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Key Points:

- Geomorphic observations and topographic reconstruction indicate the Missoula floods caused widening of the Columbia Gorge
- Peak discharge estimates decline by 30%–40% when accounting for a narrower canyon
- Megafloods of moderate frequency and magnitude, rather than the largest flood, transported most of the eroded rock from the Columbia Gorge

Supporting Information:

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

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Narrower Paleo-Canyons Downsize Megafloods

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Abstract Catastrophic drainage of glacial Lake Missoula through the Columbia River Gorge, USA, produced some of the largest floods ever known. However, erosion of the gorge during flooding has not been quantified, hindering discharge reconstructions and our understanding of landscape change by megafloods. Using a neural network and geomorphic observations, we reconstructed the gorge topography and found ~7.4 km^3 of rock was eroded from gorge walls. Accounting for a narrower canyon and matching flood high-water marks resulted in peak-flood discharge reconstructions of 6×10^6–7×10^6 m^3 s^{-1}, which are 30%–40% lower than prior estimates based on the present-day topography. Sediment transport modeling indicated that more frequent intermediate-sized floods transported most of the eroded rock. Thus, similar to alluvial rivers, discharge magnitude-frequency tradeoffs may also govern canyon formation by repeated megafloods.

Plain Language Summary Some of the largest floods in Earth's history occurred 20–14 thousand years ago from the catastrophic drainage of glacial Lake Missoula. The floodwaters coalesced near the Columbia Gorge, where the water flowed through a single channel. Prior work focused on the Columbia Gorge to reconstruct the magnitude of these floods. However, these estimates did not account for erosion by the massive floods, which changed the topography. In this study, we used a machine learning computational technique to reconstruct the topography prior to megaflood erosion. Our results show ~7.4 km^3 of rock was eroded from gorge walls. Accounting for a narrower gorge and matching flood high-water marks resulted in a peak-flood discharge that is 30%–40% lower than prior estimates, thus downsizing the largest floods in Earth's history. Modeling sediment transport over a series of floods indicated more frequent intermediate-sized floods transported most of the eroded rock, rather than the largest floods. This finding is similar to observations in rivers with sediment banks where tradeoffs exist between the size and frequency of floods in governing channel shape. Thus, it is possible that the same principles that govern the form of alluvial rivers also govern bedrock canyon formation by repeated megafloods.

1. Introduction

Erosion by outburst floods created some of the most dramatic topography on Earth (Bretz, 1923; Carling et al., 2010; Lamb et al., 2008) and Mars (Baker, 1982). Megafloods can trigger abrupt climate change, as large fluxes of freshwater can alter ocean circulation (Praetorius et al., 2020). Yet our ability to reconstruct the paleo-flood discharge is limited due to a lack of understanding of megaflood erosion (Lapotre et al., 2016; Larsen & Lamb, 2016).

Quantifying bedrock canyon erosion is critical for constraining the discharge of Earth's largest floods (Larsen & Lamb, 2016; Lehnigk & Larsen, 2022). Paleo-flood depth and discharge are often constrained using field evidence of the elevation of high-water relative to the present-day topography (e.g., Baker, 2001; Benito & O'Connor, 2003; Gupta et al., 2007). However, erosion during floods is often substantial (Cook et al., 2018; Lamb & Fonstad, 2010; Lapotre et al., 2016)—in some cases, eroding canyons in their entirety during the floods (Bretz, 1923)—making the use of present-day topography in paleo-hydraulic reconstructions uncertain (Larsen & Lamb, 2016; Lehnigk & Larsen, 2022). Work on a modern flood-carved canyon (Lamb & Fonstad, 2010) and mechanistic models (Lapotre et al., 2016) indicate jointed bedrock can rapidly erode where flood-induced shear stresses exceed plucking thresholds. Thus, modeling floods over the present-day topography provides only a maximum constraint on discharge where any canyon deepening or widening following the emplacement of high-water marks would cause the paleo-flow depth and width to be over-estimated (Lamb & Fonstad, 2010; Larsen & Lamb, 2016; Lehnigk & Larsen, 2022; O'Connor & Baker, 1992).

2. Study Area: The Columbia Gorge

Repeated catastrophic drainage of glacial Lake Missoula during the Pleistocene generated immense floods that eroded basalt and carved canyons into the Columbia Plateau, forming the Channeled Scabland in the northwest USA (Baker, 1973; Bretz, 1923; O'Connor et al., 2020). The flood waters eventually funneled into the pre-existing Columbia River Gorge, which has been a key location used to reconstruct peak discharges because it has been argued that the floods did not substantially modify the shape of the canyon (Benito & O'Connor, 2003; O'Connor & Baker, 1992; O'Connor et al., 2020). By matching field evidence of flood stage in models run over present-day topography to field evidence, individual floods have been estimated to range from 1×10^6 to 10×10^6 m^3 s^{-1} (Benito & O'Connor, 2003; O'Connor et al., 2020), which are some of the largest floods known in Earth history.

The argument that Missoula Floods did not substantially erode the Columbia Gorge was based, in part, on the Haystack Butte basalt flow at Miller Island, which dates to 830 ka (O'Connor et al., 2021), and extends down one side of the gorge into the modern channel (Figures 1a and 1b) (Bjornstad et al., 1991; O'Connor & Baker, 1992). However, the basalt flow exists on only one side of the canyon and comprises about 1% of the gorge length. Field evidence shows that outburst floods widened the gorge at this location; floods caused tens of meters of erosion across a bend in the channel that dissected the inner portion of the meander bend (Benito, 1997) and severed the once-continuous basalt flow, forming a trenched spur (O'Connor & Waitt, 1995a). Moreover, the Columbia Gorge lacks evidence that would preclude erosion elsewhere. Geomorphic indicators of bedrock erosion throughout the Columbia Gorge by the Missoula Floods are well documented, including scoured and steepened canyon walls, butte-and-basin scabland topography, and plucked blocks (Benito, 1997; O'Connor & Waitt, 1995b)—all attributes of megaflood erosion that have been documented throughout the Channeled Scabland (Baker, 1973; Bretz, 1923). Hence, it is not clear that the present-day gorge geometry accurately represents the topography when the megafloods occurred.

3. Methods

We reconstructed the pre-Missoula flood topography in the Columbia Gorge using geomorphic evidence of erosion and an artificial neural network (ANN). The ANN was originally developed to predict the geometry of bedrock valleys beneath sedimentary fills (Mey et al., 2015; Wang et al., 2014) and has been used to predict valley geometries with >80% accuracy (Mey et al., 2015). We estimated the gorge geometry before the floods based on the assumption that the lower portion of the gorge walls which were eroded by megafloods were originally morphologically similar to the adjacent, uneroded topography. The ANN was trained to minimize the error between observed and predicted elevations where no flood erosion occurred (Figures 2 and 3) and then was used to predict pre-flood elevations in eroded areas. To determine the extent of the training area, we used high-resolution lidar topography to map evidence of flood erosion following previous work (Benito, 1997; Benito & O'Connor, 2003; Bretz, 1924), including hanging tributaries, butte-and-basin topography, and breaks in hillslope profiles caused by near-vertical escarpments at the base of the gorge walls (Figure 3). The ANN input was a 10 m resolution digital elevation model (DEM) augmented with electronic navigation chart (ENC) bathymetric data. The DEM was edited to remove dams and landslides that intersect the present-day river channel (Figure 2); elevations at those sites were interpolated using ENC data. We resampled the DEM to 90 m for computational efficiency.

The contact between the Haystack Butte basalt and underlying Pleistocene Columbia River gravels is presently inundated at high flow, which has been interpreted to indicate the gorge has not substantially incised since eruption of the basalt (25 Waitt et al., 2021). Hence we made the conservative assumption the gorge floor has not changed in elevation. The reconstructed topography only accounts for gorge widening, and should be considered a minimum estimate of the amount of erosion that occurred. We quantified the change in gorge width and cross-sectional area between the present-day and reconstructed topography by generating transects every 500 m along downstream. We report widths calculated from gorge wall to wall, measured just above the elevation of the present-day channel, at the lowest elevation we reconstructed topography.

Flood modeling was conducted using ANUGA, which solves the 2D depth-averaged shallow water equations on a triangular mesh (Mungkasi & Roberts, 2013). The modeling domain extended along a ~170 km reach of the Columbia Gorge. We assigned a Manning's roughness coefficient (n) of 0.03 to the present-day river channel and adjacent alluvium, and a value of 0.05 to the dry gorge floor and walls to match prior work (Benito

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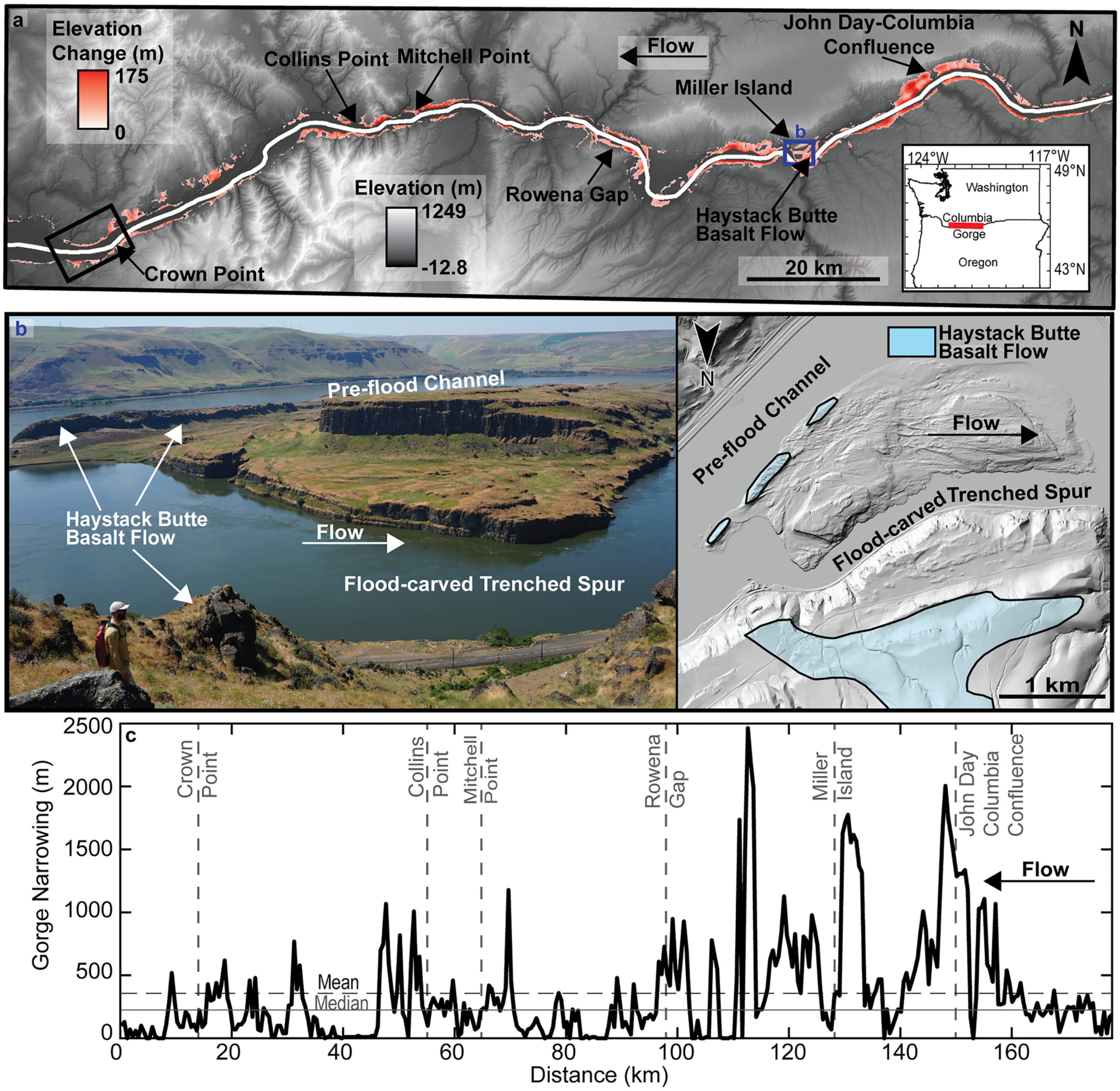

Figure 1. Study Site in the Columbia Gorge. (a) Elevation image of the study reach. The black box outlines the location of sediment flux analyses; water surface profiles were extracted from the white line, and the red shading indicates the predicted amount of lateral erosion. Inset shows the study location (red line). (b) Photograph and lidar-derived hillshade of Miller Island showing a once-contiguous basalt flow that was segmented due to flood erosion. (c) Decrease in gorge width from subtracting the artificial neural network-reconstructed topography from the present-day topography. The vertical lines show locations marked in (a).

& O'Connor, 2003). The downstream boundary was a fixed water surface elevation to allow water to exit the domain (Figure S1a in Supporting Information S1), which was located ~8 km from our area of interest to ensure the boundary did not influence the results. Model runs explored steady input water discharges that ranged from 1×10^6 to 10×10^6 m^3 s^{-1}, at increments of 1×10^6 m^3 s^{-1} (Figure S1b in Supporting Information S1).

4. Results

By subtracting the present-day topography from the ANN-reconstructed pre-flood topography, we found that approximately 7.4 km^3 of rock was eroded from the walls of the Columbia Gorge by the Missoula Floods (Figure 1a). The volume of rock eroded corresponds to a median elevation difference of ~40 m (Figure 1a), a median gorge width increase of ~224 m (interquartile range = 80–449 m) (Figure 1c), and a median cross-sectional area increase of ~0.026 km^2 (interquartile range = 0.008–0.06 km^2) (Figure S2 in Supporting Information S1).

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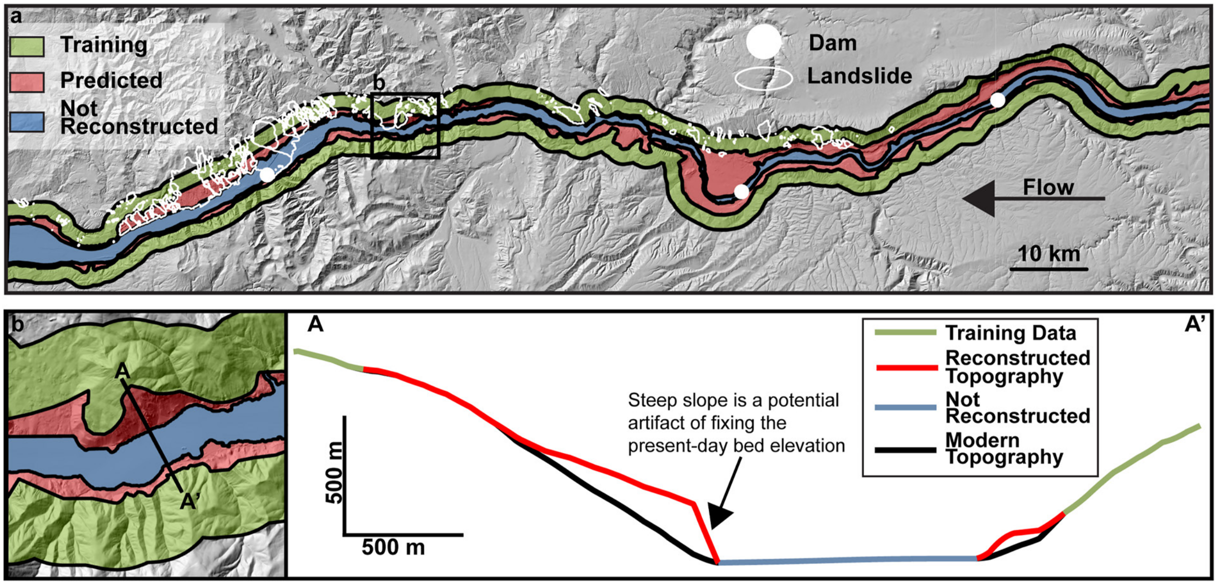

Figure 2. Artificial neural network (ANN) setup. (a) Extent of data used in the ANN showing the extent of the training data (green), the area where the ANN is predicting the topography (red), and the active river channel and alluvium where topography was not reconstructed. Locations of landslides are shown with white polygons and dams with white points. (b) Example of the reconstruction near Collins Point. Cross-section showing locations of training data above the limit of flood erosion, the present-day topography, reconstructed topography, and the unreconstructed river channel.

Comparison of water surface elevations for each simulated discharge against previously mapped field evidence of high-water (Benito & O'Connor, 2003; O'Connor et al., 2020) indicates a discharge between 8×10^6 and 9×10^6 m^3 s^{-1} was needed to inundate high-water indicators for floods routed over the present-day topography (Figure 4). In contrast, simulations using the narrower pre-flood topography required discharges of only 6×10^6–7×10^6 m^3 s^{-1} to reach the same water surface elevations (Figure 4; Table S1 in Supporting Information S1). The largest flood through the Columbia Gorge is thought to have occurred early in the sequence of Missoula floods (Benito & O'Connor, 2003), and therefore would have emplaced high-water marks prior to gorge erosion by subsequent floods. Overall, accounting for erosion of the gorge walls led to a 20%–30% reduction in the estimated peak flood discharge among our simulations.

We computed boundary shear stresses (Supporting Information S1; Figure 3) along the base of the gorge wall at Crown Point, Collins Point, and Mitchell Point (Figure 3), which are important constrictions in gorge width that control water surface profiles (Figure 3). Additionally, we calculated bed shear stresses at other locations with megaflood erosional features: on a flood-scoured bench near Rowena Gap containing butte-and-basin topography, at Miller Island where the Haystack Butte basalt was eroded, and near the John Day-Columbia River confluence where valley wall retreat created topographic discontinuities (Figure 3).

Modeled bed shear stresses generally exceed the threshold required for block sliding (Lamb et al., 2015) at discharges between 3×10^6 and 4×10^6 m^3 s^{-1} (Figure 3). Locations where we predicted erosion are consistent with our mapping of geomorphic indicators of erosion (Figure 3) and are co-located with constrictions in gorge width (Figures 1 and 3), as expected (e.g., Benito, 1997; O'Connor, 1993; Venditti et al., 2014). For example, at Miller Island we predicted 0.26 km^3 of bedrock erosion, which was focused primarily at the cutoff meander and along vertical escarpments (Figure 3a). Hence, the erosion predictions are consistent with geomorphic evidence. Near the confluence of the Columbia and John Day Rivers the reconstructed topography is a smooth hillslope profile where there is now an erosional escarpment (Figure 3b), and erosion increased the median width by 1,177 m and cross-sectional area by 0.14 km^2. The constrictions that are key hydraulic controls on upstream flood stages (Benito & O'Connor, 2003) also show evidence of erosion. For instance, at the Mitchell Point constriction we predict flooding increased the median gorge width by 220 m (Figure 1c) and the cross-sectional area by 0.05 km^2, consistent with geomorphic evidence of erosion, including hanging tributaries and an escarpment (Figure 3d). Gorge constrictions at Collins and Crown Point also show evidence of widening, such as hanging tributaries and erosional escarpments, and we predicted the width and cross-sectional areas increased

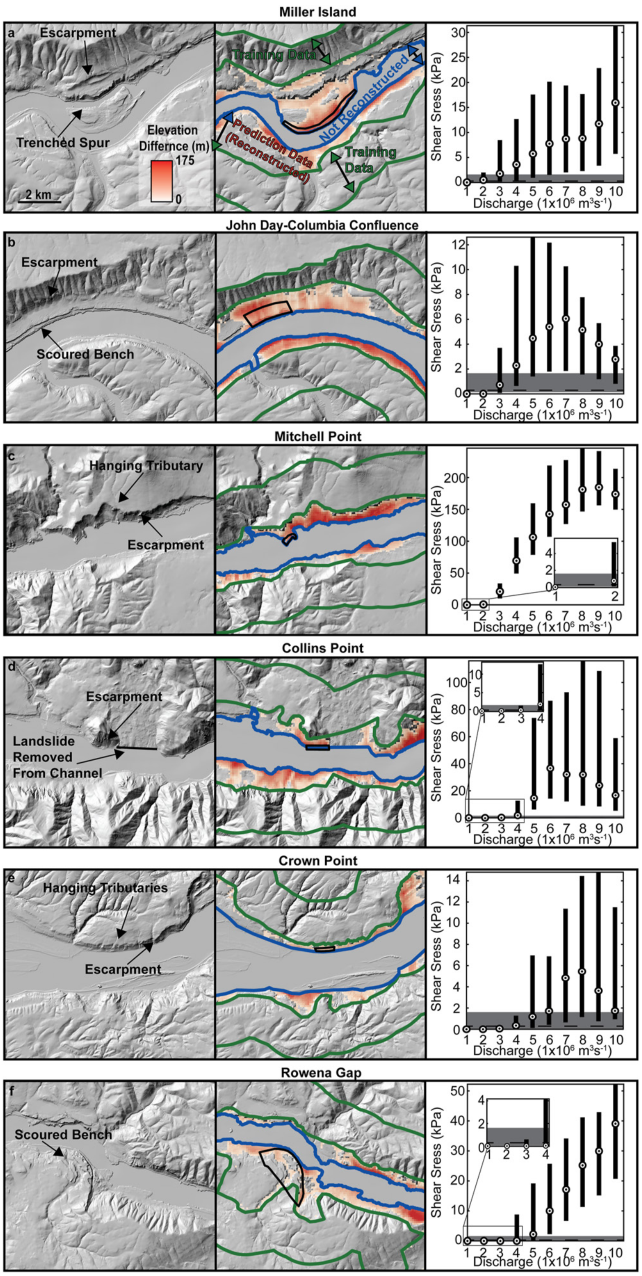

Figure 3. Examples of erosional features and shear stress measurements. The panels on the left show examples of erosional features on lidar-based hillshade images. The middle panels show elevation differences (red shading) from subtracting the present-day topography from the artificial neural network (ANN)-reconstructed pre-flood topography. The black polygons show where shear stress data were measured. Green lines outline the extent of ANN training data; topography between the green and blue lines was reconstructed by the ANN; and the area between blue lines is channel and alluvium, which is not reconstructed. Shear stress distributions are shown on the panels on the right. The back dots indicate the median and the black bars show the first and third quartile shear stresses. The dashed black line indicates the shear stress threshold to cause erosion by sliding a 33 cm block of bedrock. The gray bars show the range needed to slide a 13 and 83 cm blocks. The location of each site is shown on Figure 1.

by 229 and 109 m and 0.05 and 0.02 km^2, respectively, at these locations (Figures 3d and 3e). We predicted the gorge widened 90 m near Rowena Gap at a flood-scoured bench, where butte-and-basin scabland topography provides evidence of flood-induced erosion (Figure 3f).

5. Analysis: Erosion Rates and Geomorphic Work

It has been argued that megafloods that exceed the threshold for block plucking in well-fractured rock—like in the Columbia Gorge—might erode so rapidly that erosion is limited only by the ability of the flow to transport the entrained blocks (Lamb & Fonstad, 2010; Lamb et al., 2015; Lapotre et al., 2016). Perhaps ∼100 floods passed through the gorge (O'Connor et al., 2020) but evidence for most of these floods, many of which were likely low-magnitude, is not preserved. However, ∼25 megafloods do have discharge constraints (Benito & O'Connor, 2003) and we calculated the sediment transport capacity for these floods over four unique floodwaves (Figure 5a) to partition the eroded volume, which we found in Section 4, among different sized floods.

We constrained the shape of the floodwaves based on a previous simulation of a dam-break flood starting at Lake Missoula (Denlinger & O'Connell, 2010) (Figure S3 in Supporting Information S1). Prior work using field observations and 1D step-backwater modeling to match highwater marks indicated the Columbia Gorge experienced one flood with a peak discharge of 10×10^6, six floods of at least 6.5, eight floods of 3–6×10^6, and 10 floods of 1–3×10^6 m^3 s^{-1} (Benito & O'Connor, 2003). However, the peak discharge estimates were based on modeling flow over the present-day topography. We rescaled these peak discharge estimates, which also reduces flood volumes (Supporting Information S1), by adjusting water surface elevations based on our steady-state simulations (Figure 4) over the reconstructed topography to find corresponding peak discharges of 6.3×10^6, 4×10^6, 2×10^6 and 1×10^6 m^3 s^{-1}.

We found that a median sediment diameter of 33 cm, which is within the range of median bedload sizes reported elsewhere in the Channeled Scabland (Larsen & Lamb, 2016), results in the total transported sediment volume (Supporting Information S1) closely matching the amount of erosion we reconstructed from the ANN (Figure 5b). Using a sediment diameter of 33 cm for all floods, we multiplied the number of floods of a given magnitude by the transport rate per flood to find the total amount of sediment moved for each flood magnitude, which is a classic measure of geomorphic work (Wolman & Miller, 1960). Results indicate that floods with relatively moderate discharges (i.e., the six floods at 4×10^6 m^{3}s^{-1}) caused most of the erosion within Columbia Gorge (Figure 5c), not the largest reconstructed flood of 6.3×10^6 that is recorded only once.

6. Discussion

Although accounting for gorge widening reduces peak discharge estimates, the Missoula Floods were still large enough to surpass erosion thresholds. For instance, at the three main hydraulic constrictions, shear stresses at peak discharge were 5–150 times greater than the threshold for plucking (Figure 3); hence, it is untenable to assume these areas did not erode during the floods. Our results suggest that bedrock erosion would have occurred at discharges smaller than those required to inundate high-water marks

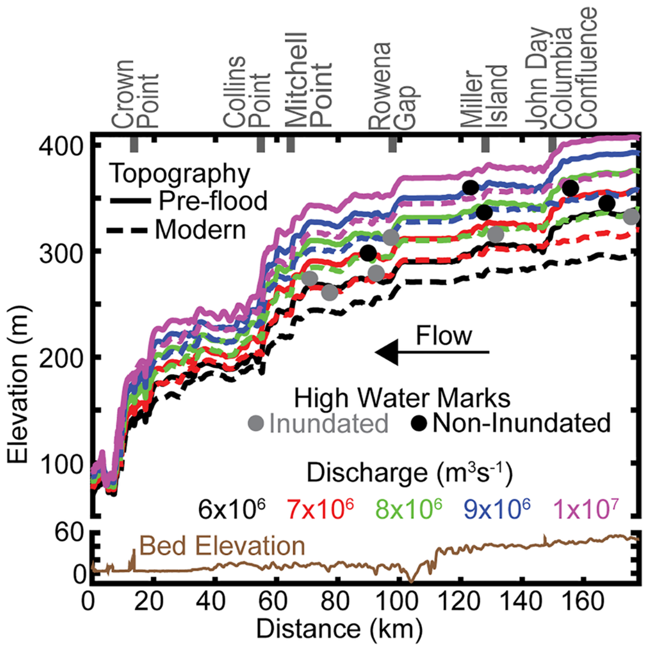

Figure 4. Water surface elevation profiles. The brown line shows the centerline Columbia River bathymetric profile. The colored lines show the simulated water surface using the present-day (dashed lines) and the reconstructed pre-flood (solid lines) topography. The circles show high-water marks (Benito & O'Connor, 2003; O'Connor et al., 2020), where gray and black denote sites that were inundated and non-inundated by floods, respectively. The gray ticks show locations marked in Figure 1a.

(Figure 4), consistent with work elsewhere in the Channeled Scabland (Larsen & Lamb, 2016; Lehnigk & Larsen, 2022), illustrating that changes in topography due to erosion can substantially affect paleo-discharge reconstructions.

Due to limitations in the ANN approach, the magnitude of topographic change we calculated is a minimum that only accounts for gorge widening and not deepening. Stage-discharge relationships (Figure 4) indicate that 18 m of water depth corresponds to about 1×10^6 m^3 s^{-1} at peak discharge throughout much of the gorge. Hence, 18 m of vertical channel erosion, would reduce the discharge needed to reach a high-water mark approximately by an additional 1×10^6 m^{3}s^{-1}.

Previous 1D step-backwater modeling of the Missoula Floods using the present-day topography predicted a maximum discharge of 10×10^6 m^3 s^{-1} (Benito & O'Connor, 2003), which is 30%–40% larger than our 2D model runs that accounted for lateral erosion. A different model simulated the flood wave from glacial Lake Missoula using the present-day topography and produced a discharge of 6×10^6 m^3 s^{-1} in the Columbia Gorge (Denlinger & O'Connell, 2010), which is substantially lower than prior 1D results (Benito & O'Connor, 2003) but similar to our results. The 6×10^6 m^3 s^{-1} discharge predicted by prior 2D modeling reached the elevation of high-water marks in the present-day topography (Denlinger & O'Connell, 2010), whereas our results indicate a higher discharge of 8×10^6–9×10^6 m^3 s^{-1} is required to inundate the same high-water marks (Figure 4). We suspect the lower discharge estimated by Denlinger and O'Connell (2010) may have been due to their use of a coarser resolution DEM (250 m) relative to our simulations (90 m). Coarse resolution DEMs can artificially narrow canyon topography by averaging elevations from the lower-relief uplands that surround the gorge with those of the steep canyon walls (Figure S4 in Supporting Information S1), thus resulting in smaller discharges needed to reach higher water marks.

At other locations in the Channeled Scabland (Bretz, 1923; Larsen & Lamb, 2016), and at other sites on Earth (Baynes et al., 2015; Carling et al., 2010; Lewis et al., 2006) and Mars (Carr, 2012; Lamb et al., 2008), megafloods formed canyons in their entirety, rather than by widening pre-existing canyons. In such cases the relative magnitude of erosion, and hence the possibility of overestimating discharge by using high-water marks to constrain flood depth, is much greater than for the case of the Columbia Gorge (Larsen & Lamb, 2016). Moreover, as shown by our analysis, more moderate-sized and frequent floods might be responsible for more erosion than the largest floods that emplaced the highest high-water marks. Since the more modest floods are thought to have occurred after the largest flood (Benito & O'Connor, 2003), it is possible that much of the gorge widening occurred after the emplacement of high-water evidence.

Canyons carved by outburst floods are common in columnar basalt or similar well-jointed rock (Baynes et al., 2015; Bretz, 1923; Carling et al., 2010; Lewis et al., 2006), where erosion rates can be rapid if the threshold for plucking is surpassed (Lamb & Fonstad, 2010; Lamb et al., 2008, 2014). Hence bedrock canyons may rapidly adjust their morphology during megafloods so that stresses might never greatly exceed the threshold for transport (Larsen & Lamb, 2016), similar to gravel-bedded river channels (Parker, 1978; Phillips & Jerolmack, 2016). Our results suggest that megaflood canyons that experienced multiple floods may have been shaped most prominently by moderate floods, similar to the role that bankfull-floods play in gravel-bedded river morphodynamics (Parker et al., 2007).

7. Conclusions

The discharge of some of the largest floods on Earth are often reconstructed from the canyons and highwater marks that they leave behind. However, these methods can be problematic because megafloods can substantially modify the canyon topography through erosion during flooding. Although the Columbia Gorge existed at the

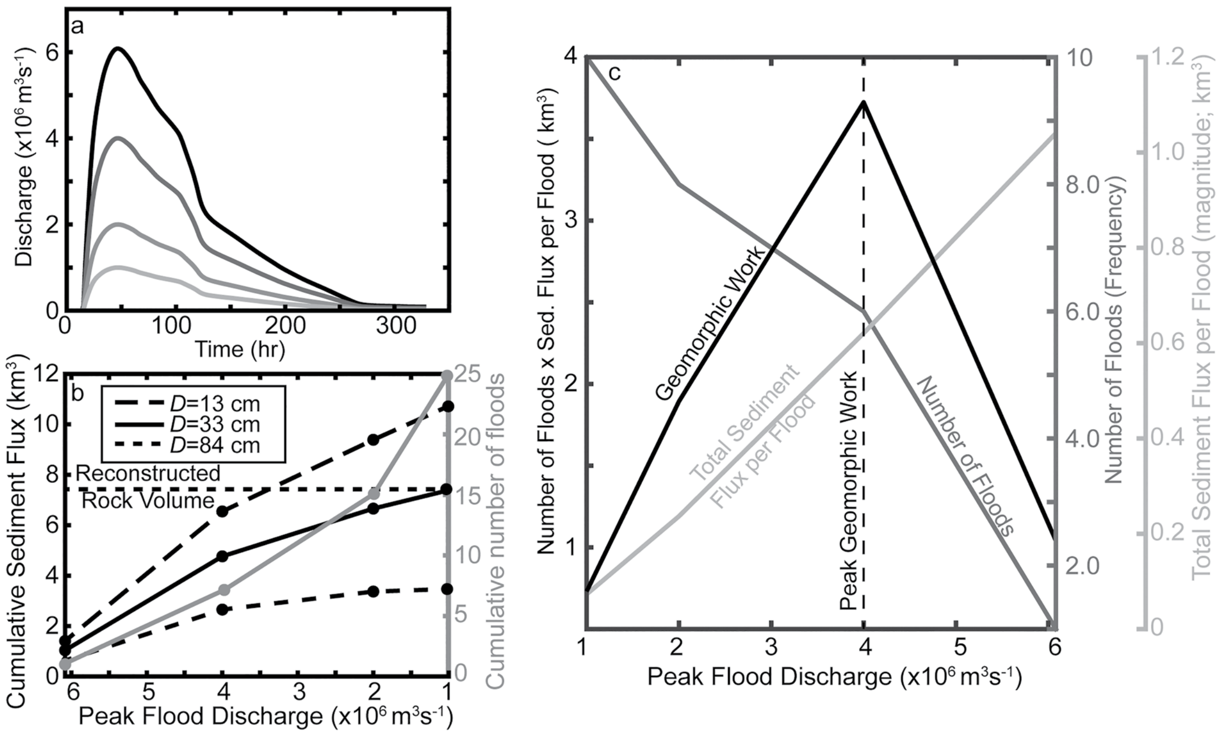

Figure 5. Sediment transport rates and geomorphic work. (a) Hydrographs used to model sediment flux out of the Columbia Gorge. (b) Cumulative number of floods (gray line) and cumulative sediment flux for different grain sizes (black lines). (c) The number of floods and total sediment flux per flood (using a 33 cm grain diameter) that occurred for each discharge (gray lines) and geomorphic work, the product of the number of floods and the sediment flux for each flood (black line).

time of the Missoula Floods, our ANN analysis indicated the floods widened the canyon by 224 m on average. Accounting for the narrower canyon during the earliest and largest of the Missoula floods that likely emplaced the high-water marks reduced the reconstructed peak flood discharges by 2–3 million m^3 s^{-1}. Sediment flux analyses suggest that the later occurring, more frequent and moderate-sized floods—with stages lower than the highest flood evidence—potentially dominated gorge erosion.

Data Availability Statement

Data, models, and analysis scripts are available via the University of Massachusetts ScholarWorks data repository (https://doi.org/10.7275/2d19-f718). The 10-m digital elevation model data are available at: https://apps.nationalmap.gov/ and the electronic navigation chart data are at: https://charts.noaa.gov/ENCs/ENCs.shtml. The lidar data can be acquired at https://lidarportal.dnr.wa.gov/ and https://gis.dogami.oregon.gov/maps/lidarviewer/.

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