

Glacial and Lahar Terrace Erosion Along Puget Sound Rivers

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Key Points:

- Glacial and lahar terraces deliver substantial sediment volumes to Puget Sound Rivers primarily via relatively frequent mass movements.
- Terrace sediment has a substantial coarse-grained fraction, is likely resistant to attrition, and is generally low in river networks.
- Terrace sediment is likely an important contributor to sediment loads in lowland Puget Sound Rivers.

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Abstract

Mass movements from glacial and lahar terraces in the middle and lower reaches of rivers draining the Washington Cascade Range to Puget Sound may represent a substantial portion of those rivers' sediment supply and pose significant mass movement hazards. However, the quantitative importance of this sediment source is unknown, and the magnitudes, spatial distribution, styles, and controls of these mass movements have only been characterized over limited spatial and temporal extents. We used repeat LiDAR elevation data, aerial imagery, and well logs to quantify and characterize terrace sediment delivery in nine major watersheds over a median period of 12 years. In the 1946 river kilometers for which repeat LiDAR was available (71% of the 2736 total river kilometers flanked by terraces), mass movements eroded $853,300 \pm 19,500 \text{ m}^3/\text{yr}$. This sediment source is low in river networks, well connected to streams, has a substantial coarse-grained and durable component, and is dominated by frequent, relatively small mass movements, all of which increase its significance to sedimentation in developed, lowland reaches. However, rates of terrace sediment delivery vary between basins and between adjacent terraces, which are stratigraphically laterally heterogeneous. While lateral fluvial erosion is usually necessary to initiate terrace mass movements, fluvial characteristics and terrace stratigraphy poorly predict erosion volume, which is better predicted by hillslope geometry and mass movement style. Effective management of sedimentation and mass movement hazard should acknowledge the importance of terrace sediment delivery and the variability between and within watersheds in sediment influx, sediment characteristics, and failure mechanisms.

Plain Language Summary

Large sediment deposits on the sides of valleys in the Puget Sound region known as glacial and lahar terraces deliver substantial amounts of sediment to rivers and present landslide hazards. The sediment delivered from these deposits can transport downstream in rivers and settle in developed, lowland areas, affecting the shape of rivers and river hazards like flooding. We used topographic data to determine how much sediment these terraces deliver to rivers and found that not only do they deliver large volumes of sediment, but that the sediment they deliver is large and durable enough to likely impact lowland rivers, especially in certain Puget Sound watersheds. We also examined how both river erosion and the composition of hillslopes influence the volume of sediment delivered to rivers by landslides from these terraces and found that both of these factors contribute to determining how much sediment is delivered to rivers from landslides. This implies that to effectively manage landslide and river hazards in the Puget Sound region, we must develop a detailed understanding of the composition of these terraces, as well as the erosion patterns of the rivers they are adjacent to.

1 Introduction

The sediment load of rivers draining the Cascade Range and the Puget Lowland of Washington (Figure 1) includes contributions derived from terraces composed of Pleistocene glacial and Holocene lahar sediments. Glacial terraces formed by subglacial erosion of the regional fill of Pleistocene till, outwash, and glaciolacustrine sediments during the late stages of the Vashon Glaciation (Booth, 1994) or by post-glacial fluvial incision into that fill driven by changes to base level and isostatic rebound (Dethier et al., 1995; Thorson, 1980). Lahar terraces formed by extensive deposition of lahars from Cascade volcanoes in a number of these river valleys (Crandell, 1971; Dragovich et al., 2002a) and subsequent fluvial incision (e.g., Beechie et al., 2001). Steep bluffs formed in these glacial and lahar terraces (hereafter referred to simply as terraces; Figure 1) are landslide prone (LaHusen et al., 2016). As glacial sediments being modified by glacially-conditioned fluvial processes, these terraces constitute a paraglacial sediment source (Church and Ryder, 1972; Slaymaker, 2009); sediment production from Holocene lahar terraces is an analogous phenomenon, as both involve remobilization of relict sediment deposits from landforms in a “transitional” (Slaymaker, 2009) or “unstable” (Ballantyne, 2002) state of incomplete adjustment to climate and base level.



Figure 1. An actively eroding glacial terrace along the Skykomish River, at 47.841° , -121.657° facing west (terrace is “snohomish19” in Dataset S1). Inset shows detail of top of terrace.

In other paraglacial regions, expansive terraces can deliver substantial quantities of sediment to the middle and lowland reaches of river networks (Church and Slaymaker, 1989). This runs counter to the expectation that sediment delivery is greatest in headwaters (Schumm, 1977; Wohl, 2020), and disrupts the expectation of downstream decreasing specific sediment yield (Ballantyne, 2002; Kovanen and Slaymaker, 2015; Slaymaker, 2003). In rivers draining to the Puget Sound lowland, a large sediment influx low in the channel network could disproportionately induce lowland channel response compared to sediment supplied from headwaters (Anderson and Jaeger, 2019; Collins et al., 2019): the coarse fraction of continental glacial deposits is composed primarily of resistant lithologies (Armstrong et al., 1965; Collins and Dunne, 1989) and, because of its origin low in the channel network, is subject to shorter transport distances and less potential for attrition. Deposition in these inherently aggradational reaches (Collins and Montgomery, 2011) exacerbates hazards from lateral channel migration and flooding (Anderson and Jaeger, 2019; Collins et al., 2019; Stover and Montgomery, 2001). In addition, understanding sediment supply and sediment transport dynamics, especially in rivers with major lowland sediment sources, is key to effectively restoring valley bottom habitat (Beechie et al., 2001; Benda et al., 1992) and predicting the effects of restoration strategies such as levee removal and Stage 0 restoration (Powers et al., 2019) that give rivers more freedom to reshape their valley bottoms (Wohl et al., 2015). While identified as an important sediment source in the nearby Fraser lowlands (Church and Slaymaker, 1989; Kovanen and Slaymaker, 2015), the quantitative importance, spatial distribution, sedimentologic characteristics, and delivery mechanisms of terrace sediment have yet to be systematically quantified in the Puget Sound region.

The first of two primary objectives of this study is thus to measure the spatial distribution, magnitude, and characteristics of terrace sediment delivery to Puget Sound rivers (Objective 1). This includes determining how much eroded sediment makes it to rivers (i.e., the lateral sediment connectivity (*sensu* Wohl et al., 2019) between terraces and rivers) and what fraction of the delivered volume is coarse enough to act as bed material load that can affect downstream channel morphology. Another aspect of terrace sediment delivery is the magnitude and frequency of mass movements that deliver sediment (Kovanen and Slaymaker, 2015; LaHusen et al., 2016; Perkins et al., 2017). The 2014 Oso Landslide was only the latest in a Holocene history of large mass movements (Booth et al., 2017; LaHusen et al., 2016), which are widespread along Puget Sound rivers (Perkins et al., 2017). However, such large mass movements are less frequent than much smaller mass movements that regularly occur along terrace bluffs (e.g., Gardner et al., 2009; Radloff and Bunn, 2018). Here, we seek to determine if, over time, most terrace sediment enters rivers from infrequent, very large mass movements, or from frequent, smaller failures.

The substantial variability in size and frequency of terrace mass movements motivates the second major broad question of this study: what geomorphic processes determine the occurrence, size, and resulting flux of sediment from terrace mass movements (Objective 2)? Terrace mass movements are commonly associated with lateral fluvial erosion (e.g., Gardner et al., 2009; Wartman et al., 2016), which implies that fluvial processes, hillslope processes, or some combination of the two may regulate terrace sediment delivery flux. Here, we explore the relative importance of fluvial versus hillslope processes in regulating the occurrence and volume of terrace mass movements, although this spatially extensive investigation does not address in detail the processes that regulate mass movement volume or frequency.

Several hypotheses guide this investigation. Terrace mass movement volume is likely a function of hillslope processes modulated by the fluvial erosion that oversteepens terrace bluffs and primes them for failure (LaHusen et al., 2016; Wartman et al., 2016). There is substantial variability in failure mechanisms (i.e., landslide types; Varnes, 1958) that occur along terrace bluffs (e.g., contrast Gardner et al., 2009; Wartman et al., 2016). This motivates us to hypothesize that failure mechanism and associated failure geometry correlate with mass movement volume (Hypothesis 1), which would imply that the processes that regulate failure mechanism (hillslope materials, hydrology, fluvial erosion rates) also control terrace mass movement volume. Fluvial incision is the primary driver of relief and oversteepening of terrace bluffs (LaHusen et al., 2016; Wartman et al., 2016), so we also hypothesize that lateral fluvial erosion into the base of terrace bluffs is necessary to initiate mass movements (Hypothesis 2a). If fluvial erosion is necessary for terrace mass movement, then it also stands to reason that more intense lateral fluvial erosion, such as may occur on steeper, more confined valley bottoms, or more laterally mobile rivers should increase the frequency of terrace mass movements and produce higher fluxes of terrace sediment delivery (Hypothesis 2b). The presence of impermeable and low strength glaciolacustrine (Ql) sediment in terrace stratigraphy can cause elevated pore pressures and act as a low strength layer in terraces and has been proposed as a likely control on mass movement volume (Perkins et al., 2017). This implies that terrace mass movement volume should positively correlate with the proportion of Ql in terraces (Hypothesis 3).

To address these objectives and hypotheses, we mapped terrace mass movements and measured associated valley bottom morphology and failure geometry using aerial imagery and LiDAR Digital Elevation Model (DEM) data along nine river networks draining from the east and south into Puget Sound. We used these data to estimate the magnitude, lateral connectivity, spatial distribution, and sediment caliber of sediment delivery from terraces to Puget Sound rivers (Objective 1). Using ancillary topographic and geologic data, we tested potential controls on mass movements from terraces guided by the hypotheses outlined above (Objective 2, Hypotheses 1-3).

2 Study Area

We measured sediment delivery to valley bottoms from valley bottom-adjacent, terrace-forming sediment reservoirs along rivers draining from the west flank of the Cascade Mountains of Washington to Puget Sound (Figure 2). These terraces mostly consist of glacial sediments deposited by the Puget Lobe of the Cordilleran Ice Sheet and interglacial sediments (Armstrong et al., 1965; Troost, 2016), although small portions are composed of lahar deposits from Glacier Peak in the Skagit (Dragovich et al., 2002a) and Stillaguamish basins (Dragovich et al., 2002b) and from Mt. Rainier in the Puyallup, Green, and Nisqually basins (Crandell, 1971; Vallance and Scott, 1997).

The nine river networks (Figure 2) drain from steep, formerly or presently glaciated alpine headwaters through confined mountain valleys into broader, partially confined mountain valleys, and then through valleys carved into the Puget Sound lowland's glacial fill before reaching Puget Sound (Collins and Montgomery, 2011). Averaged across these basins, approximately 56% (range between 29 and 77%) of the stream length with a drainage area over 15 km², totaling 2736 river kilometers, has adjacent Pleistocene glacial and/or Holocene lahar terraces, generally located in the lower and middle portions of each basin (Figure 2).

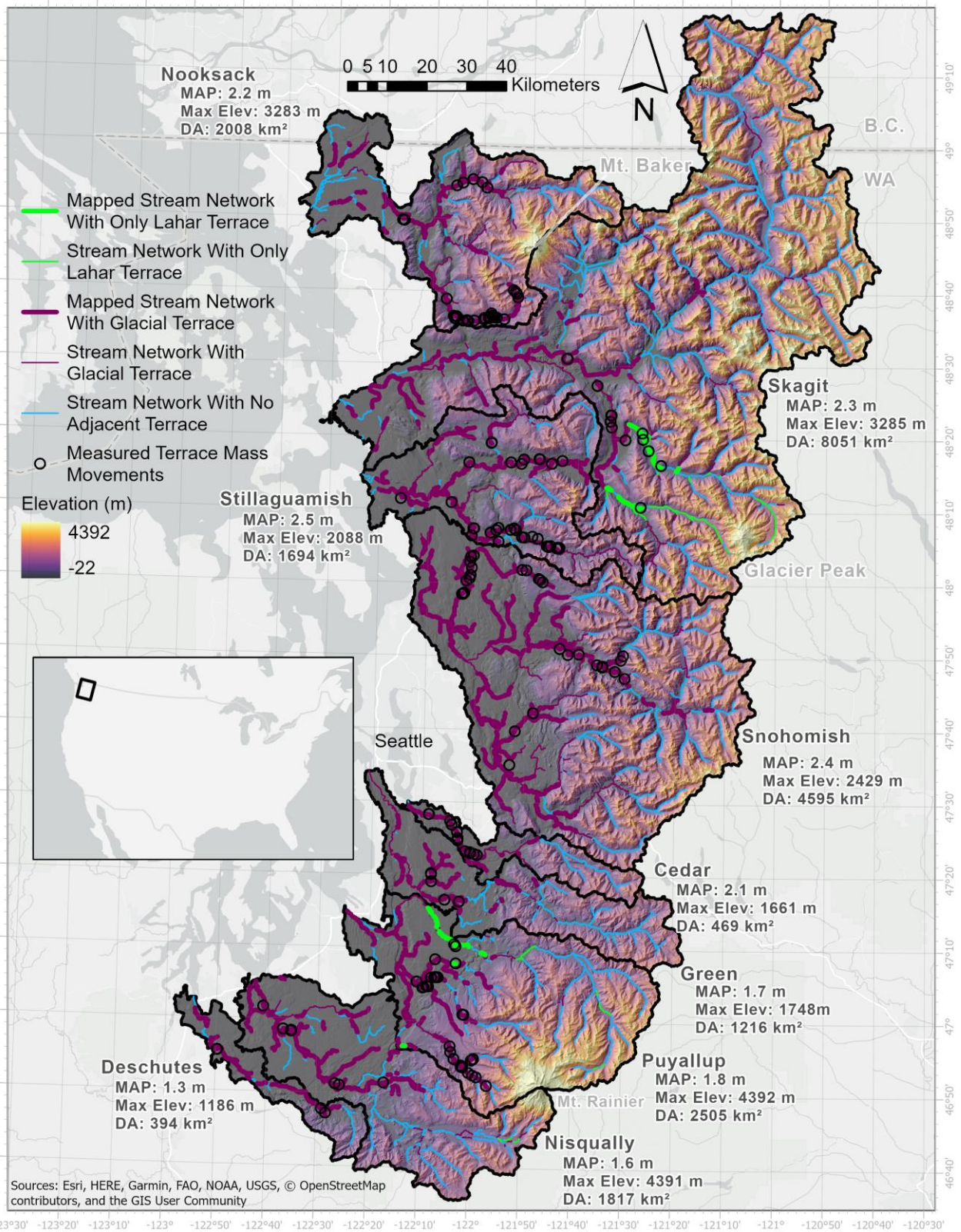


Figure 2. Map showing study basins, measured terrace mass movements, and stream networks in each basin. Stream networks (blue) are colored by the presence of glacial (dark purple) or lahar

(light green) terraces adjacent to the valley bottom and whether the stream network with adjacent terraces (i.e., in the terrace domain) had sufficient repeat LiDAR coverage to enable mapping and measuring terrace mass movement volumes (bolded). Inset shows map coverage (black rectangle). Mean annual precipitation (MAP; PRISM Climate Group, Oregon State University, 2012), maximum elevation (all basins drain to sea level with the exception of the Cedar, which drains to Lake Washington, just above sea level), and drainage area (DA) are listed for each basin. Note that for the Skagit and Nooksack basins, mean annual precipitation applies only to the portion of the basins within the United States.

3 Methods

3.1 Mapping and Measuring Terrace Mass Movements using LiDAR

To measure the volume of sediment eroded from glacial and lahar terraces (Objective 1), we constructed Digital Elevation Models (DEM) of Difference (DoD) using repeat LiDAR data. For each study basin, we collected all publicly available LiDAR datasets from 2002 to 2017. Using ArcGIS Pro, we bilinearly resampled higher resolution DEMs to the lowest common resolution of the earliest LiDAR dataset, then subtracted earlier DEMs from later DEMs to obtain a DoD raster. We converted all DoD values less than ± 0.9 m (3 ft) to 0 to exclude values likely to be DEM noise as opposed to real elevation change. We used this thresholded DoD in conjunction with shaded relief representations of DEMs, aerial imagery, and a 1:100k scale geologic map of Washington State (Washington Division of Geology and Earth Resources, 2016) to identify and delineate the eroded area of terrace mass movements (i.e., excluding landslide deposits).

To identify a patch of negative values in the DoD (i.e., elevation loss) as a terrace mass movement, that patch needed to: 1) not appear to be the result of (i.e., not be adjacent to) human activities such as mining, grading, road-building, or urban development; 2) not erode alluvial fan-shaped deposits from tributaries, unless those fan-like deposits mantled thicker terrace deposits; and 3) erode or be adjacent to glacial sediment or lahar deposits with relatively low-slope tops (i.e., terrace-like features) that do not exhibit morphologic evidence of modern fluvial reworking and exhibit a maximum terrace bluff height, measured from the slope break at the base of the bluff to the mean terrace top elevation, of at least 6.1 m (20 ft). We chose this height threshold based on observations of the boundaries between glacial and lahar terraces and modern, fluvial terraces mapped on 1:100 k and 1:24 k geologic maps, as well as our field experience working on rivers in the region, where alluvial banks can be as high as 20 ft. A kernel density estimator fit to the distribution of maximum terrace heights in our dataset identified a distribution peak at 13.5 m, indicating that we likely excluded most or all active alluvial surfaces and included most or all glacial and lahar deposits (Figure S1).

We computed terrace mass movement volume by multiplying each DoD raster by its cell area, then summing the values of the resulting raster within the mapped extent of each mass movement. To estimate the measurement uncertainty in each volume estimate, we compiled the LiDAR vertical root mean square (RMS) error for each DEM. Where LiDAR datasets had no reported vertical RMS error, we used the average vertical RMS error of all LiDAR datasets having a similar resolution and that reported a vertical RMS error. We then summed the vertical error for each pair of LiDAR datasets in quadrature to obtain a DoD RMS error, which we multiplied by the area of each mapped mass movement to obtain an uncertainty estimate for the eroded volume of each mass movement. We generally report terrace erosion as a volume per

year (i.e., divided by the LiDAR DoD timespan), as most of the events we mapped appeared to occur in more than a single, noticeable event (59%, or 91 of the 154 that did not appear to fail continuously via ravel; see section 4.4 and Figure S2). To scale up estimates of terrace erosion for each basin, we conservatively made maximum and minimum estimates using the high and low bounds, respectively, defined by the RMS error for each individual mass movement in each basin. While these estimates only represent a short period of time (6 – 14 years, with LiDAR datasets from 2002 to 2017), peak streamflows in this period were neither abnormally high nor low compared to peak streamflows in the historical flow record (Figure S3).

3.2 Delineating Terrace Spatial Distribution Along River Networks

To quantify the spatial distribution of terraces and potential terrace sediment delivery in each basin (Objective 1), we used 1:100 k-scale geologic maps (Washington Division of Geology and Earth Resources, 2016) and 10- to 30-m resolution DEMs to delineate the portion of the channel network having stream-lateral glacial or lahar terraces, which we refer to as the “terrace domain” (thin and bold green and purple lines in Figure 2), as well as the stream length along which active channels were in contact with and possibly eroding the base of terrace bluffs (not shown in Figure 2). We only examined the portion of the stream network in these basins where the drainage area was greater than 15 km² (all green, purple, and blue lines in Figure 2). This threshold included tributaries that had incised deeply enough through mainstem terraces to promote mass movement of the terraces but excluded incised, gully-like channels cutting through terraces that are otherwise being eroded primarily by larger streams. We then further delineated the proportion of the terrace domain in each basin along which repeat LiDAR DEM data were available, which represents the proportion along which we were able to map terrace mass movements (bold green and purple lines in Figure 2; approximately 71% of the total stream network length in the terrace domain across all basins). We normalized volumetric terrace erosion by the length of river network along which we were able to map terrace mass movements in LiDAR in the terrace domain (bold green and purple lines in Figure 2), reporting results in units of m³/yr per river kilometer.

To characterize the basin location of terrace mass movements, we normalized drainage area at individual mass movements by the entire basin area. We also normalized the valley bottom elevation at each mass movement by the maximum elevation of the valley bottom having a drainage area greater than 15 km² in each basin.

3.3 Determining Glacial Terrace Stratigraphic Characteristics

We used the Washington Department of Ecology Well Log Database (Washington State Department of Ecology, 2020) to characterize the subsurface stratigraphy and grain size of terraces, including the occurrence of Q1, which Perkins et al. (2017) suggested can be a primary control on the eroded volume of mass movements (Objective 1, Hypothesis 3). For each mapped mass movement, we consulted all well logs inferred to be from the same terrace as the mass movement. We then chose the one that likely represented the largest amount of the total height of the terrace and, if it was not the closest well log to the mass movement, was similar to the stratigraphy recorded in the closest well log. For that well log, we recorded the top depth and thickness of each layer likely to be Q1 (i.e., dominantly silt or clay, although irregular well log core descriptions made this determination difficult and subjective). Finally, we computed the total thickness of likely Q1 layers for the portion of the core that intersected the elevation range

of the mapped mass movement. Well logs were available to make this determination for 55 of the 167 mass movements that we mapped.

3.4 Measuring Terrace Mass Movement Characteristics

To evaluate potential controls on mass movement volume (Objective 2, Hypotheses 1 – 3), we measured failure plane slope, failure length approximately parallel to the adjacent stream, and bluff height from the stream or depositional zone to the top of the terrace as an average of three measurements along the feature's length using the most recent LiDAR DEM for each feature. We also used the most recent DEM to measure total bankfull width of active channels and floodplain width, including the portion on which the channel could potentially migrate in the absence of anthropogenic constraints. We used the Fluvial Corridor toolbox (Roux et al., 2015) and a 10 m DEM (30 m for the Nooksack and Skagit basins, which lack full 10 m DEM coverage) to record channel slope, mean elevation, and drainage area for the 500 m stream segment closest to each mass movement. We also noted whether the stream contacted the terrace bluff base, which we took to indicate direct delivery of sediment to the stream. For the few mass movements that were not adjacent to active channels, we used historical aerial imagery and King County (King County, 2020) and Army Corp of Engineers (United States Army Corp of Engineers, 2020) levee and revetment databases to determine whether those mass movements are artificially isolated from active channels by levees or revetments.

We used all Google Earth imagery available within the time period defined by the two sets of LiDAR to determine the minimum number of times a terrace bluff face appeared to fail within that period. We interpreted substantial change to the terrace face texture or vegetation or visual evidence of terrace top edge retreat as evidence of failure. From this, we calculated a minimum rate of failures per year for each mapped mass movement.

To determine whether failure mechanism and geometry control mass movement volume (Hypothesis 1), we used LiDAR and Google Earth imagery to classify failures by mechanism using the updated Varnes landslide typology (Hungr et al., 2014; Varnes, 1958) modified to accommodate fluvially-induced mass movements. From Google Earth aerial imagery and LiDAR DEMs, we described failures as being either: (1) flows or slides, with clear evidence of fluidized mass movement (channelization, long runouts, no visible slip surface, entirely toppled vegetation) or movement along a defined shear plane (no channelization, visible intact blocks possibly with intact vegetation, noticeable slump block cracks); (2) outer bend lateral retreats, which displayed simultaneous fluvial lateral migration along an outer bend and terrace bluff face retreat on a relatively steep face with no runout; (3) outer bend falls, which showed little noticeable lateral retreat or bluff retreat despite changes to the bluff face appearance through time, likely indicating continuous ravel of material; and (4) complex failures that exhibited characteristics of both flows or slides as well as outer bend lateral retreat. Figure S4 shows examples of each failure mechanism.

3.5 Statistical Analyses

To test our hypotheses, we used a combination of multiple comparisons and evaluations of monotonic trends. To compare groups of data, we computed estimates of central tendency with 95% confidence intervals, used boxplots for visual analysis, and conducted pairwise Wilcoxon rank-sum (or Kruskal-Wallis for greater than two samples) tests using a Holm correction factor to account for multiple comparisons. To evaluate correlations between data, we used Spearman rank-sum correlation coefficients (ρ) and associated 95% confidence intervals

(Bishara and Hittner, 2017), which nonparametrically determine the presence of a monotonic correlation (values near 1 or -1 indicate a near-monotonic, positive or negative correlation, respectively and values near 0 indicate no correlation). All statistical analyses were performed in the RStudio (RStudio Team, 2016) interactive development environment for R (R Core Team, 2018) using the car (Fox and Weisberg, 2019), asbio (Aho, 2019), and tidyverse (Wickham et al., 2019) packages. Figures were produced using ggplot2 (Wickham, 2016), cowplot (Wilke, 2019), and EnvStats (Millard, 2013) packages. All uncertainties reported below indicate 95% confidence intervals unless otherwise defined.

4 Results and Discussion

4.1 The Magnitude, Spatial Distribution, Frequency, and Characteristics of Terrace Erosion (Objective 1)

The importance of terrace erosion as a sediment source to Puget Sound rivers is a function of three characteristics: 1) the volume of sediment eroded from terraces, 2) sediment connectivity between terrace and rivers, represented by the proportion of the volume eroded from terraces that is directly accessible by fluvial erosion over short timescales, and 3) the grain size distribution and lithology, because of its control on rate of attrition in fluvial transport, of delivered terrace sediment, which together determine the degree to which terrace sediment may act as bed material load that can alter river morphology, especially in lowland reaches. We examine each of these in the three following sections.

4.1.1 Terrace Sediment Eroded Volume

Terrace failures in our period of examination eroded $853,300 \pm 19,500 \text{ m}^3/\text{yr}$, corresponding to $3,500 \pm 100 \text{ m}^3/\text{yr}/\text{km}$ in the repeat LiDAR mapped portion of the terrace domain (71% of the total stream length in the terrace domain). Excluding the 2014 Oso Landslide, which eroded $359,000 \pm 3,400 \text{ m}^3/\text{yr}$, or 42% of the total across all nine basins, those values are $493,900 \pm 16,100 \text{ m}^3/\text{yr}$ and $2,100 \pm 100 \text{ m}^3/\text{yr}/\text{km}$, respectively. Total eroded volume and eroded volume normalized by river kilometer vary between basins, the latter varying by a factor of 27 (or a factor of 99 if the 2014 Oso Landslide is included) (Figure 3). Lahar sediments account for a substantial portion of the totals in only the Puyallup and Skagit River basins (4% and 19%, respectively) and a small portion (54 km, or 2.8%) of the total LiDAR mapped river length in the terrace domain.

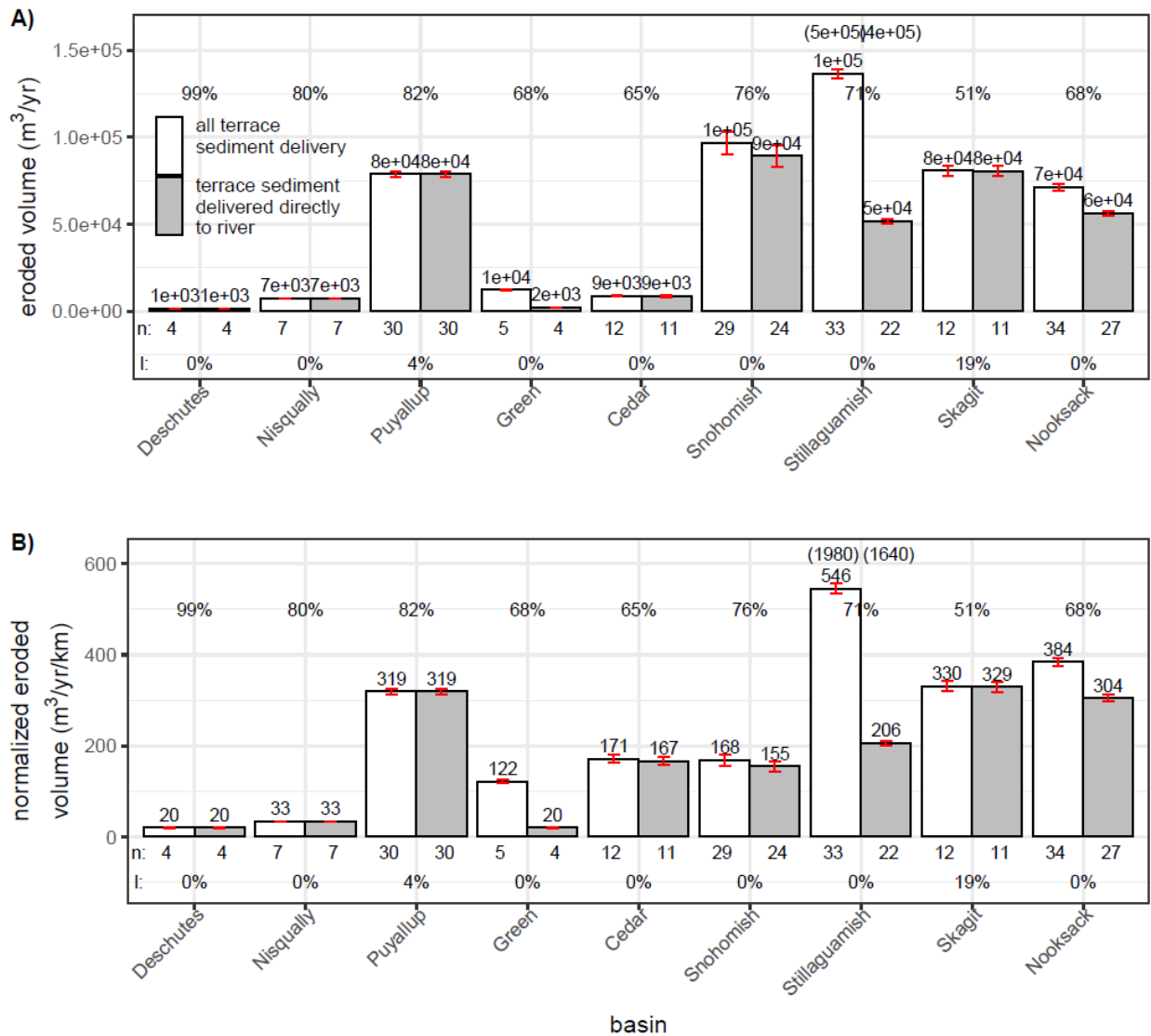


Figure 3. Bar plots showing the volume of terrace sediment eroded during the period of examination for each basin examined: (A) normalized by the period between repeat LiDAR datasets used to compute eroded volume and (B) normalized by repeat LiDAR mapped stream network length in the terrace domain. Values above bars show the value of each bar. Percentages above bars for each basin show the percent of the repeat LiDAR mapped stream network length in the terrace domain. Red error bars represent uncertainty due to measurement error. Values in parentheses above the bars for the Stillaguamish basin represent the values of the bars if the 2014 Oso Landslide is included. At the base of each plot, “n” shows the number of mapped erosion events for each bar and “l” shows the percent of the eroded volume sourced from lahar terraces.

4.1.2 Sediment Transport Connectivity Between Terraces and Adjacent Rivers

Nearly all of the terrace mass movements that we mapped deliver sediment directly to adjacent rivers or form deposits that are rapidly eroded by rivers. Of the 167 mapped mass movements, 141 (84%; gray bars in Figure 3) appeared to deliver sediment directly to rivers (i.e., had no remaining deposit outside the channel in the latter LiDAR DEM), although that sediment may not be transported downstream immediately. Of the remaining 26 mass movements that did

not deliver sediment directly to rivers, 22 exhibited fluvially eroded deposits, most of which had been mostly eroded by the river at the time of our mapping. Only four (three in the Stillaguamish and one in the Snohomish, totalling only $6,100 \pm 300 \text{ m}^3/\text{yr}$, or approximately 1% of the non-Oso terrace erosion we mapped) had deposits that were entirely untouched by fluvial erosion, two of which were isolated from the river by revetments or levees.

4.1.3 Spatial Distribution of Pleistocene Glacial and Lahar Terrace Sediment Delivery Along River Networks

Terrace erosion is concentrated at low normalized elevations (Figure 4) because incised, oversteepened terraces prone to landsliding in glacial and lahar valley fill are generally in high-order stream valleys (Figure 2). This is especially true of four elongate basins characterized by mainstems that are relatively much larger than their small tributaries, which contrast the five basins characterized by large tributaries and a more equant shape (Figure S7). In equant basins, sediment is sourced from terraces incised by large tributaries, whereas in elongate basins, sediment is sourced from terraces incised by mainstems, presumably due to the lack of large, erosive tributaries. This difference in basin shape also results in differences in where in the drainage basin terrace erosion is located; equant basins display a peak in both the number of mass movements and in eroded volume at low normalized drainage areas, whereas elongate basins display a peak at relatively high normalized drainage areas (Figure 4).

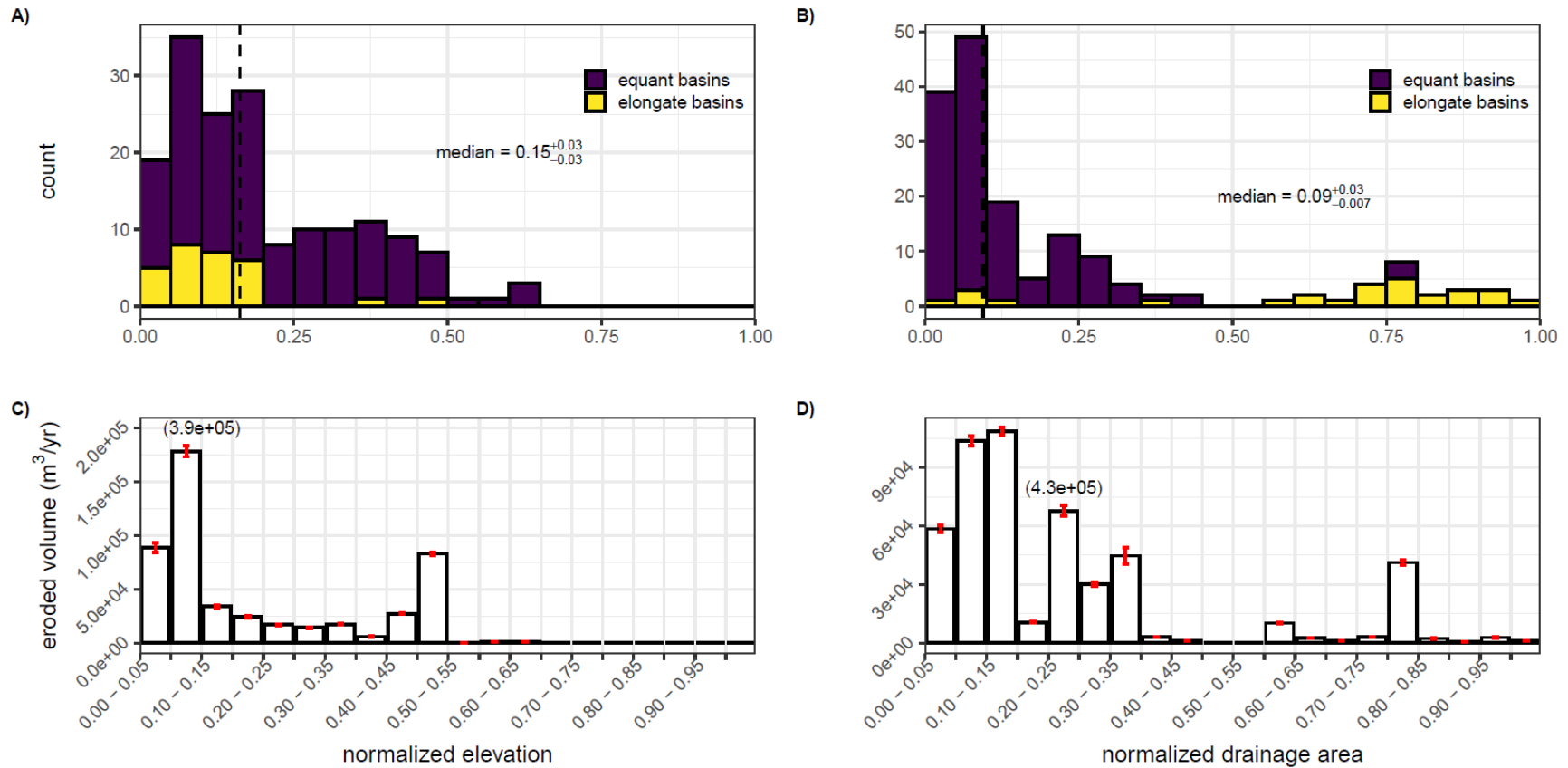


Figure 4. Spatial distribution of mapped terrace mass movements by frequency (A and B), and by total eroded volume (C and D), binned by normalized elevation (the elevation of the stream adjacent to the mass movement divided by the maximum elevation of the stream network with over 15 km² drainage area in the basin; A and C) and normalized elevation (the drainage area of the stream adjacent to the mass movement divided by the basin drainage area; B and D). For histograms (A and B) the vertical dashed line shows the median value. In C and D, red error bars represent measurement uncertainty, and values in parentheses indicate the value of the bar directly underneath if the 2014 Oso Landslide is included in the plot. Note the differing y axes. Equant basins include the Nooksack, Puyallup, Skagit, Snohomish, and Stillaguamish, and elongate basins include the Cedar, Deschutes, Green, and Nisqually.

4.1.4 Comparing Sediment Delivery Flux from Smaller, More Frequent Terrace Mass Movements with Larger, Less Frequent Mass Movements

We mapped relatively small mass movements (median eroded volume per terrace mass movement of 1146^{+190}_{-201} m³/yr; Figure 5A) that occurred over a period of only 6 – 14 years (median of 12 years; Figure 5B), whereas glacial and lahar terraces across the Puget Sound have been eroding since deglaciation, about 16,400 years ago (Porter and Swanson, 1998). However, the 2014 Oso Landslide, with an eroded volume 315 times the median volume of all other mass movements, contributed $42.1^{+0.6}_{-0.6}$ % of annualized terrace erosion during the period we examined. This raises the question of whether, over long periods of time, frequent, smaller failures or rare, larger failures account for more total terrace erosion.

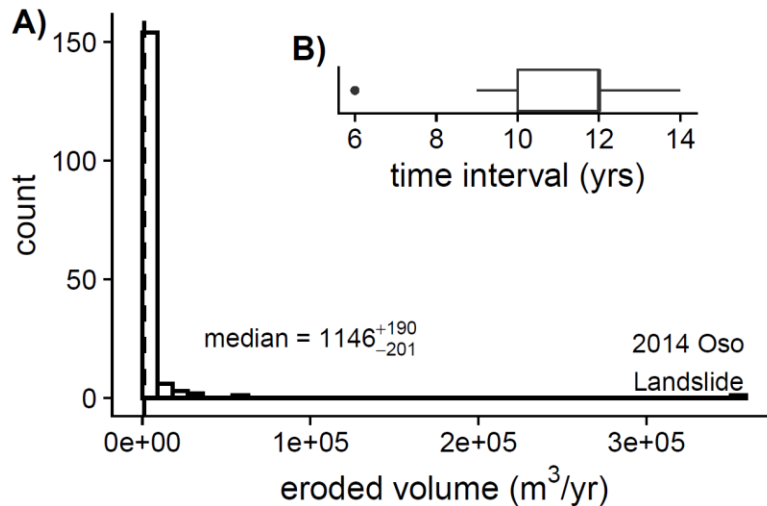


Figure 5. (A) Histogram of terrace erosion volume and (B) inset boxplot showing the time interval over which terrace erosion volume was measured by LiDAR differencing. Vertical dashed line shows median eroded volume, which is also given with 95% confidence interval uncertainty. Each histogram bin covers a span of approximately 8900 m³/yr. For inset boxplot, bold vertical line represents the median, box edges represent the first (25th percentile) and third (75th percentile) quartiles, and ends of horizontal lines represent the 1.5 times the interquartile range. Solid black circle represents outliers (outside of 1.5 times the interquartile range). Sample size (n) for both plots is 167.

To address this question, we use as a recurrence interval for very large mass movements the dated record of large failures from terraces in the North Fork Stillaguamish River over the last 2000 years, which indicates a frequency of one event in 140 years (LaHusen et al., 2016). This recurrence interval from a single stream valley may not represent all Puget Sound basins and may be higher than the mean recurrence interval in the post-glaciation period, as landslide frequency may have increased through time (Booth et al., 2017). However, if large, infrequent landslides deliver between 5,000,000 m³ (our estimate for the 2014 Oso Landslide, which is less than the approximately 8,000,000 m³ estimate of (Iverson et al., 2015)) and 35,000,000 m³ (estimate by Iverson et al. (2015) for the nearby Rowan Landslide) on average, similarly-sized events deliver $143,000 \pm 107,000$ m³/yr of terrace sediment to Puget Sound rivers. By comparison, the numerous small (166 mapped mass movements, excluding the 2014 Oso Landslide) mass movements in the short (median 12 years) period of our study produced 493,900

$\pm 16,100 \text{ m}^3/\text{yr}$, which is much more than the amount produced by larger, infrequent events as estimated above. This estimate, while derived from limited data, suggests that smaller mass movements produce more sediment over time than infrequent, very large events, such as the 2014 Oso Landslide.

4.1.5 Importance of Terrace Erosion to Puget Sound Rivers

The significance of terrace sediment delivery to the sediment load of Puget Sound rivers is a function of the volume of sediment eroded from terraces that reaches rivers, the caliber and resistance to attrition of terrace-derived sediment, and where terrace failures are located in river networks.

Sediment eroded from terraces may constitute a substantial portion of sediment delivery to Puget Sound rivers, as mass movements erode substantial volumes of sediment and nearly all of the sediment eroded from terraces is rapidly eroded by rivers. Comparing our estimates of terrace erosion to published sediment yield data indicates that terrace erosion may be a more significant contributor to the sediment load of rivers draining unglaciated basins than to rivers draining glaciated basins. Our estimated eroded volume from terraces, extrapolated to the entirety of the terrace domain in each basin (i.e., values in Figure 3B divided by the proportion of the terrace domain we were able to map in repeat LiDAR for each basin), is 12 to 24 % of the magnitude of published sediment yields for glaciated basins and 12 to over 100 % of the magnitude of measured sediment yields for non-glaciated basins (Table 1). The substantial variability in this proportion for non-glaciated basins comes primarily from the Cedar River, where basin sediment yield is only estimated as bed material load, and hence is likely far lower than the total or suspended load of the basin. A previous investigation concluded that most of the Cedar River's coarse sediment yield comes from terrace erosion (Perkins Geosciences and Harper Houf Righellis, Inc., 2002). The White River, a tributary to the Puyallup, is an unusual case of a glaciated basin where lowland-derived glacial and lahar sediment dominates coarse sediment supply, but from headcutting and vertical incision from a base level drop rather than from terrace mass movements (Anderson and Jaeger, 2019). While our sample design is not suited to determining the root cause of the substantial variability in terrace sediment delivery magnitude or relative importance between basins, future work systematically evaluating the geometry and subsurface stratigraphy of terraces across the Puget Sound may be able to do so.

Table 1. Comparison of published basin sediment yields to estimated terrace sediment erosion from this study. Percentages of basin-wide sediment yield reported here are given as a proxy for the relative importance of terrace sediment erosion in each basin, which cannot be compared directly to sediment yield.

Basin	Sediment yield (m³/yr)¹	Sediment yield type	Terrace erosion (m³/yr)	Terrace erosion as percent of sediment yield
Glaciated				
Nooksack	440,000 ²	total load	104,500	24%
Skagit	1,275,000 ³	total load	158,400	12%
Puyallup	430,000 ⁴	suspended load	96,000	22%
Nisqually	50,000 ⁵	suspended load	9,100	18%
Not glaciated				
Stillaguamish	640,000 ⁶	suspended load	192,600	30%
Snohomish	250,000 ⁷	suspended load	127,400	51%
Cedar	6,000 ⁸	bed material load	13,600	226%
Green	53,000 ⁹	suspended load	18,000	34%
Deschutes	13,000 ¹⁰	suspended load	1,500	12%

¹We use a bulk density of 2 tonnes/m³ to convert sediment yield estimates (typically reported in tonnes/yr) to units comparable to mass movement volume estimates (Collins et al., 2019; Savage et al., 2000), ²Anderson et al. (2019). ³Curran et al. (2016b). ⁴Czuba et al. (2012). ⁵Curran et al. (2016a). ⁶Anderson et al. (2017). ⁷Nelson (1971). ⁸Northwest Hydraulic Consultants, Inc. (2018). ⁹Senter et al. (2018). ¹⁰Nelson (1974).

Well log data and our field observations indicate that terraces likely contain high proportions of coarse sediment, making terrace sediments important contributors to coarse bed material load and therefore downstream morphodynamics. Well logs covering the full height of the terrace mass movements we mapped (28 of the 55 records we examined) indicate that, on average, 50 ± 14 % by volume of the material delivered from mapped terrace mass movements is coarse, non-QI sediment. This inference from well log data is limited, however, as the coarse fraction of terrace sediment likely varies substantially between basins. Our field observations of actively eroding terraces (described in Text S1 and Figures S5 and S6) indicate that sediment size in exposed terrace faces agrees with well log descriptions and that exposed bluff faces contained substantial amounts of coarse sediment, but the stratigraphy exposed in bluff faces is strongly laterally heterogeneous, varying over distances as small as a few dozen meters, making the uncertainty on our estimate likely a lower bound on actual uncertainty. This is consistent with previous estimates of terrace gravel proportions in Cedar River terrace faces (range 0 to 100 %, median 35 %, from Perkins Geosciences and Harper Houf Righellis, Inc. (2002). We lack sufficient well log data to estimate sediment size for lahar terraces, but previous sedimentologic investigations of Osceola mudflow terraces suggest they may contain 82 ± 3 % (Crandell, 1971) and 84 ± 2 % (Vallance and Scott, 1997) sand or coarser material. However, like glacial terraces, lahar terraces are likely laterally heterogeneous (Gomez and Lavigne, 2010).

The position of terrace sediment sources low in drainage basins (Figure 4) likely also increases the relative importance of terrace sediments to basin yield and to sedimentation in lowland reaches because lower travel distances would result in less attrition and loss to the

washload (e.g., O'Connor et al., 2014). Terrace sediment, dominantly continental glacial drift, is dominated by resistant metamorphic and igneous rocks (Armstrong et al., 1965), and similar continental outwash in the nearby, southern Olympic Peninsula Satsop River basin is relatively resistant to attrition (Collins and Dunne, 1989). The limited data reported here indicate that because terrace sediments have a substantial coarse fraction dominated by relatively resistant lithologies and enter rivers low in the drainage basin and thus undergo shorter travel distances, their role in affecting morphologic change in lowland reaches may be large relative to more voluminous sediment delivery from distant glaciated headwaters. This finding motivates more in-depth analysis of sediment attrition rates in this region, which, while broadly poorly understood, will be necessary to determine the actual importance of various sediment sources across the region.

Unlike many drainage basins, where sediment is sourced from the headwaters and transported to depositional areas in the lowlands, Puget Sound rivers have substantial sediment supply in middle and lower reaches, very close to depositional zones, similar to the paraglacial Fraser Lowlands (Kovanen and Slaymaker, 2015) but in contrast to sediments sourced from glacial bluffs, triggered by a post-glacial, upstream-progressing headcut, in the middle to headwater reaches of the La Sueur River, Minnesota, USA (Gran et al., 2013). The supply of coarse, relatively resistant sediment from terraces low in river networks, much of it from frequently-occurring mass movements, highlights the potential importance of the paraglacial and, in some basins, “paravolcanic,” sediment source in regulating the sediment dynamics of Puget Sound rivers and especially channel morphodynamics in developed, lowland reaches.

4.2 Geomorphic Controls on Pleistocene Glacial and Lahar Terrace Erosion (Hypotheses 1-3)

4.2.1 Variability in Terrace Sediment Delivery Magnitude by Failure Mechanism (Hypothesis 1)

The style, or failure mechanism, of terrace mass movements vary in their geometry, as defined by stream-parallel length, terrace bluff height, and failure plane slope (Figure 6A-C). In general, flows/slides tend to be channelized and thus have small stream-parallel lengths (Figure 6A); occur on taller bluffs (Figure 6B), which may less frequently fail via slumping or ravel compared to shorter bluffs; and have relatively low-angle failure planes (Figure 6C) compared to other failure mechanisms. Outer bend falls tend to occur only on steep bluffs (Figure 6C) formed in cohesive materials and to fail continuously (we observed continual delivery of gravel from the especially coarse outer bend falls along the Cedar River; Figure S6) as opposed to failing episodically. Outer bend lateral retreat, the most common failure type, accounting for 56 %, or 93 of 166 mapped features (Figure 6D), tends to occur on shorter bluffs (Figure 6C), likely by a process similar to slump-failure of stream banks (e.g., Klösch et al., 2015). We speculate that taller bluffs comprised of heterogeneous or otherwise poorly cohesive material may tend to fail via a combination of the outer bend lateral retreat and flow/slide mechanisms, and in most of these types of failures, we observed outer bend lateral retreat to only affect the lower portion of bluff faces, whereas the flow/slide portion usually extended above the scour of the outer bend lateral retreat.

These geometric differences between failure mechanisms lead to substantial differences in eroded volume (Figure 6D). Flow/slide and outer bend lateral retreat failures tend to have similar annually-normalized volumes. Outer bend falls, despite their likely tendency to fail

almost continuously, deliver the least annually-normalized volume. Compound failures consisting of outer bend lateral retreat combined with flow/slides deliver significantly more material than outer bend lateral retreat or flow/slides alone.

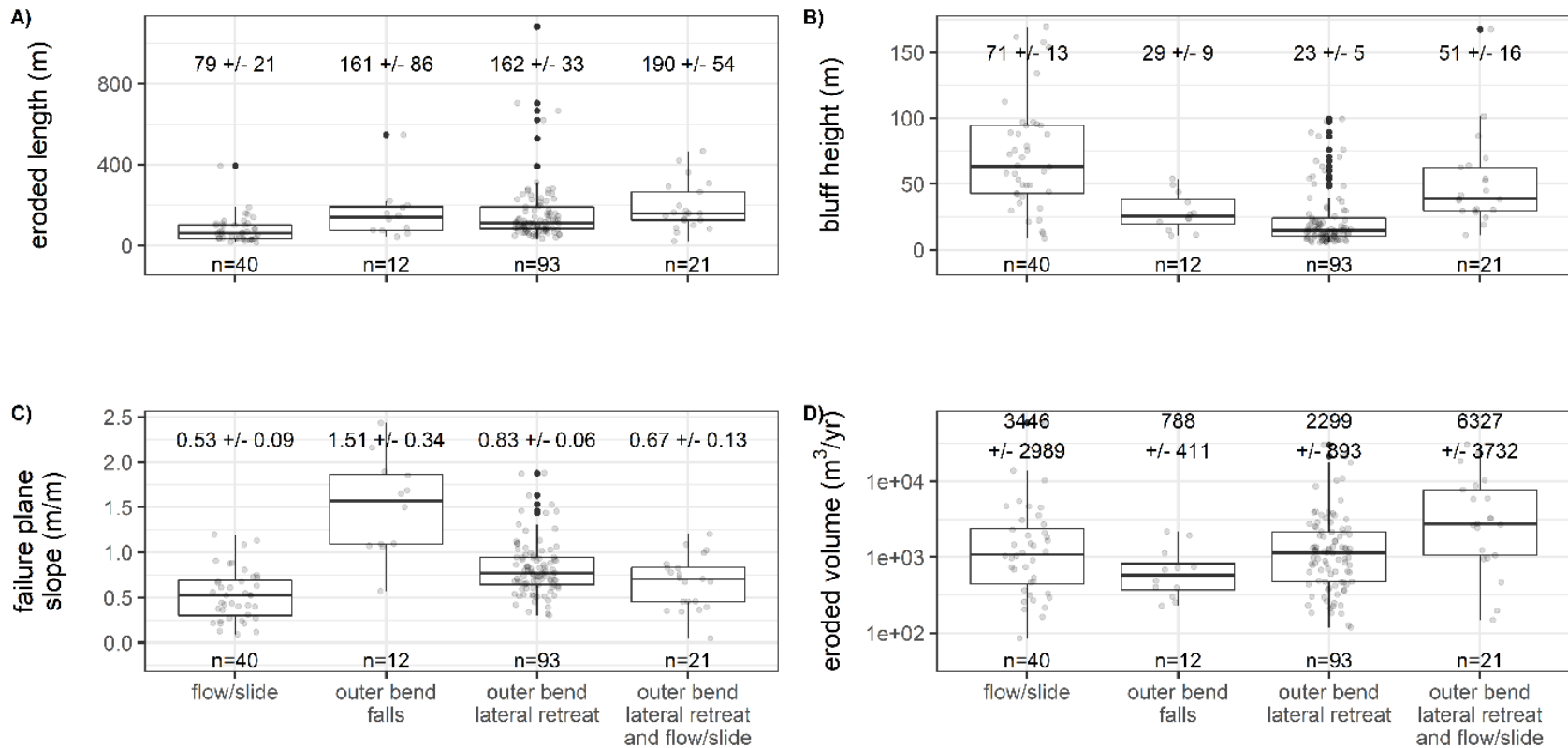


Figure 6. Boxplots showing: (A) differences between failures mechanism and the stream-parallel length of each measured landslide, (B) the mean height of the bluff on which landslides occurred, (C) the slope of the resulting failure plane following landsliding, and (D) the volume eroded by each landslide. Bold horizontal lines represent the median, box edges represent the first (25th percentile) and third (75th percentile) quartiles, and ends of vertical lines represent the 1.5 times the interquartile range. Solid black circles represent outliers (outside of 1.5 times the interquartile range), and transparent gray circles show all data. The mean of each group and associated 95% confidence interval uncertainty are shown above each box. Note that these analyses and this figure excludes the 2014 Oso Landslide, as it is a single, infrequent, and much larger event than the ones shown here and would skew our estimates of these central tendencies.

4.2.2 The Role of Fluvial Erosion in Priming Terrace Mass Movements (Hypothesis 2)

If lateral fluvial erosion is necessary to initiate terrace mass movements, we would expect that most mass movements would occur when the adjacent river is actively eroding the base of the terrace bluff. Indeed, 89%, or 141 of the 167 mapped mass movements, occurred while the river was immediately adjacent to, and assumedly eroding, the terrace base; exposed, actively eroding banks observed in aerial imagery for most of these mass movements support this assumption. However, active lateral fluvial erosion does not appear to be consistently sufficient to initiate failure: the degree to which streams contact terraces does not correlate to terrace erosion volume or the frequency of terrace mass movements in a basin, which implies that many of the mapped mass movements were triggered by hillslope, not fluvial, processes. We found no correlation between basin-wide annual terrace erosion volumes ($\rho = 0.18_{-0.74}^{+0.58}$, $n = 9$) or the number of terrace mass movements per repeat LiDAR mapped river km in the terrace domain ($\rho = -0.15_{-0.59}^{+0.74}$, $n = 9$) and the proportion of the stream network that we mapped in LiDAR as contacting terraces. Similarly, steeper and more laterally confined valley bottoms, which might be expected to have more frequent contact between the stream and adjacent terraces, don't tend to produce higher rates of terrace sediment erosion: We found no correlations between channel slope ($\rho = -0.11_{-0.37}^{+0.16}$, $n = 166$) or the ratio of valley bottom width to channel width (i.e., confinement, $\rho = -0.02_{-0.16}^{+0.16}$, $n = 166$) and the rate of terrace erosion volume. While fluvial lateral migration primes terraces for eventual mass movement, it is likely not sufficient on its own to consistently cause mass movements or to regulate their volume.

4.2.3 The Role of Glaciolacustrine Sediment in Regulating the Magnitude of Sediment Delivery from Terraces (Hypothesis 3)

Terraces with greater proportions of QI have been hypothesized to have a greater incidence of larger mass movements than terraces lacking QI, due to the hydrologic and material strength effects of QI on overall terrace stability (Perkins et al., 2017). However, the proportion of QI in the terraces measured in this study only weakly correlates with the volume of material eroded from those terraces (Figure 7A). Terraces with higher proportions of QI likely deliver marginally more sediment per discrete failure, as opposed to more frequently delivering sediment via mass movements (Figure 7B shows no correlation between mass movement frequency and QI proportion) or failing by modes that tend to deliver more sediment per event (we found no significant difference between QI for various failure modes).

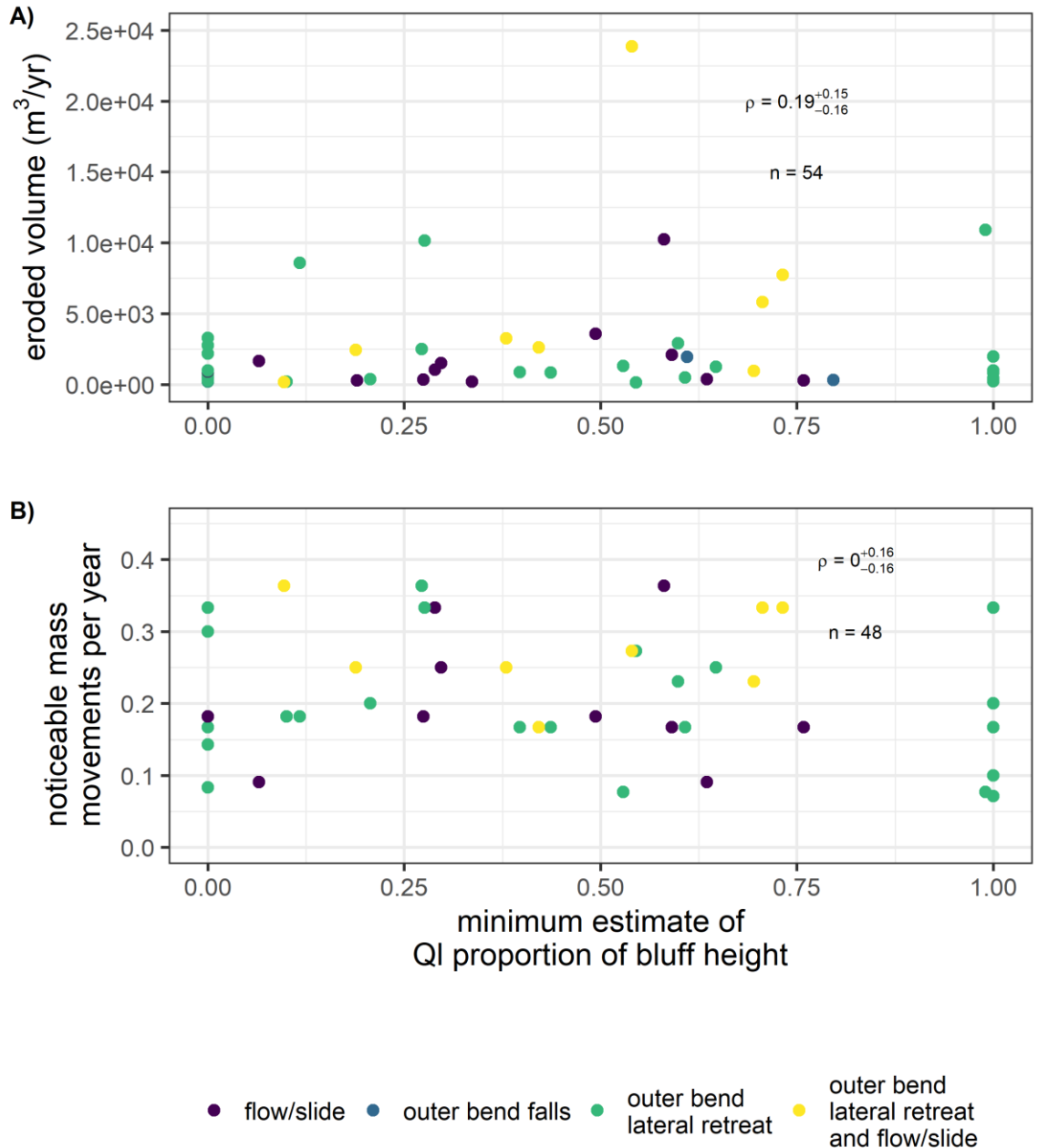


Figure 7. Scatterplots showing: (A) the relationship between the ratio of QI thickness to total bluff height versus the annual eroded volume for each landslide and (B) the frequency of noticeable failures (i.e., for each mass movement, whether terrace face texture or vegetation appearance changed substantially, or the terrace edge appeared to retreat). Data are colored by failure mechanism. Spearman correlation coefficient (ρ), 95% confidence interval on ρ , and sample size (n) are shown on each plot. Note that outer bend falls are not shown on plot B.

4.2.4 Synthesizing Controls on Terrace Mass Movement Volume

For the smaller, frequent mass movements that we document here (i.e., excluding the 2014 Oso Landslide), failure mechanism correlates with mass movement volume, supporting our Hypothesis 1. This contrasts with previous work that found that terrace bluff geometry does not correlate with mass movement volume (Kessler et al., 2013), although bluff erosion in that study

was largely due to undercutting, seepage, piping, and freeze/thaw, which may play a much lesser role in the larger bluffs examined in this study. For the bluffs studied here, bluff geometry, especially the length in contact with the adjacent river, and bluff height at least partially correlate with failure mechanism and resulting eroded volumes. This implies that both hillslope geometry, set by hillslope material strength and hydrology, as well as lateral fluvial erosion both play a role in regulating terrace mass movement volume; over half of the mass movements we mapped were due to outer bend lateral retreat, indicating a strong component of fluvial lateral erosion in terrace sediment delivery. While the mechanism of fluvial lateral erosion oversteepening bluffs and triggering mass movements, similar to bank slump erosion (Klösch et al., 2015), is somewhat understood, our work highlights questions related to how hillslope materials and processes regulate failure mechanism and resulting mass movement volume and hazard. For instance, we are unsure why outer bend falls are so common along bluffs adjacent to the Cedar River, whereas outer bend lateral retreat is more common on outer bends elsewhere, or why some outer bend lateral retreat mass movements don't seem to trigger further flow/slide mass movements in the bluff above their scour extent when some seem to do so.

That most mapped mass movements occurred while rivers were contacting terrace bluffs supports the idea that lateral fluvial erosion is usually necessary to prime terraces for failure. This supports our Hypothesis 2a and corroborates inferences of past investigations of terrace mass movements that have concluded that fluvial oversteepening is necessary to generate terrace mass movements (LaHusen et al., 2016). However, the lack of correlation between the proportion of the stream network in contact with bluffs or valley bottom geometry and eroded volume or terrace mass movement frequency indicates that while lateral fluvial erosion is likely necessary to oversteepen bluff faces and, usually, to trigger mass movements, it is insufficient alone to regulate their size. This fails to support our Hypothesis 2b and indicates that the frequency and magnitude of terrace erosion is better explained by terrace geometry, hillslope material properties, and hydrology. This also suggests that levees and revetments that restrict fluvial lateral erosion may reduce the frequency of terrace mass movements, especially outer bend falls and outer bend lateral retreat mass movements low in watersheds where levees and revetments are more common. However, terraces have been primed for failure from fluvial erosion over thousands of years, and human alterations to rivers are likely not widespread enough and have not inhibited fluvial lateral erosion long enough to significantly reduce long-term terrace sediment flux to Puget Sound rivers, despite perhaps reducing mass movement incidence in some areas.

The proportion and position of Q1 layers has previously been hypothesized as the dominant hillslope characteristic regulating terrace mass movement volume (Perkins et al., 2017). The weak correlation between the proportion of Q1 and terrace erosion volume in our data only marginally supports our Hypothesis 3, although a more comprehensive stratigraphic investigation of the mass movements we mapped would be needed to more robustly test this hypothesis, as the well log data used here is inherently uncertain and limited to only a few dozen mass movements. We also note that we observed in the field and well log data multiple, discrete Q1 layers in many terraces, which presents a more complicated stratigraphy than the conceptual stratigraphy modeled by Perkins et al. (2017). The complex stratigraphy of some terraces and bluff faces presents an additional challenge for understanding the net influence of Q1 in terrace mass movement hazard and volume. Other processes and characteristics that we were unable to measure on the extensive scale of this study, like groundwater hydrology, hillslope vegetation cover, and climatic factors likely also regulate terrace erosion magnitude and would be

reasonable targets for further investigation of the hillslope-specific controls on terrace sediment delivery.

4.3 Managing Terrace Mass Movements and Sediment Delivery in Puget Sound Watersheds

Terrace sediment delivery is an important sediment source to Puget Sound rivers. Especially for unglaciated basins like the Stillaguamish, Snohomish, Cedar, Green, and Deschutes, management of sediment dynamics and estimates of sediment supply should consider terraces as a particularly important sediment source in lowland reaches. However, mass movement style, volume, and sedimentology vary substantially between individual terrace mass movements. That implies that efforts to manage terrace-derived sedimentation would be well-served by site-specific evaluations of terrace sedimentology, the flux of sediment from terraces to rivers, and routing to lowland depositional reaches, as opposed to relying on regional estimates. Effective evaluation of terrace mass movement hazard should likewise focus on determining the specific sedimentologic characteristics, failure mechanisms, and failure frequency, especially due to the substantial variability in fluvial and hillslope processes that result in these failures. Efforts to stabilize terrace mass movements by restricting lateral migration may work for outer bend falls and outer bend lateral retreats, but terrace bluffs are inherently unstable and can fail even without fluvial erosion at their base. While we show correlations between failure style and mass movement volume, more investigation is needed to determine the processes that determine failure mechanism and the probability of terrace mass movements. The indication that fluvial lateral erosion likely triggers most terrace mass movements suggests that the high sediment transport capacity floods may also result in substantial sediment delivery from terraces. This coincidence of sediment supply and transport implies that sediment currently stored adjacent to rivers in terraces is generally directly fluvially available, and further reinforces the need for detailed, basin-specific investigations of terrace sediment delivery to inform the management of sedimentation influences on issues such as flood hazard, levee and revetment evaluation, and restoration in Puget Sound rivers.

5 Conclusions

Erosion of Pleistocene glacial and Holocene lahar terraces is a substantial sediment source to Puget Sound rivers, and while large, infrequent landslides such as the 2014 Oso Landslide contribute substantially to the total terrace sediment delivery to rivers, smaller, infrequent mass movements likely dominate long-term sediment flux. As a voluminous source of laterally connected, coarse, and resistant sediment low in river networks, these terraces may be especially important in regulating channel morphodynamics in lowland, depositional reaches. While we characterized the magnitude and spatial distribution of terrace sediment supply, further, more detailed characterization of terrace stratigraphy and sediment size will be needed to determine the actual effects of terrace sediment in lowland depositional reaches. The variability in the magnitude of terrace sediment flux between basins also motivates a more explicit comparison of terraces versus erosion of alpine glacial, valley wall, and modern alluvial fill as sources of sediment driving channel morphodynamics.

Terrace sediment delivery flux is a complex function of both short-term fluvial erosion and hillslope characteristics conditioned by longer-term fluvial erosion and past glacial and volcanic sediment deposition. Rivers initiate terrace mass movements, but fluvial characteristics poorly predict mass movement volume. While we show that the geometry of terrace bluffs, likely

set by long-term fluvial incision and terrace stratigraphy, correlates with failure mechanism and resulting terrace erosion volume, we do not address the detailed, mechanistic controls on terrace mass movement volume or frequency. We suggest that hillslope sedimentology and hydrology would be appropriate targets for further testing of controls on terrace mass movement volume. However, unlike mass movements elsewhere on hillslopes, future development of our understanding of river-adjacent terrace mass movements must acknowledge the simultaneous importance of both fluvial and hillslope processes in regulating terrace mass movement volume and occurrence.

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7 Data Availability Statement

Data supporting the analyses presented here can be found in Dataset S1 (data organized by mass movement) and Dataset S2 (data organized by basin) as well as ...

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