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Channel Conveyance Variability can Influence Flood Risk as Much as Streamflow Variability in Western Washington State

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Key Points:

- Conveyance is commonly unsteady at 50 Washington river gages and its variation can be equal to variability of moderate flood streamflow
- Short-term changes in channel conveyance can have a greater influence on flood risk than long-term, steady adjustments
- In rivers where flow regulations suppress moderate floods, channel conveyance losses can counteract reductions to streamflow

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Changes in the severity and likelihood of flooding events are typically associated with changes in the intensity and frequency of streamflows, but temporal adjustments in a river's conveyance capacity can also contribute to shifts in flood hazard. To assess the relative importance of channel conveyance to flood hazard, we compare variations in channel conveyance to variations in the flow magnitude of moderate (1.2 years) floods at 50 river gauges in western Washington State between 1930 and 2020. In unregulated rivers, moderate floods have increased across the region, but in regulated rivers this trend is suppressed and in some cases reversed. Variations in channel conveyance are ubiquitous, but the magnitude and timing of adjustments are not regionally uniform. At 40% of gages, conveyance changes steadily and gradually. More often, however, conveyance variability is nonlinear, consisting of multidecadal oscillations (36% of gages), rapid changes due to unusually large sediment-supply events (14% of gages), and increases or decreases to conveyance following flow regulation (10% of gages). The relative importance of conveyance variability for flood risk depends on the mode of adjustment; in certain locations with historic landslides, extreme floods, and flow regulation, the influence of conveyance changes on flood risk matches or exceeds that of streamflow at the same site. Flood hazard management would benefit from incorporating historic long-term and short-term conveyance changes in predictions of future flood hazard variability.

Plain Language Summary

River flood hazards change through time due to variations in streamflow and variations in the channel's ability to convey flood flows or "conveyance." We study the importance of both factors to variability in flood hazard over time at 50 river gages in western Washington State. Conveyance variability contributes to shifts in flood hazard at nearly all 50 gages, but rivers do not adjust at the same time nor by the same amount across the region. Conveyance changes steadily and gradually at 40% of gages and varies nonlinearly at 60% of gages. The most common nonlinear patterns are oscillations in conveyance with a period of one or more decades. Less common are rapid changes to conveyance from unusually large sediment-supply events and conveyance changes following flow regulation. Conveyance variations interact with variations in streamflow due to climate change or human regulations in ways that can worsen or alleviate flooding. Moderate flood streamflows increase through time at gages unaffected by flow regulation, but flow regulations typically reduce flood flows. Rivers with upstream dams sometimes lost substantial conveyance, resulting in increased flood hazard despite regulated streamflows. Considering how river conveyance variability combines with or offsets streamflow shifts can improve flood hazard planning.

1. Introduction

Damages and costs of river flooding have increased globally in recent decades (Ward et al., 2017; Winsemius et al., 2016). The frequency and magnitude of heavy precipitation are projected to increase as climate changes in the 21st century in many areas of the world (Murray & Ebi, 2012), substantially increasing human exposure to flood hazard (Arnell & Gosling, 2016). As more people live in flood risk zones, there is a pressing need for accurate flood risk predictions to foster human safety (Jongman et al., 2012).

Flooding occurs when streamflow exceeds a channel's conveyance capacity, driving flows overbank. Increases in overbank flow intensity and frequency can be driven by increases in streamflow or losses to channel conveyance capacity (Figure 1); however, flood risk assessments have generally focused on systematic increases in streamflow through time rather than conveyance changes. Streamflow data are, hence, used to understand changing flood potential with trends in flood hazard inferred from trends in peak flows (e.g., Hodgkins et al., 2019; Mastin

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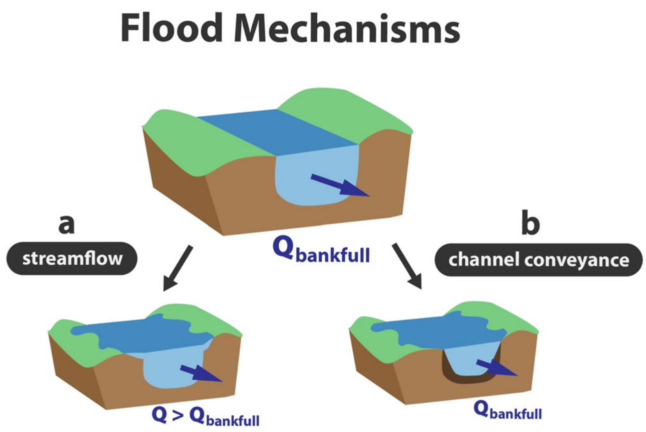

Figure 1. A conceptual understanding of flooding driven by (a) streamflow versus and (b) channel conveyance: (a) streamflow-driven flooding results from runoff events inducing channel flows (Q) that exceed the bankfull flow capacity ($Q_{bankfull}$) of the channel. (b) Channel-driven flooding results from reductions in the conveyance of the channel through mechanisms such as sediment aggradation, channel narrowing, or increases in roughness. This leads to flooding at flows that were previously in-bank.

et al., 2016), and frequency and intensity of floods estimated from mean daily discharge data (e.g., Hamed & Rao, 2019; Kjelstrom, 1998; Pilgrim & Cordery, 1975).

Recent studies of flood risk, however, focus on river morphodynamics as an important control on flooding (e.g., Li et al., 2020; Slater et al., 2015; Sofia & Nikolopoulos, 2020). A decrease in channel cross-sectional area or an increase in roughness can increase water stage for a given discharge, resulting in channel overflow at discharges that were once within bank (Figure 1b). Indeed, case studies show that reductions in local river conveyance capacity can increase flood frequency without a change in peak flows (Collins et al., 2019; Stover & Montgomery, 2001); flooding on the Missouri River now occurs at flows that were entirely in-bank in the early 20th century (Pinter & Heine, 2005).

To quantify the influence of morphodynamics on flooding, Slater et al. (2015) developed a method for separating the relative contributions of channel conveyance and mean daily streamflow changes to trends in flood frequency. They used this method to search for monotonic trends in flood hazard from 1950 to 2013 in 401 river gauges across the United States and found that more than half the sites had a nonstationary flood frequency, with significant changes in channel conveyance contributing to trends at just under half of the stations.

However, both changes to channel conveyance capacity and streamflow regime can be nonmonotonic, and neglecting this can obscure short-term changes in flood hazard as well as climatic and geomorphic processes that drive such trends. For example, comparing monotonic trends in streamflow and channel conveyance fails to account for the importance of abrupt geomorphic changes occurring during tropical cyclone events in Puerto Rico, where short-term conveyance capacity changes can exceed peak streamflow changes (Li et al., 2020). Additionally, climate variability can simultaneously affect patterns of streamflow and channel conveyance change, where discharge and channel form adjust to cycles of increases in precipitation and sediment supply (Anderson & Konrad, 2019; Rumsby & Macklin, 1994; Slater et al., 2019). Fitting long-term, monotonic trends to cyclic patterns of streamflow and channel conveyance change can overlook short-term hydrologic and morphologic behavior that could amplify or offset flood hazard.

Here, we modify the approach of Slater et al. (2015) by considering monotonic, nonmonotonic, short-term, and long-term changes to flood hazard. We focus on western Washington State, a region in the northwestern United States where recent floods have been attributed to conveyance capacity losses; extensive flood damages caused by the White River during January 2009 occurred after a 25% channel conveyance reduction during a 2-month period between winter storms (Czuba et al., 2010; Green, 2009). Slater et al. (2015) also document channel capacity decreases across the northwestern United States that increased flood hazard, although relatively few sites were analyzed in western Washington. We separate the influence of channel conveyance and streamflow variability by analyzing the relative magnitude of flow displaced by channel conveyance adjustments versus changes in the streamflow rate of 1.2 years recurrence interval floods over time, which is the typical frequency of bankfull flow for alluvial rivers in western Washington (Castro & Jackson, 2001). We apply the method to 50 river gages in western Washington State using field measurement and mean-daily flow data over the last 30–90 years to better understand the causes of flooding and how and why it may change in the future. This analysis resolves the temporal variability of conveyance changes. Spatial variability is addressed by comparing responses in rivers across the region and, where possible, by comparing gages on the same river.

Specifically, we ask: (a) What are the magnitudes and time scales associated with both monotonic and nonmonotonic changes in moderate flood streamflows and channel conveyance and how do these compare to one another? (b) Are there regional patterns to changes in flood risk driven by streamflow and/or channel conveyance change? (c) How do flood risk changes in regulated rivers that have had substantial modifications to water and sediment continuity compare with changes in unregulated rivers?

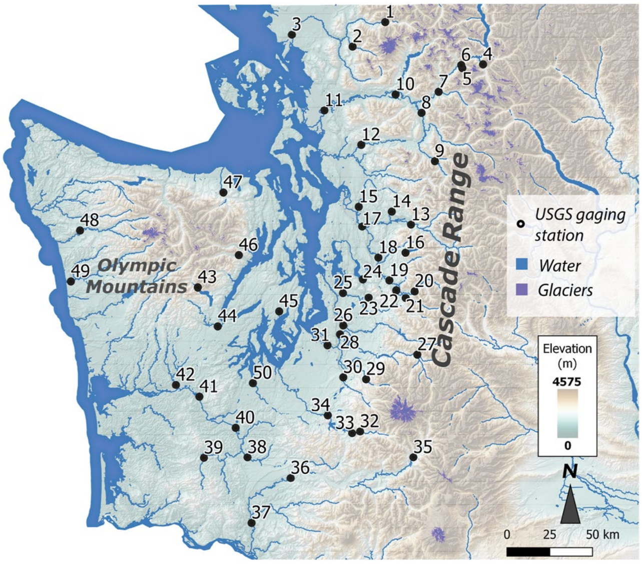

Figure 2. Map of study region. Alpine glacial coverage is highlighted in purple, and the location of United States Geological Survey gaging stations (USGS) used in this study are marked and numbered. Corresponding gage names and information may be found in Data Set S1 in Supporting Information S1. Site numbers correspond to those in Figures 6, 7 and 8. Elevation data are from a 30 m mosaicked Digital Elevation Model (DEM) of Washington (UW Geomorphological Research Group, 2021) resampled from USGS 10 m DEM products (USGS, 2017).

2. Study Area

Rivers in western Washington head in the Olympic Mountains and the Cascade Range (Figure 2). The Cascade Range, where most of our study sites are located, hosts alpine proglacial zones, which deliver sediment to proximal channels through rockfall and proglacial debris flows particularly from Quaternary volcanoes (e.g., Anderson & Pitlick, 2014; Czuba et al., 2012). The episodic nature of this delivery is associated with high variability in river bed elevation downstream of glaciated basins (Pfeiffer et al., 2019), and downstream-propagating bed waves (Anderson & Konrad, 2019). However, proglacially derived sediment can also remain stored in upland valley floors (Anderson & Jaeger, 2020) and sediment transit times in headwater channels can be on the order of 10^3 years (Lancaster & Casebeer, 2007); as a result, the connectivity between proglacial areas and downstream channels is not well understood.

The Cascade and Olympic ranges are bisected north to south by the Puget Sound lowland which includes a sedimentary fill of lacustrine silts and clays, outwash sands, and gravels from successive advances and retreats of the Puget Lobe of the Cordilleran ice sheet (Booth, 1994). Postglacial fluvial incision into the lowland fill has created terraces prone to channel-adjacent landsliding (Booth et al., 2017; LaHusen et al., 2016) which contribute substantial coarse sediment low in the channel network (Scott & Collins, 2021). While the extent to which mass flux from glacial terraces contributes sediment directly to the channel varies between rivers, the grain size and lithology of these sediments suggest their potential importance for downstream sedimentation (Scott & Collins, 2021). Within the Puget Sound region, rivers are still responding to relict Pleistocene glacial and volcanic landforms; rivers are aggrading where they flow through valleys carved by subglacial processes during the last ice age and incising in valleys downcut by Holocene fluvial activity, postglaciation (Collins & Montgomery, 2011). Human engineering has in some cases exacerbated Holocene sedimentation; e.g., in the Puyallup system engineered rerouting of the White River channel has increased sedimentation (Anderson & Jaeger, 2020) in locations prone to severe flooding (e.g., Czuba et al., 2010; Green, 2009).

Western Washington rivers have been dammed for flood control, water supply, and hydroelectricity generation (Gendaszek et al., 2012; Lee et al., 2016), modifying connectivity with upstream sediment supply and stream power available for downstream sediment transport, the balance of which determine whether rivers downstream of dams aggrade or degrade (Grant, 2012). Aggradation happens when flow regulations reduce competence for transporting sediment delivered by tributaries (e.g., Andrews, 1986; Van Steeter & Pitlick, 1998; Wilcock et al., 1996) or when coarse, bed-sized sediment is eroded from downstream banks (e.g., Gaeuman et al., 2005). In the eastern Puget Lowland, coarse sediment eroded from terraces is mostly downstream of dams (Scott & Collins, 2021). On the Skokomish River, dam reductions in discharge in concert with continued, high sediment supply from a downstream tributary caused drastic conveyance losses in the lowland mainstem channel (Collins et al., 2019).

Both streamflow and sediment supply are sensitive to variations in climate. Mean monthly streamflow fluctuates on annual to multidecadal time scales in relation to climate cycles that include the El Nino/Southern Oscillation (ENSO; Kahya & Dracup, 1993) and the Pacific Decadal Oscillation (PDO; Mantua et al., 1997). Flood insurance claims are positively correlated with La Nina cycles of ENSO in the Pacific Northwest (Corringham & Cayan, 2019). Warming winter temperatures have decreased snowpack storage, resulting in higher fall and winter peak flows in basins with a high fraction of elevation above historic snowpack lines (e.g., Mote et al., 2018; Neiman et al., 2011). Atmospheric river events were responsible for 96% of peak annual daily streamflows in the region between 1998 and 2009 (Neiman et al., 2011) and are forecasted to increase the frequency of days with heavy and severe precipitation over the next century (Gershunov et al., 2019).

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That climate influences both streamflow and sediment supply highlights the need for understanding the corresponding effects of climate on channel morphodynamics and flooding. Pfeiffer et al. (2019) suggest that in this region, river bed variability is driven by changes in sediment supply rather than peak flows resulting in regionally asynchronous variation in bed elevation. Anderson and Konrad (2019) demonstrate river bed patterns that are lag-correlated to the PDO as a sediment disturbance propagating downstream from proglacial regions on Mt. Baker. However, Slater et al. (2019) presents a correlation between climate signals and adjustments to channel capacity across the United States under the assumption that changes in river form occur synchronously with climatic shifts. Understanding whether channel conveyance responds to climate-driven changes as a propagating downstream signal, a system-wide adjustment in channel form, or in other ways is important for understanding how flood hazard will change in the future.

3. Methods

3.1. Analysis of Channel Conveyance Change

We include 50 USGS river gages spanning sites from steep mountain headwaters to lowland, managed channels (Figure 2). Gage elevations range from sea level to 536 m, contributing drainage areas range from 16 to 5,774 km^2, and mean basin slopes range from 4% to 59% (GAGES-II data set: Falcone, 2011). To analyze channel conveyance variability, we use USGS field records of simultaneous stage and discharge measurements accessed from the National Water Information System (NWIS) web interface (USGS NWIS, 2021). We limit our study to gages with long, relatively continuous records that extend to within 5 years of the present year (2020); we include gages with a minimum of 30 years of data with measurement gaps <20 years. Some gages have a shift in datum as the gaging location was moved upstream or downstream from its original location. Where the USGS has published values for this shift, we use this value to adjust our data to a unified datum by offsetting the data with the minority number of stage measurements on one side of the shift to match the majority of the record. We implement this shift for three gaging sites. At 13 gages where published datum shifts are not available, we trim gage data records to exclude measurements made prior to the shift. The resulting gage records range from 30 to 92 years and average 59 years.

We infer changes in channel conveyance capacity from shifts in the stage-discharge relationship at a gaging station as the difference between the field-measured flow and the flow predicted by a static rating curve (Figures 3a and 3b). This method, conventionally termed "specific gage analysis" (Blench, 1969), has long been used to detect how geomorphic changes affect river water level heights and corresponding flow capacity (e.g., Biedenharn et al., 1997; Gilbert, 1917; Jemberie et al., 2008; Pinter & Heine, 2005). In our application of specific gage analysis, we use a rating curve for the channel near its maximum capacity to avoid limitations imposed by using the most recent (e.g., Anderson & Konrad, 2019; Pfeiffer et al., 2019) or time-averaged (Slater, 2016; Slater et al., 2015) ratings: in rapidly aggrading channels, the most recent rating curves cannot accommodate flow-residual values for stages below the current channel bottom; at sites with sudden changes to channel capacity, or an uneven sampling record, a time-averaged rating can be unusually skewed and misrepresent channel change over time.

We create rating curves for the channel near the maximum capacity using the BaRatin method and software (Le Coz et al., 2014). This approach combines hydraulic channel geometry data and stage-discharge field gagings to create rating curves and is beneficial because it allows for a physically based estimation of discharge above the range provided in the field gagings (Lundquist et al., 2016). We obtain cross-sectional geometry and channel slope for these calculations from a 0.5–2 km reach around each gaging station using 1-m resolution LiDAR-derived DTMs (WA DNR, 2021) and USGS stage-discharge measurements for a 5-year time span when the channel was vertically stable. A detailed account of rating curve data selection and processing is available in Text S1 in Supporting Information S1. This method of rating-curve formulation ensures that (a) all flow-residual values representing channel conveyance change can be predicted by the current rating curve (i.e., no values fall below the minimum stage value in the rating curve), (b) the rating curve represents a single channel geometry for a broad range of flows, and (c) we can compare morphologic changes between sites with respect to a stable, near-maximum channel conveyance.

We confine our channel conveyance analysis to high flows to focus on changes relevant to flooding by using measurements made around the "flood flow" (Q_{flood}) or the discharge at which flows begin to overtop the banks. We

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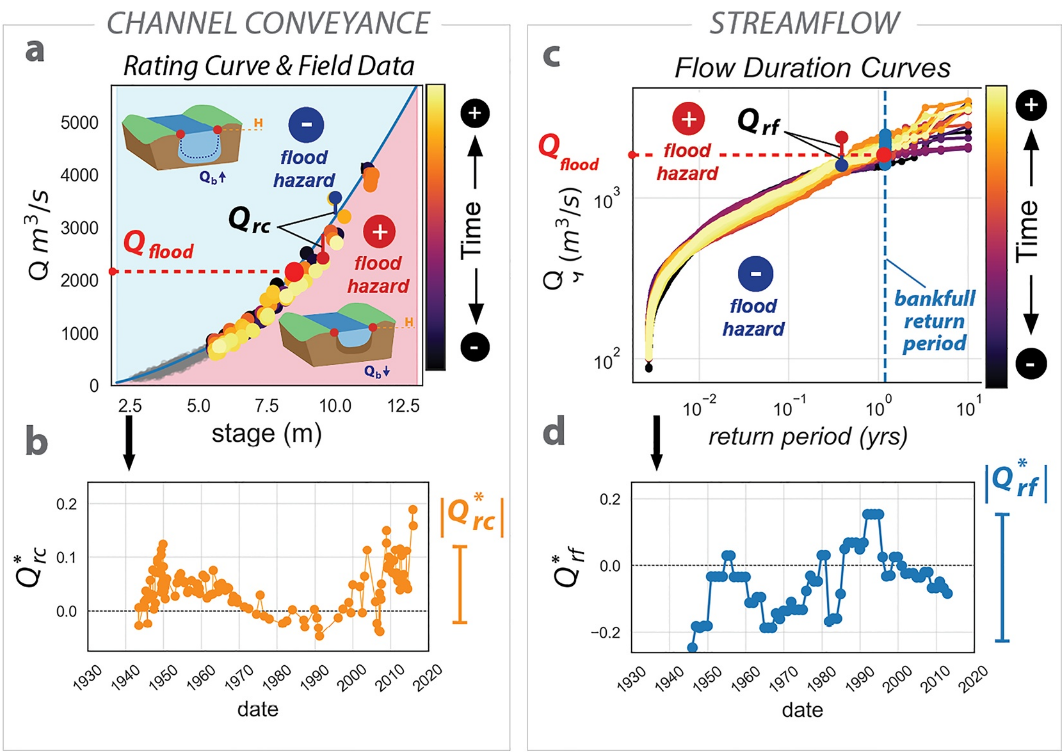

Figure 3. Methods for calculating (a) channel conveyance changes and (b) moderate flood streamflow changes at a representative United States Geological Survey (USGS) gauging station. (a) The calculation of Q_{rc} as the difference between field measurements of river stage and discharge and a rating curve representing the hydraulic relationship between flow and depth for a static time. Q_{flood} denotes the flood flow. (b) Q^*_{rc} represent normalized channel conveyance change over time. Data are normalized as Q_{rc}/Q_{flood}. $|Q^*_{rc}|$ represents the range calculated from a 5-point moving median across the Q^*_{rc} time series and is considered "potential" for change in channel conveyance altering Q_{flood} at a site. (c) Calculation of Q_{rf} as deviations from Q_{flood} at the bankfull return period (1.2 years). Q_{rf} are interpolated flows at the bankfull return period from flow-duration curves built from a 10-year moving window of mean-daily flow data. (d) Shows normalized Q^*_{rf} over time $\left(Q^*_{rf} = Q_{rf}/Q_{flood}\right)$ which are interpreted to indicate hydrologic changes in high-flow regime such as peak flow magnitudes and flood duration that would cause streamflow-driven flooding. $|Q^*_{rf}|$ represents the range of the Q^*_{rf} time series and is considered to represent the "potential" for changes in Q_{flood} driven by streamflow at a site.

obtain an estimate for this discharge based upon the 1.2 years return period flow computed from a flow-duration curve using the Weibull plotting position formula (Helsel & Hirsch, 1992; Weibull, 1939) with 10 years of mean-daily flow data bracketing the time for which we create a site's rating curve. The 1.2 years flow is chosen as a representative flow based upon Castro and Jackson (2001) who computed return periods of bankfull flow from field measurements of hydraulic geometry and stream statistics for the Pacific Northwest. A mean bankfull return period of 1.2 years was reported for the Pacific Maritime Mountains where the majority of our study gages are located. While variations in bankfull channel geometry resulted in a return period range of 1–1.5 years reported for the sites consistent between our study and Castro and Jackson (2001), using a single return period allows us to also compare streamflow statistics consistently across stations. We trim our data to analyze measurements made to one-half of the "flood depth" on either side of flood stage, where flood stage is interpolated from a site's rating curve as the stage predicted for Q_{flood}, and flood depth is calculated as the difference between flood stage and the minimum measured stage within the field data.

We quantify channel conveyance variation over time by calculating flow residuals as the difference between flows predicted by our rating curve and measured flows (Figure 3a). We refer to these as Q_{rc}, or flow residuals associated with conveyance change. Q_{rc} represent temporal changes in channel conveyance at a gaging station that result from adjustments in channel cross-sectional area or hydraulic roughness. Positive Q_{rc} indicate conveyance losses with respect to the capacity predicted by the rating curve and result in excess overbank flow. To assess the influence of channel conveyance variability on flooding and to compare results between rivers of different sizes, we normalize Q_{rc} by a site's "flood flow" (Q_{flood}) to obtain Q^*_{rc}.

To identify outliers due to errors in field measurement data, we fit a 10-point moving median to the time series of Q^*_{rc} and ignore data that falls outside three standard deviations of this moving median. This resulted in a mean of three points and median of one point being removed from each gage data record. We quantify the magnitude of variability in channel conveyance by taking the range of the moving median Q^*_{rc} as: $|Q^*_{rc}| = \max(Q^*_{rc}) - \min(Q^*_{rc})$ (Figure 3b). Since temporal trends in Q^*_{rc} were often nonmonotonic resulting in equal amounts of channel conveyance gain and loss over time (e.g., Figure 3b), we consider $|Q^*_{rc}|$ to represent the *potential* for conveyance driven flood hazard at a given site rather than magnitudes of change from a single trend.

3.2. Analysis of Streamflow Change

We analyze time series of streamflow variability at the bankfull return period to quantify how hydrological changes such as shifts in precipitation and runoff rates affect overbank flood flows over time. We use the mean daily discharge record at USGS gaging sites, trimmed to the same length as the field measurement data, to build flow-duration curves and quantify increases and/or decreases in the high-flow regime over time (Figure 3c). Changes in this part of the flow-duration curve tend to represent a range of drivers of streamflow change including shifts from snowmelt-to rain-dominated floods and changes in the influences of flow regulation on hydrologic storage (Searcy, 1959). While many flood risk analyses use peak flows to characterize hydrologic trends, this can neglect flood severity that arises from a moderate flood extending through multiple days and will not account for the occurrence of multiple flood events of lesser magnitude within the year (Slater et al., 2015). Using flow-duration curves built with mean-daily flow accounts for flood intensity, frequency, and duration. Our analysis ultimately aims to quantify shifts in moderate flood streamflows that *persistently* affect overbank flooding rather than trends in the highest flows which may be rare and short-lived.

To compute streamflow variability over time, we hold the bankfull return period constant, and calculate the flow predicted by a suite of flow-duration curves built with a 10-year moving window of mean-daily flow data offset by yearly increments (Figure 3b). By testing the sensitivity of the interpolated bankfull discharge to data windows from 3-year to 25-year (Figure S1 in Supporting Information S1), we determine that 10 years of mean-daily flow data is long enough to represent return periods on the 1-year to 3-year scale with reasonable confidence and short enough to capture changes in hydrological forcings driven by climatic and basin processes. The residuals, which we term Q_{rf}, quantify the difference between calculated flow values and Q_{flood} (Figures 3b and 3c). The temporal pattern Q_{rf} agrees well with estimates of flood flow over time for a test gage on the Skagit River (Figure S2 in Supporting Information S1). An increase to Q_{rf} over time means that higher discharges are occurring for the same return period and indicates increased potential for flooding. To obtain a normalized Q^*_{rf}, we divide the change in Q_{rf} by Q_{flood}, as we normalized Q_{rc}. We calculate the range of $Q^*_{rf}\left(|Q^*_{rf}|\right)$ similarly to the range of Q^*_{rc} to quantify the degree of variability in near-bankfull streamflows over the temporal record. To asses the relative influence of streamflow versus channel conveyance variability on flood magnitudes we compare $|Q^*_{rf}|$ to $|Q^*_{rc}|$.

3.3. Analysis of Combined Changes in Flood Hazard

To analyze cumulative change in flooding as a result of both channel conveyance and flow regime changes, we add the time series of Q^*_{rc} and Q^*_{rf} to estimate combined changes in Q_{flood} over time (hereafter $Q^*_{r,comb}$). Computing both effects independently allows us to consider potential interactions between channel conveyance and streamflow-driven effects on long-term flood risk; e.g., long-term increases in Q^*_{rf} may be offset by equivalent increases in the channel conveyance represented as negative Q^*_{rc}, resulting in lower $Q^*_{r,comb}$. Conversely, if increases in Q^*_{rf} and Q^*_{rc} occur in tandem, $Q^*_{r,comb}$ can be higher than either effect alone.

Because the sampling frequency of Q^*_{rc} depends on the frequency of field observations whereas Q^*_{rf} are regularly spaced at 1-year intervals, we linearly resample Q^*_{rf} to match the frequency of Q^*_{rc}. We subsequently add the time series together and fit a 10-point moving median to the data as we fit to the time series of Q^*_{rc}. We interpret the range of the moving median of $Q^*_{r,comb}$ across the time series, $|Q^*_{r,comb}|$, to indicate combined potential for changes in Q_{flood} due to both channel conveyance and streamflow-driven changes.

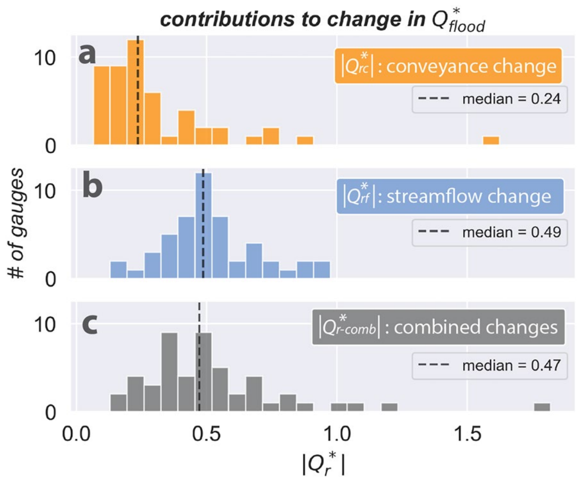

Figure 4. Distribution of magnitude changes in Q_{flood} influenced by (a) channel conveyance changes represented by $|Q^*_{rc}|$, (b) streamflow changes represented by $|Q^*_{rf}|$, and (c) combined change in flood risk incorporating both factors represented by $|Q^*_{r,comb}|$. Dashed lines note the median value for each distribution.

3.4. Identifying Gage Characteristics and Regional Patterns

We use published basin statistics for gages including watershed mean elevation, mean slope, and drainage area (GAGES-II data set: Falcone, 2011) to identify whether these are predictive characteristics for certain types of channel conveyance responses. We additionally separate gages at locations with minimal to no flow regulations from regulated locations by consulting the USGS NWIS "Water-Year Summary" which notes whether there are regulations or diversions upstream from a station. If regulations are characterized as "some" or "minor" on the USGS Water-Year Summary, we assess whether these are significantly affecting the flow by calculating what percent of the average published value for diverted flow is of Q_{flood}. We consider sites where this fraction is <3% of Q_{flood} to be characterized as unregulated since such changes to a small fraction of flow are unlikely to substantially influence variability in Q_{flood}.

To investigate regional temporal patterns in channel conveyance and streamflow change, we calculate the 3-year average of the time series of Q^*_{rc} and Q^*_{rf} across the study domain. We choose a 3-year average because this falls on the lower bound of the period of fluctuations in precipitation and temperature conditions in response to ENSO which typically range from 3 to 7 years (Halpert et al., 2016). We take the median of the 3-year time series average for both Q^*_{rc} and Q^*_{rf} to aggregate time series across the region for unregulated and regulated gage sites, respectively. Nonzero median values indicate consistency in behavior between sites across the study area.

4. Results

4.1. Overall Variability of Channel Conveyance, Streamflow, and Cumulative Flood Hazard

The median magnitude of temporal variation in channel conveyance is about half of the magnitude of streamflow variation. The median $|Q^*_{rc}|$ at our 50 gages is 0.24 (Figure 4a), indicating a median channel conveyance variability of 24% of flood capacity, Q_{flood}. The distribution of Q^*_{rc} is skewed toward low magnitude conveyance changes with a modal $|Q^*_{rc}|$ of 0.19. Changes in the streamflow of moderate floods over the same time period are greater than than channel conveyance changes, with a median $|Q^*_{rf}|$ of 0.49 (Figure 4b). At 40 of the 50 sites, $|Q^*_{rf}|$ is higher than $|Q^*_{rc}|$, however one river shows high magnitude changes in channel conveyance that exceed the highest values of $|Q^*_{rf}|$ (Figures 4a and 4b). In comparison to $|Q^*_{rc}|$, the distribution of $|Q^*_{rf}|$ is less skewed with a greater range and fewer outliers. This is likely because we did not focus on the most rare and extreme floods in favor of discharge changes for moderate floods, which persistently affect overbank flooding.

The median of combined channel conveyance and streamflow variability, $|Q^*_{r,comb}|$, at the 50 gages is 0.47 (Figure 4c). If both Q^*_{rc} and Q^*_{rf} were consistently additive (e.g., channels were losing conveyance in concert with increasing discharge) we would expect a median $|Q^*_{r,comb}|$ of 0.65. Instead, median $|Q^*_{r,comb}|$ is slightly lower than $|Q^*_{rf}|$. This indicates that in some cases, changes in channel conveyance and streamflow must offset the change in Q_{flood} imposed by each factor alone and occurs because channel conveyance and streamflow variability are often temporally asynchronous.

4.2. Temporal Patterns in Channel Conveyance and Streamflow Variability

Channel conveyance changes typically do not occur at the same time across the region; the median of the time series of Q^*_{rc} shows a near-zero trend for unregulated sites (Figure 5a) and a slightly positive trend for regulated sites (Figure 5b). There are small fluctuations (3–5%) in median channel conveyance in unregulated channels on multidecadal time scales, although this is substantially less than the spread of the data (Figure 5a). Regulated rivers tended to lose conveyance across the period of record (Figure 5b) with median conveyance losses of 10%

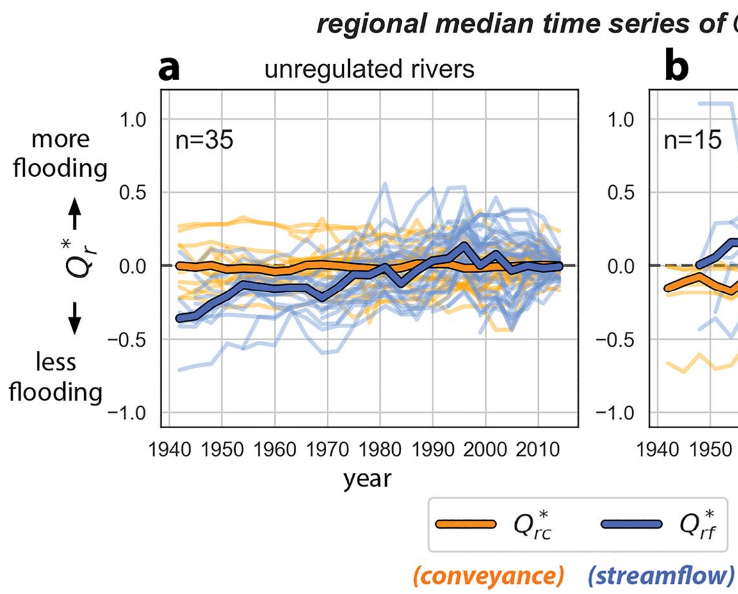

Figure 5. Change in conveyance and streamflow through time at study gages. Medians of the time series for channel conveyance (Q^*_{rc}: orange curve) and streamflow regime variations (Q^*_{rf}: blue curve) with respect to 2015 are shown for (a) unregulated and (b) regulated channels. Data are aggregated into 3-year median Q^*_{rc} and Q^*_{rf}. Q^*_{rc} and Q^*_{rf} time series for all study sites are plotted as the light orange and blue curves, respectively.

extending to 70% on the upper bound. Two sites on regulated rivers showed steeper loss trends than this for shorter records; however, other sites showed minimal change to slight gains in channel conveyance (Figure 5b).

In contrast, streamflows at sites on unregulated rivers increased over time; median Q^*_{rf} increases by 0.4 between 1940 and 2000 at unregulated sites (Figure 5a). A majority of sites on unregulated rivers show a steepening of the flow-duration curve for 0.5–10 years return periods reflecting the increase in the magnitude of moderate floods and Q_{rf} (Figure 6a). The generally positive trend in Q^*_{rf} shown in Figure 5a becomes a noisy, near-zero trend between 2000 and 2015.

In regulated rivers, streamflow does not consistently increase. In contrast to unregulated rivers, seven of the Q^*_{rf} time series on regulated rivers show net negative changes in streamflow on the upper bound of the distribution

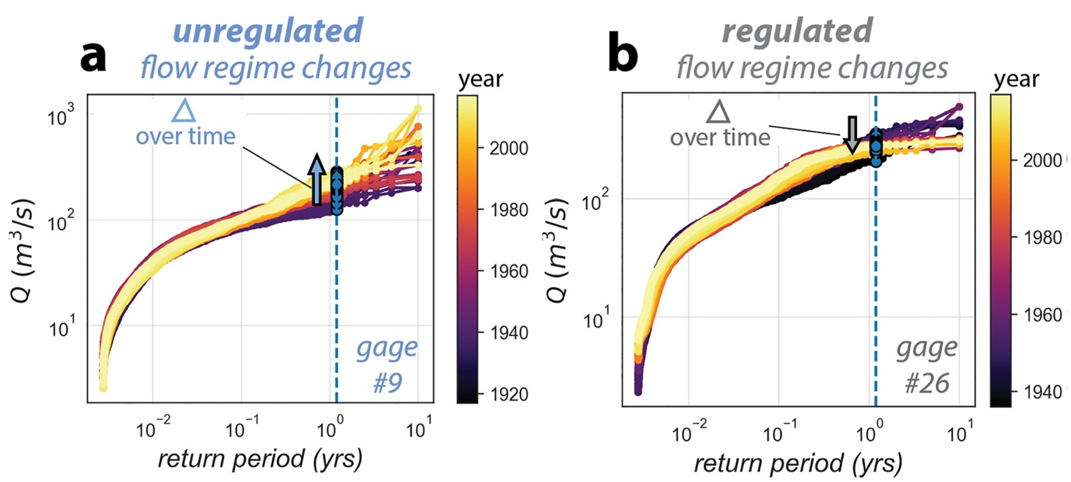

Figure 6. Examples of the ensemble of flow-duration curves showing flow regime changes in an (a) unregulated and (b) regulated site. Flow-duration curves are colored by time and the bankfull return period of 1.2 years is noted by a vertical dashed line. The interpolated flows are represented as dots on the bankfull return period line, and the overall change in Q_{rf} with time is noted by an arrow.

(Figure 5b) with the largest negative trends being comparable in magnitude to the most positive changes in streamflow on unregulated rivers (Figure 5a). Gages with decreasing trends tended to show a flattening in the high-flow regime resulting in a reduction in 2–10 years return period flows (Figure 6b). In some sites such as the example shown in Figures 6b and 6a, reduction in infrequent flows imposed by flow regulations is compensated by relatively higher flows at the 0.5–1 year return period.

Streamflow decreases the most at gages 6, 16, 36, and 34 (Q^*_{rf} decreases ranging from −30% to −97%) which are located relatively close to the dam (within 10 km downstream) in comparison to other sites (ranging between 18 and 116 km downstream). These sites also do not have major tributary input between the gauging site and the dam. In contrast, gages with major upstream tributary input between the gauging site and the dam, including sites 31, 11, 17, and 44, show a near-zero or positive change in Q^*_{rf} of up to 40% across the study period. This suggests that the influence of flow regulations on streamflow at a given gauging location, in particular, the degree of streamflow decrease, is likely a function of the fraction of flow that is regulated. This may also explain why the median Q^*_{rf} for regulated sites does not reflect the decreases in streamflow observed in many individual time series since trends are affected by input from unregulated tributaries.

4.3. Modes of Channel Conveyance Change and Interactions With Streamflow Change

Channel conveyance and flow regime changes do not interact consistently across western Washington due to regionally asynchronous Q^*_{rc} time series. Additionally, patterns in channel conveyance often display variability that is not captured by a linear trend (Figure 5). We distinguish sites with monotonic trends by testing the Q^*_{rc} time series for linearity and identifying sites that do not have significant lag-1 autocorrelation. We use this autocorrelation test in combination with flood and sediment records and history of flow regulations to subset the results into four modes of conveyance change: monotonic changes, multidecadal oscillations, sudden sediment-supply events, and regulated conveyance responses. In what follows, we describe these patterns of behavior and investigate how and why $|Q^*_{rf}|$, $|Q^*_{rc}|$, and $|Q^*_{r,comb}|$ vary between modes of conveyance variability.

4.4. Channels Conveyance Change: Linear Versus Nonlinear Behaviors and Relative Magnitudes of Adjustment

Trends in residuals are monotonic at 20 gages (Figure 7a) and nonmonotonic at 30 gages (Figures 7b–7d). Of the records with monotonic trends, trend slopes ranged from +3.5% to −2.8% channel conveyance loss per decade, with 10 sites showing conveyance loss of 1% or more per decade (gages 15, 50, 29, 49, 45, 41, 7, 13, 14, and 31) and five sites showing conveyance increase of 1% or more per decade (gages 17, 19, 2, 22, and 24; Figure 7a). The median $|Q^*_{rc}|$ for monotonically changing channels is 0.14 (Figure 7e) which is lower than the overall median $|Q^*_{rc}|$ of 0.24 and the median $|Q^*_{rc}|$ of 0.24 for gauges with nonlinear modes of change (Figures 7b–7d).

In the majority of gages (18 out of 30) with Q^*_{rc} that change nonmonotonically, channel conveyance oscillates at periods ranging from 30 to 70 years (Figure 7b). The median $|Q^*_{rc}|$ for these sites is 0.24 and indicates a median amplitude of conveyance oscillations (Figure 7f). Since these sites underwent periods of both channel conveyance gain and loss, $|Q^*_{rc}|$ is often much higher than the net change between the beginning and end of the record. At many gages, the change in conveyance between the beginning and end of the record is near zero; however, short-term trends in conveyance tend to be of greater magnitude than channels that are changing monotonically resulting in a relatively higher $|Q^*_{rc}|$ for gages showing oscillations in conveyance versus steady shifts (Figures 7f versus 7e). Oscillatory conveyance behavior occurred across a broad range of channel elevations, slope, and drainage areas when considering the basin statistics of all gages (Figures 9b–9d).

Large, rapid changes in channel conveyance capacity occurred on instantaneous to annual scales in seven sites in response to extreme events capable of delivering a high volume of sediment to the river nearby a gaging station. These events include lahars from the 1980 Mt. St. Helens eruption (gage 37; Major et al., 2019), intermittent debris flows in proglacial streams (gages 1 and 32; Czuba et al., 2012; Tucker et al., 2014), a landslide on the NF Skokomish River (gage 43, USGS Water-Year Summary) and a 2003 peak flow event in Thunder Creek delivering 1.2 times the discharge of the next highest flood on record (gage 4; Figure 7c). These sites have a median $|Q^*_{rc}|$ of 0.47 (Figure 7g), which is 2-fold and 3-fold higher than the median $|Q^*_{rc}|$ for conveyance oscillations and monotonic changes, respectively. These modes of responses tend to occur in headwater rivers with higher mean basin elevation and slope and smaller drainage areas (Figure 9).

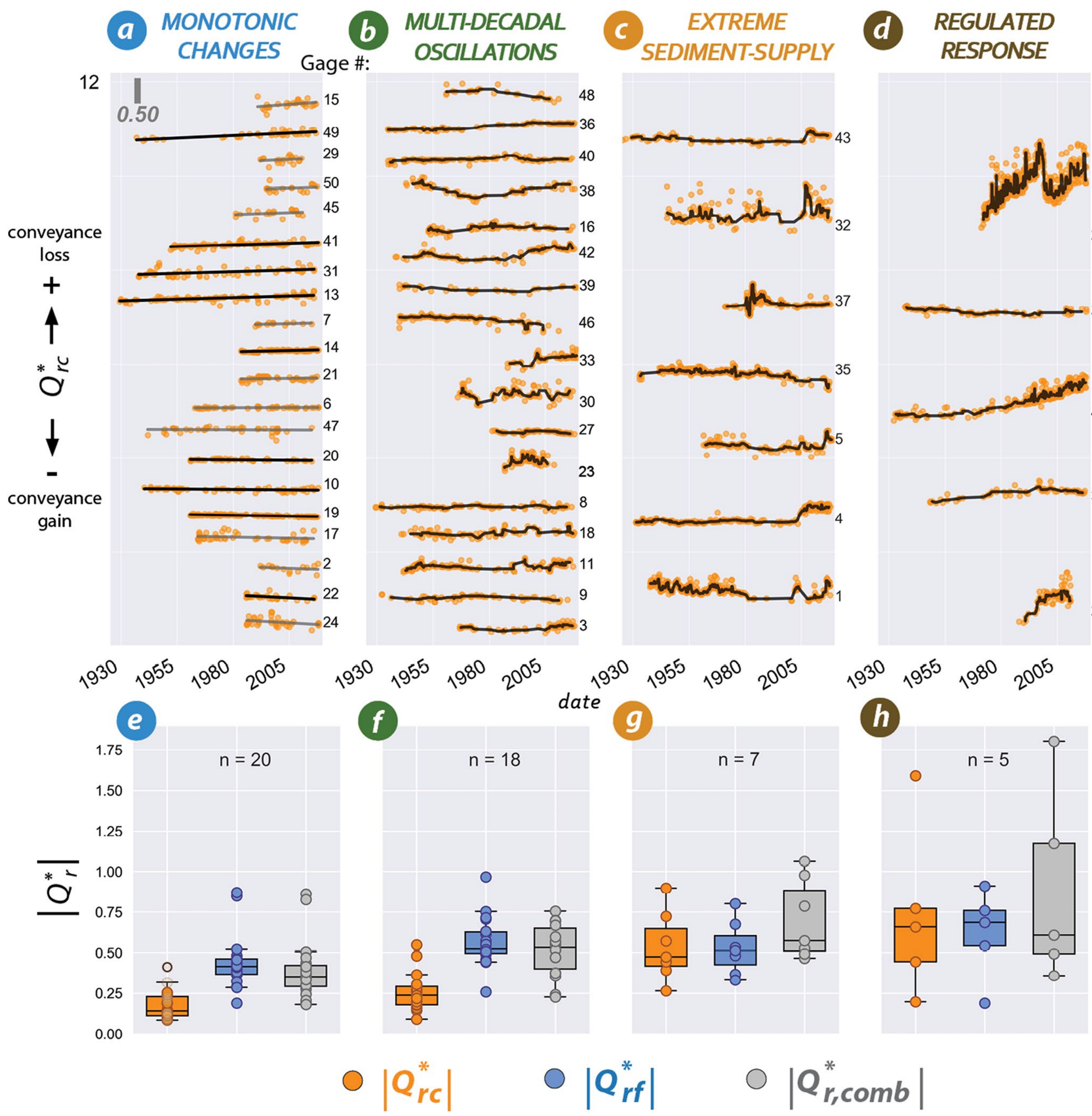

Figure 7. Comparing temporal patterns and magnitudes of change for different styles of channel conveyance adjustment. (a–d) Channel conveyance patterns from each of the four styles of channel change. Channel conveyance data for monotonic changes are plotted with a linear fit. Bold trend lines represent statistically significant trends ($p < 0.05$). Channel conveyance data for other categories are plotted with a 5-point moving median. The vertical scalebar in the top left of the plot represents the magnitude of a 50% change in channel conveyance. Gage numbers correspond to Figure 2. (e–h) Box-plots representing the normalized magnitude of channel conveyance changes ($|Q^*_{rc}|$), streamflow changes $\left(|Q^*_{rf}|\right)$, and cumulative flood risk changes $\left(|Q^*_{r,comb}|\right)$ for the four categories of morphological response. $|Q^*_{rc}|$ values for monotonic changes in channel conveyance that are not statistically significant are shown on the boxplot as light colored dots.

Some of the largest nonlinear channel conveyance changes occurred in mainstem channels affected by flow regulation with a median $|Q^*_{rc}|$ of 0.66 (Figures 7d and 7h). Here, we highlight five sites, based upon existing literature (gages 25, 44, 28; Anderson & Jaeger, 2020; Collins et al., 2019; Gendaszek et al., 2012), observable conveyance changes concurrent with dam installation (gage 34) or conveyance changes consistent with the magnitude and time scales of typical geomorphic responses to dams (gage 26). Four of these sites lost conveyance (gages 24,

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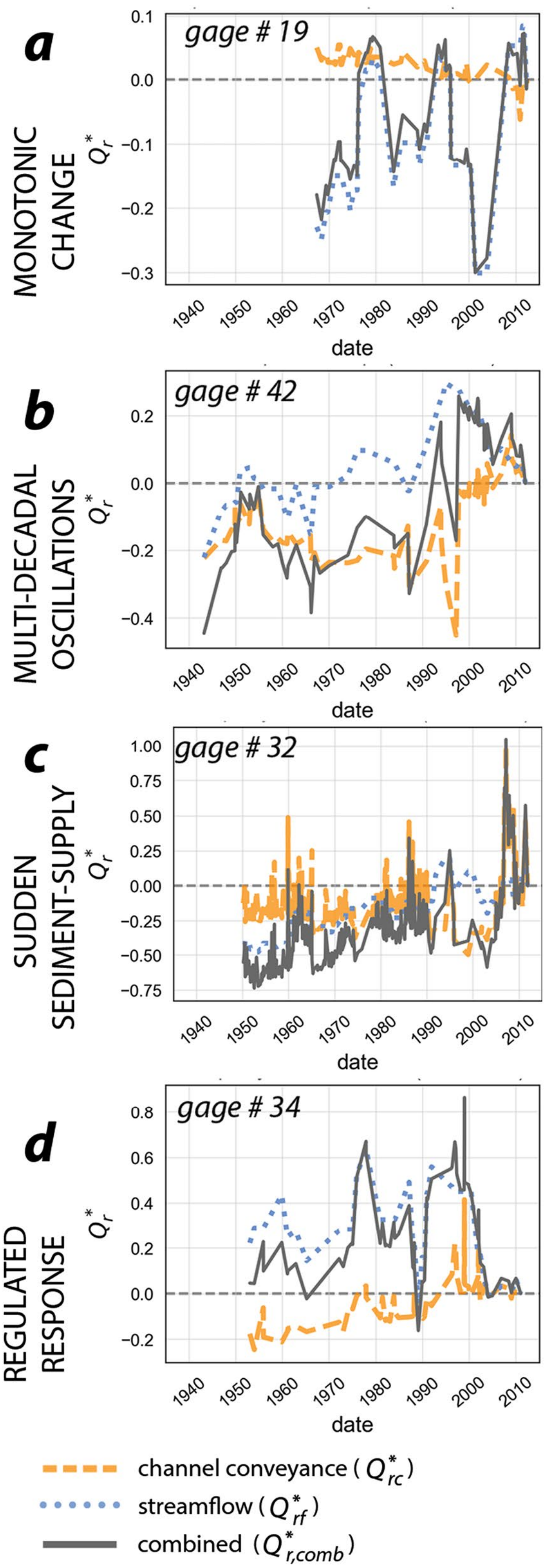

Figure 8. Differing interactions between conveyance, streamflow, and combined flood hazard variability for (a) monotonic, (b) oscillating, (c) sudden sediment-supply events, and (d) regulated modes of channel conveyance change.

44, 34, and 28) and one gained conveyance (gage 26) across the measured record. Conveyance losses were greater than conveyance gains, and in three of the sites, conveyance loss occurred relatively steadily over prolonged periods of time ranging from 30 to 80 years (gages 25, 44, 28; Figure 7d). In the Cedar River (gage 25), conveyance losses were extreme, resulting in periodic channel dredging to reduce flood risk (Gendaszek et al., 2012), which is why the channel conveyance shows an abrupt increase in the late 90s followed by continued loss (Figure 7d).

The presence of both conveyance gain and loss indicates that flow regulation does not affect conveyance changes universally across the region. At gage 26 (Figure 7d), regulations suppressed the magnitude of the most infrequent flood flows, but augmented flows at lower return periods (Figure 6b). An increase in frequency of flows around the threshold of sediment mobilization in concert with sediment deficit is predicted to cause channel degradation (Grant, 2012). Lateral mass failures between 2002 and 2016 were less numerous between the dam and gage location in comparison to the sites where channels lost conveyance (Scott & Collins, 2021; Data in Supporting Information S1). Thus, the particular effects of dam influence on sediment supply and streamflow are necessary to consider when predicting whether channels will respond through conveyance increases or decreases.

4.5. Comparing Conveyance Versus Streamflow Variability and Combined Influence on Flood Hazard

The relative contribution of conveyance variability ($|Q_{rc}^*|$) and streamflow variability $\left(|Q_{rf}^*|\right)$ to flood hazard varies with the mode of conveyance change (Figures 7e–7h). Median $|Q_{rf}^*|$ was more similar between modes than median $|Q_{rc}^*|$ indicating that the degree of streamflow variability alone does not account for differences in the degree of channel stability. Monotonic and oscillating conveyance variations have median $|Q_{rf}^*|$ values of 0.42, and 0.52, respectively, which are higher than $|Q_{rc}^*|$ for both styles of conveyance change (Figures 7e and 7f) indicating that streamflow variability typically contributes more to total flood hazard variability for these modes of channel response. In channels responding to extreme sediment-supply events, the degree of streamflow and channel conveyance variability are similar, with the median $|Q_{rf}^*|$ of 0.51 falling within the upper quartile of the $|Q_{rc}^*|$ distribution (Figure 7g) indicating conveyance and streamflow variability typically contribute similarly to total flood hazard variability. The magnitude of streamflow change is highest at sites in regulated rivers (median $|Q_{rf}^*| = 0.69$; which is comparable to the median changes to channel conveyance ($|Q_{rc}^*| = 0.66$) in the same systems (Figure 7h), indicating conveyance variability can play a comparable role to streamflow variability in total flood hazard variability in some regulated systems.

In sites with monotonic trends in Q_{rc}^*, channel conveyance changes are most likely to offset the pattern of Q_{rf}^* across the study region, resulting in a value of the median $|Q_{r,comb}^*|$ of 0.35, which is lower than that observed in all the other modes (Figure 7e); e.g., in the Snoqualmie River (gage 19; Figure 8a) increasing streamflows $\left(Q_{rf}^*\right)$ are offset by channel conveyance gain (decreasing Q_{rc}^* values), resulting in a reduced impact on flood risk (lower $|Q_{r,comb}^*|$). Nonlinear changes to channel conveyance had higher relative contributions to total flood hazard variability. Oscillating channel conveyance most

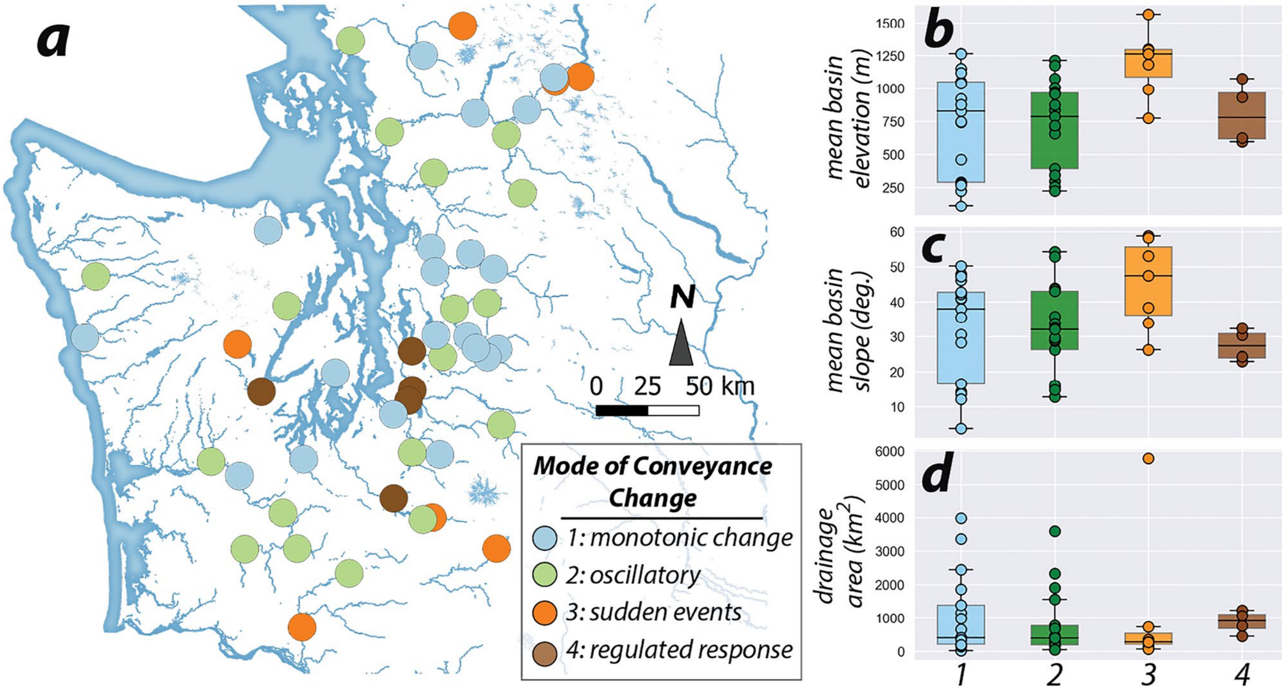

Figure 9. Spatial distribution of channel conveyance modes and basin statistics within each category. (a) United States Geological Survey (USGS) river gauging sites included in the study colored by mode of channel conveyance change. (b–d) Basin statistics for each category including mean elevation, mean slope, and drainage area, respectively.

commonly combines with streamflow regime changes to cause higher changes in Q_{flood} than each effect alone, and resulting in a $|Q^*_{r,comb}|$ of 0.53 (Figure 7f). This is because decadal-scale peaks in Q^*_{rc} (channel conveyance minimums) and Q^*_{rf} (streamflow maximums) often occur in tandem resulting in additive channel conveyance and streamflow influences on $Q^*_{r,comb}$ (e.g., Chehalis River gage 42, Figure 8b). Since extreme sediment-supply events are also often independent of concurrent streamflow behavior, Q^*_{rc} and Q^*_{rf} are also additive for this mode of conveyance change resulting in a relatively higher value of $|Q^*_{r,comb}| = 0.57$ (Figure 7g); e.g., gage 32 on the Nisqually River is located downstream of a proglacial debris flow zone (Czuba et al., 2012) where punctuated losses in channel conveyance are superimposed on a generally positive Q^*_{rf} trend, exacerbating changes in $Q^*_{r,comb}$ (Figure 8c). In regulated channels, temporal changes in Q^*_{rf} offset some of the losses in channel conveyance resulting in a $|Q^*_{r,comb}| = 0.61$ (Figure 7h); e.g., in gage 34 on the Nisqually River (Figure 8d), Q^*_{rf} decreases offset channel conveyance losses (increasing Q^*_{rc}).

The differences in median total variability in flood hazard $\left(|Q^*_{r,comb}|\right)$ vary between modes of conveyance adjustment due to the differences in the ways short-term and long-term changes in Q^*_{rc} and Q^*_{rf} combine or offset temporally (Figures 7e–7h). This demonstrates that in order to accurately quantify variability in total flood hazard, it is important to consider short-term trends in channel conveyance and streamflow data which can change in magnitude or direction over time.

5. Discussion

Our primary goal is to characterize the relative magnitudes and time scales of channel conveyance-driven and streamflow-driven changes to flood risk in western Washington State, considering both monotonic and nonmonotonic temporal changes. We find that the magnitude of flood flow variability is about twice the magnitude of channel conveyance variability, although in some cases variation in channel conveyance is equal to or greater than that of streamflow. These findings are consistent with Slater et al. (2015) who, in their analysis of monotonic trends between 1950 and 2013 across the United States also showed that hydrologic change was typically a greater contributor to temporal changes in flooding than morphologic change. However, conveyance change is nonsteady at nearly all the gages in western Washington. Since USGS gages are intentionally located at stable sites, this analysis likely underestimates the importance of conveyance changes. While at seven gage locations conveyance changed gradually and slowly (<1% per decade), at most gages the variability in conveyance was substantial (median of 24% at all gages in the last 30–90 years) and in some cases occurred rapidly, indicating that conveyance unsteadiness is an important contributor to variability in flood hazard.

Nonlinear conveyance changes are important to consider in order to capture total variability in flood hazard because they occur at over half the gages (60%). Not only were nonlinear conveyance changes more common, but total variability and short-term trends at sites with nonlinear adjustments were of higher magnitude than long-term, linear trends (Figures 7f–7h versus 7e, respectively). For example, had we considered only monotonic trends, many of the gage locations with oscillating conveyance would have shown a trend of zero slope since there were equal amounts of conveyance loss and gain; however, the magnitude of conveyance gains and losses over the course of an oscillation (about one to two decades) at these locations are typically greater than the total conveyance adjustment in locations with steady monotonic change (Figures 7f versus 7e). Li et al. (2020) showed that short-term, transient capacity change due to tropical storms in Puerto Rico was frequently higher magnitude than long-term trends. Here, we find that rapid and nonlinear conveyance changes are also widespread in space and time in a temperate zone. We also find that fitting monotonic trends to nonlinear conveyance records would have smoothed out rapid or cyclic changes to capacity and resultant influence on flood hazard variability. Thus, the methods used in this analysis of flood hazard shifts driven by streamflow versus conveyance *variability* are a necessary and important improvement to previous approaches that assume monotonic change (e.g., Slater, 2016; Slater et al., 2015).

Instead of fitting monotonic trends to the gage time series of conveyance capacity variation, we identify four temporal modes of conveyance change in an effort to describe total variability in flood hazard (Figure 7). While these modes are not exhaustive representations of the ways rivers might adjust in other areas of the world, this type of analysis provides useful information on reach-scale conveyance changes that can affect overbank flooding at USGS gages. Adding recent conveyance adjustments to the daily and long-term flood forecasting at USGS gages which are presently computed using streamflow and precipitation data (NOAA, 2021) could improve local flood hazard predictions. For example, gage 3 on the Nooksack River has multidecadal oscillations in conveyance and presently has around 15% less capacity than it did in 1990 but relatively similar capacity to the mid-1960s. There has been recent debate amongst stakeholder groups about whether flood prevention actions in the Nooksack River should involve sediment removal (Kempe, 2021). Considering that channels can locally be in phases of conveyance loss would be valuable for forecasting local flood hazards and could facilitate development of sediment-removal plans that strategically interrupt short-term minimums in conveyance. In what follows, we discuss the implications of different modes of conveyance variability for flood hazard and investigate potential drivers of these patterns in an effort to predict when a given mode is expected to arise.

5.1. Are Increases in Streamflow-Driven Flood Hazard Being Moderated by Increases in Conveyance Capacity?

While channel conveyance is changing in many systems, regional trends in flooding are better predicted by streamflow behavior. Shifts in moderate flood flows in unregulated rivers are generally positive in western Washington (Figure 5a). However, channel conveyance variability in western Washington State does not alter flood risk uniformly or simultaneously across the region (Figure 5a). This is at odds with some studies that suggest channels adjust coherently to changes in climate; Slater et al. (2019) found that across the United States, two-thirds of 67 USGS study gages showed correlation between channel capacity and climate indicators representative of patterns in regional rainfall and temperature. Rumsby and Macklin (1994) found that channels in northern England had widespread, alternating phases of channel incision and stability in response to decadal-scale fluctuations in flood frequency.

However, asynchronous channel bed adjustments have been previously documented in western Washington and attributed to variation in sediment supply rather than streamflow (Pfeiffer et al., 2019). Studies of individual western Washington rivers have demonstrated that sediment supply alters channel bed morphology as downstream-propagating disturbances over multidecadal time scales with behavior similar to a Gilbert Wave (Nelson & Dubé, 2016) or a nondiffusive series of river bed elevation changes with celerity related to slope (Anderson & Konrad, 2019). Presumably, increases in runoff and temperature also activate delivery of sediment from proglacial, alpine regions (Costa et al., 2018) and an increase in the magnitude of moderate floods could

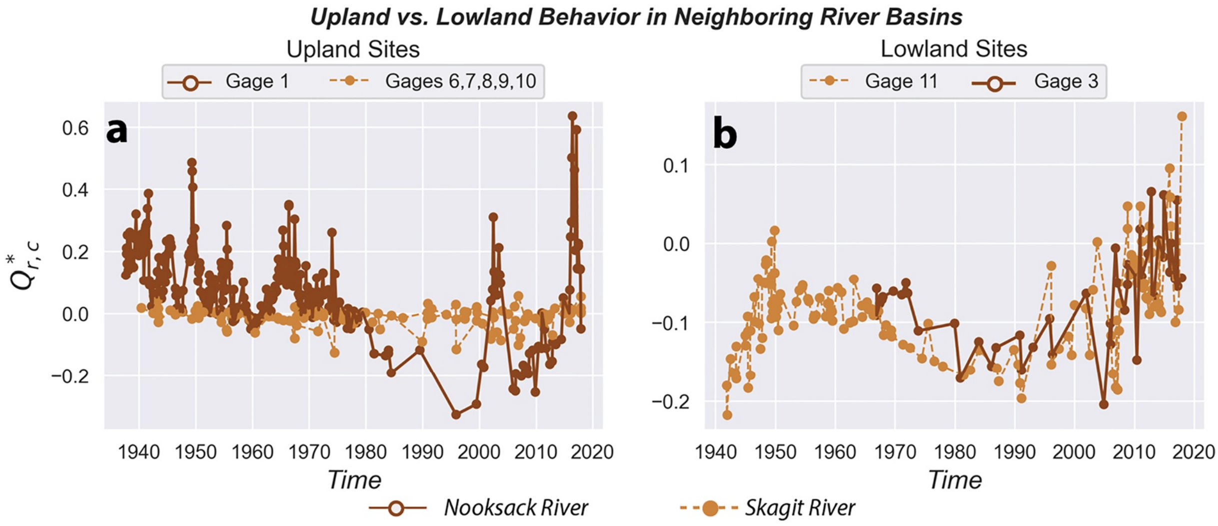

Figure 10. Time series of normalized channel conveyance change Q^*_{rc} in (a) upland versus (b) lowland sites in neighboring river basins demonstrate different along-profile morphodynamic behavior. In (b), lowland river gauging sites show remarkably similar temporal patterns of similar magnitude despite differing degrees of channel stability in upland gauging sites shown in (a). Q_{rc} are plotted with respect to 2015.

increase sediment delivery from channel-adjacent terrace failures that are predominantly triggered by lateral fluvial erosion (Scott & Collins, 2021). Intermittency in magnitude and timing of sediment delivery is likely to add noise to a climate-driven signal (Jerolmack & Paola, 2010) and could obscure the influence of climate on river adjustment in this region.

While the magnitude and intermittency of sediment supply likely contribute to observed asynchronous conveyance changes, differences in routing between systems likely affect the propagation of sediment signals downstream. Gage locations downstream from extreme sediment-supply type responses do not necessarily show the same response mode; they can show both monotonic shifts and multidecadal oscillations in conveyance (Figure 9a). Conversely, common downstream responses do not correspond to common upland inputs. For example, channel conveyance variations at gages on low-elevation reaches of the Skagit and Nooksack Rivers show very similar behavior despite differing degrees of headwater conveyance change (Figure 10), the headwater Nooksack gage being relatively more active than high-elevation Skagit gages. Thus, we do not observe clear connectivity between the conveyance responses in headwater and lowland reaches based upon the sites analyzed in this study.

Overall, regional flood hazard is increasing in unregulated rivers, but this trend is dominated by regional streamflow patterns rather than conveyance patterns (Figure 5a). Steepening of the high-flow region of the flow-duration curve in unregulated sites (Figure 6a) is typical in rivers transitioning from snowmelt-dominated to rain-dominated floods (Searcy, 1959). Previous studies have shown dramatic declines in western United States snowpack (e.g., Mote, 2003; Mote et al., 2018) in concert with regional warming over the last century (May et al., 2018). This results in statistically significant increases in winter maximum streamflows as previously snow-dominated basins transition toward rain-dominated basins in winter (Wagner et al., 2021). Thus, changes in snowpack likely explain some of the observed shifts in the flow-duration curve. Flood event frequency and severity are expected to increase under future climate conditions due to further warming (May et al., 2018), and an increase in precipitation volume and intensity from atmospheric river events (Gershunov et al., 2019). It is thus probable that streamflow-driven flood hazards will continue to increase in unregulated western Washington basins. On aggregate, conveyance adjustments do not offset these changes to streamflow, but can locally increase or reduce flood hazard depending on the mode of response.

5.2. Flood Hazard Drivers in Regulated Rivers

In contrast to unregulated basins, flow regulation mutes or eliminates decadal increases in moderate flood streamflow (Figure 5b). This is because dams increase flood storage (e.g., Collier et al., 1996). Indeed, flow-duration curves from regulated systems typically show a reduction in flow volume at the most infrequent floods (Figure 6b) which can represent an increase in water storage (Searcy, 1959). It is likely that dams will continue to suppress the influence of changing climate and hydrology on regional streamflow; in a comparison of regulated and unregulated Columbia River Basin streamflow projections over the next century, flow regulation dampens the shifts in timing and volume of cool season high flows projected to occur in unregulated rivers (Harrell, 2021).

However, flow regulation does not necessarily reduce total flood hazard, because downstream channel conveyance losses can exceed reductions in flood flows. Regulated rivers on aggregate show a tendency for conveyance loss, although the upper envelope of the distribution also includes modest trends toward channel conveyance gain (Figure 5b). While the aggregate decrease in conveyance capacity is only ~10% over 70 years and is much less than the variability between individual rivers, this trend is supported by other observations of channel adjustment in the region. Previous studies show that channels narrowed in four regulated rivers in the region (Anderson & Jaeger, 2020; Collins et al., 2019; Gendaszek et al., 2012; Konrad et al., 2011), and shallowed in at least three rivers (Anderson & Jaeger, 2020; Collins et al., 2019; Gendaszek et al., 2012). Since dams can potentially cause conveyance loss or gain depending on how they influence the downstream flux of water or sediment (Grant, 2012), further studies comparing the natural and anthropogenic geomorphic drivers present in regulated basins are needed to understand how channel conveyance responds to the interactions of flow regulation and sediment supply in the region (e.g., Anderson & Jaeger, 2020; Collins et al., 2019). Overall, it is critical to consider flood hazard change as a composite of conveyance change and streamflow variation in regulated rivers; assumptions of future flood hazard based solely on streamflow projections could under-predict hazards.

5.3. Modes of Channel Conveyance Change and Their Relative Importance for Flood Hazard

Our results show that conveyance variability can be more or less important for flood hazard depending on the ways in which cyclic, episodic, or gradual changes to conveyance capacity augment or reduce changes to streamflow (Figures 7e–7h). However, can we predict when and where different modes of conveyance change will occur? Basin statistics do not correlate with certain conveyance modes, except for the seven cases of channel response to extreme sediment-supply events which tended to occur in steeper, lower-order basins (Figure 9b). While the sample size of basins included in this study is small, this observation is consistent with Slater and Singer (2013), who also find that basin statistics including mean watershed slope, elevation, and drainage density do not predict trends in alluvial river bed elevation or river bed variability across the United States. As discussed in Section 5.2, channels downstream of dams may be susceptible to conveyance changes influenced by dam operation and flow regulation. However, monotonic change and multidecadal oscillations (Figures 7a and 7b) are common across a range of watersheds and lack correlation with basin slope, drainage area, or mean basin elevation (Figure 9b).

In a region where unregulated rivers show an increase in moderate flood magnitude (Figure 5a), it is interesting that monotonic conveyance changes show nearly equal occurrence of steady decreases and increases (Figure 7a). Flow magnitudes around the bankfull return period (typically 1–3 years; Castro & Jackson, 2001) are generally considered important for establishing cross-sectional channel form for low-gradient and moderate-gradient alluvial channels in temperate regions (Leopold et al., 1964; Wolman & Miller, 1960). While many studies have explored the concept of defining a channel-forming discharge (e.g., Blom et al., 2017; Castro & Jackson, 2001), channel adjustments in response to gradual changes in discharge are more complex because adjustments in alluvial channel gradient and bed elevation require some relaxation time in response to a change in inputs (Howard, 1982). The response of gravel-bed rivers downstream of dams indicate that channels adjust their width and bed elevation on the order of several decades after dam installation (Grant, 2012). Assuming no change to sediment supply, the cases where conveyance is steadily increasing are consistent with what theory suggests for river response to increasing discharge (Lane, 1955). However, the fact that steady conveyance gains appear to lag streamflow changes suggests that the rate of change to moderate flood discharge exceeds the response time scale for conveyance adjustment.

Steady conveyance decreases may be the result of changes to sediment supply, especially lateral sediment sources that are sensitive to fluvial processes. Puget Sound rivers have high, coarse sediment supply from paraglacial terraces relatively low in the drainage basin (Scott & Collins, 2021). Nearly all terrace failures mapped in Scott and Collins (2021) deliver sediment directly to the adjacent river with lateral fluvial erosion being the dominant trigger of mass failure. Steady increases in moderate flood streamflow may thus activate unstable bluffs and increase the transport of paraglacial material to depositional zones. For example, the Skykomish River is an unregulated stream experiencing increasing moderate flood flows. Records from gage 13 (Figure S3 in

Supporting Information S1) document a long-term, monotonic trend toward channel conveyance loss. This site is located on a bend downstream of a long-term outer bank failure that is documented to yield ~8,000 m^3/yr of sediment directly to the channel (Scott & Collins, 2021). Future investigation of sediment supplied by lateral terraces as a function of antecedent streamflow characteristics could illuminate how hydrologic changes feedback into sediment delivery from sources connected to rivers in the region.

Temporal oscillations in conveyance capacity can augment or reduce variations in streamflow, potentially amplifying total shifts in flood risk. Previous studies show that flood hazard can be nonstationary (e.g., Read & Vogel, 1969; Slater et al., 2015; Vogel et al., 2011) but often neglect the complexities of incorporating short-term behavior that can shift the direction of flood hazard trends. Periods of fluctuation (between 30 and 70 years) are of similar scale to cycles of wet/dry climate associated with the ENSO and the PDO. However, conveyance fluctuations did not correlate with regional precipitation anomalies and there is little correlation in the phase of higher and lower conveyance between basins. This suggests that variations in sediment supply are a significant driver of conveyance fluctuations; while variations in sediment supply are presumably influenced by climate (e.g., Anderson & Konrad, 2019; Leggat et al., 2015; Menounos, 2006; Menounos & Clague, 2008), the particulars of erosion in a given river basin may dominate over any regionally consistent climate-driven trends, resulting in a lack of regional synchronization in conveyance oscillations.

5.4. Flood Hazard Predictions Involving Conveyance Variability

Operational assessments of flood hazard predominantly rely on metrics such as inundation area and overbank flow velocity obtained from numerical simulations or observations that rely on hydrologic data alone (e.g., FEMA, 2012; Yang et al., 2006). However, in this study, we show that variability in channel conveyance is also an important metric for exacerbating or alleviating flood hazard through channel adjustments (Figure 1b). While the four modes of conveyance change we present have different magnitudes and styles of variability (Figure 7), the potential for conveyance variability to modify flood inundation area will depend on the surrounding floodplain topography, which we did not explicitly consider in this study. Since slight adjustments to river geometry could propagate into large changes in inundation across low-gradient regions, moderate channel conveyance variability in reaches with low-gradient surrounding topography (e.g., the Puget Lowland) is likely to be of greater significance for flood inundation than high conveyance variability in reaches confined by valley walls. Thus, the information about historic conveyance variability presented in this study could be combined with topographic data surrounding USGS gages to identify at-risk areas, targeting inundation assessments in regions with both moderate or high conveyance variability and low-gradient surrounding floodplains.

Changes in flood inundation as a result of conveyance variability would be particularly valuable for assessing residential hazards. During the January 2009 White River flood event where extensive flooding was attributed to channel conveyance losses (e.g., Czuba et al., 2010; Green, 2009), residents of surrounding towns relied on outdated flood maps for purchasing flood insurance (Cornwall, 2009). Incorporating inundation variability due to conveyance changes as an uncertainty buffer in flood maps could additionally help communicate risk more transparently to residents and stakeholder groups.

6. Conclusions

Channel conveyance variability is an important contributor to temporal variability in flood hazard in western Washington state. While the median regional variability in moderate flood streamflow is approximately twice that of median conveyance variability, conveyance variability contributed to flood hazard shifts in almost all systems considered. Moderate flood streamflow is consistently increasing in unregulated rivers, but conveyance change is not regionally consistent. Channel conveyance changes can be linear, oscillating, dominated by singular sediment-supply events or influenced by flow regulation, and the relative importance of conveyance variability versus streamflow variability on flood hazard varies with the mode of channel adjustment. The influence of conveyance variability on flood hazard was more important than streamflow variability following unusually large storm or sediment-supply events and can also be higher in regulated rivers, counteracting the effects of flow regulation on flood risk. Short-term conveyance adjustments are more common and of higher magnitude than steady trends, indicating that it is necessary to quantify short-term channel behavior to accurately predict total changes in flood hazard. The time series of conveyance variability could be added to streamflow projections at USGS gages to improve predictions of flood hazard. Furthering our understanding of the mechanisms and controls on the different patterns of temporal variability in channel conveyance would aid in modeling and mapping future flood hazards.

Data Availability Statement

The data used in this study are available on the USGS NWIS online interface at: https://waterdata.usgs.gov/nwis. Digital Terrain Models for Washington State are available for download on the Department of Natural Resources Lidar Database: https://lidarportal.dnr.wa.gov/. Other processed data and code used are available at https://shelbyahrendt.github.io/Washington-State-channel-change-and-flood-risk/ and within Supporting Information S1.

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