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RESEARCH ARTICLE

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Rediscovering, reevaluating, and restoring Entiatqua: Identifying pre-Anthropocene valleys in North Cascadia, USA

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Abstract

A maturing body of evidence suggests that anthropogenic impacts on river-wetland corridors (RWCs) are greater and more widespread than previously recognized. Partly, this stems from the difficulty of differentiating between legacy anthropogenic impacts and channel evolution resulting from natural disturbances. Here, we apply the geomorphic grade line (GGL) relative elevation model (REM) method to reveal pre-Anthropocene fluvial features for a 42-km reach of Entiatqua (English translation—the Entiat River) in the North Cascade Mountains, USA. We began by long profiling the entire length of the river valley and defining distinct valley segments based on breaks in profile. Next, we developed models of the valley profile for each segment, known as GGLs, and used them to develop high-resolution REMs by detrending LiDAR-derived digital elevation models. We then used the GGL-REMs to map relict fluvial features in the valley floor. Validating the GGL-REMs using surficial geologic maps, ^{14}Cdated soil profiles, and the identifiable remnants of historic dams allows us to differentiate surfaces associated with the pre-Anthropocene from those resulting from anthropogenic activities, including splash damming, channel straightening, large wood removal, and beaver extirpation. Our findings reveal 1–2.5 m of anthropogenically-driven channel incision in unconfined and partially-confined valley segments, wherein fluvial sediment balances transitioned from being net depositional to erosive, and later neutral, with river environments in these segments shifting from being complex, ecologically-rich, RWCs to simpler, ecologically-impoverished, single-thread channels, like those found in confined valley segments. The adverse impacts of post-Anthropocene fluvial responses on salmon habitats were likely profound and may help explain historical and ongoing declines in populations of listed species, including Chinook Salmon (*Oncorhynchus tshawytscha*) and Steelhead Trout (*Oncorhynchus mykiss*). Our study of Entiatqua, together with evidence from other western US rivers, demonstrates that the GGL-REM approach can be used to re-envisage pre-Anthropocene fluvial process-form domains including identifying valley segments wherein fluvial responses to human development have disconnected RWCs.

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Once the pre-Anthropogenic conditions of rivers like Entiatqua have been recognized, the case for restoring lost RWCs to unlock their ecological potential becomes compelling.

KEYWORDS
anabranching, Anthropocene, degradation, GGL-REM, river-wetland corridor, salmon habitat, Stage 0 restoration, state change

1 | INTRODUCTION

1.1 | Anthropogenic impacts on river forms, functions and responses to disturbances

River-wetland corridors (RWCs) have particularly high ecological values (Cluer & Thorne, 2014), serving as an ecological nexus for biodiversity (Hauer et al., 2016), but they are among the most threatened ecosystems, globally (Wohl et al., 2021). These corridors have been systematically altered by humankind, at increasingly larger scales, for perhaps 7000 years, with no part of the globe being excepted (Brown et al., 2018; Mays, 2008; Sendzimir & Schmutz, 2018; Skidmore & Wheaton, 2022). In the Pacific Northwest (PNW), anthropogenic impacts did not begin in earnest until the arrival of substantial numbers of European and US settlers, during the 19th century. Initially, human impacts were largely inadvertent, resulting from widespread eradication of beaver (Wohl, 2021). Subsequent, more purposeful alterations included extensive land clearance and drainage, pervasive river channelization, water diversions, and removal of large wood and other obstructions from waterways (NRC, 1996; Sedell & Froggatt, 1984; Wohl, 2014).

These anthropogenic impacts triggered hydrologic, hydraulic, and morphologic responses that changed the relationship between rivers and their valleys and distorted how rivers accommodate natural disturbances (Livers, Wohl, Jackson, & Sutfin, 2018). As a result, disturbances such as floods and fires are generally viewed as having "catastrophic" impacts on contemporary rivers, while historically such events were crucial to sustaining multiple riverine functions (Benda et al., 2004; Bisson, Dunham, & Reeves, 2009). By the end of the 20th century, many rivers flowing through unconfined or partially-confined valleys had been transformed from net sediment stores into net sediment sources or net-balanced transport reaches. The outcome has been to convert many complex, multi-threaded, pre-Anthropocene RWCs bounded by fully connected floodplains into incised, single-threaded channels flowing between dry terraces and parched valley floors (Cluer & Thorne, 2014; Polvi & Wohl, 2013; Wohl et al., 2021).

1.2 | River restoration

River restoration is a global enterprise in which large sums are being invested. In the Columbia Basin alone, nearly US$300 million is spent annually to fund restoration projects intended to aid the recovery of salmonids and other native fish species (Rieman et al., 2015). Restoration practice evolves continuously, in response to its perceived successes and shortcomings (Bernhardt et al., 2005; Roni, Hanson, & Beechie, 2008; Tullos, Baker, Crowe Curran, Schwar, & Schwartz, 2021; Wohl, Lane, & Wilcox, 2015). Contemporary approaches tend to be "process-based" in that they emphasize river function and welcome dynamism (Beechie et al., 2010, Booth, Scholz, Beechie, & Ralph, 2016, Fuller et al. 2021, Ciotti, Mckee, Pope, Kondolf, & Pollock, 2021). Increasingly, process-based approaches also explicitly account for biotic, as well as the geologic and hydrologic, processes in approaches that now represent restoration best practice (Castro & Thorne, 2019; Ciotti, Mckee, Pope, Kondolf, & Pollock, 2021; Johnson et al., 2020; Pollock et al., 2014).

Effective implementation of process-based restoration requires robust conceptual and analytical frameworks and analysis of the governing processes at multiple spatial and temporal scales (Beechie et al., 2010; Cluer & Thorne, 2014). Moreover, successful outcomes require integrated analysis of biophysical and historical data to interpret past and ongoing watershed processes and trajectories and the signatures of human activities (Booth et al., 2020; Woelfle-Erskine, Wilcox, & Moore, 2012). In the context of process-based restoration, acquiring a sound understanding of geologic, historic, and current channel and valley floor forms and functions is critical to restoration design (Walter & Merritts, 2008). Without such understanding, the morphological impacts of past natural and anthropogenic disturbances can be conflated, and evidence of former and potential future river conditions can be easily misconstrued (Wohl, 2019). As noted by Brown et al. (2018), "Anthropocene rivers are largely imprisoned in the banks of their history." Without recognition of that fact, restoration goals for a given river valley may be set far below its full ecological potential.

To address this issue, Powers, Helstab, and Niezgoda (2019) developed the geomorphic grade line (GGL) and relative elevation model (REM), which can help geomorphologists reconstruct the river's past in ways that facilitate process-based restoration design. The GGL-REM approach combines analytical analysis of a high resolution (1 m or finer), digital elevation model (DEMs) with field evaluation to define the long profile of the valley floor, identify vertical and lateral geomorphic controls, and map both contemporary and relict valley features. The aim of the GGL-REM approach is to differentiate between current and legacy geologic/geomorphic and anthropogenic controls that govern a river's access to its alluvial process space, which is the fluvial domain of the river (Prominski et al., 2012).

1.3 | Study purpose

The purposes of this study are (i) to test and evaluate the reliability of the GGL-REM method, and (ii) demonstrate how the results of a

GGL-REM analysis can be used to evaluate restoration potential by reevaluating what a degraded river once was and envisaging what it could be again. Testing of the GGL method is accomplished via comparisons with independent mapping and dating of geomorphic surfaces and soil profiles in Entiatqua (a.k.a. the Entiat River Valley [ERV]), together with historical channel bed elevations inferred from the remnants of now defunct dams. Additionally, to help guide future restoration efforts, we interpret these data to broadly define pre-Anthropocene conditions in the valley and make inferences about past and present ecological conditions and functions. We use these inferences to identify what likely has been lost from Entiatqua during the last century and a half, and what might be recovered, through river restoration. Lastly, using more parsimonious investigations, we show how GGL-based REMs for other valleys are consistent with and complementary to a range of other mapping products available to support river analysis and restoration design.

1.4 | Study area

This study focuses on the Entiat River, which drains a 1210 km^2 basin on the eastern flanks of the North Cascade Mountains in Washington State, USA (Figure 1a). From its source, the river flows southeast to its confluence with the Columbia River at Rkm 777, near the town of Entiat. Relatively dry pine/fir forests found at the upper elevations currently transition to sage brush steppe at lower elevations. Like most rivers in Northern Cascadia, the Entiat valley was shaped by glaciation, and continues to be influenced by episodic sediment inputs following wildfires and major floods, both of which initiate landslides and debris flows that, in turn, create tributary confluence fans that encroach on the valley floor at many locations (USBR, 2009).

The Moses-Columbia Salish people who first occupied the valley named it "Entiatqua". Given that the suffix "qua" equates to the English term " river", the familiar name" Entiat River" is simply an anglicized version of its original, Salish word. "Entiatqua" translates literally as "place of grassy water", suggesting that, in the past, vegetated, RWCs were the defining feature of the river valley (Bright, 2004, Jeremy FiveCrows, personal communication, January 20th, 2022).

Complex and well-connected rivers (at all discharge levels) and wetland habitats extending across a valley floor have been shown to be highly productive and would have served as a foundation of the basin's capacity to support salmon and other aquatic biota (Bond,

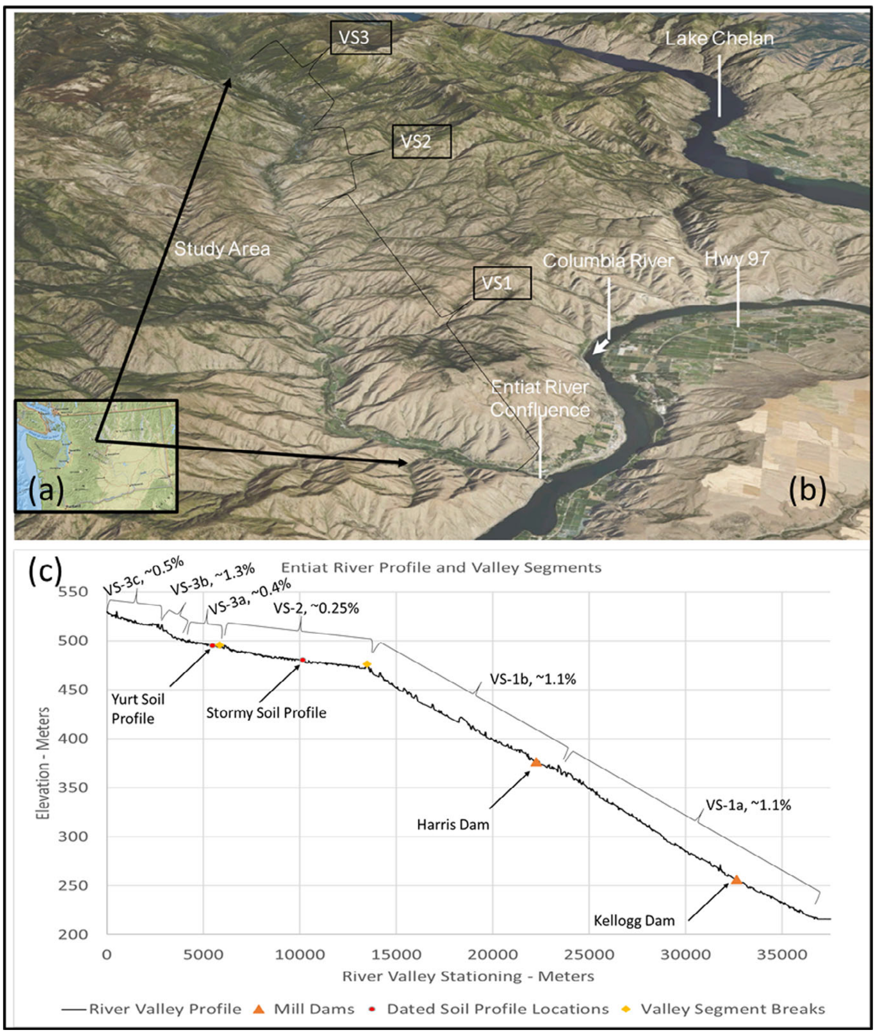


FIGURE 1 Entiat River Valley, North Cascades Mountains (a) Washington State, (b) Valley segments designated by USBR (2009), (c) Valley long profile with refined valley segment designations and locations of key features identified in this study [Color figure can be viewed at wileyonlinelibrary.com]

Nodine, Beechie, & Zabel, 2019; Cordoleani, Holmes, Bell-Tilcock, Johnson, & Jeffres, 2022; Jeffres, Holmes, Sommer, & Katz, 2020; Munsch, Greene, Mantua, & Satterthwaite, 2022).

Land use since European colonization includes grazing, fur trapping, timber harvesting, homesteading, floodplain farming, and road construction (USBR, 2009). Survey maps of 1918 reveal that homestead or tract claims were almost continuous along the lower 36 km of the river valley. Logs were transported downstream in river during this time and multiple dams were constructed for their storage (Long, 2001; Parker & Lee, 1922). Well-documented mainstem dams include Kellogg at Rkm 5.9 and Harris at Rkm 16. By the mid-20th century, the towns of Entiat and Ardenvoir had been established at the confluence with the Columbia River and at Rkm 16, respectively. Streambank protection structures were constructed along various sections of the river and at least one channel straightening effort was documented (USBR, 2009). More recently, large wood was removed from mainstem, side, and tributary channels, most notably in 1971, when nearly all the large wood was removed between Rkms 26.2 and 41.0.

A study performed by the US Bureau of Reclamation (USBR, 2009) established that the lower 42 km of the river is composed of three main valley segments (VS-1, VS-2, and VS-3; Figure 1b). Here, we analyze a valley reach comprising all three segments. In our initial examination, we identified discrete geomorphic controls (e.g., alluvial fans) and associated breaks in the valley long profile in VS-1 and VS-3. This led us to subdivide VS-1 and VS-3 into two and three sub-components, respectively (i.e., VS-1a and 1b, and VS-3a, 3b, and 3c, in Figure 1c). Our analysis focuses primarily on unconfined and partially-confined valley segments capable of providing sufficient process space for the river to develop a river-wetland corridor of the type defined by Wohl et al. (2021).

2 | METHODS

2.1 | Geomorphic grade line

We applied the GGL method developed by Powers, Helstab, and Niezgoda (2019) to define geomorphic surfaces on the valley floor, acquire insights concerning their condition and ecological function, and evaluate the geomorphic processes responsible for generating the surfaces, through space and time. The novel GGL approach to detrending valley floor elevations uses relic valley features as reference points, as opposed to features related to the current channel, such as water surface (Greco et al., 2008) or bankfull elevations (c.f., Rosgen, 1996). In applying this method, we first specified the extents of six valley segments based on the three segments originally defined by USBR (2009) and our analysis of topographic data at 1-meter resolution. Specifically, we identified valley segments with distinct fluvial processes based on their longitudinal profiles and confinement (Figure 1c).

Next, we used ArcMap Version 10.7.1 (ESRI, 2019) to digitize a valley centerline onto the digital elevation model (DEM) of each of the six valley segments and added long-stream stations and their associated elevations at 1 m intervals. Station spacing was sufficient to detect the full range of valley floor features (e.g., relic flow paths, wetlands, riparian surfaces). We fitted a polynomial regression equation to the station distance and elevation data to create the GGL, a model of the long valley profile, for each valley segment. Note: valley segment GGLs and their regression equations are included in the Supplemental Materials.

Finally, we developed a relative elevation model for each valley segment. This was achieved by subtracting existing valley surface elevations along a valley-wide cross-section at each station from the GGL elevation at that station. The GGL-REM is the detrended topographic map produced by combining the relative elevations of several thousand valley-spanning cross-sections. It is a quantitative, three-dimensional surface representing how much features present in the current valley floor and local elevations match or deviate from that of the GGL.

Field-validated applications of the GGL method in multiple ecoregions across the Pacific Northwest (Powers, Helstab, & Niezgoda, 2019) have established that in rivers similar in scale to the Entiat, elevations relative to the GGL that fall into a band between 0 and −0.2 m represent shallow channel bed surfaces (Figure 2b). Relative elevations in a band between −0.2 and −1 m are likely to represent pools and/or beaver ponds, while areas with relative elevations lower than −1 m and channel beds that are persistently more than −0.5 m below the GGL may well result from channel incision driven by changes in valley-scale process drivers, such as lowered base-level control or channelization.

Elevations between 0 m and +1.5 m above the GGL are often associated with fluvial features that formed within the pre-Anthropocene fluvial process domain. In contrast, surfaces with elevations higher than +1.5 m are likely to have been created either by landslides, debris flows, or tributary fans, by fluvial processes that operated under climatic or geologic conditions substantially different from those of the present or the recent past (e.g., river terraces), or by anthropogenic activities (e.g., flood embankments, raised roads).

In Figure 2, we use these general observations to interpret surfaces within the analyzed segments of the Entiat valley. For example, all the channels, ponds, wetlands, riparian fringes, bars, islands, and floodplains active under pre-Anthropocene conditions are found within a fluvial process space with relative elevations in the range of −1 to +1.5 m (Figure 2a,b). We interpret un-degraded, relic channels as being within −0.5 to 0 m of the GGL, and channels with beds lower than −0.5 m as being incised. These ranges capture most, though not all, of the natural features within these valley segments. For example, the beds of some deep pools and wetland ponds have relative elevations lower than −1 m. Hence, while the elevation ranges outlined above and illustrated in Figure 2 are neither fixed nor applicable to all situations, they do serve to discern the fluvial process space and associated environments that existed in the pre-Anthropocene ERV.

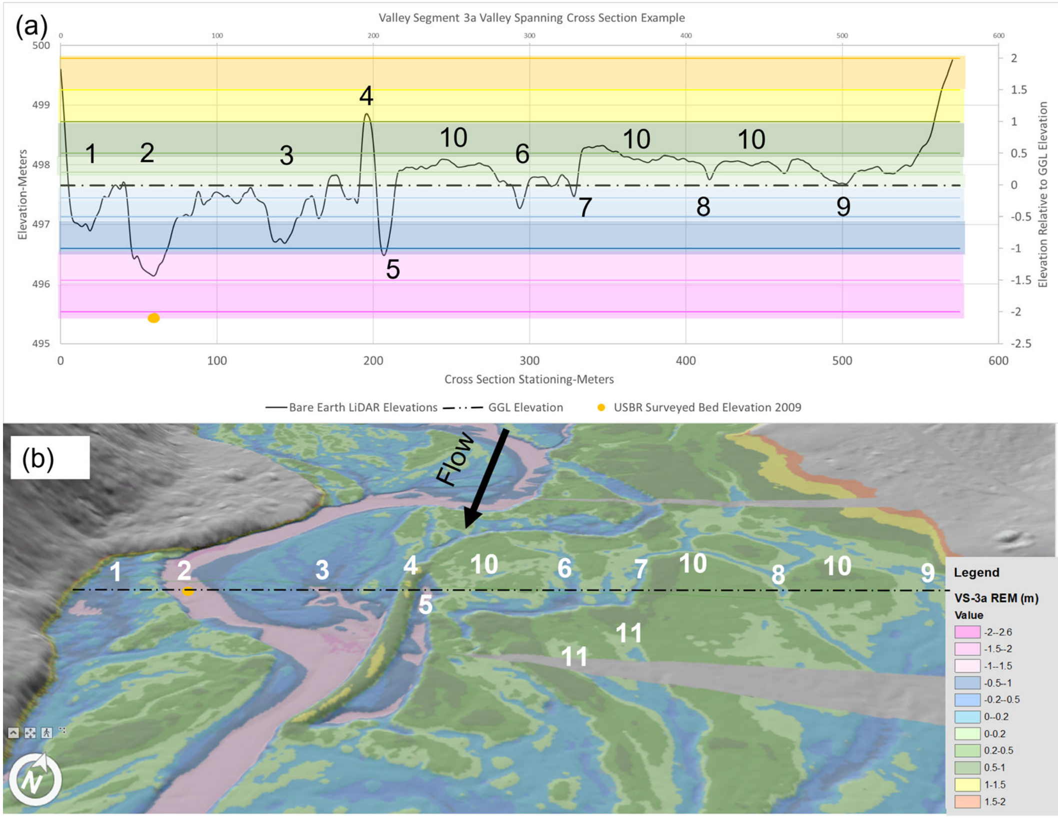


FIGURE 2 (a) Valley-spanning cross-section (station 1240 m) in valley segment VS-3a. GGL elevation is indicated by the dashed line, and color-coded bands correspond with the colors used in the GGL-REM. (b) 3D REM, which is comprised of several thousand cross-sections. Numbers indicate interpreted features within this river segment: Point 1. Relic wetland complex at western valley margin. Point 2. Current incised mainstem channel. Point 3. Relict side channel that has incised to match the current elevation of current mainstem. Local tributaries to this incised channel are dissecting an area at about the GGL elevation, which was formerly a wetland without discernible channels. This pattern of headward incision is visible across most of the relic valley floor in the study reach. Point 4. Linear embankment that extends along the left bank of the Entiat throughout this valley segment. Point 5. Linear depression which appears to be the borrow pit for soil used to build the embankment at point 4. Point 6. Another relic flow path that is incising to match the lowered base elevation at point 5. Points 7, 8, and 9. relic anabranching channels either at the GGL or within the −0.2 m range. These channels have not yet been incised. Point 10. vegetated riparian islands within the anabranching channel system. Point 11. Spring brook heads in the relic floodplain supported by an alluvial aquifer near the GGL [Color figure can be viewed at wileyonlinelibrary.com]

2.2 | United States Bureau of Reclamation (2009) datasets

Our aim was to assess the reliability of GGLs and REMs based on relic valley features to facilitate interpretation of valley floor terrain. In particular, we sought to test the consistency with which the GGL-REM method can help users to differentiate between valley floor landforms created by natural processes from features and surfaces resulting from past, anthropogenic actions and fluvial responses to those actions. The existence of an extensive dataset developed by the US Bureau of Reclamation (USBR, 2009) makes achieving those goals possible in the ERV.

2.2.1 | Surficial geology, alluvial stratigraphy

USBR (2009) used stereo images and ground truthing to map the surficial geology of the ERV into multiple age and process domain units. These data were integrated with previously developed maps of the lower 9.6 km of the valley. USBR (2009) then digitized the mapping units and compared them with LiDAR-derived DEMs and inundation depths estimated from hydraulic modeling. Soil descriptions were generated for each unit, and the deposits within them were dated at various depths. The planforms of historical mainstem and side channels were mapped using aerial photographs and LiDAR-derived DEMs. Our analysis focuses on the alluvial units, which we grouped into three broad classes: active channel, active floodplain, and Holocene floodplain (Figure 3).

USBR (2009) surveyed streambed profiles in some portions of the three main valley segments depicted in Figure 1. Where available, these data were used. However, bed elevation data are not available throughout our study reach. Where not available, we used LiDAR-derived water surface elevations as a surrogate. Elevational comparisons were generated by profiling the current channel and measuring the elevation of the water surface relative to the elevation of the GGL

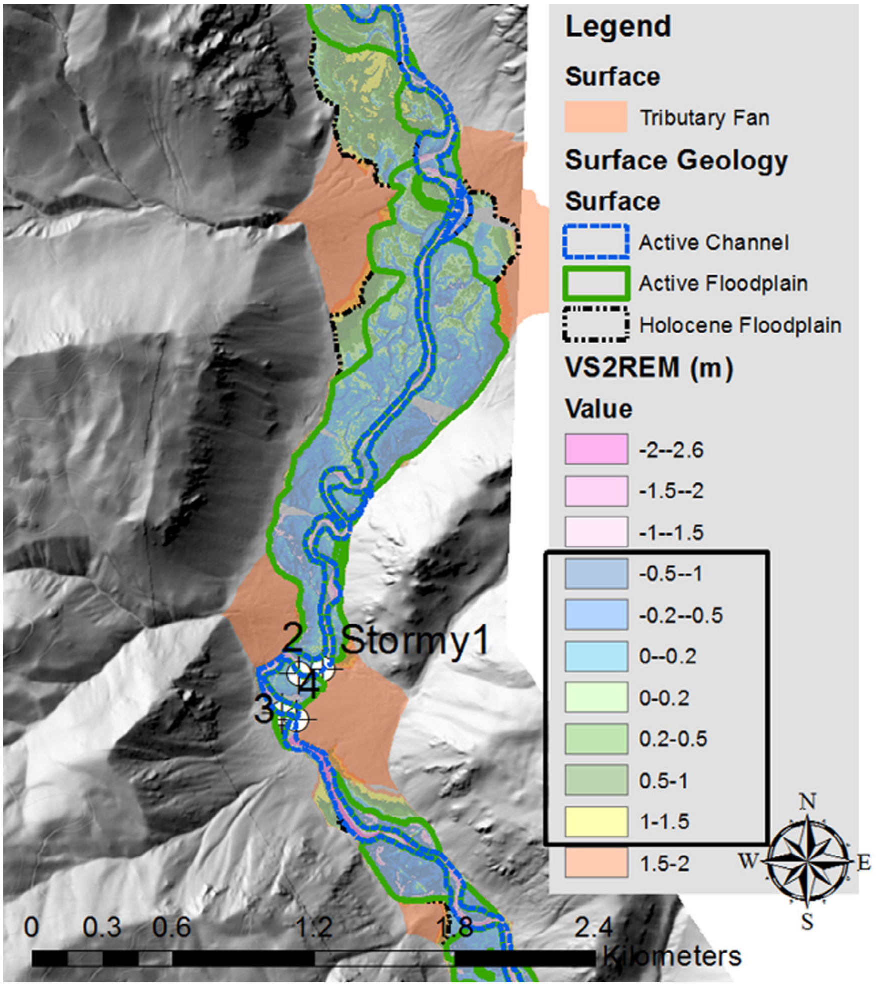


FIGURE 3 Valley segment VS-2 map prepared by USBR (2009) combined with the GGL-REM developed in this study (see Figure 1 for location). The area interpreted as the pre-Anthropocene fluvial process space in the GGL-REM (−1 to +1.5 m, highlighted with the black box within the legend) coincides with the area mapped by USBR as "active floodplain" and "active channel" in plan view. In the GGL-REM, the water surface in the single-thread, "active channel" mapped by the USBR is pink, indicating that it is incised by >0.5 m (plus depth from water surface to bed). In the USBR map, the "active channel" and "active floodplain" are mapped as separate features. In contrast, the GGL-REM suggests that, prior to anthropogenic disturbance, the anabranched river and its islands and wetlands occupied the full width of the valley floor even at base flow. The only exception to this finding is at the "Stormy 3" location, where the width of the active floodplain was (and remains) constrained by a valley-wide, tributary fan. Note: "Stormy 1 to 4" are sites with ^{14}C dated soil profiles discussed in the section titled "Human Impacts in the Entiat River Valley" [Color figure can be viewed at wileyonlinelibrary.com]

at that location. We interpret channel beds lower than −0.5 m below the GGL as being indicative of channel incision. Consequently, a channel with a water surface elevation of -1 m relative to the GGL is interpreted as being incised by 0.5 m plus the unknown depth to bed.

2.2.2 | Historical land use

USBR (2009) compiled a comprehensive, historical description of land use changes (in the valley and across the Entiat basin) that have the potential to impact river, wetland, and floodplain processes and conditions.

2.2.3 | Stream evolution model and predicted channel pattern

Valley segments were evaluated both in their current condition and as they existed during the age of Entiatqua—that is, prior to the Anthropocene, which began in this region during the mid-19th century. Conditions were assessed by reference to their stages in the Cluer and Thorne (2014) stream evolution model (SEM). We then compared these interpretations with channel patterns predicted for streams in the Columbia Basin by Beechie and Imaki (2014).

3 | FINDINGS

3.1 | GGL-REM validation

3.1.1 | Surficial geologic mapping

We found strong concordance between the GGL-REMs and the surficial geologic maps produced by USBR (Figure 3). Significantly, the fluvial process space derived from the GGL-REM (GGL −1 m to +1.5 m) encompasses practically all the valley floor mapped by USBR as active channel, active floodplain, historical alluvium, or paleochannel. While the USBR surface geology mapping and GGL-REM analyses showed comparable results in the horizontal and longitudinal dimensions, the USBR did not quantify vertical incision. GGL-REM analysis adds the vertical dimension, thereby revealing the degree of vertical disconnection between features. Within unconfined and partially-confined valley segments, the active channel described by USBR (2009) was consistently mapped in the GGL-REM as being incised by more than a meter plus the unknown depth of the bed below the water surface. The mainstem channel within the analyzed valley segments is interpreted as being incised by at least the following, plus the unknown depth of the bed below the water surface: VS-1a = 1.0 m, VS-1b = 2.4 m, VS-2 = 1.0 m, VS-3a = 0.5 m, VS-3b = 1.7 m, and VS-3c = 0.9 m.

3.1.2 | Alluvial stratigraphy

GGL-REM values for the Yurt Site in VS-3a display a broad, unconfined active floodplain featuring anabranched channels, wetlands, islands, and the currently incised, single-thread mainstem channel (Figure 4a). Note that, as in Figure 3, the black box in the legend shows that the relic features are all encompassed by the pre-Anthropocene, fluvial process space. The relic features revealed by the GGL-REM suggest a relatively low-energy, depositional environment, which is consistent with conditions in a river-wetland corridor. Radiocarbon (^{14}C) dates from USBR (2009) establish that fine-grained sediment accumulation occurred at this location between 1700–1540 (95% C.I.) CalPB and 1090–960 (95% C.I.) CalBP (i.e., between 250–410 CE and 860–990 CE) (Figure 4b). Hence, ^{14}C dating confirms that prior to human disturbance, deposition had been the dominant fluvial process in this valley segment for at least several hundred and, more likely, a few thousand years.

3.1.3 | Dams: records and remnants

Two mill dams built in the ERV during the early-20th century provided opportunities to check the reliability of pre-disturbance mainstem channel bed elevations inferred using the GGL-REM method. In 1913, the 2.4-m high Kellogg Dam was built at Rkm 5.9, in VS-1a (see Figure 1b). It was used for log storage and splash damming until it was destroyed by fire in 1917 (USBR, 2009). We used written records and photographs of the dam, in conjunction with contemporary imagery and topographic data, to locate the remnants of this dam. We then subtracted the known height of the dam (2.4 m) from the observed elevation of a remnant of the dam crest (258 m ASL) to estimate the elevation of the mainstem channel bed at the time of construction. This indicated that in 1913 the elevation of the bed was 255.5 m ASL, which coincides with the elevation of the GGL at that location (Figure 5). Based on this concordance, we conclude that the GGL accurately represents the pre-incision elevation of the pre-disturbance channel in VS-1a. Bed elevations in the mainstem channel surveyed by USBR confirm that, by 2009, incision had lowered the bed to −2 m relative to the GGL (Figure 5).

In 1930, the 4.1-m high Harris Dam was built at Rkm 16, in VS1a (see Figure 1b). This dam operated until 1948, when it was destroyed by the flood of record for the basin. Using the same approach as that for the former Kellogg Dam site, we again found that the channel bed elevation estimated from the known height of the dam and the

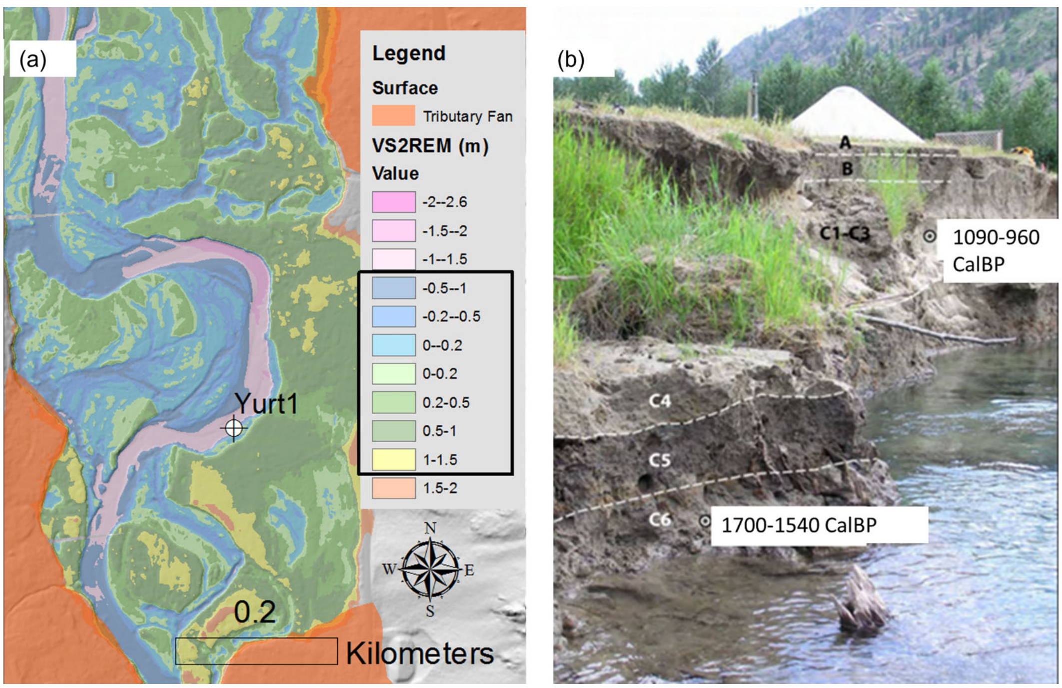


FIGURE 4 (a) GGL-REM for VS-3a showing the pre-Anthropocene, valley-wide, active floodplain that was occupied by a river-wetland corridor prior to mainstem incision (see Figure 1 for location). Black box in legend brackets the fluvial process space. (b) bank profile at the "Yurt" Site showing soil horizons (A through C6) with markers for ^{14}C dates published by USBR (2009) [Color figure can be viewed at wileyonlinelibrary.com]

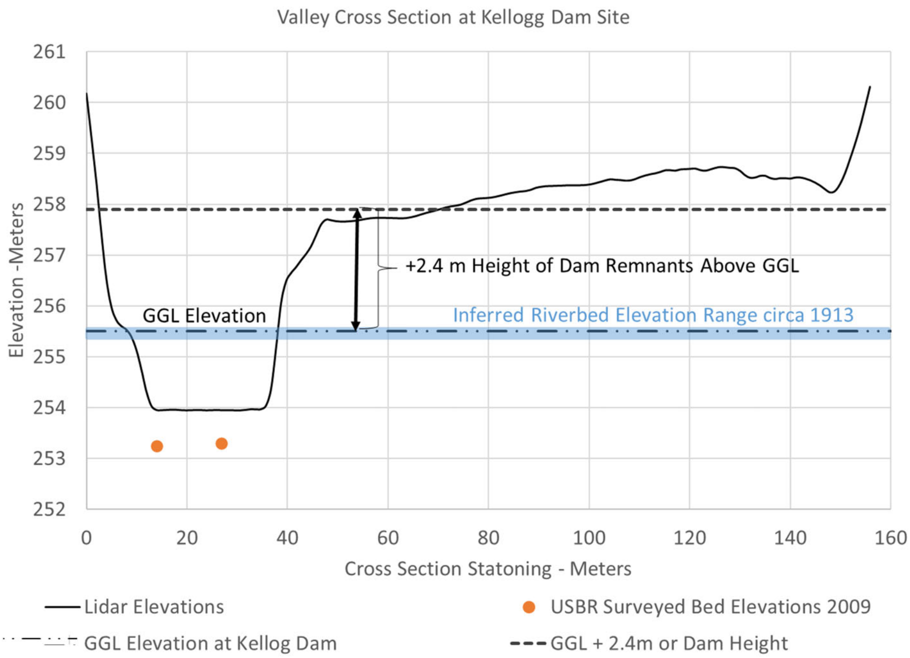


FIGURE 5 Valley cross-section at the Kellogg Dam site in VS-1a extracted from contemporary, LiDAR-derived DEM (black lines). Subtracting the described dam height (2.4 m) from the elevation of remnants of the dam top matches the elevation of the GGL at this location. We interpret this match as indicating that the GGL elevation accurately indicates the elevation of the bed of the mainstem channel when the dam was built in 1913. The LiDAR-derived cross-section indicates subsequent lowering of the water surface. Two nearby bed elevations (orange dots) surveyed by USBR (2009) confirm further recent bed incision [Color figure can be viewed at wileyonlinelibrary.com]

observed elevation of its remnants coincided with the GGL elevation. Based on this second validation, we conclude that the GGL accurately represents the pre-incision elevation of the pre-disturbance channel in VS-1b.

3.2 | Human impacts in the Entiat River Valley

Integrated analysis of novel GGL-REMs, re-interpretation of evidence compiled by USBR (2009), and an original investigation of the remnants of former dams suggest that significant incision of the Entiat River into its valley floor was triggered by the actions of European and US settlers during the late-19th and early-20th centuries. In this section, we summarize the apparent links between human actions and changes in fluvial morphology throughout the study reach of the ERV.

3.2.1 | Valley Segments 1a and 1b

Concurrence between the pre-dam bed elevations and the GGL elevation at the Kellogg and Harris dam sites establishes that in 1913 and 1930 respectively, the channel bed was at an elevation consistent with the GGL, suggesting that, at that time, the fluvial process space was intact and the Entiat was relatively undisturbed.

Field surveys conducted by the USBR establish that between 1913/1930 and 2009, the bed of the mainstem channel at the Kellogg Dam incised by ~2 m (Figure 5). While no field survey data are available for the Harris Dam site, an October 2016 LiDAR-derived DEM establishes that the water surface elevation in the mainstem channel was 1.5 m below the elevation of the GGL at that time. If we conservatively assume a late-autumn flow depth of 0.5–0.8 m at the time of the 2016 LiDAR survey, this suggests ~2.0 to ~2.3 m of mainstream incision at this site between 1930 and 2016.

Based on these findings, we conclude that Valley Segments 1a and 1b have experienced 2–2.3 m of anthropogenically-triggered incision.

3.2.2 | Valley Segments 3b and 3c

Evidence of recent channel incision in VS-3b and VS-3c is substantial. Historical accounts document that VS-3b and the lower portion of VS-3c were mechanically channelized during the early-20th century (USBR, 2009). Planform and long profile analyses using the USBR (2009) topographic data and the GGL-REM suggest that channelization lowered the base level for VS-3c, triggering headward erosion that extended incision further upstream than the extent of the channelized reaches themselves. Channelization has lowered the water surface profile throughout VS-3c to the extent that, on average, its elevation is −1.4 m relative to the GGL. Based on a similar water depth assumption to that made in VS-1 (0.5–0.8 m), we estimate that the channel bed is an average of 1.9–2.2 m below the GGL, which we interpret as indicating that 1.4–1.7 m of anthropogenically-triggered incision has occurred in these valley segments.

3.2.3 | Valley Segments 3a and 2

In these valley segments, in addition to GGL-REM and historical artifacts, stratigraphic soil analyses and dating by USBR (2009) at the Yurt Site in VS-3a (Rkm 34.4, see Figure 1c) and the Stormy Creek site in VS-2 (Rkm 29.6, see Figure 1c) provide a third line of evidence

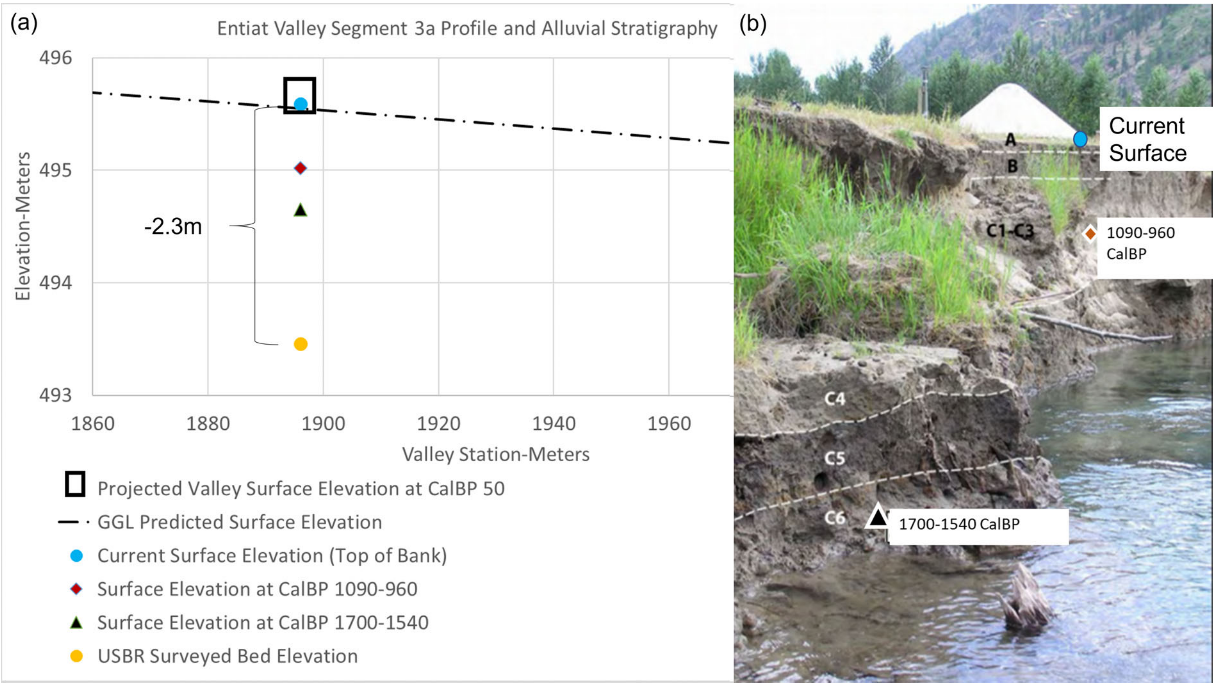


FIGURE 6 (a) Alluvial stratigraphy of the Yurt Site in VS-3a (see Figure 1b for location), showing accretion of fine-grained sediments between 1700–1540 CalBP and 1090–960 CalBP (250–410 CE and 860–990 CE). Bank top and valley floor surface are within 0.15 m of the GGL at this location and both are composed of fine-grained deposits. Projected valley surfaces at 50 CalBP (i.e., 1900 CE), based on elevations at 1090–960 CalBP and average accretion rates from hundreds of years prior, match both the GGL and the current elevations of the unchanneled valley floor. In contrast, the channel bed at the time of the USBR (2009) survey was 2.3 m below the GGL and is interpreted as being incised by 1.8 m.
(b) Bank profile at the 'Yurt' Site showing soil horizons with markers for ^{14}C dates published by USBR (2009). Letters in the photograph refer to soil horizons [Color figure can be viewed at wileyonlinelibrary.com]

indicating that substantial river incision in the ERV was triggered anthropogenically.

At the Yurt Site in VS-3a, radiocarbon (^{14}C) dating of soil profiles indicates that ∼0.4 m of net accretion occurred between 1700–1540 CalBP (95% C.I.) and 1090–960 CalBP (95% C.I.) (i.e., between 250–410 CE and 860–990 CE: Figure 6). This corresponds to an average accretion rate of ∼0.5–0.8 mm/year, which is within the range of the published long-term (>1000 years) average aggradation rates for streams and floodplains (0.1–0.8 mm/year) published by Beechie, Pollock, and Baker (2008). If we assume that accretion continued at this rate until ∼50 CalBP (i.e., circa 1900 CE), the valley floor at this location would have risen to somewhere between 495.5 and 495.8 m ASL. This elevation range matches both the observed elevations of the remaining, unchanneled portions of the valley floor in VS-3a and the elevation of the GGL at the Yurt Site (Figure 6a).

However, the bed of the current mainstem channel is 2.3 m lower than the elevations of the relic fluvial features, unchanneled valley floor, and GGL. This suggests that around 50 CalBP (i.e., circa 1900), the centuries to millennia-long accretionary trend was replaced by incision into the valley floor.

The soil analyses performed by the USBR (2009) establish that the sediments accumulating on the valley floor were predominantly fine-grained. According to the Shields (1936) graph, for sand to be deposited, bed shear stresses must be <0.5 N/m^2. This indicates that a low-energy fluvial system operated most of the time during the centuries to millennia over which fine-grained sediments accumulated in these valley segments. In contrast, a study by Interfluve (2013) found that under the 2-year flow, bed shear stresses in the mainstem channel of ∼32 N/m^2, which is sufficient to transport small cobbles into and through this reach.

The evidence presented here, taken together with available historical accounts, and the known sensitivity of these fluvial environments to human disturbance, strongly suggests that anthropogenic impacts associated with European/US settlement likely triggered a rapid state and process change in these valley segments. The outcome is that reaches that were naturally sinks for both coarse and, especially, fine sediments have been transformed into, and remain, transport reaches for both the suspended and bedload components of the incoming sediment load.

Findings at the Stormy Creek site in VS-2 also suggest a transition from net sediment accretion to net erosion or balance. Specifically, radiocarbon dates from two locations (Stormy 2 and 4) indicate that fine-grained materials accumulated here from 1065–970 CalBP (95% C.I.) to, or beyond, 520–440 CalBP (89% C.I.) (i.e., between 885–980 CE and 1430–1510 CE). Again, if the estimated average accretion rate during that period (1.3–1.8 mm/year) is assumed to have persisted until 50 CalBP (i.e., 1900 CE), the elevation of the valley floor

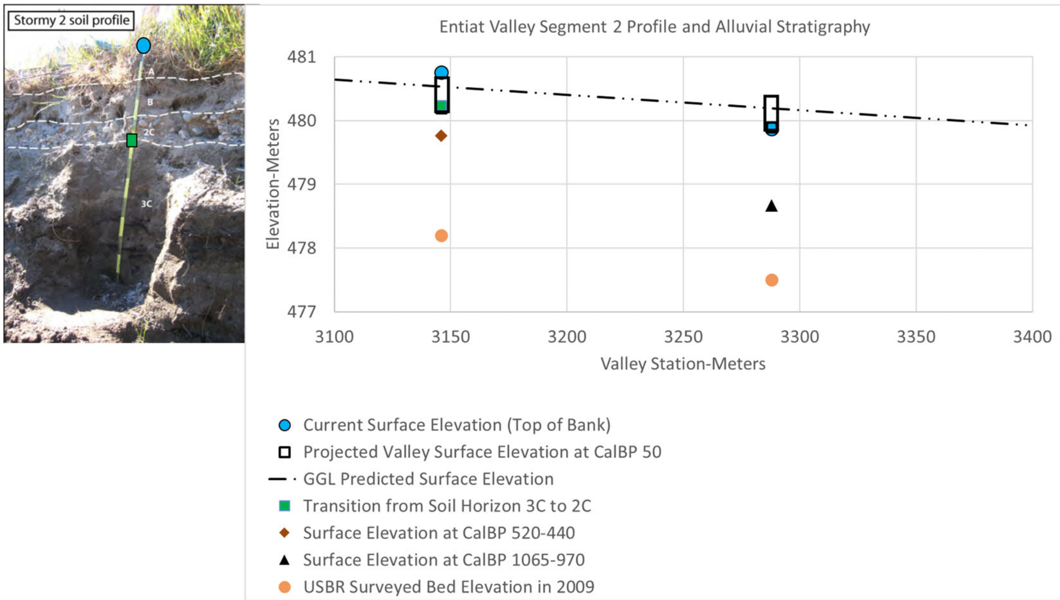


FIGURE 7 Alluvial stratigraphy at Stormy 2 (~station 3,140) and 4 (~station 3,290) sites in VS-2 with inset photo (USBR, 2009) of Stormy 2 soil profile (sampled locations are mapped in Figure 3). ^{14}C dates and soil characterizations (USBR, 2009) establish that fine-grained sediments accreted from 1065–970 CalBP to beyond 520–440 CalBP (855–980 CE to beyond 1430–1510 CE). Fine-grained deposits at the bank top elevation at Stormy 4, and fine-grained deposits at the top of soil profile layer 3C at Stormy 2 are within ±0.3 m of the GGL and valley floor elevation, indicating that the top of fine grain surfaces was likely the bed of a river-wetland corridor. Projected valley surfaces at 1900 CE, as described in Figure 6, further support this conclusion. The channel bed at the time of the USBR study (2009), however, was 2.3–2.8 m below the GGL. We interpret this as indicating 1.8–2.3 m of channel incision since around 1900 CE. Note: USBR (2009) soil profiles at the Stormy 1 and Stormy 3 sites have not been displayed or analyzed in this study, as these profiles are associated with tributary fan deposits, not Entiat alluviation [Color figure can be viewed at wileyonlinelibrary.com]

at Stormy 4 would have been between 479.9 and 480.3 m ASL. That range again corresponds with the elevation of the current unchanneled valley floor (Figure 7). Using a similar approach at Stormy 2, the elevation of the pre-Anthropocene valley floor would have been between 480.2 and 480.6 m ASL. Tellingly, this elevation range matches that of the interface between soil horizons 2C and 3C (480.2 m), where fine-grained deposits lie below a mantle of coarse-grained sediment. The upper boundary of soil horizon 3C at Stormy 2 would also correspond with wetland/beaver pond type alluvium similar to that observed at the Yurt site.

As found at the Yurt site, the GGL at the Stormy Creek site reasonably approximates both the elevation of the unchanneled surfaces in the valley floor and our interpretation of the pre-disturbance channel bed in this valley segment. The elevations of the top of fine-grained sediment layers at Stormy 2 and 4 are both at −0.3 m relative to the GGL, which is within the zone where fluvial and wetland features are expected.

However, observed channel bed elevations at Stormy 2 and 4 are, respectively, −2.3 m and − 2.8 m relative to the GGL. This further corroborates that circa 50 CalBP (i.e., circa 1900 CE), laterally-unconfined reaches in the Entiat fluvial system experienced a rapid state and process change. They ceased accreting fine-grained sediments and abruptly began exporting stored sediment as the river incised through centuries of accumulated material until the system attained the balanced sediment input–output condition that pertains today.

4 | DISCUSSION

4.1 | GGL-REM validation

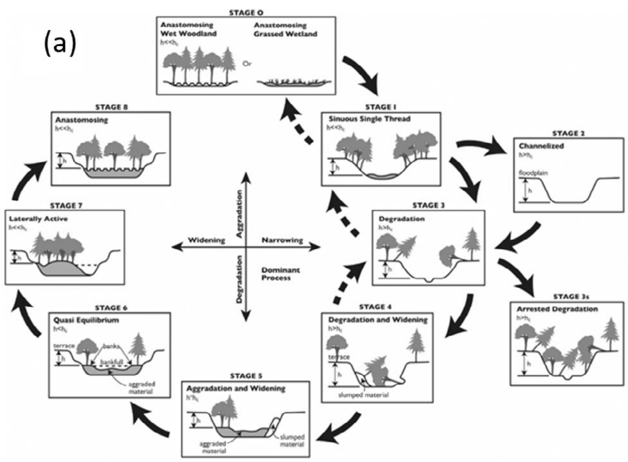
Our analysis demonstrates the utility and reliability with which GGL-REMs can be used to (a) identify and delineate fluvial process spaces and domains and (b) characterize pre-Anthropocene conditions in the ERV. Three lines of evidence support this statement:

1. We show that channel bed elevations inferred from the GGL correspond with pre-construction channel bed elevations at the dam sites in VS-1a and VS-1b.
2. Our GGL-derived REMs show strong concordance with independently mapped surficial geology. Specifically, our modeled pre-Anthropocene alluvial surfaces comprise the active channel, floodplain, and other Holocene alluvial surfaces mapped by USBR (2009).
3. Dated soil profiles and sedimentary analyses published by USBR (2009) confirm that the GGL-REM method can be used to accurately identify naturally depositional reaches and estimate the bed

elevations of pre-Anthropocene channels prior to recent incision in VS-2, VS3a, and VS-3c.

4.2 | Changes in the Entiat River Valley: interpreting the GGL-REMs using the stream evolution model

It has long been recognized that alluvial rivers respond to disturbance through a sequence of adjustments that can be conceptualized using channel evolution models (Schumm, Harvey, & Watson, 1984; Simon & Hupp, 1987). The stream evolution model (SEM) (Cluer & Thorne, 2014) built on the earlier channel evolution models by adding a pre-disturbance, river-wetland corridor condition (Stage 0), and later evolutionary stages involving lateral instability (Stage 7) and development of an inset river-wetland corridor (Stage 8) (Figure 8a). As streams evolve through the nine stages, changes take place in both their hydrologic & geomorphic attributes and the habitat and ecosystem benefits they provide. Stages 0 and 8 feature dynamically meta-stable networks of anastomosing channel-wetland systems that are fully connected to the active floodplain. In the SEM, these conditions confer the greatest ecosystem benefits and are the most resilient to



(b)

Valley Segment	SEM Stage and Dominant Processes		
	Pre-Anthropocene	Current	Anabranching Prediction (Beechie and Imaki, 2014)
VS-1a	mostly Stage 0, deposition, RWC in unconfined and partially-confined reaches, Stage 1 equilibrium in confined reaches	mostly Stages 3/4, channel incision, transport	56%
VS-1b	mostly Stage 1, equilibrium in confined areas	mostly Stage 3 incision, transport	48%
VS-2	mostly Stage 0, deposition, RWC	mostly Stage 3, incision, transport	100%
VS-3a			92%
VS-3b	mostly Stage 1, equilibrium	mostly Stage 3, incision, transport	82%
VS-3c	mostly Stage 0, deposition, RWC	mostly Stage 3, incision, transport	81%

FIGURE 8 (a) Stream Evolution Model (Cluer & Thorne, 2014). (b) Comparisons between pre-Anthropocene and current SEM stages inferred in this study and percentage of anabranching channel planform predicted in each valley segment by Beechie and Imaki (2014)

natural disturbance, primarily due to buffering associated with their large accommodation spaces, which facilitate net deposition and storage of watershed products, longer periods of floodplain saturation and inundation, and activation of the hyporheic alluvial aquifer beneath the floodplain.

The SEM provides a framework within which to characterize the pre-Anthropocene and current conditions identified in our study (Figure 8b). Unconfined and partially-confined valley segments (i.e., portions of VS-1a and b, all of VS-2 and VS-3a, and part of VS-3c) display similar trends of response to human disturbance, with the Stage 0 conditions interpreted to have persisted into the early-20th century transitioning to Stages 3 and 4. Confined valley segments (i.e., portions of VS-1a and b, and VS-3b), where Stage 1 is the expected pre-Anthropocene condition, have progressed to Stage 3s, being prevented from widening by their naturally narrow fluvial process spaces.

Our findings generally concur with the work of Beechie and Imaki (2014), who used morphometric analysis of 10-m DEMs to predict natural channel patterns for streams throughout the Columbia River Basin (Figure 8b). For example, we interpret Valley Segments VS-2, VS-3a, and VS-3c as having been mostly RWCs prior to anthropogenic disturbance. This is consistent with expectations from Beechie and Imaki (2014) that natural planforms in these segments would be predominantly anabranching (81–100%). Similarly, we conclude that RWCs were present but less abundant in VS-1a due to greater levels of confinement, which aligns with model expectations. Our interpretations differ from Beechie and Imaki (2014) for only VS-1b and the smallest segment, VS-3b, where we conclude RWCs may have been less common than model expectations suggest. These varying interpretations may be due to differences in DEM resolution (1 m vs 10 m), model error, or other factors.

While river incision is a well-documented natural process, including in glaciated landscapes like the ERV (Collins & Montgomery, 2011), it can be initiated or accelerated by human activities (Knighton, 2014; Simon & Darby, 2002). Our integrated analysis of geologic, sedimentary, and historical data in the ERV strongly points toward a significant anthropogenic signature on the timing and magnitude of the incision. Most conspicuously, the onset of incision coincides with the arrival of European and US settlers.

In this, our findings are comparable to those of Booth et al. (2020), who concluded that human activities such as those known to have impacted the ERV caused the Merced River to incise and partially disconnect from its historical floodplain. Specifically, they found that alluvial deposits 2–2.5 m above baseflow are now activated only half as frequently as they were a century ago. Similar levels of incision stemming from removal of large wood have been documented in coastal Oregon (Beschta, 1979) and the Olympic Mountains of Washington (Brummer, Abbe, Sampson, & Montgomery, 2006). Beechie, Pollock, and Baker (2008) found greater rates of anthropogenically-triggered incision in basins across eastern Washington and Oregon. Incision like that we documented at the former Kellogg and Harris dam sites has also been observed in other locales (Maaß & Schüttrumpf, 2019).

With respect to stream evolution, our findings are consistent with those of Gendaszek, Magirl, and Czuba (2012), Livers, Wohl, Jackson, and Sutfin (2018), and Cienciala, Nelson, Haas, and Xu (2020), who concluded that channel straightening and hardening, large wood removal, beaver eradication, and other land use impacts can transform complex, multi-threaded channels into simpler, single-threaded channels with lower channel migration rates. Importantly, Green and Westbrook (2009) established the rapidity with which such changes can occur by chronicling the transition of a 3-km stretch of Sandown Creek in British Columbia, Canada from an anabranched to a single-thread form in just 36 years following the removal of 18 beaver dams.

Lastly, while our findings support and confirm many of the outcomes of the USBR (2009) study, we add important new insights regarding the significance of assessing both the relative elevations of fluvial features, valley surfaces, and their degrees of lateral connectivity. Our work strongly supports the USBR's conclusion that, at the basin-scale, channel conditions, hydraulics, and sediment transport in the ERV are naturally influenced by geologic and geomorphic features. For example, tributary fans encroach across the valley floor at multiple locations, constricting the width of the Entiat's fluvial process space and providing local base-level control. However, USBR (2009) concluded that the impacts of human activities were limited in magnitude and extent. We have shown that a suite of anthropogenic disturbances resulted in a geomorphic state change that profoundly altered the riverine environment of the ERV, most notably by triggering transition of complex, depositional, RWCs to simple, single-thread, transport channels. Along significant portions of the unconfined and partially-confined portions of the study reach, the elevational differences between the pre-Anthropocene, anabranching Entiat River, and the Holocene floodplain were much less than they are today and in many areas were near zero (i.e., the elevation of the former riverbed coincided with that of Holocene floodplain). Given the disproportionately high value of well-connected river-wetland systems valleys to salmonids, we conclude that human impacts on those fishes may be greater than previously surmised.

4.3 | Restoration potential: what Entiatqua was, and the Entiat River Valley could again be

The magnitude and extent of changes wrought in these critically important valley segments have substantial implications for achieving salmon recovery goals. Recent research (e.g., Bond, Nodine, Beechie, & Zabel, 2018; Bond, Nodine, Beechie, & Zabel, 2019; Crozier, Burke, Chasco, Widener, & Zabel, 2021; Jeffres, Holmes, Sommer, & Katz, 2020), recovery plans (NOAA, 2007), and biological opinions (NOAA, 2020) recognize the critical role of floodplain restoration in recovering populations of salmonids from their currently depressed states and negative trends. This suggests that to facilitate salmon recovery in the ERV, future restoration projects need to reconnect, as much as possible, the fluvial process space that has been lost in the unconfined and partially-confined segments. Where feasible, this may be best achieved by resetting the valley floor to its pre-degradation condition: an approach colloquially termed "restoration to Stage Zero" (see http://stagezeroriverrestoration.com/). Simply put, the restoration goal should be to maximize the habitat and ecosystem benefits that the ERV can provide. Restoring the Entiat's fluvial process space would also enhance its hydrologic and geomorphic attributes (Cluer & Thorne, 2014), building resilience by increasing the number of degrees of freedom the fluvial system has available (Hey 1978) to accommodate future disturbances and evolve in response to them, while maintaining its morphological complexity and biodiversity (Wohl et al., 2021). This is especially important in the context of a rapidly changing climate and uncertain future (Beechie et al., 2013; Crozier, Burke, Chasco, Widener, & Zabel, 2021; Skidmore & Wheaton, 2022).

If we compare the habitats within the current channel to those that we interpret to have been lost through the progression from a Stage 0 to a Stage 3/4 condition, we find a much simpler, less connected riverscape than the one that existed prior to human-induced degradation. We conclude that the highly connected and diverse habitats associated with pre-Anthropocene ERV would have provided: (i) a greater extent and wider array of wetted environments, and (ii) habitats that were more abundant, diverse, and accessible to aquatic, riparian, and floodplain organisms.

Our integrated analysis reveals how the pre-Anthropocene ERV may have looked and functioned prior to human-induced degradation. The GGL-REMs provide a three-dimensional view of the river that had persisted in the unconfined and partially-confined valley segments for centuries to millennia, which is a view of Entiatqua (Figure 9).

Re-envisioning the ERV as it was and why it is no longer in that state is crucial to understanding what it could be again. Once the potential of the river to create habitat mosaics and support biodiversity has been recognized, the next step is development of a strategy for restoring key processes (e.g., sediment deposition in unconfined valley segments), functions (e.g., nutrient cycling), and connectivities (lateral, vertical, and longitudinal). Of particular relevance to restoring lateral connectivity are the relative elevations of features and surfaces identified in the pre-Anthropocene valley floor (i.e., prior to human-triggered incision). While pre-Anthropocene and current conditions might appear similar when regarded in plan view (e.g., seasonally-inundated side channels and sloughs are still visible in the current condition), their elevations relative to the water surface (and alluvial aquifer) at base flow and degrees of lateral connectivity are vastly different. Rather than intermittent connectivity with these floodplain

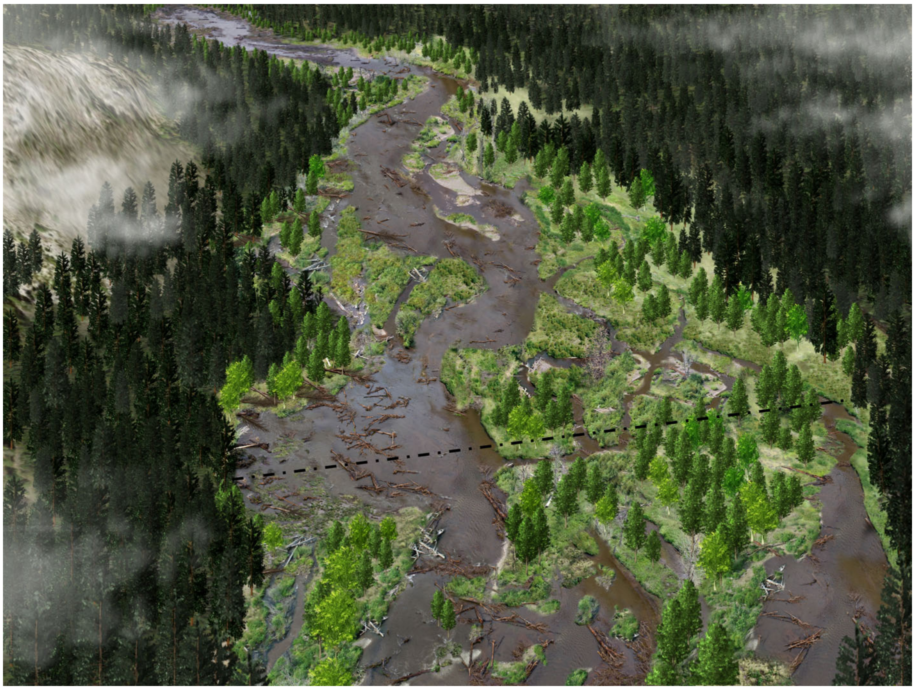


FIGURE 9 A view of Entiatqua—a fully connected river-wetland corridor wherein biogeomorphic processes (e.g., large wood accumulation, beaver dam construction, vegetation dynamics) and river-wetland attributes (e.g., valley geometry, channel planforms, channel migration, connected alluvial aquifers) interact in complex ways, via multiple, nested feedback loops. The perspective is looking upstream along the valley in VS-3a, with the valley-spanning cross-section in Figure 2a in the middle distance (dashed line). Side-by-side images of the REM and Entiatqua are provided in the Supplemental Materials. Vegetation assemblages are related to landforms identified in the GGL-REM shown in Figure 2b, based on vegetation surveys and observations made in reaches of Whychus Creek, OR that have been restored to their pre-disturbance condition, which is also known as Stage 0. The fully connected river-wetland corridor would likely be perennially wetted due to greater inundation area and reduced depth to the alluvial aquifer, as has been observed at Whychus Creek and other locales where valley floor restoration has been implemented (Flitcroft et al., in press) Wetted area assumes the elimination of inferred anthropogenically-triggered channelization and a water surface elevation at +0.1 m relative to the GGL. [Color figure can be viewed at wileyonlinelibrary.com]

features, creation and interpretation of the GGL-REM reveal that under pre-Anthropocene conditions, anabranched channels and wetlands were connected perennially. Lateral and vertical hydrological connectivity are exceedingly important to sustaining the vitality of river systems because they make the difference between side channels that are connected only during infrequent flood events, and complex RWCs that are fully connected at all discharges. Furthermore, connectivity promotes key functions including fine-sediment deposition, nutrient retention and cycling, and hyporheic exchange while endowing the fluvial system with the suite of attributes needed to sustain the most productive riverscapes.

Restoration goals should therefore focus on providing the maximum degrees of freedom for the river to once again self-form and re-form within the bounds of its available process space and so accommodate the effects of all the combined process drivers affecting it (Ciotti, Mckee, Pope, Kondolf, & Pollock, 2021). Restorative actions taken to achieve these objectives may include removing artificial constraints (e.g., revetments, levees), filling anthropogenically-incised channels, adding large wood, building logjam complexes, and promoting beaver-related restoration (Pollock et al., 2014; Powers, Helstab, & Niezgoda, 2019; Wohl et al., 2021).

4.4 | Broader implications for restoration

Wohl et al. (2021) stressed the need to rediscover, reevaluate, and restore RWCs globally. Our investigation of the ERV and more parsimonious analyses in other valleys suggests that GGL-REMs can be a valuable tool in revealing the history, valley process domains, and full restoration potential of these systems. For example, GGL-REMs correspond with surficial geologic mapping of the Yosemite Valley at a resolution comparable to that reported here for the ERV (Booth et al., 2020; Figure 10a), while a similar agreement has been found with coarser resolution geologic mapping of the Methow and Twisp River Valleys (USBR, 2009; Figure 10b), and even with General Land Office mapping of the Willamette River (Sedell & Froggatt, 1984; Figure 10c).

The significance of our work stems from the fact that GGL-derived REMs are novel tools for river valley analyses in that they use the elevations of relic valley features as the point of reference (Powers, Helstab, & Niezgoda, 2019), rather than the more commonly used surface water elevation (Greco et al., 2008) or bankfull elevation. Moreover, because high-resolution digital topographic data are now widely available, the GGL-REM method can be applied rapidly and inexpensively across large valleyscapes.

We recognize that, like all topographic analysis tools, GGL-derived REMs have limitations. Most notably, depending on geomorphic context, similar valley landforms can be created by different processes and similar processes can create diverse landforms. Nonetheless, the geometry of valleys and the topographic signatures of features within them reflect both past and ongoing processes, while also strongly governing future valley and channel responses to large disturbances initiated both within and outside the valley floor (Grant & Swanson, 1995; Livers & Wohl, 2016; Wohl & Cadol, 2011). As such, the GGL-REM method can provide important tools for valley-scale analyses and systemic river restoration planning. The GGL-REM method can be particularly revealing when used in concert with geologic, hydrologic, and historical information and SEMs, as was done in this study.

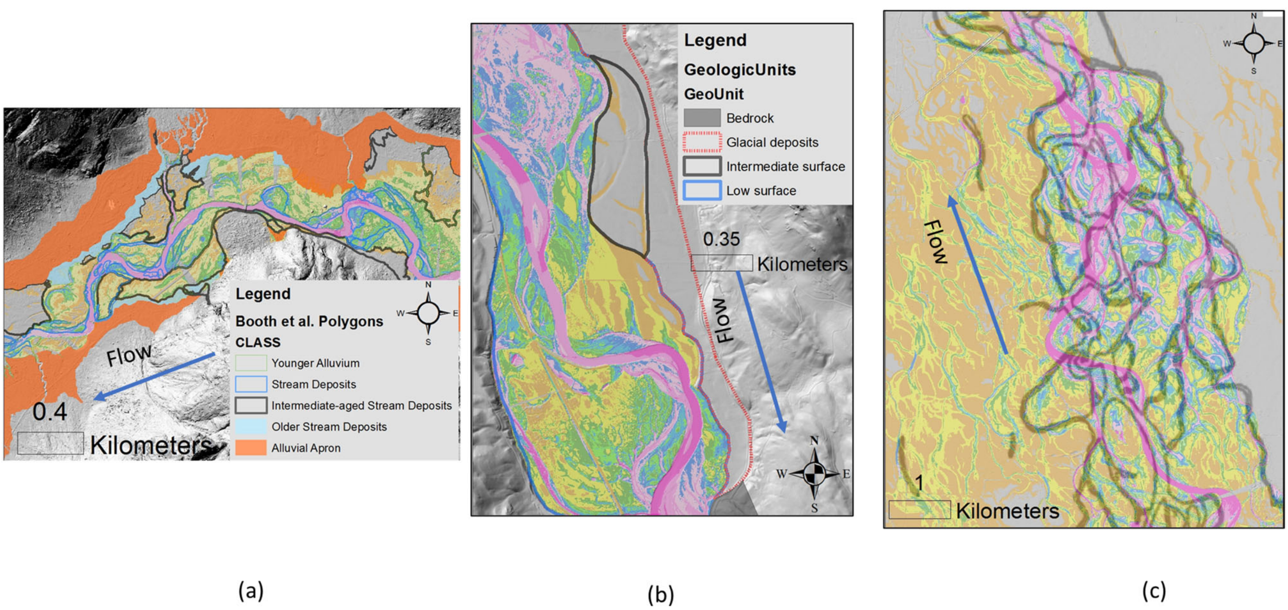


FIGURE 10 GGL-REMs compared with (a) surficial geology of the Merced River Valley, Yosemite, CA (Booth et al., 2020). (b) Coarser geologic mapping of the Methow and Twisp River Valley, WA (USBR, 2009). (c) General Land Office mapping of the Willamette River Valley, OR (Sedell & Froggatt, 1984) [Color figure can be viewed at wileyonlinelibrary.com]

5 | CLOSURE

Based on mapped surficial geology, dated sediment deposits, remnants and records of the Kellogg and Harris Dams from around the turn of the 20th century, and guided by the indigenous name for the Entiat River, we infer that our GGL-REMs accurately capture pre-Anthropocene conditions in the ERV. These multiple, converging lines of evidence indicate that RWCs in unconfined and partially-confined valley segments had been accreting fine-grained sediments for centuries to millennia until a geomorphic state change occurred following the arrival of European and US settlers. At around that time, the river began incising into the valley floor to current depths that exceed 2 meters in many reaches. Incision converted the pre-disturbance riverbed to the floodplain of the current river channel. Bold restoration actions could reverse the anthropogenically-triggered geomorphic state change, resuscitate key biogeomorphic processes, and facilitate the reestablishment of the networks of anabranching channels, wetlands, and vegetated islands that previously characterized this river and for which it was named: Entiatqua—*the place of grassy water*. The diverse and accessible riverine and wetland habitats recreated by such actions could contribute toward the recovery of listed salmon populations (Bond, Nodine, Beechie, & Zabel, 2018; Bond, Nodine, Beechie, & Zabel, 2019; Crozier, Burke, Chasco, Widener, & Zabel, 2021; Jeffres, Holmes, Sommer, & Katz, 2020). More broadly, GGL-derived REMs can be used to conceptualize and plan process-based restoration in naturally unconfined and partially-confined valley segments in any locales for which high-resolution DEMs exist. The GGL-REM method is, however, best used in concert with other datasets and analysis tools.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

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REFERENCES

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Beechie, T., & Imaki, H. (2014). Predicting natural channel patterns based on landscape and geomorphic controls in the Columbia River basin, USA. *Water Resources Research*, *50*, 39–57. https://doi.org/10.1002/2013WR013629

Beechie, T., Imaki, H., Greene, J., Wade, A., Wu, H., Pess, G., … Mantua, N. (2013). Restoring salmon habitat for a changing climate. *River Research and Applications*, *29*(8), 939–960.

Beechie, T. J., Pollock, M. M., & Baker, S. (2008). Channel incision, evolution and potential recovery in the Walla Walla and Tucannon River basins, northwestern USA. *Earth Surface Processes and Landforms*, *33*(5), 784–800.

Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., … Pollock, M. M. (2010). Process-based principles for restoring river ecosystems. *Bioscience*, *60*(3), 209–222.

Benda, L. E. E., Poff, N. L., Miller, D., Dunne, T., Reeves, G., Pess, G., & Pollock, M. (2004). The network dynamics hypothesis: How channel networks structure riverine habitats. *Bioscience*, *54*(5), 413–427.

Bernhardt, E. S., Palmer, M. A., Allan, J. D., Alexander, G., Barnas, K., Brooks, S., … Sudduth, E. (2005). Synthesizing US river restoration efforts. *Science*, *308*(5722), 636–637.

Beschta, R. L. (1979). Debris removal and its effects on sedimentation in an Oregon Coast Range stream. *Northwest Science*, *53*, 71–77.

Bisson, P. A., Dunham, J. B., & Reeves, G. H. (2009). Freshwater ecosystems and resilience of Pacific salmon: habitat management based on natural variability. *Ecology and Society*, *14*(1).

Bond, M. H., Nodine, T. G., Beechie, T. J., & Zabel, R. W. (2018). Estimating the benefits of widespread floodplain reconnection for Columbia River Chinook salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, *76*(7), 1212–1226.

Bond, M. H., Nodine, T. G., Beechie, T. J., & Zabel, R. W. (2019). Estimating the benefits of widespread floodplain reconnection for Columbia River Chinook salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, *76*(7), 1212–1226.

Booth, D. B., Ross-Smith, K., Haddon, E. K., Dunne, T., Larsen, E. W., Roche, J. W., … Mahacek, V. (2020). Opportunities and challenges for restoration of the Merced River through Yosemite Valley, Yosemite National Park, USA. *River Research and Applications*, *36*(9), 1803–1816.

Booth, D. B., Scholz, J. G., Beechie, T. J., & Ralph, S. C. (2016). Integrating limiting-factors analysis with process-based restoration to improve recovery of endangered salmonids in the Pacific Northwest, USA. *Water*, *8*(5), 174.

Bright, W. (2004). *Native American Placenames of the United States*. Norman, Oklahoma: University of Oklahoma Press.

Brown, A. G., Lespez, L., Sear, D. A., Macaire, J. J., Houben, P., Klimek, K., … Pears, B. (2018). Natural vs anthropogenic streams in Europe:

history, ecology and implications for restoration, river-rewilding and riverine ecosystem services. *Earth-Science Reviews*, *180*, 185–205.

Brummer, C. J., Abbe, T. B., Sampson, J. R., & Montgomery, D. R. (2006). Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA. *Geomorphology*, *80*(3–4), 295–309.

Castro, J. M., & Thorne, C. R. (2019). The stream evolution triangle: Integrating geology, hydrology, and biology. *River Research and Applications*, *35*(4), 315–326.

Cienciala, P., Nelson, A. D., Haas, A. D., & Xu, Z. (2020). Lateral geomorphic connectivity in a fluvial landscape system: Unraveling the role of confinement, biogeomorphic interactions, and glacial legacies. *Geomorphology*, *354*, 107036.

Ciotti, D. C., Mckee, J., Pope, K. L., Kondolf, G. M., & Pollock, M. M. (2021). Design criteria for process-based restoration of fluvial systems. *Bioscience*, *71*(8), 831–845.

Cluer, B., & Thorne, C. (2014). A stream evolution model integrating habitat and ecosystem benefits. *River Research and Applications*, *30*(2), 135–154.

Collins, B. D., & Montgomery, D. R. (2011). The legacy of Pleistocene glaciation and the organization of lowland alluvial process domains in the Puget Sound region. *Geomorphology*, *126*(1–2), 174–185.

Cordoleani, F., Holmes, E., Bell-Tilcock, M., Johnson, R. C., & Jeffres, C. (2022). Variability in foodscapes and fish growth across a habitat mosaic: Implications for management and ecosystem restoration. *Ecological Indicators*, *136*, 108681.

Crozier, L. G., Burke, B. J., Chasco, B. E., Widener, D. L., & Zabel, R. W. (2021). Climate change threatens Chinook salmon throughout their life cycle. *Communications Biology*, *4*(1), 1–14.

ESRI. (2019). *ArcMap version 10.7.1*. Redlands, California: Environmental Systems Research Institute.

Flitcroft, R., Brignon, W. R., Staab, B., Bellmore, R., Burnett, J., Burns, P., … Wondzell, S. (in press). Rehabilitating valley floors to a Stage 0 condition: A synthesis of opening outcomes. *Frontiers in Ecology*, 1-25.

Gendaszek, A. S., Magirl, C. S., & Czuba, C. R. (2012). Geomorphic response to flow regulation and channel and floodplain alteration in the gravel-bedded Cedar River, Washington, USA. *Geomorphology*, *179*, 258–268.

Grant, G. E., & Swanson, F. J. (1995). Morphology and processes of valley floors in mountain streams, Western Cascades, Oregon. *Geophysical Monograph-American Geophysical Union*, *89*, 83–83.

Greco, S. E., Girvetz, E. H., Larsen, E. W., Mann, J. P., Tuil, J. L., & Lowney, C. (2008). Relative elevation topographic surface modelling of a large alluvial river floodplain and applications for the study and management of riparian landscapes. *Landscape Research*, *33*(4), 461–486.

Green, K. C., & Westbrook, C. J. (2009). Changes in riparian area structure, channel hydraulics, and sediment yield following loss of beaver dams. *Journal of Ecosystems and Management*, *10*(1), 68-79.

Hauer, F. R., Locke, H., Dreitz, V. J., Hebblewhite, M., Lowe, W. H., Muhlfeld, C. C., … Rood, S. B. (2016). Gravel-bed river floodplains are the ecological nexus of glaciated mountain landscapes. *Science Advances*, *2*(6), e1600026.

Interfluve. (2013). Entiat Upper Stillwaters Reach Assessment (–161). Hood River, Oregon: Inter-fluve.

Jeffres, C. A., Holmes, E. J., Sommer, T. R., & Katz, J. V. (2020). Detrital food web contributes to aquatic ecosystem productivity and rapid salmon growth in a managed floodplain. *PLoS One*, *15*(9), e0216019.

Johnson, M. F., Thorne, C. R., Castro, J. M., Kondolf, G. M., Mazzacano, C. S., Rood, S. B., & Westbrook, C. (2020). Biomic river restoration: A new focus for river management. *River Research and Applications*, *36*(1), 3–12.

Knighton, D. (2014). *Fluvial forms and processes: a new perspective*. Abingdon, UK: Routledge.

Livers, B., & Wohl, E. (2016). Sources and interpretation of channel complexity in forested subalpine streams of the Southern Rocky Mountains. *Water Resources Research*, *52*(5), 3910–3929.

Livers, B., Wohl, E., Jackson, K. J., & Sutfin, N. A. (2018). Historical land use as a driver of alternative states for stream form and function in forested mountain watersheds of the Southern Rocky Mountains. *Earth Surface Processes and Landforms*, *43*(3), 669–684.

Long, A. (2001). *Under the guard of old Tyee*. Wenatchee, WA: Cascade Graphics and Printing.

Maaß, A. L., & Schüttrumpf, H. (2019). Elevated floodplains and net channel incision as a result of the construction and removal of water mills. *Geografiska Annaler: Series A, Physical Geography*, *101*(2), 157–176.

Mays, L. W. (2008). A very brief history of hydraulic technology during antiquity. *Environmental Fluid Mechanics*, *8*(5), 471–484.

Munsch, S. H., Greene, C. M., Mantua, N. J., & Satterthwaite, W. H. (2022). One hundred-seventy years of stressors erode salmon fishery climate resilience in California's warming landscape. *Global Change Biology*, *28*, 2183–2201.

National Oceanic and Atmospheric Administration, National Marine Fisheries Service (2007). *Upper Columbia spring Chinook salmon and steelhead recovery plan*.

National Oceanic and Atmospheric Administration, National Marine Fisheries Service (2020). *Endangered Species Act Section 7(a)(2) Biological Opinion and Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Response for the Continued Operation and Maintenance of the Columbia River System*.

National Research Council. (1996). *Upstream: Salmon and society in the Pacific Northwest*. Washington, DC: National Academies Press.

Parker, G.L., & Lee, L. (1922). Water powers of the cascade range part IV. Wenatchee and Entiat Basins. USGS, 88 pp. with 8 plates.

Pollock, M. M., Beechie, T. J., Wheaton, J. M., Jordan, C. E., Bouwes, N., Weber, N., & Volk, C. (2014). Using beaver dams to restore incised stream ecosystems. *Bioscience*, *64*(4), 279–290.

Polvi, L. E., & Wohl, E. (2013). Biotic drivers of stream planform: implications for understanding the past and restoring the future. *Bioscience*, *63*(6), 439–452.

Powers, P. D., Helstab, M., & Niezgoda, S. L. (2019). A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network. *River Research and Applications*, *35*(1), 3–13.

Prominski, M., Stokman, A., Stimberg, D., Voermanek, H., Zeller, S., & Bajc, K. (Eds.). (2012). *River Space Design: Planning Strategies, Methods and Projects for Urban Rivers* (First ed., p. 296). Basel: Birkhäuser p. ISBN 9783035610420.

Rieman, B. E., Smith, C. L., Naiman, R. J., Ruggerone, G. T., Wood, C. C., Huntly, N., … Smouse, P. (2015). A comprehensive approach for habitat restoration in the Columbia Basin. *Fisheries*, *40*(3), 124–135.

Roni, P., Hanson, K., & Beechie, T. (2008). Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. *North American Journal of Fisheries Management*, *28*(3), 856–890.

Rosgen, D. L. (1996). *Applied river morphology*. Fort Collins, CO: Wildland Hydrology Books.

Schumm, S. A., Harvey, M. D., & Watson, C. C. (1984). *Incised channels: morphology, dynamics, and control*. Littleton, Colorado: Water Resources Publications.

Sedell, J. R., & Froggatt, J. L. (1984). Importance of streamside forests to large rivers: The isolation of the Willamette River, Oregon, USA, from its floodplain by snagging and streamside forest removal: With 2 figures and 1 table in the text. *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen*, *22*(3), 1828–1834.

Sendzimir, J., & Schmutz, S. (2018). Challenges in riverine ecosystem management. In *Riverine ecosystem management* (pp. 1–16). Cham: Springer.

Shields, A. (1936). Awendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung, Mitt. Preuss. Versuchsanst. Wasserbau Schiffbau, *26*, 26.

Simon, A., & Darby, S. E. (2002). Effectiveness of grade-control structures in reducing erosion along incised river channels: the case of Hotophia Creek, Mississippi. *Geomorphology*, *42*(3–4), 229–254.

Simon, A., & Hupp, C. R. (1987). Geomorphic and vegetative recovery processes along modified Tennessee streams: an interdisciplinary approach to distributed fluvial systems. *International Association of Hydrological Sciences*, *167*, 251–262.
Skidmore, P., & Wheaton, J. (2022). Riverscapes as natural infrastructure: Meeting challenges of climate adaptation and ecosystem restoration. *Anthropocene*, *38*, 100334, ISSN 2213-3054. https://doi.org/10.1016/j.ancene.2022.100334, https://www.sciencedirect.com/science/article/pii/S2213305422000157
Tullos, D., Baker, D. W., Crowe Curran, J., Schwar, M., & Schwartz, J. (2021). Enhancing resilience of river restoration design in systems undergoing change. *Journal of Hydraulic Engineering*, *147*(3), 03121001.
US Bureau of Reclamation. (2009). *Entiat tributary assessment* (p. 92). Denver, CO: Chelan Co. Washington.
Walter, R. C., & Merritts, D. J. (2008). Natural streams and the legacy of water-powered mills. *Science*, *319*(5861), 299–304.
Woelfle-Erskine, C., Wilcox, A. C., & Moore, J. N. (2012). Combining historical and process perspectives to infer ranges of geomorphic variability and inform river restoration in a wandering gravel-bed river. *Earth Surface Processes and Landforms*, *37*(12), 1302–1312.
Wohl, E. (2014). A legacy of absence: Wood removal in US rivers. *Progress in Physical Geography*, *38*(5), 637–663.
Wohl, E. (2019). Forgotten legacies: understanding and mitigating historical human alterations of river corridors. *Water Resources Research*, *55*(7), 5181–5201.
Wohl, E. (2021). Legacy effects of loss of beavers in the continental United States. *Environmental Research Letters*, *16*(2), 025010.
Wohl, E., & Cadol, D. (2011). Neighborhood matters: patterns and controls on wood distribution in old-growth forest streams of the Colorado Front Range, USA. *Geomorphology*, *125*(1), 132–146.
Wohl, E., Castro, J., Cluer, B., Merritts, D., Powers, P., Staab, B., & Thorne, C. (2021). Rediscovering, reevaluating, and restoring lost river-Wetland Corridors. *Frontiers in Earth Science*, *9*, 511.
Wohl, E., Lane, S. N., & Wilcox, A. C. (2015). The science and practice of river restoration. *Water Resources Research*, *51*(8), 5974–5997.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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