. As a test of the validity of our zeroing and time-adjusting procedures, we visually inspected all stage residual time series to check for abrupt changes in behavior that coincide with a datum shift (purple asterisks, Figure 3; Wilby et al., 2017).

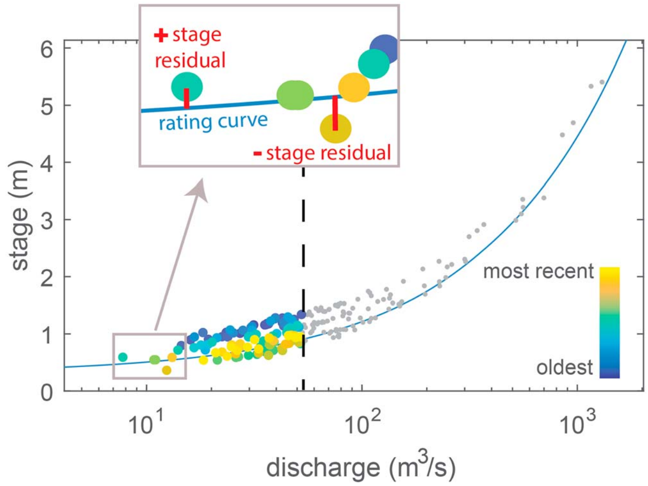

Figure 2. Example showing the method for calculating stage residuals from USGS field discharge data and a rating curve. Field measurements of discharge and associated stage are shown as points, with the lower discharge data (which we use in this analysis) colored by date of measurement according to the color bar shown in the lower right of the figure. Stage residuals are calculated as the difference between the field measurement of discharge and the discharge predicted for that stage based on the rating curve.

How do we know that the observed channel behavior reflects basin characteristics or sediment supply fluctuations and not simply the particularities of a given reach of channel? As a measure of the influence of reach location, we compare sites that lie within a common hydrologic basin and are subject to similar sediment supply, snowpack, and glacier extent.

2.1. Data Cleaning, Smoothing, and Normalizing

Stage-discharge rating curves are often poorly constrained at high discharges because field measurements are sparse. At some sites, this leads to systematic bias in the stage residual at the high discharges. To avoid such bias, we focused our analysis on the lower half of the discharge measurements for each site. This has the added benefit of focusing our analysis on changes in the channel bed, rather than changes in bank geometry or roughness due to vegetation changes on channel bars that primarily impact stage-discharge relationship at higher flows.

In order to compare channel geometry changes across a large range of river and basin sizes, we normalized changes in the stage residual by the flow depth associated with the mean discharge, calculated over the full available record for each channel. The normalized stage residual is a dimensionless variable (m/m) that measures changes in the water surface elevation for a given discharge as a fraction of the mean flow depth (hereafter fmf). We calculated flow depth from the USGS field data by dividing the reported flow area by the active channel width for each field measurement. We then estimated the mean flow depth by calculating the median of the 10 calculated depths that are closest to the mean discharge. Normalizing residuals by the mean flow depth provides a practical measure of how important changes in elevation are relative to typical flow depths: A 1-m change in channel bed elevation is of little morphologic significance in the Amazon River but is a morphologically important change in a small creek. However, because mean flow depth increases systematically with drainage area, a fixed absolute elevation change would tend to result in a progressively smaller normalized change at sites progressively farther downstream.

There are occasional outliers in the field data records resulting from typos and from instrumentation issues. To eliminate the extreme outliers, we removed all stage residuals that were more than 3 standard deviations from the mean for that site. To smooth out the more minor outliers from the time series, which may occur because of seasonal algal growth on the bed, local large wood accumulations, or ice, we used a moving median using a window of five data points. Given that most sites had about five measurements per year, this represents a smoothing over approximately 1 year. This median smoothing tended to reduce random intra-

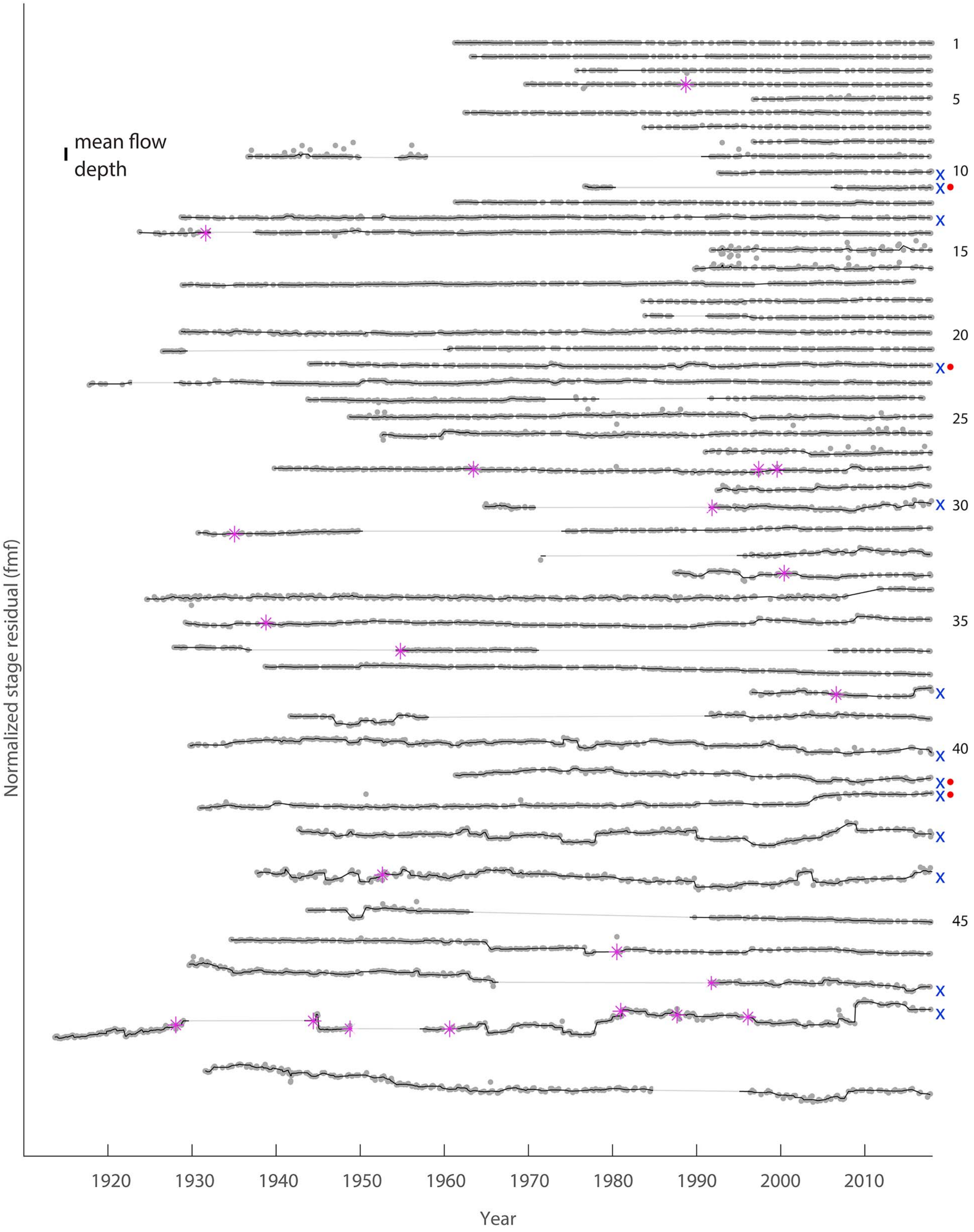

Figure 3. Stage residual time series for the 49 sites in our study. Stage residuals are normalized by the mean flow depth for each site and vertically arranged such that the lowest variability sites are at the top. The vertical scale is the same for all sites. The gray dots mark calculated stage residuals, with the black lines showing the curves smoothed by a moving-median algorithm to remove nonphysical outliers. Datum shifts are marked with purple asterisks. Sites with >0.5% glaciated basin area are marked with a blue x. Glaciated basin sites that do not drain volcanoes are marked with a red dot next to the blue x. Site numbers, referenced in the text, are on the right. The curves show the moving median smoothing.

annual variability but did not substantially modify persistent trends or major abrupt shifts, which are more likely to represent physical changes of interest in this study.

2.2. Hydrological Analysis

To explore the potential impacts of climatological trends on river response, we must first analyze the record for possible trends in the hydrological data. We analyzed long-term USGS daily discharge records for sites in the compilation. We excluded a year of data for a site if the flow record for that year includes fewer than 250 days of data. For each year of data at each site, we checked for the occurrence of flows exceeding two thresholds: 5 and 10 times the mean discharge for that site. These limits roughly corresponded to the threshold discharges at which substantial changes to bed elevation were observed to occur.

To assess whether floods of a given magnitude result in predictable channel responses, we compared the change in stage residual between sequential channel measurements with the largest discharge that occurred in that time period, which we refer to as the maximum antecedent discharge. This approach assumes that the largest flow in a given time period is responsible for channel change during that time period. The median time period between measurements is 63 days. If the window of time between measurements exceeded 1 year, we excluded that data point from the analysis, assuming that a large number of hydrologic events could have occurred in that time period, inhibiting our ability to attribute the channel change to a single event.

2.3. Analysis of the Time Series of Stage Residuals

Several of the 49 sites have trends (progressive increases or decreases in the stage residual) over a roughly decadal timescale. To explore possible synchrony of these trends in channel change, we calculated linear trends through the time series of normalized smoothed stage residuals over a 10-year moving window. This length of window was chosen because it is shorter than the scale of the Pacific Decadal Oscillation (Mantua & Hare, 2009) but sufficiently long to capture a large number of channel measurements. If fewer than 15 data points exist in a particular 10-year window, we did not calculate a trend for that window. In cases where gage records with undefined datum shifts were aligned using our zeroing procedure, trends were calculated only from the start of the most recent period of record with a consistent datum.

As a metric of overall bed elevation variability, we calculated the standard deviation of the detrended stage residuals for each site (hereafter *channel elevation variability*). We detrend using a linear fit across the full length of record in order to separate variability from gradual monotonic changes. In the results and discussion below, references to channel elevation variability are always the standard deviation of the detrended stage residuals. All other analyses described below are conducted on the time series of normalized, smoothed stage residuals that have not been detrended.

2.4. Basin Lithology, Glacier Area, and Channel Slope

We explore potential lithologic, glaciogenic, and topographic drivers of channel variability using topographic data (10 m Digital Elevation Model (DEM)) and a digital 1:100,000 scale geologic map of the region (WA DNR, 2010), which includes glaciers as a map unit. We delineated the upstream contributing basin boundaries for each of the 49 sites using the National Hydrography Dataset stream network. We then determined the fraction of the upstream contributing area covered by each mapped lithologic unit, of which glacier coverage is included. We measured the proportion of Quaternary sediments as a proxy for high supply of unconsolidated paraglacial sediment (e.g., Church & Slaymaker, 1989; Collins et al., 2019) and the proportion of glacier coverage as a proxy for modern proglacial sediment contributions. Among our study basins, glaciated basins often coincide with stratovolcanoes. As a first-order test of the relative role of glaciers and volcanoes in driving river channel response, we distinguish between the volcanic and nonvolcanic glaciated basins in the analysis below. Using the 10-m DEM, we calculated fraction of the basin area with slopes >30°, which we use as a proxy for sediment supply associated with distributed landsliding (Roering et al., 1999). We manually measured channel slope from the 10-m DEM for each site over the 1 km upstream from the gage site.

3. Results

Channel bed stability varies enormously between rivers in our compilation (Figure 3). Some rivers remain remarkably stable for decades; at 7 of the 49 sites, the total range in channel bed elevation was less than 10 cm. The median range of normalized stage residual over their entire period of record was one third the

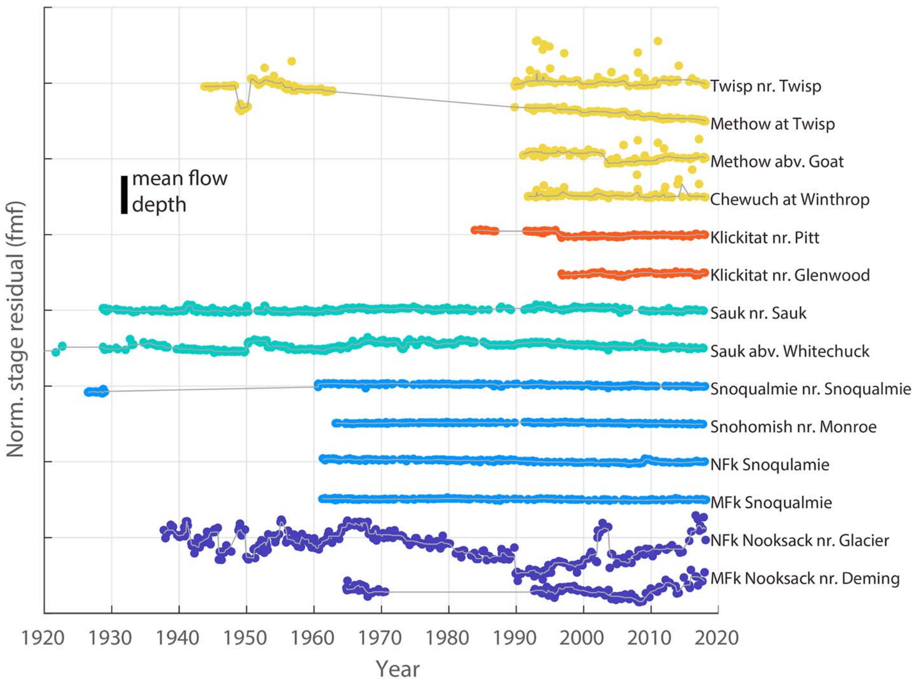

Figure 4. Consistency of channel variability within a basin. Channels within a common hydrologic basin and physiographic region are grouped by color. As in Figure 3, sites are stacked on the vertical axis.

mean flow depth. This represents a median change in river bed elevation of only ~30 cm over the multidecadal record. Other rivers are remarkably unstable: Three sites have a stage residual range greater than 2 times the mean flow depth (Figure 3, sites 49, 48, and 47). Among the unstable rivers, abrupt increases and decreases in the stage residual are common. Multidecadal increasing and decreasing trends in the stage residual are also apparent in several of the time series (e.g., SF Skokomish and Hoh, Figure 3 sites 49 and 41, respectively). Many of the unstable sites are highly variable at decadal timescales throughout the length of the record (e.g., Puyallup and Nisqually, Figure 3 sites 48 and 43, respectively). There are also a few sites that display step function shifts, abruptly changing stage residual, after a long period of stable behavior (e.g., Thunder Ck and NF Skokomish, Figure 3 sites 42 and 34, respectively); we explain these as the result of singular historical events or geologic characteristics below.

The magnitude and style of bed elevation fluctuations is consistent among gages within a common hydrologic basin (Figure 4) indicating the importance of basin characteristics in influencing channel bed variability at gage sites. Among the potential basin-scale drivers of channel variability, glacier cover (13 gages) was the only variable that yielded a significant relationship (Figure 5). For nine of these gages, glaciers are located on one of four active volcanoes (Baker Peak, Glacier Peak, Mt. Rainier, and Mt. Adams; Figure 1). While this raises the possibility of the confounding effect of high volcanogenic sediment production, we found no statistically significant difference between channel variability at gages in glaciated basins draining volcanoes and gages in basins draining nonvolcanic basins with glaciers (Welch's t test, $p = 0.35$). Channel slope at the gaged reach, proportion of the basin with hillslopes >30°, and proportion of the basin covered by Quaternary deposits all have no discernible relationship with channel bed elevation variability (Figure 6). There is a negative relation, at least in terms of the upper envelope, between channel elevation variability and basin area. However, this is primarily a function of normalizing data by the mean flow depth, which tends to increase with drainage area, and indicates that the absolute magnitude of channel elevation variability does not tend to increase moving downstream.

Three of the gage sites draining unglaciated basins have high channel bed variability. In those instances, variability can be associated with localized landslides, unusually abundant channel-marginal coarse sediment sources, and extreme floods. The Methow River at Twisp, east of the Cascade Range crest, has experienced substantial bed elevation change in the past century. The pattern of channel change is unusual

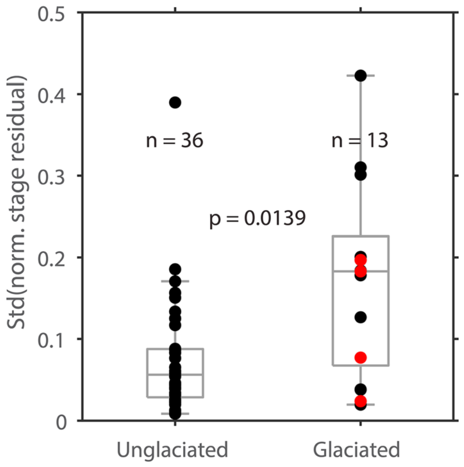

Figure 5. Influence of glaciers on channel variability. Points overlain on boxplots showing the same data. Among the glaciated points, red dots denote sites that drain glaciated basins lacking volcanoes (sites marked with red dots in Figure 3). *P* value refers to the difference between the unglaciated and glaciated populations, calculated using a Welch's *t* test for samples of unequal variance.

(Figure 3, number 45, and Figure 4), with abrupt jumps in the late 1940s, followed by nearly 70 years of gradual, monotonic decrease in the stage residual. The 1948 flood of record at this site (Rantz & Riggs, 1949) is twice the magnitude of the second largest flood. We speculate that the trend may reflect an extended response to the perturbation from that extreme high flow event. At the North Fork Skokomish River gage site (Figure 3, number 34), the time series of stage residuals exhibits a single large jump in 2008, associated with a landslide 200 m upstream, noted in the USGS Water Year Summary. The South Fork Skokomish River (Figure 3, number 49), on the southeast side of the Olympic Mountains, has the highest variability in our data set. Bed elevation change in the South Fork Skokomish has been gradual, though large in magnitude. The cause of this variability is unclear, although there has not been a systematic change in the magnitude of peak flows over the course of the gaging record, sediment influx to the South Fork basin, which is dominated by lateral channel erosion of unconsolidated sediments in Pleistocene glacial terraces, is unusually high for the region (Collins et al., 2019).

To test whether floods of a given magnitude result in consistent bed elevation response, we compare maximum antecedent daily discharge to the incremental change in stage residual (Figures 7 and S2). Many sites display a threshold discharge for channel change (Figures 7c–7f), above which the absolute value of channel change increases. High flows above this threshold result in an increase, a decrease, or no change to the stage residual. This threshold tends to occur around 5–10 times the mean discharge (marked in Figure 7 with vertical grey dashed lines). For all sites, both glaciated and unglaciated, channel bed elevation response to flows below five times the mean discharge is consistently small, as indicated by the narrow distributions, centered around zero, in Figure 8a. While the proportion of events resulting in channel change increases above 5 and 10 times the mean discharge, especially for the glaciated sites (as evidenced by the increase in the width of the distributions in Figures 8b and 8c relative to Figure 8a), the vast majority of major high flow events result in little channel change. For those high-magnitude events that are followed by a change to the stage residual, the number of instances is approximately equally split between increases to the residual (indicating deposition) and decreases (indicating incision), with a slight skew toward incision. This suggests that bed elevation change is not a simple, unidirectional function of the magnitude of individual hydrologic events.

Examining whether streambeds have responded to any decadal-scale change to the regional frequency of large floods provides a further test of the hypothesis that stream bed elevations respond primarily to peak flows. The regional frequency of peak discharges greater than 10 times the mean flow has changed systematically over time, with a period of relatively modest occurrence of high-magnitude flows extending from the mid-1930s to mid-1970s and bounded by periods of more frequent high-magnitude flows before and since (Figure 9). This is consistent with Mastin et al.'s (2016) finding of a weak increase in the magnitude of peak flows at many long-term (>50-year) stream gage sites across Washington. We did not observe similar systematic shifts in the more moderate floods (5–10 times mean discharge; Figure 9).

Despite multidecadal trends in the frequency of large floods across the study region, we do not observe coherent trends in channel bed elevation change through time; the median 10-year trend is typically close to zero (Figure 10). Among glaciated basins, the median trend varies somewhat more, though it never exceeds the time-averaged standard deviation of all trends (pink shaded zone, Figure 10). This indicates that regional trends do not exceed the *noise*. We find that while there are some periods of time with more negative trends (e.g., decade windows centered in the early 1940s) and more positive trends (e.g., the decade centered around 2010), strong regional synchrony in channel response is not apparent in the time series of stage residuals. While the amplitude of the trends in glaciated basins appears to be higher in the most recent 30 years, our ability to assess the significance of this trend is hampered by a paucity of continuous pre-1960 records for sites with upstream glaciers. The absence of a systematic trend toward incision or

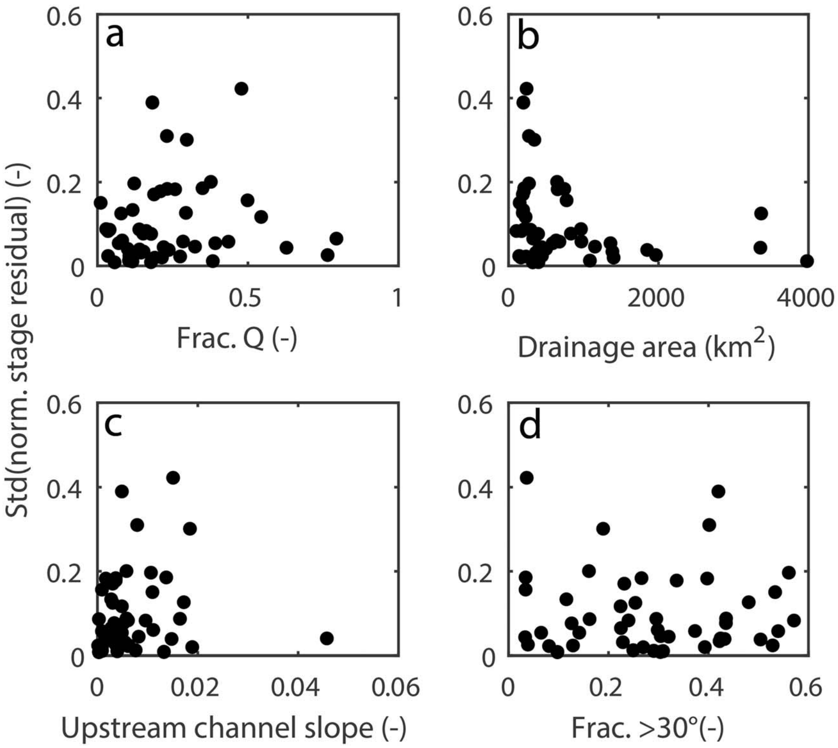

Figure 6. Testing alternative geologic or geomorphic explanations for high-variability sites: (a) fraction of the upstream basin area covered in Quaternary deposits; (b) upstream drainage area; (c) upstream channel slope, measured over the 1 km upstream from the gage site, outlier (site with waterfall 800 m upstream) excluded; and (d) fraction of the upstream basin with hillslopes >30°.

deposition associated with individual flood events (Figure 8) or with regional, decadal variations in flood magnitudes (Figure 9) implies that fluctuations in sediment supply are important in explaining variations in river bed elevations through time.

4. Discussion

We set out to understand the primary drivers of bed elevation change of mountain streams in Washington State. Based on an analysis of changes in stage-discharge relations at USGS stream gages, we find substantial differences in the magnitude of variability among rivers within the region. Most river beds are remarkably stable throughout their entire period of record, while a few change regularly, aggrading and incising by amounts equal to several times their mean flow depth. These differences in channel response help us to distinguish between proposed drivers of channel change: individual peak flows, decade-scale climatic trends in peak flows, and distributed or point source sediment pulses.

Despite the steep and tectonically active nature of our study region, the majority of rivers in our data set were vertically stable over a period of many decades. Of our 49 sites, 80% have a total stage residual range less than their mean flow depth over their full, multidecadal record. This degree of vertical channel stability is especially notable given the dynamic geological setting of the region. However, we reiterate that gage sites, including those studied here, are chosen for their lateral stability. The stable stage-discharge relationship for many of these rivers suggests that despite their regularly mobile beds (Pfeiffer & Finnegan, 2018), their channel geometries are in an (approximate) mobile bed equilibrium (An et al., 2017).

Channel bed elevation change shows no correlation with either event-level hydrology or systematic trends in hydrology, suggesting that channel change cannot be explained simply by high flow events. If channel beds were predominantly fluctuating in response to extreme high discharge events, as in the hydrograph boundary layer demonstrated by An et al. (2017), we would expect to find systematic downcutting of the bed following

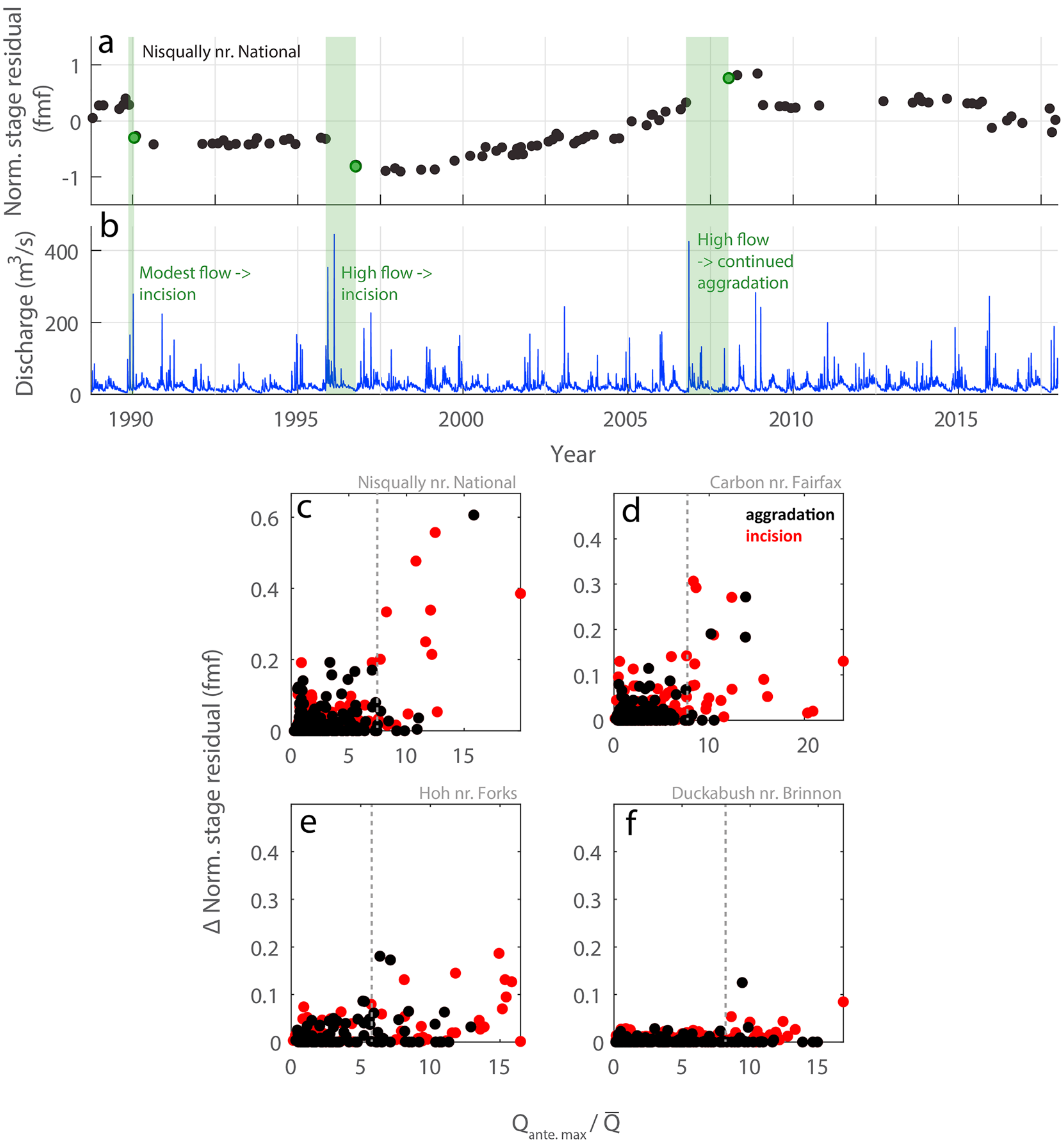

Figure 7. Connecting channel response, quantified via changes in the stage-discharge relationship, to high flow events. (a) Changes in the stage-discharge relationship over 30 years, for the USGS gage on the Nisqually River near National. Three example measurements are marked in green, with annotations below. (b) Hydrograph for the same gage, showing daily discharge record for the same time period shown in (a). (c–f) Relationship between maximum antecedent discharge and the magnitude of channel response for four rivers in Western Washington. The dashed gray lines mark the approximate location of the *threshold* discharge, above which the magnitude of channel response variability increases. Note the different responses: The Nisqually River (c), a glaciated basin, has substantial channel response, though the large responses tend to occur only above an apparent threshold discharge; while the Duckabush (f, an unglaciated river) shows little response even after the highest flows. In all four basins, high flows can result in aggradation, incision, or little response.

peak flows, resulting from an excess transport capacity relative to sediment supply. Instead, we find that the majority of peak flow events result in negligible change in channel bed elevation (Figure 8). In cases where peak flows do cause channel change, the channel is equally likely to aggrade or incise. The lack of a consistent relation between peak flow magnitude and contemporary bed elevation response allows us to reject the hypothesis that the sequence of individual peak flow events drives the patterns of river channel response in this region. We do observe that major punctuated channel elevation changes are typically associated with large peaks flows; in channels that experienced change, the threshold discharge for channel bed response was around 5–10 times Q_{mean}. However, the lack of consistent magnitude or direction of the channel response to flows above that threshold (Figure 8) points to the unsteady sediment supply as a driver of channel bed elevation variability.

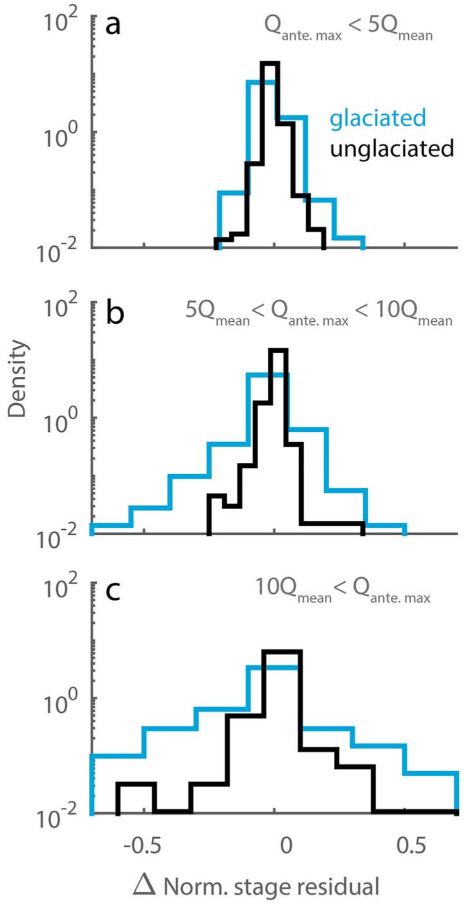

Figure 8. Normalized histograms (density plot) of the channel response to flows of different magnitudes, showing combined data for all basins, separated by the degree of glacier cover (glaciated sites have >0.5% basin area covered in modern glaciers). Note that the vertical axis is on a logarithmic scale, and all bins sum to 100.

Decadal trends in the occurrence of peak flows over the past 80 years do not explain the observed patterns of channel bed elevation change. Despite the fact that there is substantial variability in peak flows between wetter and drier time periods (Figure 9; Mantua & Hare, 2009), we do not find regional synchrony in river channel response to these shifts (Figure 10). These results are in contrast to work in other regions (e.g., Rumsby & Macklin, 1994), which has connected decade-scale climate variability to regionally synchronous channel change. In mountain streams in Washington, the effects of sediment supply variation seem to be greater than the local hydraulic effects of variation in peak flows over the past century. However, since the large storms that cause major floods are also key triggers of sediment delivery from mass wasting and bank erosion, regional variations in peak flows may directly or indirectly influence channel elevations through their control on sediment supply.

Given the importance of variable sediment supply as a control on changing channel elevations, the lack of regional synchrony in channel response over these decadal timescales is perhaps unsurprising. Since sediment supply signals may take decades to propagate downstream (Ferguson et al., 2015; Gilbert, 1917; Madej & Ozaki, 1996), even a regionally coherent shift in headwater supply would appear at different times downstream as a function of downstream distance and may differ in appearance among basins as a function of river network geometry (Czuba et al., 2012). Variations in glacier response time to a given shift in climate and the stochastic nature of mass wasting and major floods may further desynchronize the downstream response to a regional shift in climate.

Of the basin- and reach-scale physiographic characteristics explored, only the presence of upstream glaciers was statistically related to higher channel bed variability (Figures 5 and 6). This is consistent with the work of

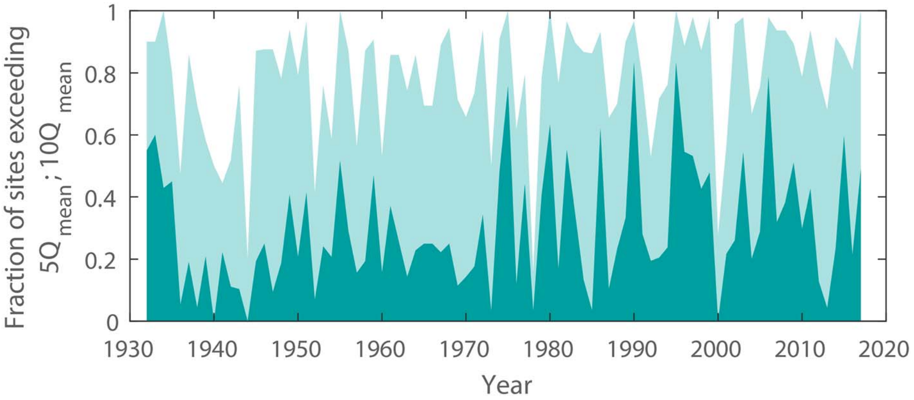

Figure 9. Trends in peak flows through time. The fraction of sites exceeding $5Q_{\mathrm{mean}}$ (light teal) and 10_{Qmean}(dark teal) in a given year.

Slater and Singer (2013) who found no correlation between bed elevation variability and dominant basin lithology or mean watershed slope. Among the glaciated basins, we found no statistical difference between the volcanic and nonvolcanic sites (Figure 5). We hypothesize that glaciers are uniquely important because they are associated with large, localized supplies of unstable coarse sediment. Debris flows emanating from proglacial zones are common in this region (Anderson & Pitlick, 2014; Copeland, 2009; Lancaster et al., 2012; Legg et al., 2014; Slaughter, 2004; Walder & Driedger, 1995), providing regular and spatially focused delivery of coarse sediment. In several of the glaciated basins draining stratovolcanoes (9 of 13), these modern sediment sources augment material from large, late Holocene lahars (Beget, 1981; Crandell, 1971), which provide abundant sources of valley floor sediment that may be remobilized in large floods. In glaciated basins, the combination of contemporary sediment delivery and abundant sources of mobile material stored in valley floors may result in sediment export rates that are both generally high and sensitive to variations in climate (through associated impacts on glacier extent, snowpack persistence, and storm hydrology). These inputs are also localized and consistently delivered from the same part of the river network, putting them at lower risk of sediment supply signal *interference* as sediment pulses from

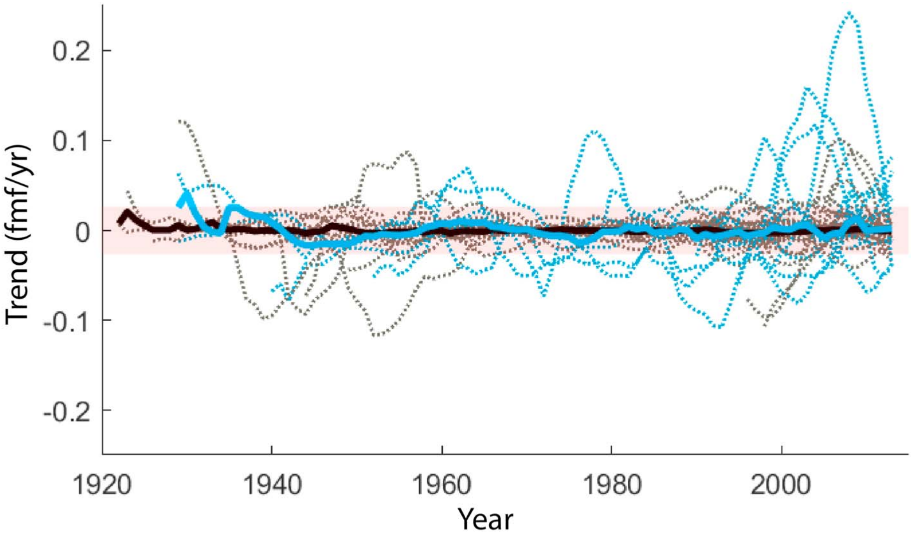

Figure 10. Lack of regional synchrony in river response. Trends for individual rivers are shown as dotted lines (blue = glaciated, grey/black = unglaciated), while the medians among all sites for each given year are shown in solid, bold according to the same color scheme. The shaded box marks one standard deviation above and below the mean. Data from all 49 sites are shown on this figure. Because many sites exhibit little variability, the trend lines overlap near 0.

tributaries converge during downstream transport (Benda & Dunne, 1997; Gran & Czuba, 2017). The sediment conditions in glaciated basins may be particularly well suited for generating significant supply variability and for allowing those signals to persist and propagate downstream.

In basins without glaciers, spatially distributed landslides and debris flows are common but do not appear to be dominant drivers of channel change. In the majority of unglaciated basins, we observe little to no elevation change over the period of record (Figure 5). We also find no relation between the proportion of slopes >30°, a proxy for the likely frequency of mass wasting events, and bed elevation variability (Figure 6). Landslides do affect channels locally: For example, the North Fork Skokomish gage (Figure 3, number 34) saw abrupt aggradation in 2008 in response to a small landslide just upstream. However, at the scale of regional patterns, these local effects appear to be rare. This indicates that the zone of bed elevation fluctuation (An et al., 2017) downstream of individual landslides tends to be small. The overall tendency for stability further suggests that over the available period of record, there have not been systematic changes in the average frequency or intensity of distributed landslides large enough to cause substantial downstream channel elevation responses in most unglaciated basins.

In this study, we have intentionally avoided rivers in the Puget Sound lowland that have complex management histories: levees, channel stabilizing structures, sediment control structures, dams, and histories of dredging. These human impacts complicate our ability to disentangle the drivers of channel change in lowland rivers. Many of these Puget Sound lowland rivers are incised into glacial sediments from the Cordilleran Ice Sheet (Collins & Montgomery, 2011). The valley-bounding bluffs composed of these glacial sediments represent another major sediment source, and one that is sensitive to channel migration and changes in channel width. Future work is needed to disentangle the role of river management history from the legacy of Cordilleran sediments to fully understand channel change in the lowland. The present study provides context for upstream factors shaping channel change in this region.

5. Conclusions

We set out to understand whether channel change is primarily driven by hydrologic variability or unsteady sediment supply, focusing on upland channels in Washington State. We find substantial differences in the magnitude of channel bed elevation variability among upland rivers within the region. As evidence against hydrological variability as the primary driver of channel bed change, we find that channel response to peak flows is inconsistent: Antecedent peak flows of the same magnitude may result in aggradation, incision, or no change to the bed elevation. Furthermore, we find that periods of wetter and drier climate across the region do not result in systematic regional channel response. Both of these findings point to variation in stream bed elevations being driven more by variations in sediment supply than by variation in peak flows. In support of sediment supply fluctuations as the primary driver of channel bed change, we find that glaciated basins, which tend to be associated with large, localized volumes of mobile coarse sediment, have statistically significantly higher channel elevation variability than unglaciated basins.

Acknowledgments
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