THESIS

RESTORATION PRIORITIZATION OF UPPER COLORADO TRIBUTARIES IN THE KAWUNEECHE VALLEY, ROCKY MOUNTAIN NATIONAL PARK, CO

Submitted by

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ABSTRACT

RESTORATION PRIORITIZATION OF UPPER COLORADO TRIBUTARIES IN THE KAWUNEECHE VALLEY, ROCKY MOUNTAIN NATIONAL PARK, CO

Collapse of tall willow habitat along the Upper Colorado River, Rocky Mountain National Park, CO has led to the loss of beaver and channel morphologic change. A diverse stakeholder group is pursuing restoration on Upper Colorado tributaries to improve willow habitat and downstream water quality. Utilizing field data, remote sensing, and flow inundation modeling, I investigate the processes driving channel morphology, levels of floodplain connectivity, and the extent of historical beaver activity. I develop and apply a ranking framework of geomorphic condition for restoration based on channel, floodplain, and catchment characteristics of three study sites: Upper Baker Creek, Lower Baker Creek, and Onahu Creek. Channel assessments indicate that Onahu Creek has the steepest gradient, coarsest bed material, and exhibited the greatest in-channel beaver dam density in 1990. Bankfull cross-sectional areas differ significantly between sites ($p < 0.001$), a product of varying channel widths. Flow inundation modeling indicates that Upper Baker has the highest degree of floodplain connectivity with a 10.3x increase in surface water extent between observed base and peak flows, relative to a 5.2x increase at Lower Baker, and a 1.9x increase at Onahu. Based on my findings, process-based restoration is a suitable technique to reconnect the channel and floodplain and promote willow growth, but the degree of restoration effort required at each site varies. Onahu Creek has the poorest relative geomorphic condition with the greatest potential for floodplain reconnection through restoration. Upper and Lower Baker Creeks have good geomorphic conditions which may benefit from less intervention to achieve the greatest river ecosystem benefit.

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1. INTRODUCTION

Although it is a billion-dollar industry (Bernhardt et al., 2005), the science and practice of river restoration is relatively new. Many projects focus on a fixed channel design rather than prioritizing restoration based on the geomorphic processes that drive channel form (Niezgoda and Johnson, 2005; Beechie et al., 2010; Kline and Cahoon, 2010; Bernhardt and Palmer, 2011; Piégay et al., 2023). Process-based restoration focuses on restoring processes of stream flow and sediment transport to create and maintain a functioning river ecosystem (Beechie et al., 2010; Ciotti et al., 2021). Where geomorphic context is considered as a primary channel restoration goal, site prioritization may determine where geomorphic processes are most likely to be enhanced or restored (Wohl et al., 2024). Multiple metrics of geomorphic character have been established, but few restoration prioritization methods are available in the literature based strictly on geomorphic context. Exceptions include prioritizing restoration of incised streams in the southeastern US (Schumm et al., 1984), catchment scale prioritization (Roni et al., 2002; Sear et al., 2009; Brierley et al., 2013), determining the degree of geomorphic process alteration (Kline and Cahoon, 2010), and guidance on how to prioritize the reintroduction of large wood or beaver (Wohl et al., 2019; Castro and Thorne, 2019). This research aims to fill the existing gap in channel restoration literature that prioritizes geomorphic potential for greatest river ecosystem benefit, an approach that is gaining more widespread use but lacks research guidance (Wohl et al., 2024).

Along the Upper Colorado River, Rocky Mountain National Park (RMNP), CO, collapse of tall willow habitat has led to loss of beavers, channel incision, floodplain disconnection, and sediment loading to downstream reservoirs. I investigated three tributaries of the Upper

Colorado River, to develop a geomorphic-based ranking method for restoration suitability based on 1) the relative geomorphic condition of channel, floodplain, and catchment characteristics to inform restoration suitability, 2) existing level of channel-floodplain hydrologic connectivity, and 3) channel sediment fluxes. Results will help inform future RMNP management and restoration decisions about where restoration is most suitable, and the level of restoration intervention required to restore beaver meadow habitat.

1.1 Background

1.1.1 Geomorphic context in restoration

Water quality, aquatic habitat, fish passage, infrastructure protection, and bank stabilization are the most commonly cited motivations for pursuing river restoration (Bernhardt et al., 2005; Bernhardt and Palmer, 2011). Project design and implementation commonly focus on form-based approaches, failing to consider the underlying drivers of degradation in a system or its geomorphic context. The geomorphic context of a river reach refers to the controls on its historical and contemporary form and processes (Wohl et al., 2024). Understanding the geomorphic context of fluvial systems is critical to effective restoration as geomorphic processes create and maintain the physical templates of riverscapes that form riparian habitat and drive ecological function (Montgomery, 1999; Brierley and Fryirs, 2005; Wohl et al., 2005, 2015). Geomorphic context also helps practitioners understand a stream system's evolutionary trajectory and develop reasonable goals for restoration efforts (Fryirs, 2015; Glassic et al., 2024).

In the river restoration community, there are increasing calls to shift attention from form-based restoration approaches to restoring the geomorphic, hydrologic, and biological processes of healthy stream ecosystems (Bernhardt and Palmer, 2011; Tullos et al., 2021; Piégay et al., 2023). Numerous geomorphic assessment frameworks exist but no agreed standards for geomorphic and habitat assessments exist to guide restoration, leading some to call for a consolidation of approaches (Beechie et al., 2008; Roni and Beechie, 2013; Fryirs, 2015; Papangelakis et al., 2023a, 2023b; Dawson and Ashmore, 2025). Many prioritization approaches exist for restoration work but due to a lack of systematization and review, practitioners have difficulty finding approaches that incorporate local knowledge and are suitable for local goals (Beechie et al., 2008; Roni and Beechie, 2013). Furthermore, there are few prioritization approaches that focus strictly on the geomorphic context of a system and its implications for meeting restoration goals (Bernhardt and Palmer, 2011; Fryirs, 2015; Piégay et al., 2023; Wohl et al., 2024; Glassic et al., 2024). Many existing approaches prioritize protecting and conserving habitats of high-quality before performing work on degraded systems (Roni et al., 2002; Fryirs et al., 2016).

While geomorphic-based restoration prioritization approaches are limited in the literature, several methodologies for geomorphic assessment have been developed (Schumm et al., 1984; Sear et al., 2009; Rinaldi et al., 2013; Brierley and Fryirs, 2016). The River Styles and Morphological Quality Index (MQI) approaches are two examples of existing frameworks that emphasize geomorphic context in their assessments. River Styles is a scalable assessment that utilizes a top-down approach to ‘reading the landscape’ to understand the contemporary geomorphic context of a system in relation to human impacts and its trajectory and recovery potential. The Rivers Styles approach informs management decisions but is not designed to address specific restoration goals (Brierley and Fryirs, 2005) and is applied for catchment-scale prioritization. Additionally, there are few documented applications of the River Styles approach for systems in which beaver are a dominant geomorphic driver. The MQI framework was developed specifically for rivers in Italy and involves classifying river units into homogenous morphologic characteristics and comparing those reaches to a reference reach using 28 ‘geoindicators’ to assess present geomorphic condition. MQI is limited in its ability to assess beyond reach scale and does not focus on developing a broader understanding of a system’s geomorphic condition or evolution (Rinaldi et al., 2013). These limitations prompted my development of a geomorphic-context based assessment for restoration of my study reaches, which are reach-scale, beaver-driven systems that have been identified for channel-floodplain reconnection.

1.1.2 Loss of Beaver and Ecosystem Services

The Kawuneeche Valley’s name is derived from a simplified transliteration of the Arapaho word meaning “Coyote Valley” (Andrews, 2011). The valley has a long history of landscape-human interaction, originally serving as the summer hunting and gathering grounds of the Nuche peoples and native peoples preceding them. In the late 1800s, Anglo-settlers began to occupy the valley in search of silver and gold. Following the rise and fall of a short-term mining boom, the proliferation of several homestead ranches occurred, which were gradually acquired and adopted into RMNP until the 1970s.

Historically, it was estimated that over 600 beaver occupied the Kawuneeche Valley (Packard, 1947) but currently none inhabit the area due to the loss of suitable willow forage. Multiple stressors are attributed to the decrease of tall willow communities in the valley and resulting loss of beaver. Ungulate overpopulation is the likely cause of rapid willow decline, but historical ranching activity, drought stress and water diversions, wildfire, and disease have also played a role in the decline of tall willow (Andrews, 2011).

1.1.3 Beaver as geomorphic agents

In mountain systems where beaver are present, valley-bottom tall willow beaver complexes increase floodplain connectivity, sediment and organic matter retention, and habitat heterogeneity (Westbrook et al., 2006; Polvi and Wohl, 2013; Wegener et al., 2017). Beaver build pond-forming dams, dig canals, and alter channel geometry, which spreads water throughout the floodplain, promotes surface and subsurface water storage, and increases floodplain roughness and complexity (Gurnell, 1998; Green and Westbrook, 2009; Jordan and Fairfax, 2022). Beaver dams and canals slow the movement of water through a valley bottom, dissipate energy flows, reduce incision, and create complexes of saturated, hydrologically-connected floodplains (Pollock et al., 2014; Jordan and Fairfax, 2022). Beaver dams and ponds also increase river corridor resiliency to wildfire and climate change (Wohl et al., 2022; Jordan and Fairfax, 2022), capturing post-fire hillslope sediments (Dunn, 2023) and slowly releasing flow during times of drought (Hood and Bayley, 2008). Beaver may abandon dam complexes but their relict features may persist for decades or centuries, continuing to play an important role in the hydraulic complexity of a system (Naiman et al., 1988; Wright et al., 2002).

In the Kawuneeche Valley, ungulate overbrowsing and loss of apex predators are considered the primary causes of the loss of tall willows and beaver (Andrews, 2011; Cooper et al., 2023), which has introduced a host of geomorphologic and ecological changes. A loss of beaver dams leads to channel incision, floodplain disconnection, and reduced geomorphic complexity necessary to create diverse aquatic ecosystems (Naiman et al., 1988, 1993; Darby and Simon, 1999; Wolf et al., 2007; Polvi and Wohl, 2012; Larsen et al., 2021). Large portions of the Kawuneeche Valley have undergone the transition from wet meadow habitat to a drier elk-moose meadow grassland community (Figure 1) since the decline of beaver in the 1990s.

Figure 1. (left) Kawuneeche Valley showing the Upper Colorado River and numerous beaver ponds in 1920 (source: NPS), (right) Kawuneeche Valley in 2019 with meanders of the Colorado River visible but no beaver ponds (source: Google Earth). Grand Ditch is visible on the hillslope in the upper right of the image.

Proliferation of non-native European pasture species is associated with the degradation of the tall willow community and lowered groundwater table (Cooper et al., 2023). Sediment loading downstream of RMNP into Shadow Mountain Reservoir (Shaw and Cooper, 2022; Northern Water, 2023) is thought to be associated with channel adjustments following the loss of beaver (Butler and Malanson, 2005; Green and Westbrook, 2009). The loss of suitable beaver habitat and consequential loss of beaver in a system may create a positive feedback in fluvial systems which perpetuates the cycle of channel incision and floodplain disconnection (Figure 2) (Wolf et al., 2007; Wohl et al., 2018; Larsen et al., 2021).

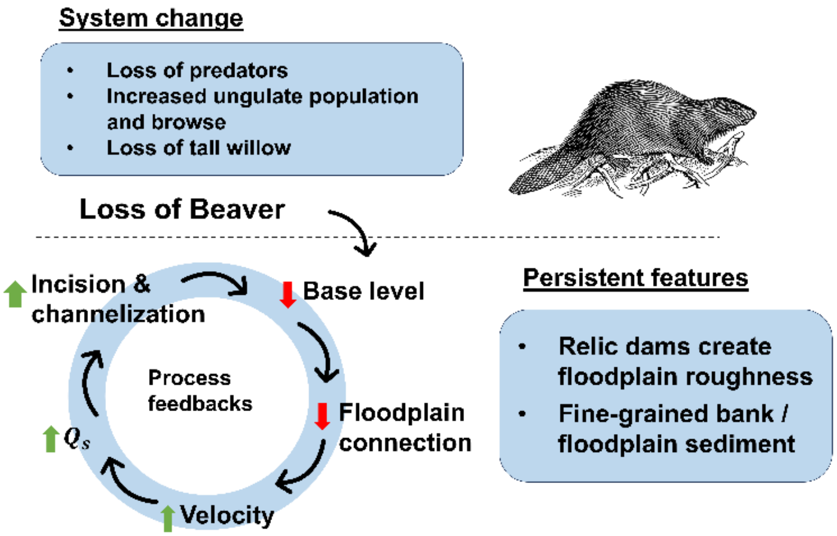


Figure 2. Conceptual model illustrating expected fluvial geomorphic response following the loss of beaver, adapted from Wohl et al. 2018.

1.1.4 The Kawuneeche Valley Restoration Collaborative & management implications

The Kawuneeche Valley Restoration Collaborative (KVRC) is a diverse stakeholder group consisting of eight organizations including federal agencies, local government, public utilities, and non-governmental conservation organizations, focused on ecosystem restoration of the Kawuneeche Valley to "support its ecological, economic, and community well-being**."** KVRC is pursuing channel restoration (and exclosure fencing) to promote channel-floodplain connectivity, willow recovery, reduced downstream flux of fine sediment, beaver recolonization, and return historical ecological benefits to Kawuneeche Valley in RMNP. Following the East Troublesome Fire of 2020, the collaborative partnered with Colorado State University faculty and research scientists to develop sustainable restoration efforts. In 2024, KVRC began restoring one tributary of the Upper Colorado River by implementing a series of low-tech structures and wildlife exclosure fencing in the attempt to reverse channel incision, reconnect the floodplain, and promote tall willow-recovery. A similar restoration approach is proposed for the reaches assessed in this study.

1.2 Research objectives and hypotheses

1.2.1 Research objectives

I have three objectives that are incorporated into my research, including:

1) Quantify channel and floodplain characteristics.
2) Quantify contemporary levels of floodplain connectivity.
3) Develop a restoration prioritization scheme based on geomorphic context.

1.2.2 Hypothesis 1

I hypothesize that tributaries with more abandoned beaver dams exhibit greater incision due to base level drop and channelization.

1.2.3 Hypothesis 2

I hypothesize that relict beaver activity is the dominant driver of floodplain surface complexity.

1.2.4 Rationale for hypothesis 1 & 2

Beaver construct dams and excavate canals that increase geomorphic complexity in fluvial systems (Gurnell, 1998; Larsen et al., 2021). The loss of beaver and dam-maintenance activities within a system result in eventual dam collapse, but relict dam and canal features persist in the floodplain (Naiman et al., 1988). Beaver dam collapse can result in an immediate base level drop and contribute to loss in channel-floodplain connectivity by necessitating greater flows to reach morphologic bankfull and access the floodplain (Butler and Malanson, 2005). With a greater proportion of flow contained in the channel, flow velocity and sediment transport capacity increase, driving more channelization and incision (Figure 2) (Marston, 1994;

Darby and Simon, 1999; Polvi and Wohl, 2012; Cluer and Thorne, 2014; Mason et al., 2025). Therefore, I expect that systems exhibiting more historical beaver dams and relict beaver activity will exhibit a greater magnitude of channel incision following dam loss (H1). Prior to the collapse of tall willow in the Kawuneeche Valley, beaver were present in far greater numbers (Packard, 1947) and left extensive relict dams, ponds, and canal structures throughout. Despite the absence of beaver in these systems, I expect relict beaver activity to be the dominant driver of floodplain heterogeneity and topographic surface complexity in these systems (H2).

1.3 Study area

Home to the headwaters of the Upper Colorado River, the Kawuneeche Valley encompasses an area of roughly 18 km^2 north of the Grand Lake. Study reaches on Baker and Onahu Creeks were selected by a multidisciplinary team of land managers and researchers affiliated with Rocky Mountain National Park (RMNP) and Colorado State University prior to the start of this research. The three reaches, Upper Baker Creek, Lower Baker Creek, and Onahu Creek (Figure 3), were selected based on observed channel incision, loss of floodplain connectivity, decreased groundwater tables, and related loss of beaver meadow habitat and transition to elk-meadow grassland. Baker and Onahu Creeks originate as mountainous headwaters stream that transition into the wide, low-gradient Kawuneeche Valley before joining the Upper Colorado River. Both are meandering single-threaded, gravel bed systems with a pool-riffle bed planform. Study reaches range between 2663-2690 m (8737-8826 ft) in elevation.

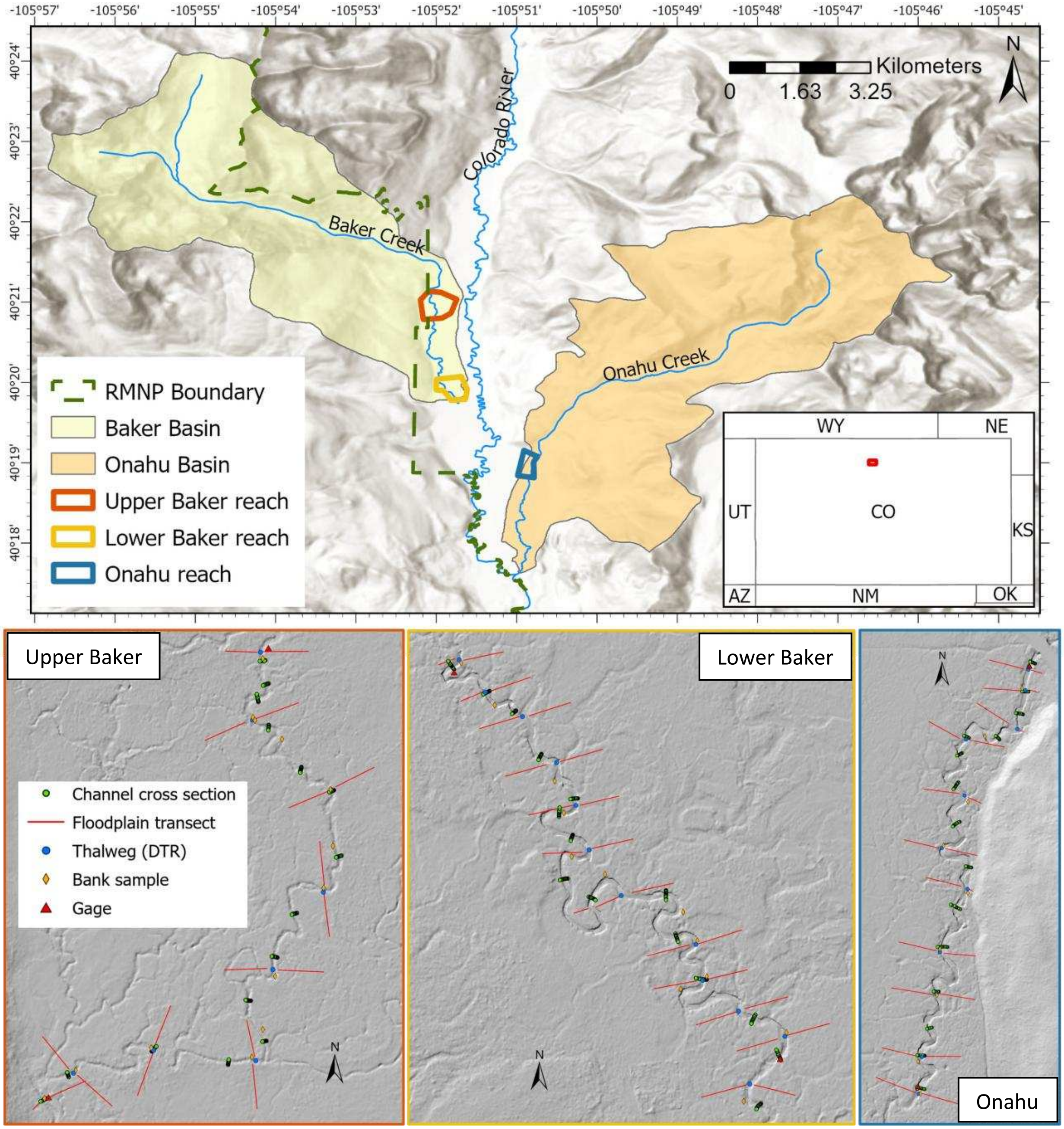


Figure 3. Study reach locations in Rocky Mountain National Park with detailed sample site insets included for each reach.

For this analysis, I treat Upper Baker and Lower Baker Creeks as independent study sites even though they are inherently linked. Any processes including surface and subsurface flows and sediment transport that occur at Upper Baker Creek influence processes occurring at Lower

Baker Creek. Basin area is similar between the three sites, and Onahu Creek exhibits the steepest channel slope, followed by Upper Baker and Lower Baker (Table 1).

Table 1. Summary table of study reach and catchment characteristics.

Characteristics	**Study catchments**		
	Upper Baker Creek	**Lower Baker Creek**	**Onahu Creek**
Basin area (km^2)	22.1	25.7	23.9
Study area (km^2)	0.31	0.22	0.14
Channel slope	0.5%	0.3%	0.6%
Lithology	Intrusive igneous & metamorphic	Intrusive igneous & metamorphic	Biotite schist & granite
Hydrologic alterations	Grand Ditch diversions	Grand Ditch diversions	Relict diversions
Fire (year, severity)	E. Troublesome (2020, low)	E. Troublesome (2020, low)	E. Troublesome (2020, low)

1.3.1 Geology & glacial history

The Kawuneeche Valley is bound by two mountain ranges, the Never Summer Range to the west and the Front Range to the east, that rise ~1200 m above the valley floor. The upper Baker basin is characterized by exposures of Proterozoic metamorphic rock (microcline-biotite-quartz-plagioclase granofels) and some intrusive igneous rock. Rock glaciers and talus from the Holocene and upper Pleistocene are scattered throughout. The Onahu Creek catchment consists of predominantly igneous intrusive rocks of middle and early Proterozoic age, primarily

Silver plume granite and early Proterozoic metamorphic biotite schist (Table 1). Both sides of the valley are bound by Pinedale glacial till (Braddock and Cole, 1990).

RMNP was glaciated multiple times during the Pleistocene with most Pinedale glaciation ending around 10-11 ka (Richmond, 1960; Madole, 1980). The Kawuneeche Valley's low gradient is the result of outwash deposition behind terminal moraines following deglaciation. Valley bottom substrate consists primarily of Holocene and upper Pleistocene alluvium with depths ranging 15 m – 122 m (Braddock and Cole, 1990). Most valley-bottom soils throughout the Kawuneeche Valley are classified as the Kawuneeche Series, described as very-deep, poorly drained soils that formed from alluvial deposition over glaciofluvial deposits. The typical soil profile is described as heavily organic 'peat' horizons overlaying very fine clay loams on top of coarse sandy loam (Soil Survey Staff, 2000).

1.3.2 Climate & hydrology

Elevation influences all aspects of climate including temperature, precipitation, humidity, and wind in the Colorado Rocky Mountains (Doesken et al., 2003). In the Kawuneeche Valley, snowmelt at higher elevations is the dominant source of runoff, with summer thunderstorms in July and August contributing to late-season high flows. The Upper Colorado and its tributaries exhibit snowmelt-driven hydrographs with peak discharge occurring in early to mid-June followed by short-duration high-flows from July-August from convective thunderstorms. Strong diurnal fluctuations in flows are observed on a daily cycle, driven by large temperature swings and weather patterns in high elevation catchments. An annual average of 65 cm of precipitation per year falls at the Phantom Valley SNOTEL gage, approximately 5.5 km north of Upper Baker Creek (NRCS, 2025). Estimates of 2-year flows derived from StreamStats were 1.72 m^3/s at Upper Baker Creek, 1.90 m^3/s at Lower Baker Creek (accounting for Grand Ditch diversions), and 3.77 m^3/s at Onahu Creek (U.S. Geological Survey, 2019).

Both natural and anthropogenic factors influence valley hydrology. Historically, beaver constructed extensive dam complexes that spread and stored water throughout the floodplain (Packard, 1947; Westbrook et al., 2006). The loss of beaver within the valley has led to drier conditions and a 94% loss of surface water ponding associated with beaver dams has been observed since 1953 (Cooper et al., 2025). Historical and contemporary water diversion and irrigation efforts have also altered flows in Baker and Onahu Creeks. The most significant is the Grand Ditch, a water diversion project that runs 24 km along the north side of the Baker Creek catchment, intercepting 11 headwater tributaries of the Colorado River between May and September each year. Diversions from the construction of Grand Ditch alter groundwater levels and wetland vegetation communities throughout the Kawuneeche Valley (Woods, 2002; Cooper et al., 2023).

1.3.3 Vegetative communities

Numerous stressors including agricultural activity, ungulate browse pressure, hydrologic stress, and disease have altered the vegetation community of the Kawuneeche Valley (Andrews, 2011; Cooper et al., 2025). Historically, abundant tall willow communities (dominated by *Salix monticola, S. geyeriana, S. planifolia, S. lasiandra, S. drummondiana,* and *S. bebbiana*) were present throughout the valley bottom. In the last 30 years, the Kawuneeche Valley has transformed from a beaver meadow ecosystem to elk-moose grasslands dominated by *Poa pratensis* and other nonnative and undesirable upland species (Figure 4). Sedges including *Carex utriculata* and *Carex aquatilis* and tall grass (*Calamagrostis canadensis*) are common near stream banks and other wetter areas (Cooper et al., 2023).

Elk were absent from RMNP in the early 1900s due to habitat loss and hunting. In 1910 and 1911, elk from Yellowstone National Park were introduced in RMNP and gradually migrated west across the continental divide (Andrews, 2011). A shift in population management decisions and the absence of large predators ultimately resulted in the overpopulation of elk throughout the park. Ungulate browse pressure on tall willow communities in the Kawuneeche Valley was exacerbated by the colonization of moose in 1980. Historically thought to be only transitory in the area, moose were introduced in North Park, Colorado in 1978 and 1979 and migrated into the Kawuneeche, where they found an abundant food source (Andrews, 2011; Cooper et al., 2023). It is estimated that 90% of the summer diet of moose consists of willow species (Dungan and Wright, 2005). Ungulate browse combined with drought and stress pressures have resulted in a 98% decrease of tall willow in the Kawuneeche Valley since 1999 (Cooper et al., 2023, 2025).

Figure 4. Exclosure fencing around a vegetation research plot shows the effects of ungulate browse pressure on tall willows. Photo is taken at Lower Baker Creek study reach looking north.

2. METHODS

I used a combination of field-based, remote sensing, and hydraulic modeling approaches (Table 2) to perform geomorphic assessments across multiple spatial and temporal scales to understand drivers of channel incision and floodplain disconnection. I assessed the geometric, topographic, hydrologic, and sedimentologic characteristics of the channel and floodplain. Historical imagery and a U.S. Geologic Survey (USGS) 2020 LiDAR-derived digital elevation model (DEM) at 0.6 m resolution were used for field mapping and channel morphologic change.

Table 2. Summary of methods, data products, and purpose.

Methods	**Data Product(s) & Purpose**
Flow and sediment discharge	· Hydrographs for upstream and downstream gage sites · Observed base and peak flows for modeling · Sediment transport rates
RTK GPS channel surveys	· Bathymetric digital elevation model (DEM) for modeling · Channel cross-sectional areas · Bankfull – thalweg elevation differences · Field erosion index (qualitative)
Pebble counts	· Floodplain sediment depth and composition
Thalweg depth-to-refusal	· Thalweg sediment depth & composition · Assess areas of bed aggradation and deposition
Bank composition sampling	· Grain size distribution of channel bed and bank substrate
Particle grain size analysis	· Assess the influence of relict dam activity on sediment characteristics · Assess channel thalweg depths to indicate areas of channel aggradation and degradation · D_{50} & D_{84} of bed substrate for mobility
Floodplain probing	· Floodplain sediment depth and composition · Determine influence of relict dam activity on sediment characteristics
Analysis of aerial imagery	· Sinuosity and avulsion time-series analysis
Geospatial analysis	· Identify relict dam locations and ages · Floodplain surface complexity characteristics · Anthropogenic impacts (ditch infrastructure) · Catchment-scale characterization
Hydraulic modeling	· Assess levels of floodplain connectivity
Statistical analyses	· Assess for significant differences in study reach characteristics

2.1 Field-based assessments

2.1.1 Discharge

I installed Solinst LevelLogger pressure transducers at both upstream (GS1) and downstream (GS2) gage sites to record river stage at 15-minute intervals throughout the 2024 snowmelt season (April-October). A barologger was also installed in a central location for barometric data correction. Discharge was measured a minimum of 11 times at upstream sites and periodically at downstream sites using a Sontek Flowtracker 2 (accuracy +/1% of measured velocity) (Figure 3). At least 20 in-channel stations were used during each discharge measurement. Rating curves were developed from field measurements of discharge paired with staff gage observations and LevelLogger data. LevelLogger data were barometrically corrected and processed to create hydrographs. I fit a two-part linear model to the rating curve of each gage site and used the models to calculate discharge from the pressure transducer data over the field season. Calculated discharge measurements were compared to field measurements of discharge taken throughout the season to assess accuracy.

2.1.2 Sediment transport

I collected four suspended sediment (SS) and bedload samples at upstream gage sites over the seasonal peak flow. Sample locations were determined using the highest velocity vectors observed in Sontek Flowtracker 2 discharge measurements. To sample SS, I used a DH-48 depth-integrating hand sampler to collect a 500 mL sample from the two stations with highest velocity vectors. A Helley-Smith bedload sampler was used to collect bedload transport at the station location with the highest velocity vector. The sampler was fixed at this location for a duration of 2 minutes before bagging samples for lab analysis.

In the lab, I filtered SS samples using a NALGENE hand-operated vacuum pump, a Sterifil filter, and 45μ filters. Loaded filters were dried in an oven at 40°C and massed with an OHAUS Adventure Pro Balance (repeatability 0.0001 g). Using the known sample volume of 500 ml and the mass of sediment sampled, I calculated the SS concentration (mg/L) at time of sampling. Discharge measurements were used to calculate the SS flux (g/s). Bedload samples were transferred to crucibles dried in an oven for 12 hours at 40°C. I burned the samples in a muffle furnace at 550°C for 2 hours (U.S. Geological Survey - Mercury Research Laboratory, 2021) to calculate loss on ignition (LOI) as a metric of percent organic material. Pre- and post-burn masses were recorded using a Bonvoisin High Precision Electronic Analytical Balance. I calculated LOI using post-burn mass and non-organic masses. Bedload flux (g/s) was calculated using post-burn masses and discharge at the time of collection.

2.1.3 RTK-GPS survey, channel geometry & bathymetric layer interpolation

I conducted channel geometry, bathymetric, and water surface elevation surveys at each site using an Emlid Reach RS2 GPS receiver with an accuracy of 2.5 m. For this study, I defined a channel reach as the stretch of active channel with consistent geometry bounded by its upper and lower gage sites. To assess channel geometry at each site, 15 channel cross sections were surveyed perpendicular to flow. Cross sections were spaced roughly equidistant to represent the whole reach between upstream and downstream gage sites. Point locations of morphologic bankfull and channel thalweg were measured. In cases of multiple bankfull locations, conservative and nonconservative bankfull estimates were surveyed. I used nonconservative estimates for analyses. In the case of misaligned left bank and right bank bankfull elevations, a linear regression model between survey points on the missing side was derived in R and used to interpolate bankfull station locations.

During each survey, the RTK base unit was set up at a fixed location and left running for a minimum of two hours to allow for sufficient data collection for post-processing corrections. Following the field season, the base station location of each survey was corrected in EmlidStudio using a Continuously Operating Reference Station (CORS) correction process (CORS site: TMG2). Any correction with an accuracy less than `fix` was discarded and the fixed base locations at each site were determined by averaging the corrected base locations at each site. A minimum of three fixed base locations were used for corrections at each site to determine an 'absolute' base location. All survey points were corrected latitudinally and longitudinally using the offset in the survey base station location and 'absolute' base location described above. All surveys were tied to two or three upstream and downstream control points to check for drift, which averaged 1.66 cm horizontally and 1.02 cm vertically.

The cross-sectional area at morphologic bankfull of each cross section was calculated using R. Additionally, for each cross section the height difference of the channel thalweg and bankfull elevation was calculated for comparison between reaches.

An extensive bathymetric survey consisting of 500+ points was conducted between gage sites for each reach. To align channel survey elevation data relative to the existing 0.6 m resolution 2020 USGS DEM layer of the floodplain (Table 3), I corrected bathymetric point elevations using the average difference between USGS DEM elevations at top of bank locations and the corresponding surveyed elevations for a minimum of 30 points per reach. Once corrected, these survey points were used to create a triangulated irregular network (TIN) using the "Create TIN" tool in ArcGIS pro. Using the "TIN to Raster" tool, the TIN layer was used to interpolate a bathymetric DEM layer, which was overlain over the 2020 DEM layer to be create the final terrain surface for modeling (Wheaton, 2001).

Table 3. Aerial imagery and digital elevation model datasets used in analysis.

Year	Dataset	Type	Resolution (m)
1953	USGS (AR1VAP000040130)	Aerial imagery	1.6
1990	Digital Orthophoto Quadrangle (DOQ)	Aerial imagery	1
1999	Digital Orthophoto Quadrangle (DOQ)	Aerial imagery	1
2005	National Agriculture Imagery Program (NAIP)	Aerial imagery	1
2009	National Agriculture Imagery Program (NAIP)	Aerial imagery	1
2015	National Agriculture Imagery Program (NAIP)	Aerial imagery	1
2019	National Agriculture Imagery Program (NAIP)	Aerial imagery	0.6
2020	CO_NWCO_2_2020_DEM	Digital Elevation Model	0.6

To assess the accuracy of the generated bathymetric layer, I compared the bankfull cross-sectional area of field-surveyed cross sections to the cross-sectional area of transects at the same locations on the generated bathymetry layer. I found average differences in area of -0.28 m^2 (std dev. 0.32 m^2, 12.6% diff) at for Upper Baker, -0.28 m^2 (std dev: 0.51 m^2, 9.4% diff) at Lower Baker, and -0.21 m^2 (std dev: 0.60 m^2, 6.3% diff). The percent difference reported is the average difference in area divided by the overall average area of bathymetry and surveyed cross sections surveyed. This approach informed topographic survey data corrections.

2.1.4 Pebble counts

Wolman pebble counts were collected at channel geometry survey transect locations (Wolman, 1954) (Figure 3). Prior to collection, a tape was laid across each transect to estimate channel width to inform sampling intervals. At each sample location, I randomly selected bed clasts at 0.3 m intervals and measured b-axis diameter using a gravelometer until 100 clasts were sampled.

2.1.5 Thalweg depth-to-refusal

I collected thalweg depth-to-refusal (TDTR) measurements along the channel thalweg corresponding with floodplain transect locations for each reach. A 2.43 m tile probe marked with 10 cm intervals was pushed into the unconsolidated bed substrate of the channel thalweg until refusal. TDTR was recorded by subtracting the depth of water from the total probe length. Channel texture characteristics were noted qualitatively, determined by probe vibrations and audible cues.

2.1.6 Bank sediment sampling & erosion index

I assessed channel bank stratigraphy and collected bank samples for size characterization at locations roughly corresponding to floodplain transect locations (Figure 3). The color, depth, texture, and root density of each bank layer were recorded in the field. In the lab, I air-dried samples before drying them in a muffle furnace at 40°C for 24 hours. Large organic material (roots and beaver chew) was removed and discarded. Bank samples were processing using a sieve nest range of ϕ -3 to 4 (8 mm – 0.0625 mm) in a Cole-Parmer One-Touch Vibratory Sieve Shaker for a period of 5 minutes. The sample proportion retained in each sieve pan was recorded using a Bonvoisin High Precision Electronic Analytical Balance.

At locations corresponding to floodplain transects, I recorded a qualitative erosion rating of the bank (1 – no risk of erosion, 4 – high risk of erosion). My classification was based on 1) the level of undercutting observed, 2) level of vegetation and root cohesion, 3) presence of active bank sloughing, and 4) accessibility to adjacent floodplain (potential for high flow energy dissipation). Average erosion index scores were compared between sites.

2.1.7 Floodplain depth-to-refusal transects

At each site, I probed floodplain sediment thickness at a minimum of 10 floodplain transects using a tile probe. Floodplain depth-to-refusal (FDTR) was measured at 2 m intervals on 40 m transects extending perpendicular from the channel left and right banks into the floodplain. I noted the depth of major textural changes based on probe vibrations and audible cues, verified at intermittent intervals using a soil corer. Sediment texture was lumped into the following categories: fines, coarse sand/gravel, compacted sand, and water. Coarse qualitative willow condition assessments (none-low, medium, high) were performed at each transect. Condition status was based on visual assessments of 1) willow presence and density, 2) shrub height, and 3) degree of burned shoots observed.

2.2 Geospatial analyses

2.2.1 Sinuosity

Using historical imagery from 1990 to 2019 sourced by USGS Earth Explorer (Table 3), I assessed changes in channel sinuosity over time and mapped relict beaver dams. Imagery from 1990 was selected as a starting date because it marks the beginning of consistent, high-resolution aerial imagery coverage in the Kawuneeche Valley, and beaver were still active at study reaches at this time. For sinuosity analysis, channel centerlines between upper and lower gage site locations were digitized in ArcGIS Pro for each year. Sinuosity is calculated by dividing the total channel distance by the linear distance between gage sites. Linear regression models of sinuosity and year were compared visually and derived statistically in R to determine statistical significance. Additionally, I recorded observations of channel avulsions at each site and the year in which they occurred.

2.2.2 Relict beaver activity

Relict beaver dams were mapped in the field using an iPad connected to a Garmin GLO 2 GPS receiver (accuracy 3 m) and via aerial imagery. I focused primarily on relict features immediately adjacent to the active stream channel, but obvious relict floodplain dams were also mapped. In the field, I surveyed each study reach for visible evidence of relict dams, expressed as nonlinear elevated berms extending a minimum of 3 m (Figure 5). A confidence status (good, moderate, poor) was assigned to each mapped feature using metrics of 1) beaver chew in the bank (Figure 5), 2) presence of willow on berm 3) surrounding topography (beaver canals), 4) soil profile cores (presence of carbon-rich fine sediments), and 5) proximity to exposed silty-clay, peat-rich layers in the bank.

Figure 5. (left) A relict beaver dam berm indicated by red dashes (looking south from Upper Baker). (right) Evidence of beaver chew in the bank indicating a historical dam location.

I verified beaver dam features mapped in the field with observations of dam activity in historical aerial imagery and DEMs to confirm the locations at each site and the year of origin.

Key indicators of dam presence included observations of ponding or clearly visible dams from aerial imagery. Features mapped as ‘poor’ in the field that were not obvious in the historical imagery were disregarded. Dam locations at each year were digitized and categorized as “channel-spanning” or “off-channel”.

2.2.3 Floodplain surface complexity

I clipped the USGS DEMs to each study area and detrended each to valley-bottom gradient to create relative elevation models (REMs) for floodplain topographic complexity analysis (Iskin and Wohl, 2023). Surface complexity metrics were assessed at 10-year flood inundation extents. Modeling parameters for determining flood inundation extent are discussed in detail in section 2.2.4. I modeled 10-year flood discharges derived from StreamStats to determine maximum surface water extent (Upper Baker – 2.86 cms, Lower Baker – 3.17 cms, Onahu – 6.06 cms). I then used the ‘Minimum Bounding Geometry’ tool (convex hull geometry type) in ESRI ArcGIS Pro to simplify the surface water extent polygon. REMs were clipped using these simplified extent polygons for analysis (Figure 6). The active channel extent of each REM was excluded from the analysis so that only floodplain characteristics were considered. Five metrics were used to assess pixel values within the REM: (standard deviation (SD) , range, coefficient of variation (CV), standard deviation of planform curvature (SD_{curv}), and ‘rugosity’ (Scown et al., 2015, 2016; Wohl, 2016; included in Appendix IV, Minár et al., 2020). Planform REM curvature was derived using the “Surface Parameters” tool to derive SD_{curv} and ‘rugosity’ was derived using the “Surface Volume” tool. All surface feature statistics were derived using the “Zonal Statistics as Table” tool in ESRI ArcGIS Pro.

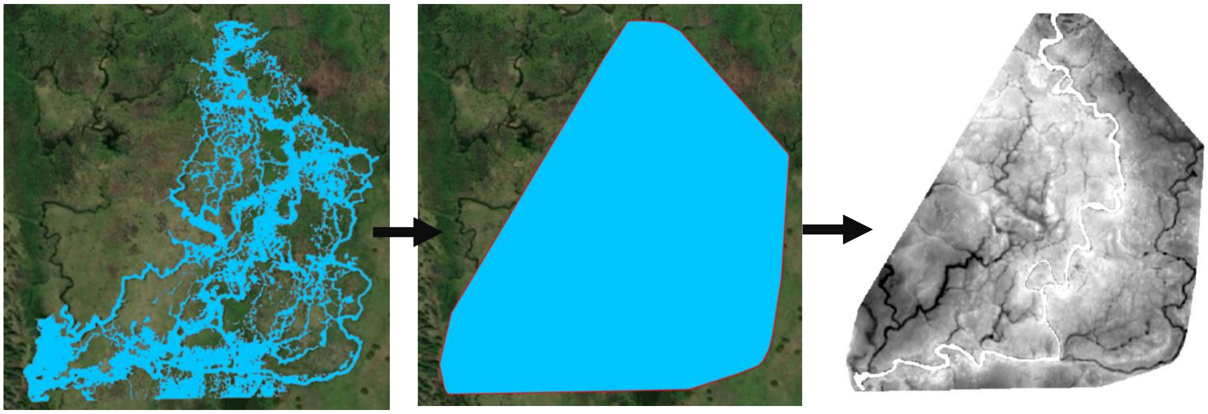


Figure 6. Methodology for determining surface complexity analysis extent. The 10-year flow surface water extent (left) was simplified using the Minimum Boundary Geometry tool in ArcGIS Pro (middle). The REM was then clipped to this extent (right).

2.2.4 Flow inundation modeling

I utilized the Hydrologic Engineering Center River Analysis System (HEC-RAS) two-dimensional model (version 5.5) to assess levels of floodplain inundation and bed mobility (Hydrologic Engineering Center, 2021). The bathymetry layers derived from field-based channel surveys were used as terrain layers, utilizing 0.5 m cell refinement regions to represent the active channel area and 1.5 m cells to represent the floodplain. Landcover data derived from the Multi-Resolution Land Characteristics (MRLC) consortium 2021 National Land Cover Database (NLCD) were used to set fixed floodplain roughness coefficient across models (U.S. Geological Survey, 2021). Initial floodplain Manning's roughness (n) values were estimated from floodplain characteristics and the modified channel method (Acrement and Schneider, 1989). Floodplain infiltration and groundwater-surface interactions were considered out of the scope of this study and not accounted for in these modeling scenarios. I calibrated each model using the peak field-measured discharge and corresponding water surface elevation (WSE). Manning's roughness coefficients (n) of the active channel and floodplain for each model were calibrated using the root means square error (RMSE) between observed WSE and modeled WSE (Table 4).

Table 4. Model calibration RMSE values.

Reach	Channel Manning's n	Floodplain Manning's n	RMSE	Mean Courant Number
Upper Baker	0.066	0.07	0.058	0.1
Lower Baker	0.062	0.09	0.058	0.2
Onahu	0.055	0.07	0.049	0.6

I ran flow scenarios at observed peak discharge and observed base flow discharge to determine floodplain inundation extent. The peak flow used was determined by averaging 15-minute flow data over the day of highest recorded discharge. Floodplain inundation shapefiles and bed shear stress raster files were exported for analysis in ArcGIS Pro and R. The area of inundation shapefiles was calculated using the “sf” package in R (Pebesma, 2018). The area inundated during peak flow was compared to the area inundated during base flow for each reach to determine relative levels of floodplain connectivity between sites. I also compared model results of flow inundation to mapped relict beaver dam activity to assess the role of abandoned beaver dams on floodplain connectivity.

2.3 Analytical methods

2.3.1 Statistical analysis

Statistical analyses were conducted on sinuosity, channel cross section area, bank grain size distribution, erosion index, and floodplain depth-to-refusal data of each reach to assess significant differences between study reaches using R 4.4.1 software and packages (R Core Team, 2024). The distribution of data was examined with histograms and the Shapiro-Wilk test for normality. Levene's test was used to test for equal variance between datasets. In the case of normality and equal variance, an analysis of variance (ANOVA) test was performed first, followed by a Tukey (HSD) test for differences between specific sites. In the case of nonnormality or unequal variances, a Kruskal-Wallis test was performed followed by Dunn's test (Bonferro method). All calculated *p*-values were evaluated for significance using a threshold of $\alpha < 0.05$.

2.3.2 Prioritization

Based on the quantitative data of channel and floodplain characteristics, I developed a conceptual ranking scheme and ranked each study site along a gradient from low to high, or poor to good based on geomorphic condition. Sites were scored from 1 to 3 (1 indicating worst condition, 3 indicating best condition) for both channel and floodplain characteristics and the cumulative total score of each site was used to rank individual characteristic types and overall condition. From a geomorphic context, Upper Baker, Lower Baker, and Onahu Creeks are shaped by very similar geomorphic process drivers and therefore have similar contexts, but differences were observed. This ranking can then be used for prioritization based on specific project goals, in this case improving channel-floodplain connectivity. The choice of factors to include in my comparisons was based on statistical results and professional judgement of expected geomorphic responses following the loss of beaver and their implications for tall willow recovery.

3. RESULTS

3.1 Channel Geomorphic characteristics

3.1.1 Discharge

The hydrographs of all sites exhibit a snowmelt-driven peak in early to mid-June (Figure 7, Table 5). Strong diurnal fluctuations in flow are observed between May and July, driven by large fluctuations in daily temperatures at upper catchment elevations and corresponding snowmelt rates. Onahu Creek experienced the earliest peak flow (6/6/24), highest recorded peak discharge (2.68 cms), and highest average base flow (0.16 cms). All hydrographs exhibit minor high flows in the receding limb driven by summer storms. Upper Baker and Lower Baker Creeks have sharper receding limbs than Onahu, possibly from Grand Ditch withdrawals.

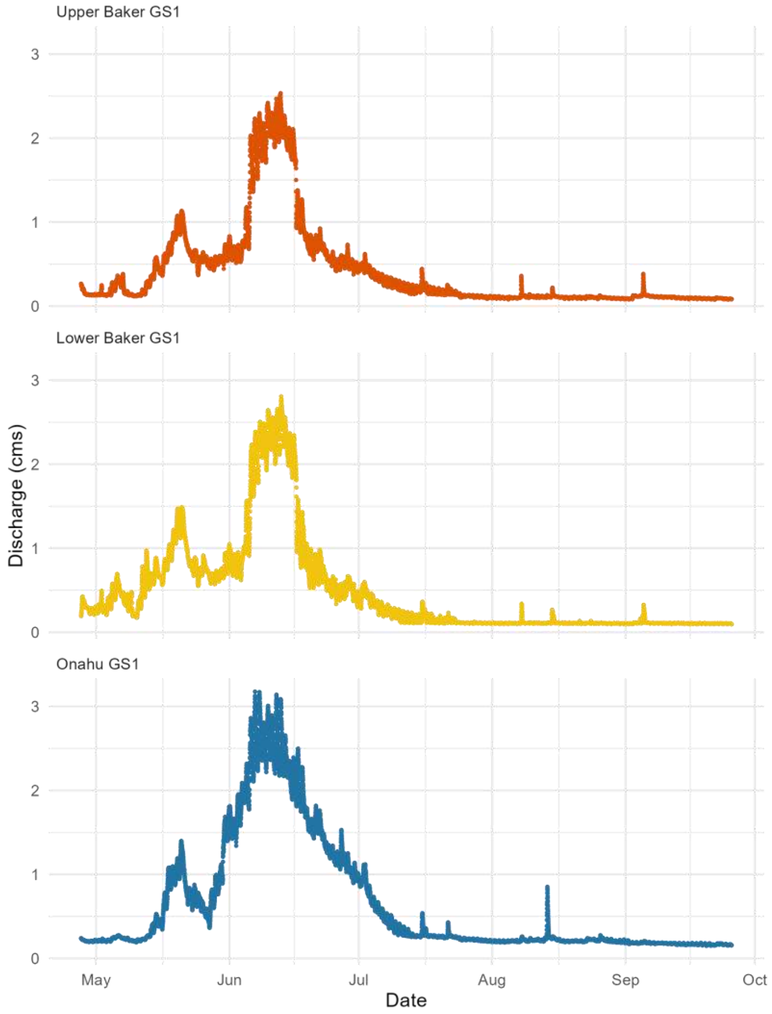


Figure 7. Hydrographs of upstream gage sites (GS1) in 2024.

Table 5. Summary of discharge data observed at upstream gage sites (GS1).

Reach	Peak flow (cms)	Date of peak flow	Average daily peak flow (cms)	Average base flow (cms)
Upper Baker	2.53	6/12/2024	2.23	0.08
Lower Baker	2.81	6/12/2024	2.47	0.10
Onahu	3.18	6/6/2024	2.68	0.16

3.1.2 Sediment transport

Limited sediment transport was observed during the 2024 snowmelt season and, hence, few measurements of suspended sediment and bedload transport were collected (Figure 8). Onahu Creek had the greatest SS transport rate (449.8 g/s), and Lower Baker had the greatest bedload transport rate (4.6 g/s). Greater transport rates of SS and bedload were observed prior to peak flows, exhibiting an expected flushing of stored sediment from the bed (Resh et al., 1988; Kondolf and Wilcock, 1996). Due to similarity in results and limited sampling data, no further discussion of sediment transport is included.

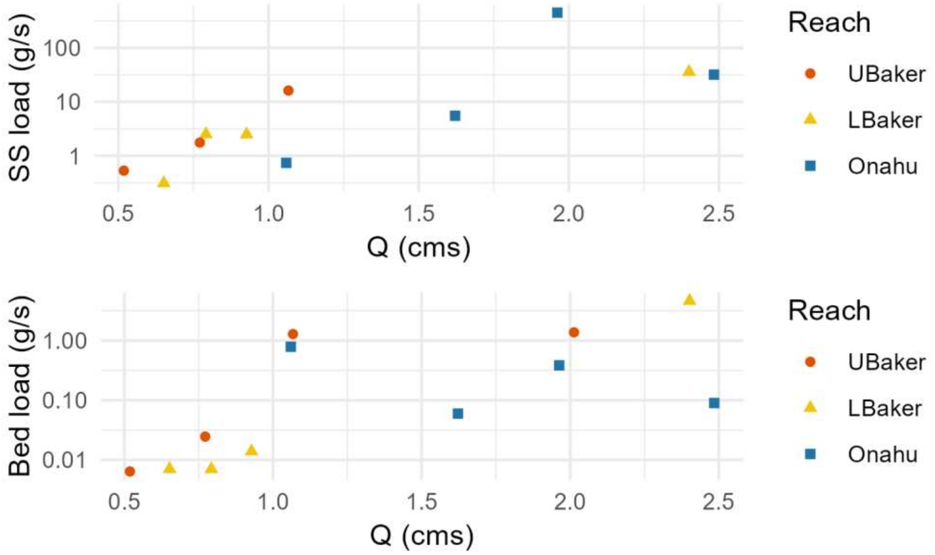


Figure 8. Suspended sediment (SS) and bedload transport rate results.

Table 6. Summary table of sediment transport results.

	Date	**Time**	**Discharge**	**Suspended sediment concentration (mg/L)**	**SS flux (g/s)**	**Bedload flux (g/s)**
Upper Baker	5/30/2024	14:20	0.52	1.02	0.53	0.01
	6/4/2024	17:02	1.07	15.16	16.18	1.28
	6/11/2024	9:12	2.01	-	-	1.37
	6/17/2024	10:34	0.77	2.27	1.75	0.02

Lower Baker	5/30/2024	16:22	0.65	0.48	0.31	0.01
	6/5/2024	11:16	0.93	2.68	2.49	0.01
	6/10/2024	14:05	2.40	14.94	35.89	4.62
	6/17/2024	14:41	0.79	3.16	2.50	0.01
Onahu	5/30/2024	11:28	1.06	0.70	0.74	0.79
	6/5/2024	14:00	1.96	229.09	449.75	0.38
	6/10/2024	9:44	2.48	12.86	31.95	0.09
	6/18/2024	9:13	1.62	3.40	5.52	0.06

3.1.3 Bankfull cross-sectional area and thalweg characteristics

I found that width-to-depth ratio was not an adequate metric for describing channel morphologic condition, specifically levels of incision. I observed low levels of incision at all three study reaches, despite varying width-to-depth ratios (Appendix II). I instead assessed cross-sectional area as a more appropriate indicator of the impact of channel geometry on channel-floodplain connectivity. Based on field cross sectional surveys, Upper Baker has the smallest average cross-sectional area (1.51 m^2) (Figure 9). Tukey tests indicate that cross-sectional area differed significantly between the Upper and Lower Baker sites ($p < 0.001$) and the Upper Baker and Onahu sites ($p < 0.001$), but not between Lower Baker and Onahu ($p = 0.646$). Morphologic bankfull elevation and thalweg difference were not statistically significant between any of the three sites, indicating differences in cross-sectional area are the product of varying bankfull widths. Channel geometries indicate differences in cross-sectional areas, but no apparent differences in levels of incision.

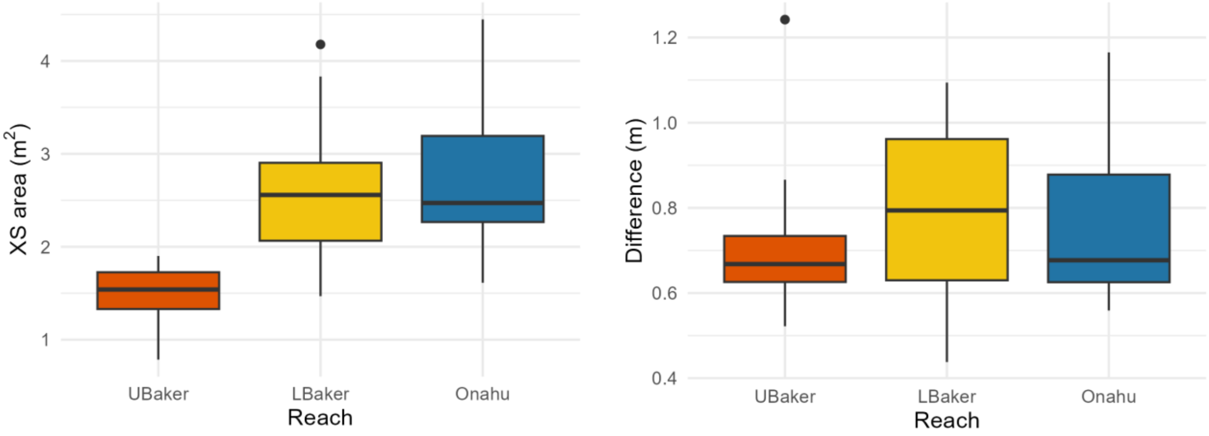


Figure 9. (left) Interquartile distributions of bank-full cross-sectional (XS) area. (right) Interquartile distributions of difference between bankfull and thalweg elevations.

Table 7. Channel geometry summary

	Upper Baker	**Lower Baker**	**Onahu**	**Significant difference (Kruskal-Wallis)**	**p-value**	**Significant difference (Dunn's test)**
Average XS area (m^2)	1.51	2.56	2.79	Y	<0.001	Upper Baker - Lower Baker (p<0.001) Upper Baker - Onahu (p<0.001)
Thalweg and bankfull elevation difference (m)	0.71	0.77	0.75	N	0.684	-

3.1.4 Bed and bank sediment characteristics

All three systems had coarse gravel bed material. Onahu Creek had the coarsest bed material with a D_{50} of 29.1 mm, Upper Baker Creek had 18.1 mm, and Lower Baker Creek had 17.4 mm (Figure 10). Field observations of bank soils largely matched the Kawuneeche Series descriptions but lacked an organic-rich peat layer and the high soil moisture conditions described throughout. Across all sites, bank profiles were similar and fell into three general categories: fines over coarse sandy gravel material, fines throughout, or fines overlaying a silty-clay and peat layer over coarse material (Figure 11). Heavy rooting of vegetation was observed throughout the channel banks, contributing to bank cohesion and erosional resistance. In some cases, root mats were observed overhanging and shielding coarser, more readily erodible bank materials. Bank undercutting of varying magnitudes (10 to 40 cm) was common, occurring predominantly in underlying coarse sand and gravel layers. The presence of intermittent, erosion resistant silty-clay and peat layers were observed throughout, likely deposits from former beaver ponds. All sites exhibited well-vegetated, largely stable banks and the qualitative erosion index (Figure 12) indicated no significant differences (p-value = 0.319) in bank failure or visible erosion between sites.

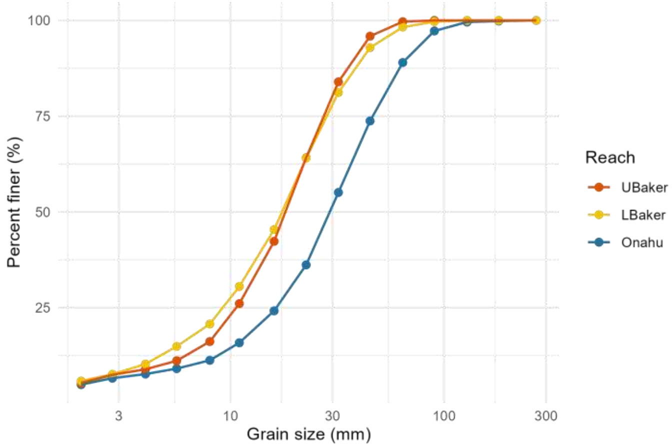


Figure 10. Bed grain cumulative frequency distribution plot results.

Figure 11. Examples of observed bank characteristics: fines over sandy gravel (left), fines throughout (middle), fines over a silty-clay peat layer over coarse material (right).

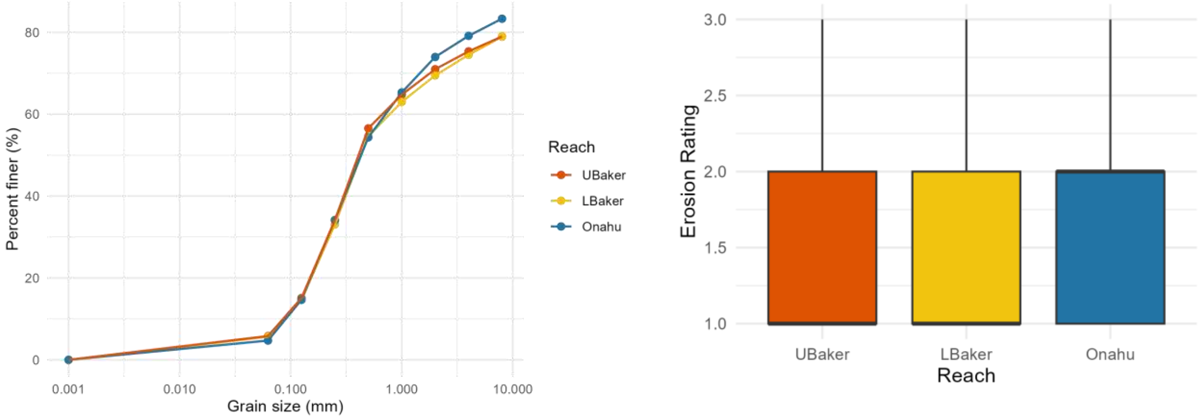


Figure 12. (left) Bank sediment cumulative frequency distribution plot results. (right) Interquartile distributions of erosion index assessments.

Bank sediment cumulative frequency distributions indicate all three sites have similar sediment characteristics (Figure 12). Upper Baker Creek had a D_{50} of 41 mm, Lower Baker Creek had 43 mm, and Onahu Creek had 43 mm.

Table 8. Summary of bed and bank sediment median grain size (D_{50}) and erosion index results

	Upper Baker	**Lower Baker**	**Onahu**	**Significant difference (Kruskal-Wallis)**	**p-value**
Bed grain D_{50} (mm)	18.1	17.4	29.1	-	-
Bank sediment D_{50} (mm)	0.41	0.43	0.43	-	-
Average erosion index rating	1.5	1.47	1.73	N	0.319

3.1.5 Thalweg depth-to-refusal

Mean thalweg depth-to-refusal (TDTR) varied from -0.09 m to -0.27 m below the thalweg surface, with the greatest thalweg sediment depth recorded at Lower Baker Creek. A

Krustal-Wallis test indicates TDTR between sites did not differ significantly (p = 0.076) (Figure 13). TDTR data are not discussed further due to similarity in results and limited sample data.

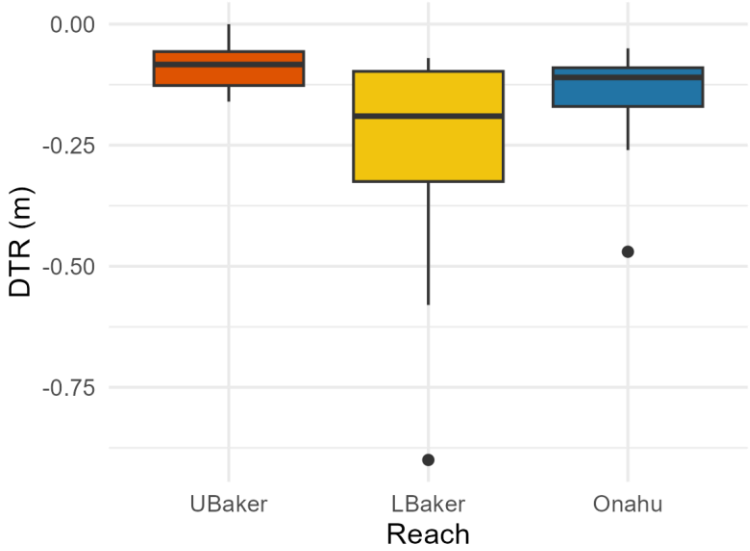


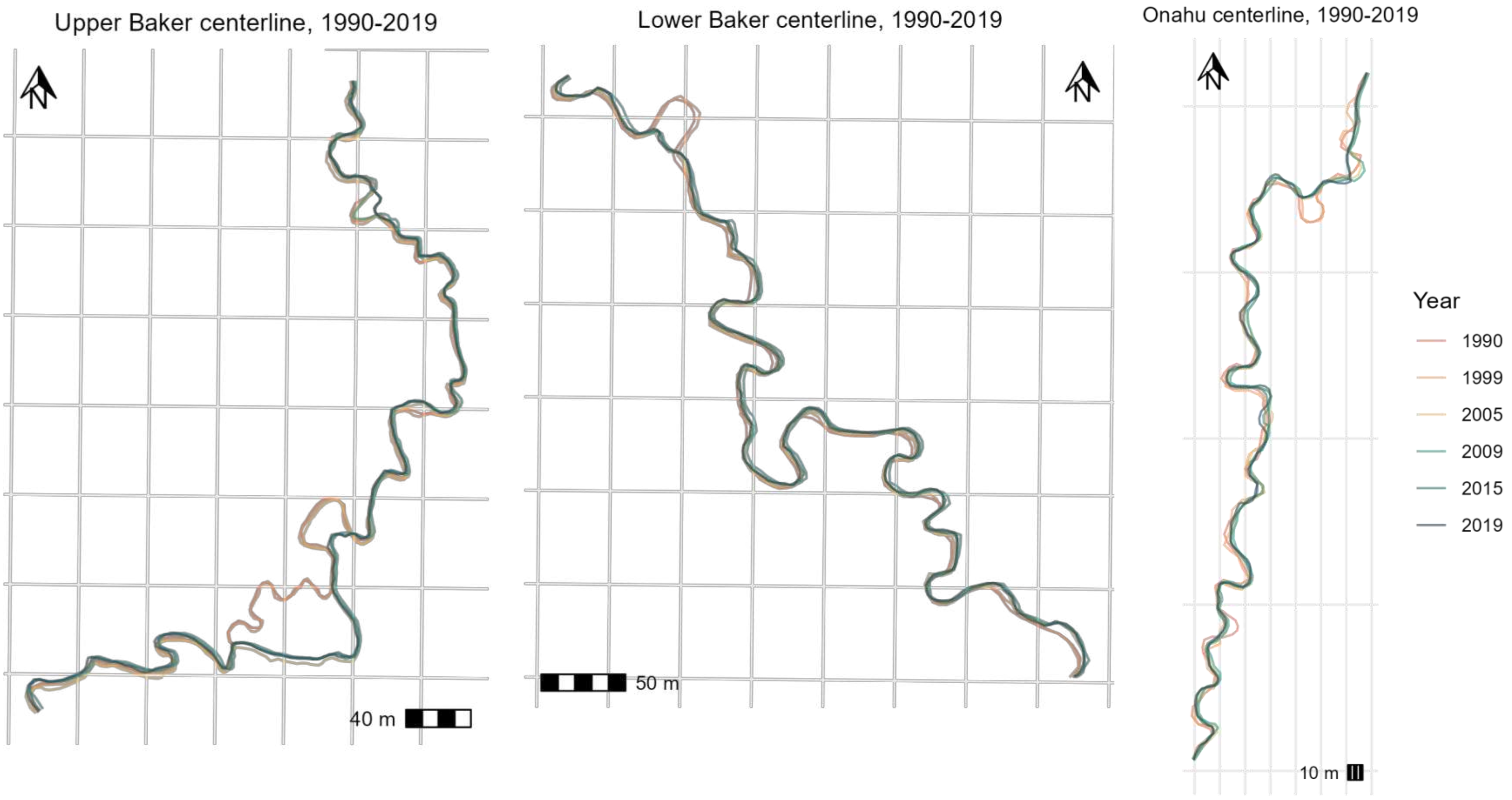
Figure 13. Interquartile distributions of thalweg depth-to-refusals below the channel thalweg surface, indicated by negative values on the y-axis.

Table 9. Summary of thalweg depth-to-refusal results

	Upper Baker	**Lower Baker**	**Onahu**	**Significant difference (Kruskal-Wallis)**	**p-value**
Mean DTR (m)	-0.09	-0.27	-0.15	N	0.076
Minimum DTR (m)	-0.16	-0.90	-0.47	-	-
Maximum DTR (m)	0.00	-0.07	-0.05	-	-

3.1.6 Sinuosity and channel form change

Based on aerial imagery from 1990 to 2019, Upper Baker Creek is the only reach to exhibit a significant decrease (p = 0.037) in channel sinuosity (Figure 15, Table 10). Over the 29-year period of observation, Upper Baker, Lower Baker, and Onahu Creeks exhibited 3, 1, and 2 channel avulsions, respectively (Table 11). Field observations indicated some avulsions were the result of beaver dam breaching. Of the three sites, Upper Baker Creek experienced the greatest level of channel planform change as indicated by decreased sinuosity and avulsions since 1990.


Upper Baker centerline, 1990-2019

Lower Baker centerline, 1990-2019

Onahu centerline, 1990-2019

Figure 14. Time series maps showing channel sinuosity change at each reach, 1990-2019.

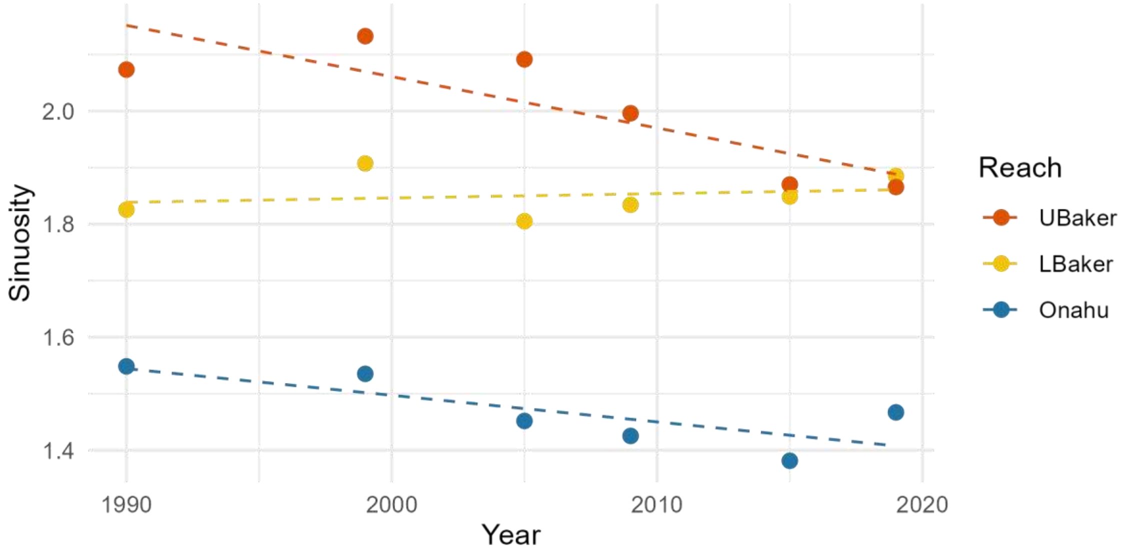


Figure 15. Channel sinuosity change, 1990-2019.

Table 10. Linear regression summary of sinuosity changes, 1990-2019.

	Linear regression model	p-value
Upper Baker	y = -0.009x + 20.21	0.04
Lower Baker	y = 0.0008x + 0.31	0.69
Onahu	y = -0.005x + 10.91	0.07

Table 11. Summary of sinuosity change and avulsions observed, 1990-2019.

	Year	Stream length (m)	Valley Length (m)	Sinuosity	Avulsions
Upper Baker	1990	902.6	435.4	2.1	0
	1999	928.4	435.4	2.1	0
	2005	910.5	435.4	2.1	1
	2009	869.0	435.4	2.0	1
	2015	814.1	435.4	1.9	1
	2019	812.2	435.4	1.9	0
Lower Baker	1990	853.2	467.4	1.8	0
	1999	891.5	467.4	1.9	0
	2005	843.7	467.4	1.8	1
	2009	857.3	467.4	1.8	0
	2015	864.1	467.4	1.8	0
	2019	881.1	467.4	1.9	0
Onahu	1990	732.8	473.3	1.5	0
	1999	726.5	473.3	1.5	0
	2005	687.1	473.3	1.5	1
	2009	674.6	473.3	1.4	1

2015	653.8	473.3	1.4	0
2019	694.3	473.3	1.5	0

3.1.7 Relict dam activity

The most persistent in-channel beaver activity was observed on Onahu Creek, with a channel-spanning dam observed in 2009. No channel-spanning beaver activity was observed at Lower Baker Creek in 1999 (Figure 16). The absence of channel-spanning dams does not imply the total loss of beaver from a system as it is possible that beaver activity still persisted in secondary channels at Upper and Lower Baker Creeks. The frequency of channel-spanning dams was standardized by reach length for comparison. In 1990, Upper Baker Creek had 0.33 dams per 100 m stream length, Lower Baker Creek had 0.59, and Onahu Creek had 1.23. Since 1990, Onahu Creek had the greatest loss of in-channel structural heterogeneity, primarily in the form of channel-spanning beaver dams.

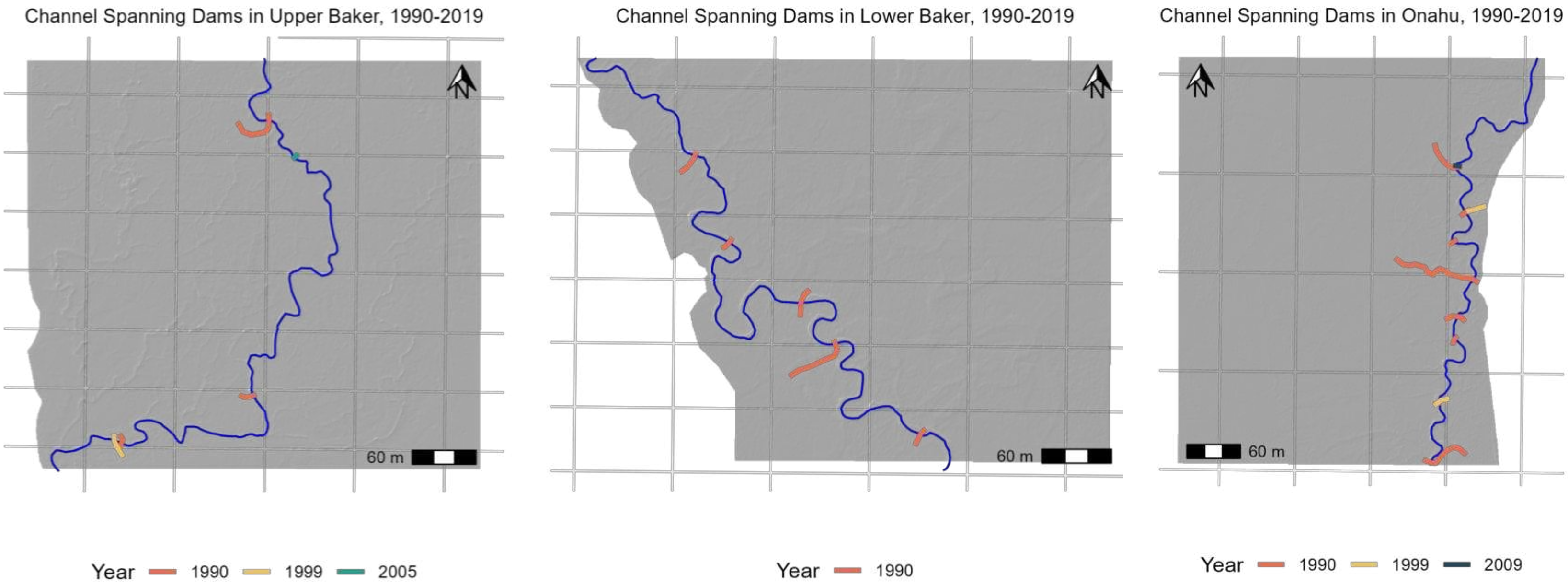


Figure 16. Time series maps of channel-spanning relict dam activity at each reach, 1990-2019. Channel centerlines indicated in blue, dam observations with corresponding years indicated in legend.

Table 12. Summary of channel-spanning dam densities by reach (number of dams per 100m).

	Upper Baker	**Lower Baker**	**Onahu**
1990	0.33	0.59	1.23
1999	0.11	0	0.28
2005	0.11	0	0
2009	0	0	0.15
2015	0	0	0
2019	0	0	0

3.2 Floodplain geomorphic characteristics

3.2.1 Floodplain sediment characteristics & willow condition

Floodplain sediment depth-to-refusal (FDTR) measurements varied from -2.35 m to 0 m below the ground surface. Upper Baker Creek has the deepest fine-grained sediments within the floodplain at -2.35 m (Figure 18). A Kruskal-Wallis test indicated significant difference in the median FDTR values at each site ($p < 0.001$) with Dunn test's indicating significant difference between each site ($p < 0.001$). Detailed plots of textural classifications for each transect can be found in Appendix III.

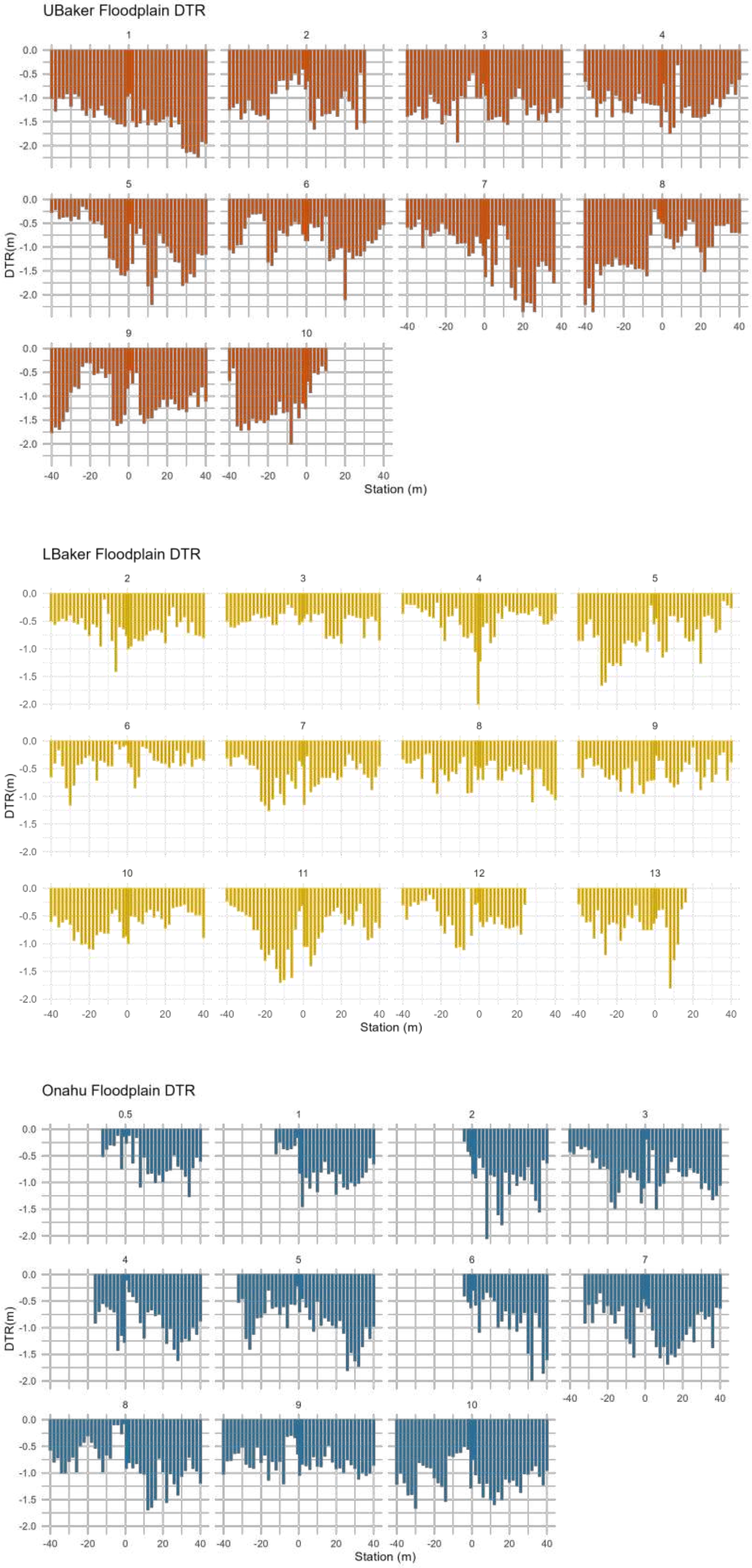


Figure 17. Transect plots of floodplain depth-to-refusal by reach. Transect number indicated above each plot. Negative stations indicate left-bank and positive stations indicate right-bank.

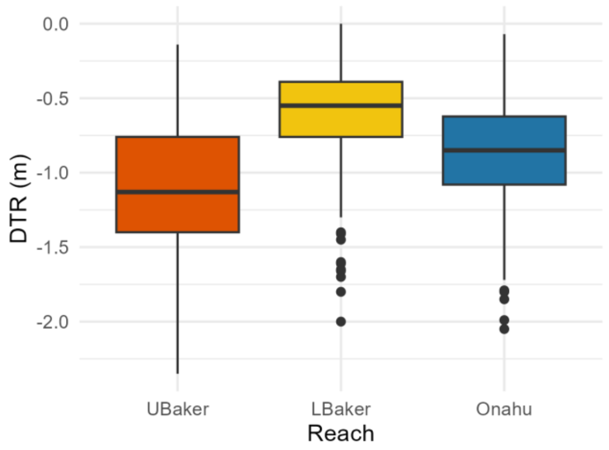


Figure 18. Interquartile distributions of floodplain depth-to-refusal below ground surface.

Table 13. Summary of floodplain depth-to-refusal results.

	Upper Baker	**Lower Baker**	**Onahu**	**Significant difference (Kruskal-Wallis)**	**p-value**	**Significant difference (Dunn's test)**
Mean DTR (m)	-1.11	-0.60	-0.87	Y	<0.001	All reach comparisons p < 0.001
Minimum DTR (m)	-2.35	-2.00	-2.05	-	-	-
Maximum DTR (m)	-0.14	0.00	-0.07	-	-	-

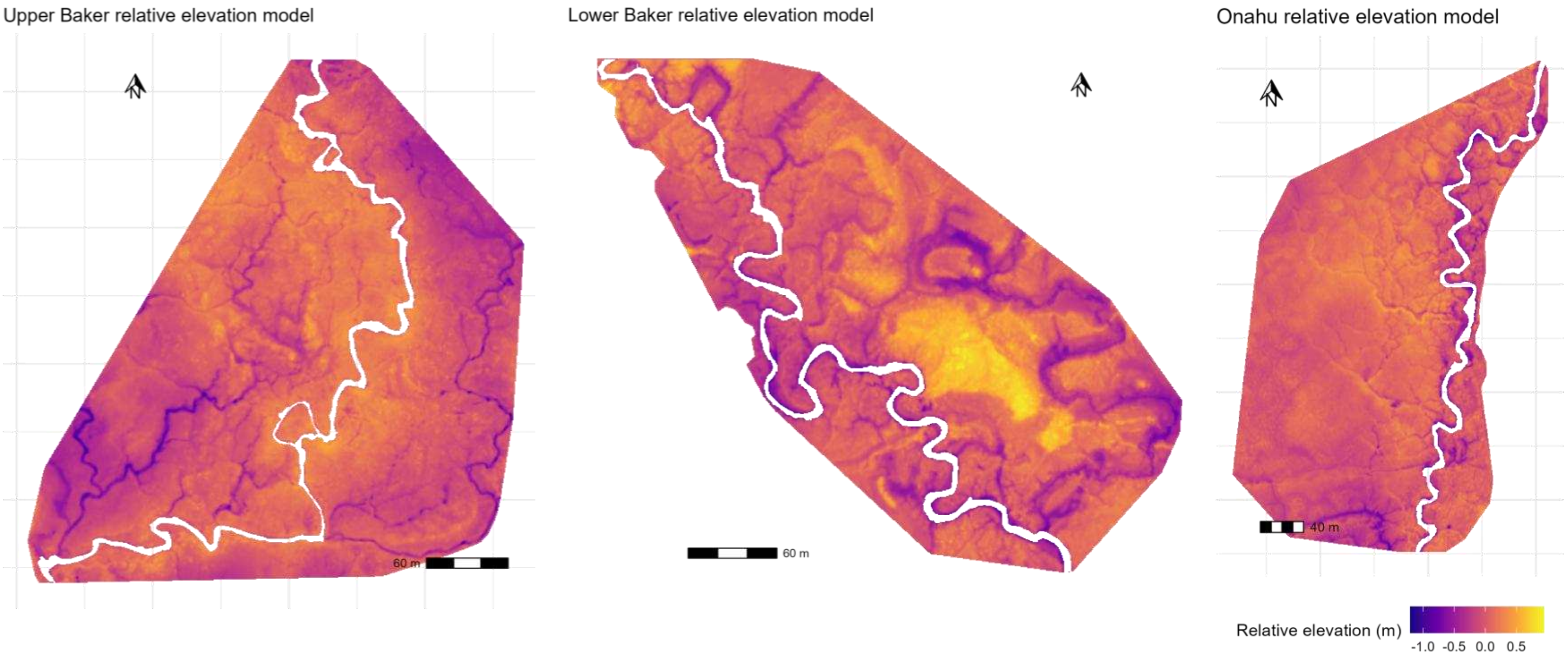
Willow condition assessments indicate varying degrees of stand health between study reaches. In all reaches, observed willow were severely stunted in height (ranging ~10 - 40 cm tall) from ungulate browse pressure. In addition, burned willow shoots from the 2020 East Troublesome fire were visible at all sites, with the highest frequency of burned willow at Onahu Creek. Most surviving willow were in proximity to the active channel or in floodplain depressions. Overall, Lower Baker Creek had the healthiest willow condition with 46% of the total transects containing a rating of “high” relative willow condition.

Table 14. Summary of qualitative assessment of willow condition indicating percent of transects falling into each condition category

	Low-none	**Moderate**	**High**
Upper Baker	68	16	16
Lower Baker	38	15	46
Onahu	80	20	0

3.2.2 Floodplain surface complexity & floodplain dam activity

Five metrics of floodplain surface complexity (SD, range, SD_{curv}, rugosity, and CV) (Scown et al., 2015, 2016; Wohl, 2016) were assessed at a 10-year flood surface water extent to compare relative complexity between sites. Floodplain Manning's n values from calibrated HEC-RAS models were also included for comparison. Lower Baker Creek had the highest relative values for SD (0.26), Range (1.89), SD_{curv} (3.76), and rugosity (1.004) and Upper Baker Creek had the highest relative value for CV (619.6) (Table 15). Higher metric values are interpreted as having greater relative surface complexity. Visual assessments of REMs at each site, symbolized at fixed scales (Figure 19), indicate differences in topographic complexity, most notably the presence of secondary channels at Upper Baker and Lower Baker Creeks. The western valley bottom of Onahu Creek exhibits a lack of floodplain surface complexity and heterogeneity. Another visualization using violin plots (Figure 20) indicates greater variation in the densities of REM pixel values at Upper Baker and Lower Baker Creeks. At a 10-year flood extent, Upper Baker and Lower Baker score the highest across all 5-complexity metrics. A detailed description of floodplain surface complexity characteristics can be found in Appendix IV.



Upper Baker relative elevation model

Lower Baker relative elevation model

Onahu relative elevation model

Figure 19. Relative elevation models at 10-year flood extent. Color scales are fixed for qualitative comparison.

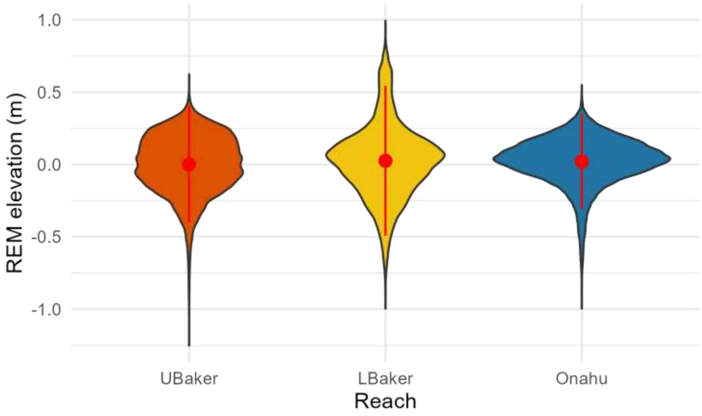


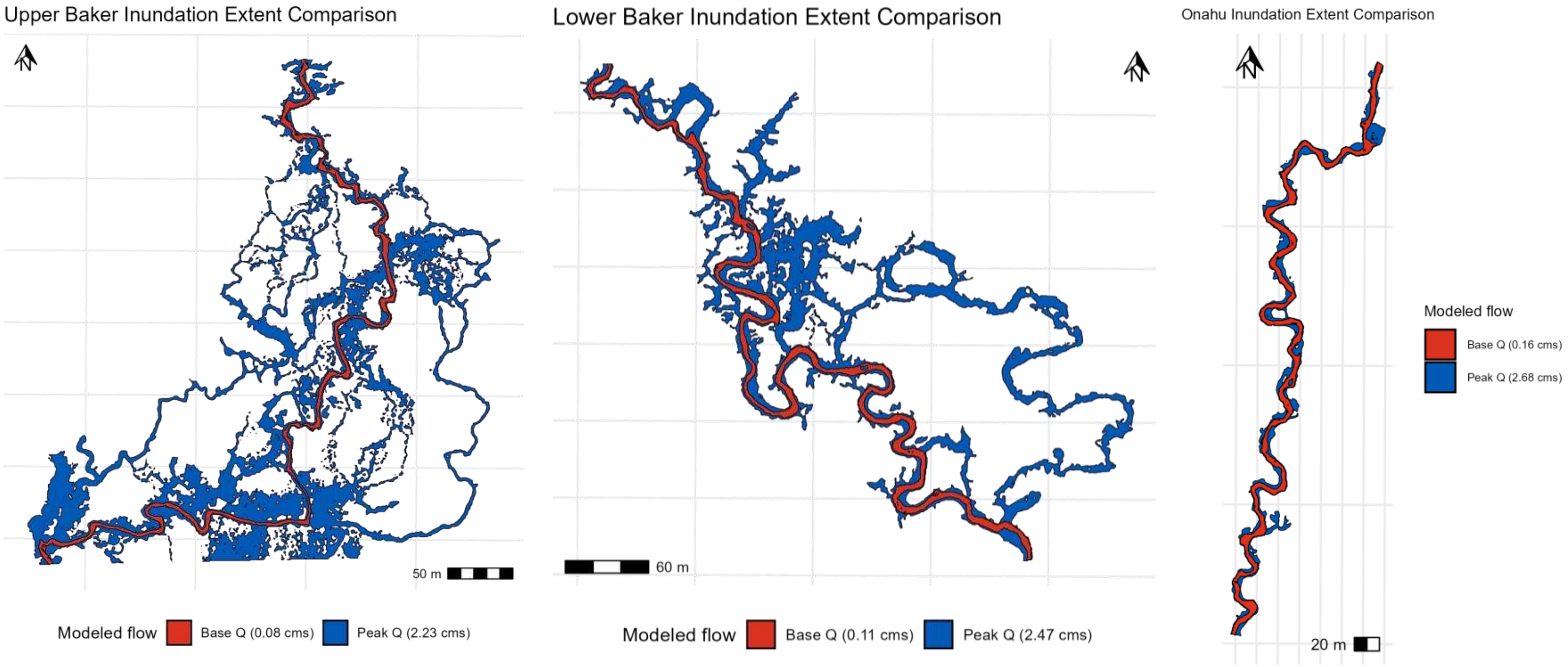
Figure 20. Violin plot of relative elevation model pixel values, red dots indicate mean pixel values with red line extent indicating one standard deviation range.

Table 15. Summary of surface complexity characteristics at 10-year flood extent (highest values in bold).

	Upper Baker	**Lower Baker**	**Onahu**
SD	0.20	**0.26**	0.16
Range	1.79	**1.89**	1.48
SD_{curv}	3.43	**3.76**	3.15
Rugosity	1.003	**1.005**	1.003
CV	**619.6**	10.1	7.9
HEC-RAS model roughness	0.07	**0.09**	0.07

3.3 Flow inundation modeling

Relative levels of floodplain connectivity were determined by comparing the change in area of modeled surface water extent between observed base flow and peak flows at each site (Figure 21). Flow inundation modeling indicates that Upper Baker Creek has the highest degree of floodplain connectivity with a 10.3x increase in surface water extent between observed base and peak flows, relative to a 5.2x increase at Lower Baker Creek, and a 1.9x increase at Onahu Creek. Modeling results confirm field observations that both Upper Baker and Lower Baker Creeks readily access their floodplains. Floodplain characteristics at these sites such as low valley-bottom slope, low-conveyance, beaver canals adjacent to the channel, and secondary channels are conducive to spreading water away from the channel and across the floodplain.


Upper Baker Inundation Extent Comparison

Lower Baker Inundation Extent Comparison

Onahu Inundation Extent Comparison

Figure 21. HEC-RAS model results comparing inundated area at base and peak flows

Table 16. Peak average Q inundated area to base average Q inundated area

Reach	Base avg Q (cms)	Peak avg Q (cms)	Area at base flow (m^2)	Area at peak flow (m^2)	Percent total
Upper Baker	0.08	2.2	2294	23645	1031
Lower Baker	0.10	2.5	3342	17345	519
Onahu	0.16	2.7	2773	5131	185

3.4 Integrated results: relict dams and impacts

Associations between relict beaver dam presence and observations of bank composition, thalweg depth, and floodplain sediment depths are complex. In all reaches, bank profiles dominated by finer grained silt and clay layers and lacking a sandy-gravel coarse layer were commonly located near a historic dam. Factors such as channel gradient (for example, Lower Baker at 0.3%) and valley position also appear to affect bank sample characteristics by increasing the prevalence of fine sediment in the profiles. Observations of TDTR do not appear to correspond to relict beaver dam locations. Channel FDTR transects show a wide range of sediment depths regardless of relict dam locations, indicating that other drivers predominantly shape floodplain topography. Some instances of thick floodplain sediments behind a relict dam were observed (Figure 22) though. Locations of relatively shallow floodplain sediment depths are often reflective of secondary channel locations, avulsions, and historical beaver canals.

Flow inundation modeling largely matches historical mapping of relict beaver dam features and confirms that relict dams still actively contribute to floodplain surface complexity and drive overbank flow dynamics in these systems (Figure 22). This is seen predominantly in Upper Baker and Lower Baker Creeks. Onahu Creek does not readily access its floodplain and therefore these features were not activated by flows measured during our period of study.

Figure 22. (left) Example of deep floodplain sediments deposited behind a historical channel-spanning beaver dam at Lower Baker Creek. Relict beaver dam in red, darkening circles indicate deeper floodplain sediment). (right) Example of relict beaver dam features reactivated on the floodplain during peak flows at Upper Baker Creek (peak flow inundated in light blue, relict beaver dams in red).

4. DISCUSSION

4.1 Condition ranking & prioritization

I developed an adaptable ranking framework for restoration based on relative geomorphic condition by assessing the historical and contemporary geomorphic context of fluvial systems. A suite of geomorphic characteristics, derived from field, remote, and modeling techniques, were measured at each study site for ranking criteria. This approach focuses strictly on the geomorphic context of systems, not accounting for other logistical constraints such as funding and access that are common to restoration planning. In the Kawuneeche Valley, all of my study tributaries are considered degraded due to the loss of tall willow. The KVRC project goal is to improve channel-floodplain connectivity to promote tall willow recovery. Here, I provide managers and restoration practitioners with an overall ranking of relative geomorphic condition, which informs site priority, and level of intervention required to meet that goal.

4.1.1 Expanding on the River Styles Approach

Existing applications of the River Styles framework focus on a catchment scale (Brierley, 2000; Fryirs, 2003; O'Brien et al., 2017). The small spatial scale of the project sites identified in the Kawuneeche Valley necessitate a more detailed, reach-scale analysis of channel and floodplain characteristics not implemented in River Styles. To address this, I included consideration of field-based metrics of channel geometric and floodplain sediment characteristics and REM-derived floodplain surface complexity. Additionally, I incorporated hydraulic modeling in my analysis to assess relative levels of channel-floodplain connectivity, a primary restoration goal identified by RMNP managers. The methodology I developed includes core elements of the River Styles approach but is more applicable for comparison of reach-scale sites of similar topographic setting or geomorphic condition. This is particularly relevant in many restoration contexts on federal and private lands, where project scopes are often small in scale due to restricted access or funding.

4.1.2 Prioritization of Upper Baker, Lower Baker, and Onahu Creeks

In the context of tall willow recovery, channel geometry, channel planform adjustments, and historical beaver activity are the most important channel characteristics to compare in these systems. Therefore, channel geometry, sinuosity changes, and relict beaver activity were used in the relative ranking of channel characteristics for Upper Baker, Lower Baker, and Onahu Creeks (Figure 23). Although all three channels exhibit low levels of incision, they differ in average cross-sectional area. Upper Baker Creek has a significantly smaller cross-sectional channel area compared to Lower Baker and Onahu Creeks (Figure 9). Cross-sectional area relates to channel conveyance, or the volume of water a channel can hold before overtopping its banks. Differences in cross-sectional area at my study sites are primarily a function of differences in width, with Upper Baker Creek showing smaller average bankfull width compared to Onahu or Lower Baker Creeks (Figure 9). This partially explains the greater levels of floodplain inundation observed in the hydraulic modeling results at Upper Baker Creek relative to Onahu Creek despite similar peak flows (Figure 21). In a geomorphic context, low conveyance, or small channel cross-sectional area, is a favorable characteristic for tall willow recovery, as it promotes floodplain inundation and lateral connectivity at lower discharges.

Channel characteristics

Since 1990, avulsions and channel straightening have occurred at Upper Baker and Onahu Creeks following the loss of channel-spanning beaver dams. Between 1990 and 2019, one avulsion was observed from aerial imagery at Lower Baker Creek, but there was no evidence of channel straightening. A comparison of aerial imagery from 1953 to 2019 indicates that overall shifts in channel centerlines were minimal but that surface water area decreased and became more concentrated as single-thread flow.

Onahu Creek shows the greatest loss of in-channel relict beaver dams that historically increased channel heterogeneity and promoted channel floodplain connectivity. In-channel dams promote overbank flows and channel-floodplain connectivity but are not the sole driver of connectivity in all three of these systems. Upper Baker and Lower Baker Creeks still readily inundate their floodplain at high flows despite the loss of in-channel dams. Onahu Creek has the lowest channel-floodplain connectivity, and the loss of in-channel structural heterogeneity has the greatest relative impact on floodplain disconnection. Considering all channel metrics, I interpret Onahu Creek to have the poorest relative channel geomorphic condition (Table 17, Figure 23).

Table 17. Channel characteristic scoring to inform relative ranking, (1 indicates poorest condition, 3 indicates best condition).

	Upper Baker	**Lower Baker**	**Onahu**
Channel geometry	3	1	1
Sinuosity change / avulsions	1	3	2
Beaver dam activity / structural heterogeneity	3	2	1
Total	**7**	6	4

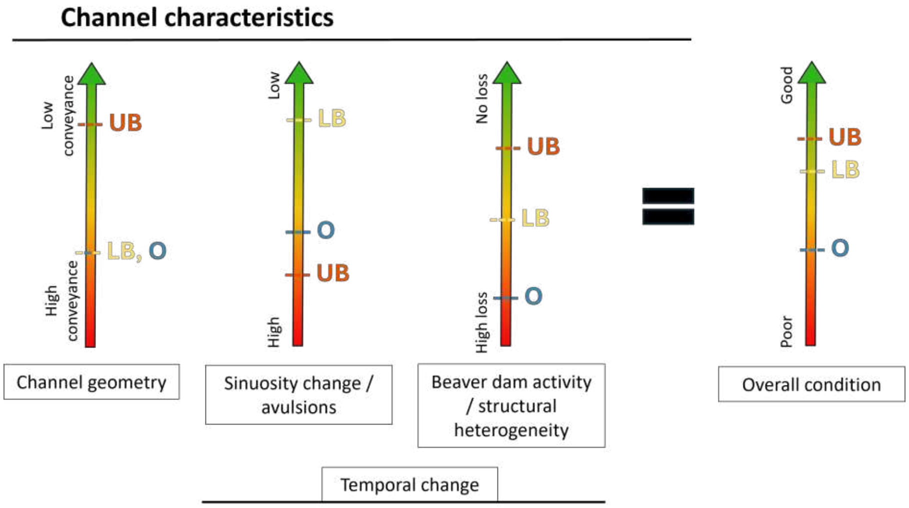


Figure 23. Condition assessment of channel characteristics (UB = Upper Baker, LB = Lower Baker, O = Onahu) indicating that Upper Baker has the best channel geomorphic condition, followed by Lower Baker then Onahu Creeks.

Floodplain characteristics

In the context of tall willow recovery, differences in floodplain sediment depths, willow condition, surface complexity, and channel-floodplain connectivity are the four most important floodplain characteristics to compare. I used these floodplain characteristics to rank the sites along gradients of condition (Figure 24), similar to the approach for channel characteristics. Upper Baker Creek has the deepest fine-grained floodplain soils, interpreted as the greatest relative ability to retain soil moisture following floodplain inundation. This is partially attributed to historical beaver activity. Beaver dams impound and store fine grained sediments capable of high water retention (Butler and Malanson, 2005; Polvi and Wohl, 2012). They also promote overbank flooding which deposits fine-grained sediments on the floodplain (Larsen et al., 2021). Across the three study sites, some instances of thicker fine-grained sediments deposited behind relict beaver dams were observed (Figure 22), but topographic position may also contribute to sediment thickness. Upper Baker Creek is located directly at the hillslope-valley bottom transition and has built an alluvial fan with greater soil depths. Lower Baker Creek has relatively thin floodplains soils, likely the result of the channel migration of the Upper Colorado River (observed in REM imagery, Figure 27), which reworked the floodplain and scoured fine-grained sediments from the area. Floodplain sediment depths and composition, flood attenuation rates, groundwater elevations, and fire activity play a role in willow dispersal and survival (Cooper et al., 2006). Qualitative surveys of willow condition indicate Lower Baker Creek has the greatest percentage of high-condition willow on its floodplain, providing potential for seed stock following recovery efforts (Table 14).

Table 18. Floodplain characteristic scoring to inform relative ranking (1 indicates poorest condition, 3 indicates best condition).

	Upper Baker	**Lower Baker**	**Onahu**
Sediment thickness	3	1	2
Willow-stand condition	2	3	1
Valley-bottom surface complexity	2	3	1
Connectivity	3	2	1
Total	**10**	9	5

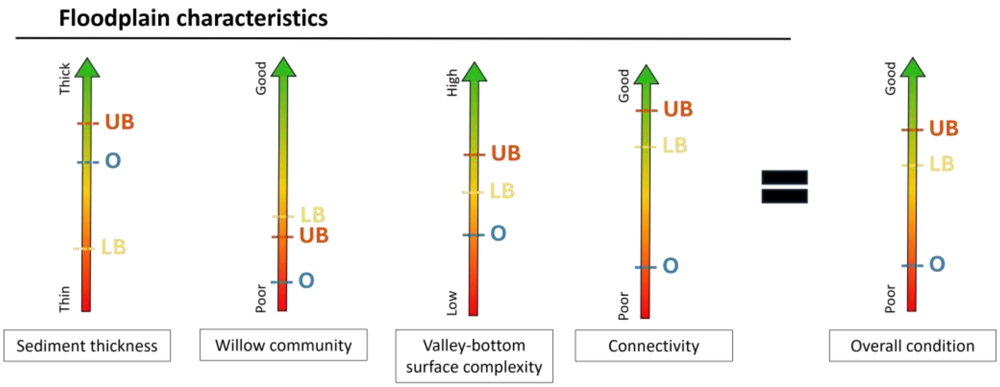


Figure 24. Condition assessment of floodplain characteristics (UB = Upper Baker, LB = Lower Baker, O = Onahu) indicating that Upper Baker has the best floodplain geomorphic condition, followed by Lower Baker then Onahu Creeks.

Upper and Lower Baker Creeks have greater overall floodplain surface complexity (Figure 20), exhibiting features that readily attenuate high flows on the floodplain. At all three sites, floodplain surface complexity is driven partially by relict beaver dam activity, but other factors play a role. Upper and Lower Baker Creeks have complex secondary channels that formed from historical channel migration driven by relict beaver activity and historical interactions with the Colorado River. The western floodplain of Onahu Creek is impacted by anthropogenic topographic alterations including irrigation and haying operations (Andrews, 2011), reducing floodplain surface complexity and leaving no active secondary channels. As a result, beaver activity was constrained to the active channel and Onahu Creek had the greatest density of channel-spanning dams in 1990. Consequentially, Onahu Creek has experienced the greatest reduction of in-stream structural heterogeneity following loss of beaver in the system.

Flow inundation models indicate that Upper Baker Creek has the highest channel-floodplain connectivity. High levels of connectivity are also observed at Lower Baker Creek, potentially a result of interactions between reach slope and floodplain characteristics that readily move water away from the active channel. Model results match field observations in which Onahu Creek shows limited channel-floodplain connectivity, even at peak flows in 2024. In the context of this assessment, channel-floodplain connectivity is the most important metric of geomorphic condition. Overall, Onahu Creek has the poorest relative floodplain geomorphic condition (Table 18, Figure 24).

Upper Baker Creek has the best geomorphic condition of the three sites, characterized by high channel-floodplain connectivity, thick floodplain soils capable of high water retention capacity at inundating flows, the best relative willow condition, and high floodplain surface complexity that diverts and stores water across the floodplain. In comparison, Onahu Creek exhibits low channel-floodplain connectivity, poor willow condition, and lower relative valley-bottom surface complexity (Figure 25).

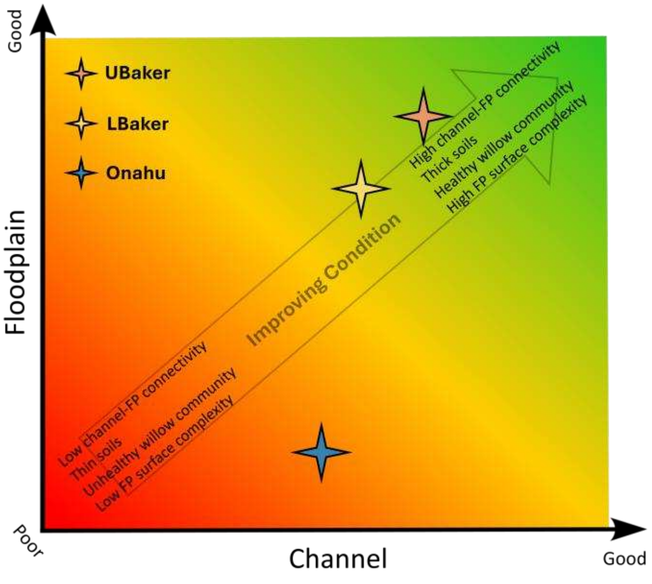


Figure 25. Conceptual ranking of existing geomorphic condition based on channel and floodplain characteristics for Upper Baker, Lower Baker, and Onahu Creeks. The diagonal arrow indicates improving channel and floodplain characteristics relative to restoration priorities. Upper Baker Creek shows the best overall geomorphic condition, followed by Lower Baker and Onahu Creeks.

My geomorphic-context-based ranking helps practitioners understand the drivers of geomorphic impairment occurring at the three study reaches to inform appropriate types and levels of work required for the restoration of tall willow communities. In a restoration context, Onahu Creek serves to benefit the most from restoration that targets channel-floodplain reconnection. Upper Baker and Lower Baker Creeks still readily access their floodplains and may be more suitable for “lighter-touch” restoration that protects floodplain vegetation but leaves the active channel undisturbed. If management goals are to conserve and protect systems in good condition, as advocated in some restoration philosophies (Fryirs, 2015), Upper Baker Creek is the highest ranking system and should be prioritized. Conversely, if management goals are to maximize ecologic uplift of a system and more resources are available for restoration, managers may choose to pursue work at Onahu Creek. The lack of channel-floodplain connectivity at Onahu Creek supports more intensive efforts to reconnect the floodplain and reestablish tall-willow communities.

4.1.3 Consideration of catchment characteristics

A wide range of spatial and temporal factors drive the processes that shape fluvial systems (Gregory et al., 1991; Montgomery, 1999; Beechie et al., 2010). To better understand the trajectory of a fluvial system and limitations for future restoration, I expanded the spatial scope of my ranking to include consideration of catchment-scale geomorphic complexity and disturbances that affect geomorphic processes (Rinaldi et al., 2013; Fryirs et al., 2016; Brierley and Fryirs, 2016).

Geomorphic complexity and valley-bottom character

Topographic (valley) position influences several differences observed across the three study sites. As mentioned earlier, Upper Baker Creek is located at the transition zone between the steep forested hillslopes and the low-gradient Kawuneeche Valley. Sediment deposition from the upper catchment has created an alluvial fan with visible multithread flow paths that disperse flows across the Upper Baker study reach (Figure 27). Large beaver dam complexes immediately above the study reach also contribute to water-dispersion and multithread flow patterns. These factors may partially explain the complex flow characteristics and deep-floodplain soils observed at Upper Baker Creek.

Table 19. Catchment characteristic scoring to inform relative ranking (1 indicates poorest condition, 3 indicates best condition).

	Upper Baker	**Lower Baker**	**Onahu**
Topographic-driven complexity	3	3	1
Disturbance (anthropogenic and natural)	2	1	3
Total	**5**	4	4

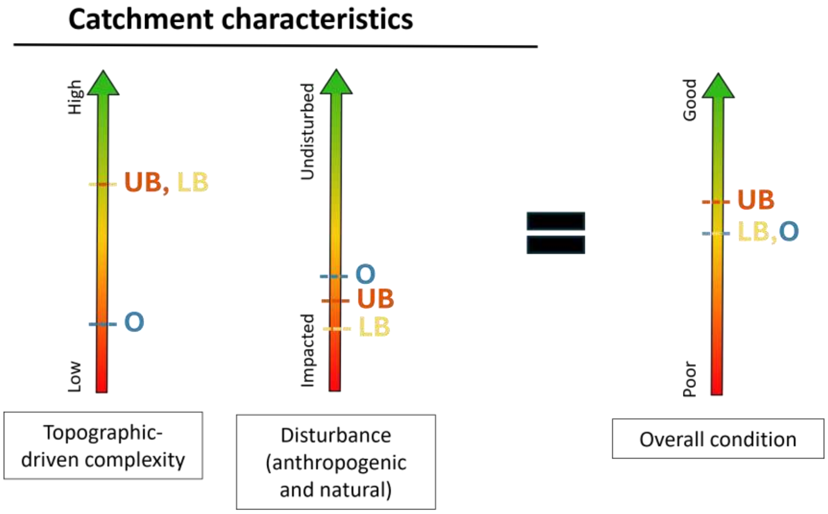


Figure 26. Condition assessment of catchment characteristics (UB = Upper Baker, LB = Lower Baker, O = Onahu) indicating that Upper Baker has the best catchment geomorphic condition, followed by Lower Baker and Onahu Creeks.

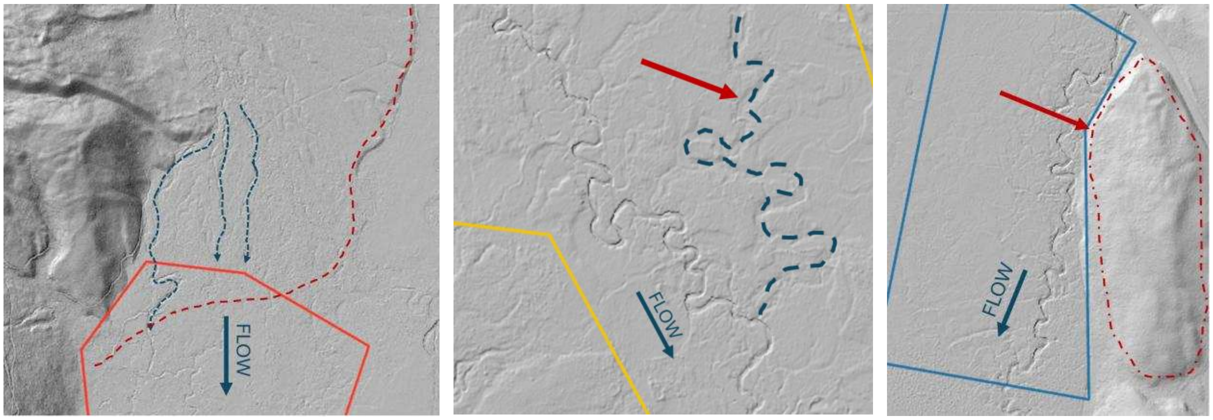


Figure 27. (left) Hillshade image of Upper Baker indicating alluvial fan deposition in the valley bottom (red dashes) and resulting multi-thread patterns (blue dashed arrows). (middle) Hillshade image of Lower Baker indicating historical channel migration path from the Colorado River (blue dashes). Hillshade image of Onahu indicating eastern moraine (red dashes) limiting lateral migration.

The valley bottom characteristics at Lower Baker Creek have been heavily influenced by interactions with the Colorado River. Since glacial retreat 10-11 ka (Richmond, 1960; Madole, 1980), the Colorado River migrated laterally across the Kawuneeche Valley, intercepting its tributary systems and altering floodplain topography and sediment characteristics. Aerial imagery and DEMs clearly indicate channel migration of the Colorado River in the eastern portion of the Lower Baker valley bottom (Figure 27). Immediately south of the study reach, Lower Baker Creek is intercepted by Bowen Creek, which likely contributes to higher overall valley-bottom wetness through backwater effects and hyporheic exchange. The Onahu Creek study reach is bound on the east by a glacial moraine (Braddock and Cole, 1990), which limits lateral migration and floodplain connectivity (Figure 27). Overall, Upper Baker and Lower Baker Creeks exhibit much greater topography-driven geomorphic complexity, which contributes to a rougher and wetter floodplain.

Anthropogenic disturbance

Humans have occupied the Kawuneeche Valley for millennia, but significant ecological and hydrologic changes began in the valley following Anglo-settlement and corresponding mining and ranching activities in the 1800s (Andrews, 2011). Grand Ditch began diverting Colorado River water in 1890 and is the single greatest anthropogenic disturbance in the Baker Creek catchment (Figure 28). Since its completion, Grand Ditch diverts an estimated 60% of peak snowmelt discharge from the Baker Creek catchment to the east side of the Continental Divide, resulting in a 0.01-0.12 m reduction in the Kawuneeche Valley water table (Woods, 2002). Grand Ditch will continue to divert water for the foreseeable future. Reduced peak flows and flood magnitudes from ditch withdrawals have implications for fluvial system evolution and tall willow repopulation. One primary mechanism of willow reproduction is seed propagation on bare sediments deposited by floods (Cooper et al., 2003). Reduced peak flows attributed to ditch diversion limit Baker Creek's ability to export sediments from floods or debris flows out of the system, further impacting channel morphology and habitat.

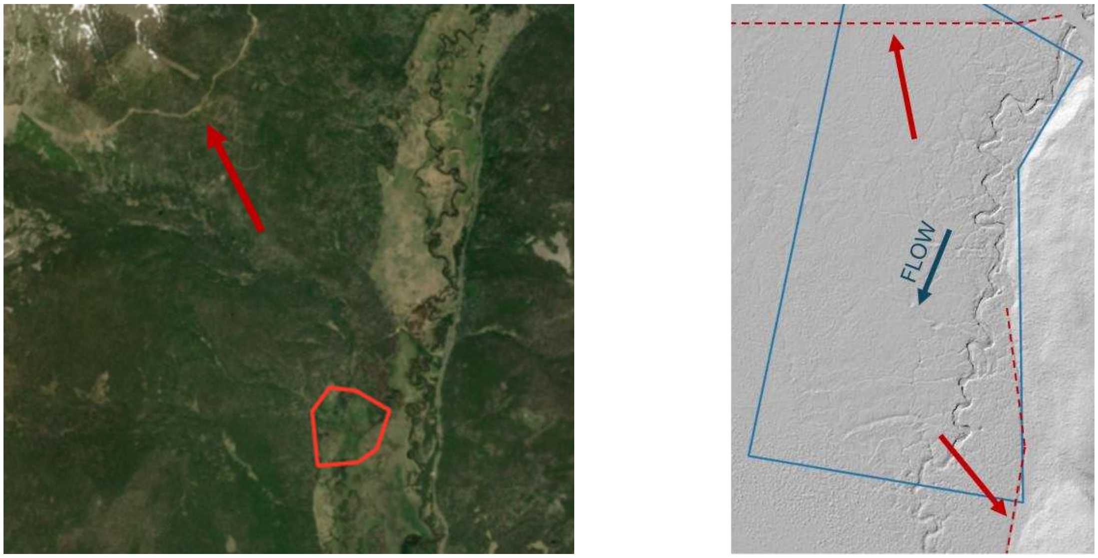


Figure 28. (left) Satellite imagery showing Grand Ditch (red arrow) diverting water north across the divide from Baker Creek (Upper Baker indicated by red polygon). (right) Hillshade image of Onahu Creek with ditch diversions visible (red dashes).

Onahu Creek is not impacted by any water diversions in its upper catchment, but two ditches running westward and southeastward at either end of the study reach indicate historical diversion activity (Figure 28). Water diversions for irrigation likely limited in-stream flows during summer months, affecting flood patterns, channel evolution, and willow establishment. Onahu Creek is also affected by culvert confinement immediately north of the reach, limiting longitudinal connectivity in the floodplain, which may contribute to bed scour immediately downstream (Abida and Townsend, 1991).

Natural disturbance

Wildfires drive geomorphic change by altering stream hydrology, sediment transport, and vegetative communities in a catchment. Impacts are variable, but fire-affected streams commonly have greater, more variable discharge and experience compounded flooding and debris flows that increase sediment loads and transport in fluvial systems (Brogan et al., 2019; Blount et al., 2020). Altered flow and sediment dynamics have implications for channel form and floodplain characteristics (Dwire and Kauffman, 2003; Brogan et al., 2019). Burn extent maps indicate all three study reaches were impacted by the East Troublesome Fire in 2020 (Figure 29), matching observations of burned willow in the field. Onahu Creek was the most severely fire-impacted catchment, with 22% of the Onahu catchment including hillslope regions burned. Only valley-bottom portions of the Baker Creek catchment were burned in the fire, accounting for 5% of the total catchment area (National Interagency Fire Center, 2025). In all three reaches, the East Troublesome Fire burned already stunted willow communities; however, existing stressors combined with the fire appear to have most affected the willow at Onahu Creek. Qualitative assessments of willow condition at Onahu Creek indicate the poorest willow condition, with very few live willows outside of the immediate channel area. Fire is a temporary disturbance but may have long term effects on the seed source and reproduction potential of burned willow communities. This has implications for condition ranking because study reaches with burned willow communities may require greater levels of intervention such as staking and planting efforts to promote willow recovery.

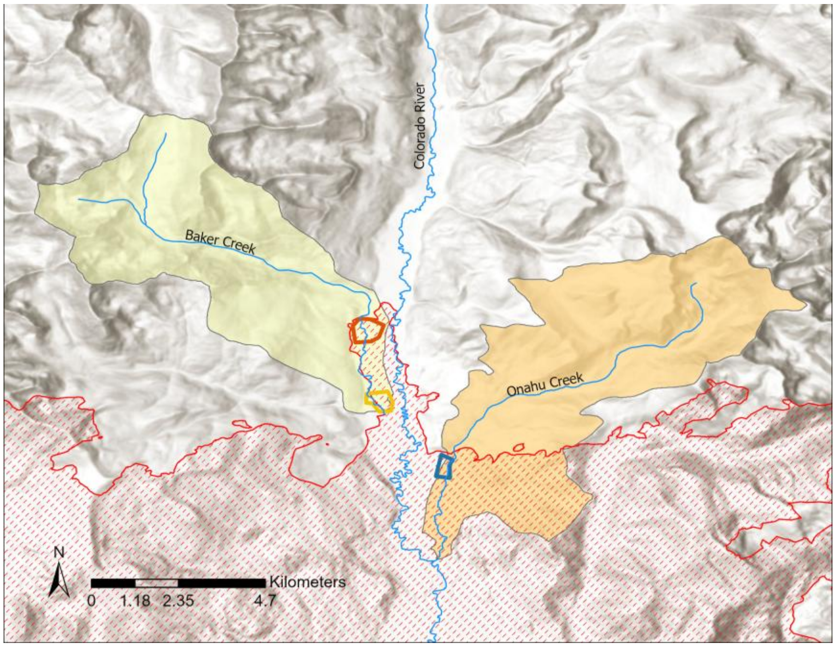


Figure 29. Burn extent map of the East Troublesome Fire (2020); burn extent is symbolized with red hatches.

In addition to flow withdrawals, Grand Ditch also contributes to hillslope instabilities, increasing the magnitude of debris flows in the Upper Colorado River catchment (Andrews, 2011; Rathburn et al., 2013; Grimsley et al., 2016). Debris flows are important natural disturbances that introduce large pulses of sediment to montane fluvial systems, altering sediment dynamics and channel form (Benda, 1990; Reneau and Dietrich, 1991). Debris flows are a natural part of the disturbance regime in the Kawuneeche Valley, originating from both sides of the valley. However, research indicates the construction of Grand Ditch may have increased the magnitude of debris flows originating from its west side including the Baker Creek catchment (Rathburn et al., 2013; Grimsley et al., 2016).

The construction of Grand Ditch has permanently impacted the hydrologic condition of Baker Creek, but historical and contemporary data indicate beaver and willow have thrived in that environment despite its impacts. In the context of increasing channel-floodplain connectivity and recovering tall willow habitat, Onahu Creek has the poorest overall geomorphic condition due to its lack of topographically driven complexity and the impact of the East Troublesome Fire on its existing willow population (Table 19, Figure 26).

4.2 Evaluation of hypotheses

H1: I hypothesize that tributaries with more abandoned beaver dams exhibit greater incision due to a base level drop and channelization.

This hypothesis is not supported. I found that Onahu Creek had the greatest density of channel-spanning dams since 1990 (Table 12) but this did not correspond to greater levels of incision. Field observations and channel geometry surveys indicate no significant differences in incision levels across study reaches (Figure 9). A more informative metric of channel morphology is cross-sectional area which allows comparisons of the levels of flow required to inundate the floodplain at each site. Upper Baker Creek has significantly lower cross-sectional area than Lower Baker or Onahu Creeks, which has implications for channel-conveyance and overbank flooding frequency (Table 7).

H2: I hypothesize that relict beaver activity is the dominant driver of channel-floodplain surface complexity.

This hypothesis is partially supported. I found that relict beaver activity in the form of dams, ponds, and canals persist on the floodplain and affect floodplain surface complexity and hydrologic processes at overbank flows (Figure 19, Figure 22). However, in Upper Baker and

Lower Baker Creeks, floodplain surface complexity is also influenced by secondary channel features driven by relict dam activity and interactions with historic channel migration of the Colorado River. At smaller scales closer to the active channel, relict beaver dams exert greater importance on floodplain surface complexity relative to valley-bottom topography.

4.3 Management Implications of Findings

KVRC is planning multi-year ecological restoration with the goal of improving channel floodplain-connectivity and tall willow habitat in the Kawuneeche Valley. My conceptual ranking approach focuses strictly on the geomorphic context of three study reaches to better understand the underlying processes driving channel-floodplain connection at these sites. It does not account for factors commonly influencing restoration including budget, site access, infrastructure risks, and social considerations such as public visibility (Bernhardt et al., 2005).

I incorporated channel, floodplain, and catchment characteristic assessments into a three-dimensional conceptual model to illustrate overall geomorphic condition of each study site (Figure 30). Onahu exhibited the poorest relative geomorphic condition due to low channel-floodplain connectivity (Table 20). The geomorphic characteristics of Upper Baker and Lower Baker Creeks still promote overbank flows and floodplain attenuation despite lacking beaver activity that drives in-channel structural heterogeneity and spreads water onto the floodplain. This has implications for the type and degree of restoration work required to promote tall willow reestablishment and long-term ecological recovery of the valley. In the case of the Upper and Lower Baker Creeks, the installation of wildlife exclosure fencing may be sufficient action to promote willow recovery. The installation of low-tech structures such as beaver dam analogs (BDAs), simulated beaver structures (SBSs), and post-assisted log structures (PALs) would promote overbank flows but suitable hydrologic conditions for recovery are already present. Onahu Creek requires more restoration effort, including the installation of in-channel, low-tech structures in addition to fencing to improve channel-floodplain connectivity and willow recovery. KVRC and RMNP may use this information to best suit project goals and resources. If project resources are abundant and the greatest level of ecological uplift is the primary goal, Onahu Creek is likely the primary candidate.

Table 20. Cumulative scoring to inform overall ranking (highest value indicates best relative geomorphic condition).

	Upper Baker	**Lower Baker**	**Onahu**
Total	22	19	13

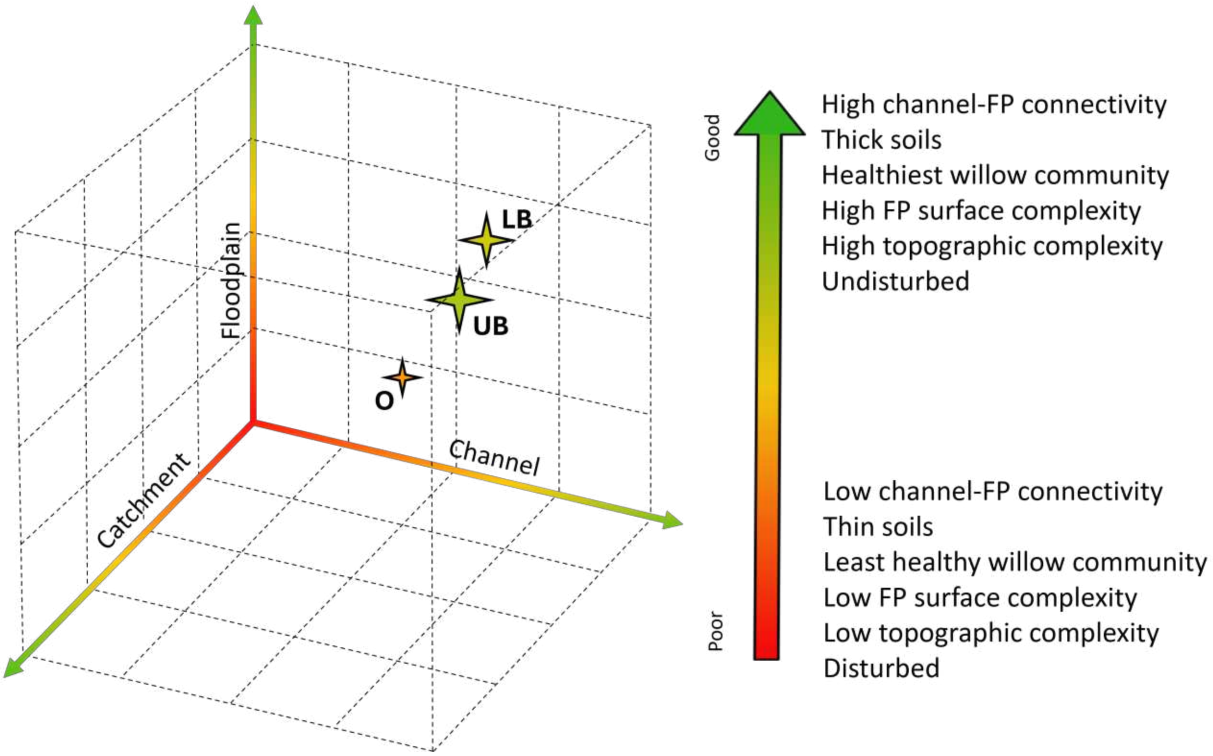


Figure 30. Conceptual ranking of existing geomorphic condition based on channel, floodplain, and catchment characteristics. Arrows run along gradients from poor to good. Upper Baker Creek has the best overall geomorphic condition, followed by Lower Baker then Onahu Creeks.

4.4 Future research

There are many ways to expand upon the findings of this research. First, evaluating the geomorphic context of sites considered for restoration would benefit from a longer time span of data collection, particularly for hydrologic and sediment transport data. There are limited long-term flow data associated with my three study reaches. Flow monitoring was performed in late 2023 and one full season in 2024, limiting our understanding of peak flow magnitudes and durations. (The closest USGS gage station is on the Colorado River located downstream of the confluence with Baker Creek, approximately 0.7 km south of Lower Baker Creek.) The development of more accurate rating curves and flood-frequency analyses for both systems would improve modeling and the contemporary understanding of flood dynamics and future channel evolution. Additionally, sediment transport measurements were limited. More rigorous suspended sediment and bedload transport measurements would contribute to a better understanding of sediment dynamics.

This conceptualization of geomorphic condition would also be improved through more extensive analysis of the vegetative condition and groundwater processes involved at each site. Qualitative assessments of willow stand health were performed in this study, but more detailed studies involving species diversity, stand density, and existing seed stock of willow and other riparian species in the study areas might improve understanding of the recovery potential of each system. Groundwater data were outside of the scope of this study, but groundwater-surface water interactions play an important role in valley-bottom wetness. Previous studies have examined the effects of beaver dams on groundwater-surface water interactions in the Kawuneeche Valley (Westbrook et al., 2006) and the role of groundwater levels and soil texture on willow survival (Woods and Cooper, 2005). Specific observations of groundwater data in my study reaches might elucidate groundwater-surface water interactions to better understand the magnitude of hillslope and hyporheic contributions to each system and implications on the local groundwater level and willow survival.

I assessed three reaches of very similar geomorphic setting and character as well as similar spatial scales. The Upper Colorado River and its tributaries are headwater systems in a formerly glaciated valley, dominated by snowmelt-driven hydrologic patterns and geomorphic processes driven largely by historical beaver activity. Although historical anthropogenic disturbances are evident, minimal infrastructural constraints exist for restoration projects, which is uncommon. Testing the field methods and applying the ranking approach developed in this study on systems of varying underlying geomorphic settings would expose suitability and limitations of this approach in systems outside of a Colorado Rocky Mountain setting.

5. CONCLUSION

With roughly 4.5 million annual visitations, RMNP is one of the most visited national parks in the country (NPS, 2023). Since its incorporation into RMNP, the collapse of tall willow habitat and subsequent loss of beaver populations in the Kawuneeche Valley have introduced a host of hydrologic and ecologic concerns that also impact visitor experience. I used a combination of field-based, remotely sensed, and hydraulic modeling approaches to assess the historical and contemporary geomorphic context of three different tributary systems of the Colorado River: Upper Baker, Lower Baker and Onahu Creeks. These data were used to develop a geomorphic context-based prioritization approach to guide restoration efforts to improve channel-floodplain connectivity and promote conditions for tall willow recovery at these sites.

I found that the channel, floodplain, and catchment-scale geomorphic conditions differed between the three sites, which has implications for the type and level of restoration intervention required to meet project goals. Upper Baker and Lower Baker Creeks exhibit channel geometry and floodplain characteristics that readily promote overbank flows and water dispersion across the floodplain at high flows. In contrast, Onahu Creek does not readily inundate its floodplain and lacks floodplain features that spread water across the floodplain and attenuate flows. Channel geometry, relict beaver dam activity, and historical channel activity promote channel-floodplain connectivity, but catchment-scale characteristics such as topographic position and groundwater inputs also play an important role. Disturbances, particularly wildfire, have implications for natural recovery potential of willow populations and need to be considered in restoration priorities.

Overall, Upper Baker Creek exhibited the best contemporary geomorphic condition to promote tall willow recovery, followed by Lower Baker and Onahu Creeks. In the context of restoration, Upper Baker and Lower Baker Creeks require a lower degree of restoration work to create conditions for tall willow recovery. Ungulate exclosure fencing is potentially a suitable restoration approach. Under contemporary conditions, implementation of more involved restoration work (low-tech structures) at Onahu Creek is recommended to increase channel-floodplain connectivity and raise groundwater levels to promote tall willow growth. These findings can be incorporated into the KVRC’s restoration goals and project resources to inform long-term recovery of tall-willow communities in the Kawuneeche Valley. Implementing the results of this research through restoration will help to expose visitors to a more diverse, complex river ecosystem that reflects historical ecological conditions in RMNP and help fill a gap in the channel restoration literature that prioritizes geomorphic potential.

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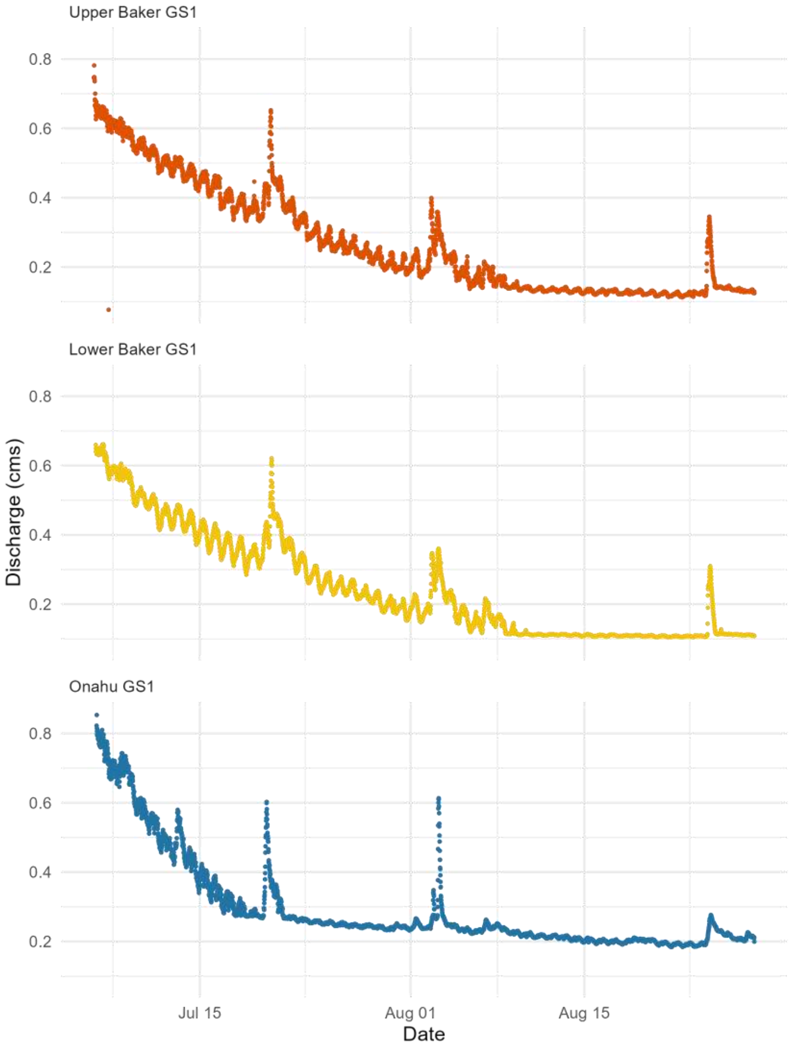
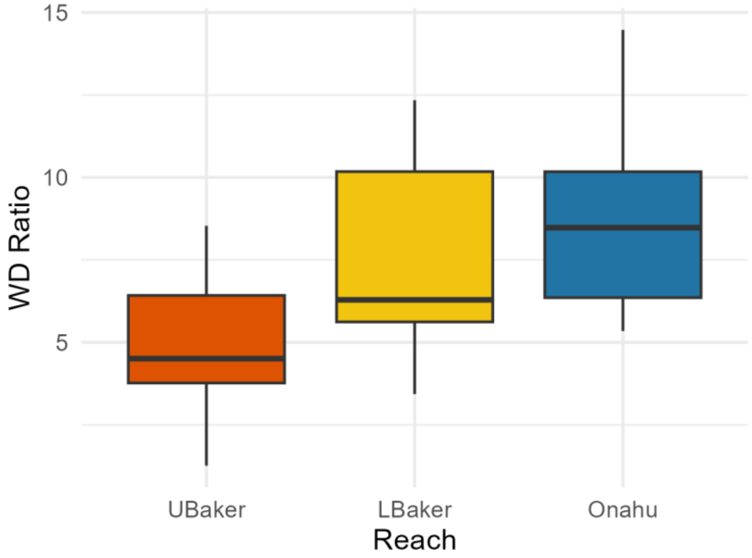
APPENDIX I – 2023 DISCHARGE DATA

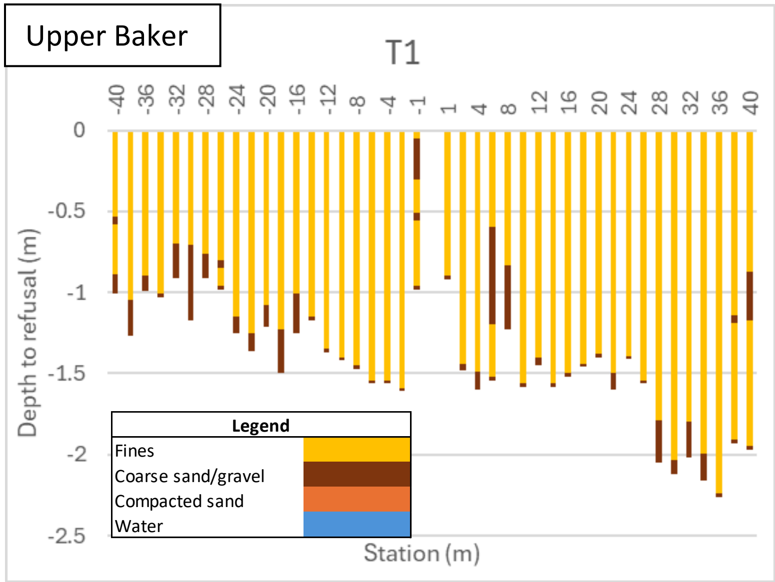


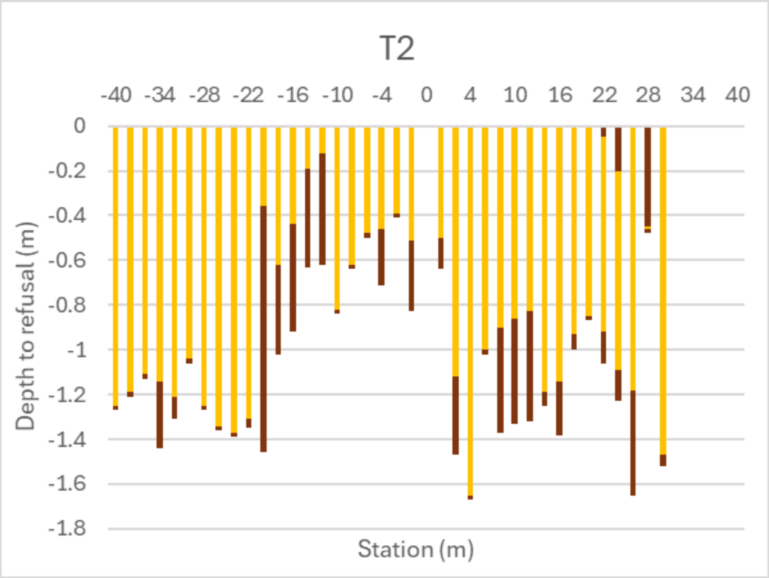
APPENDIX II – WIDTH-TO-DEPTH RATIOS

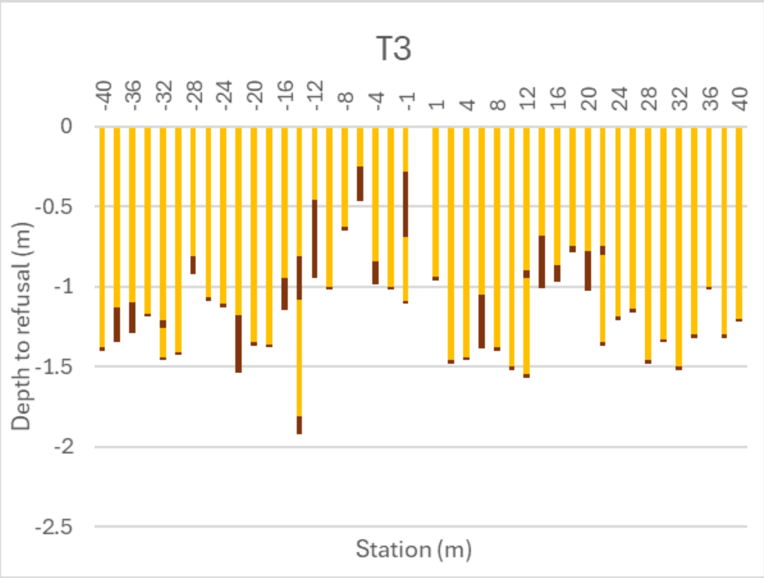


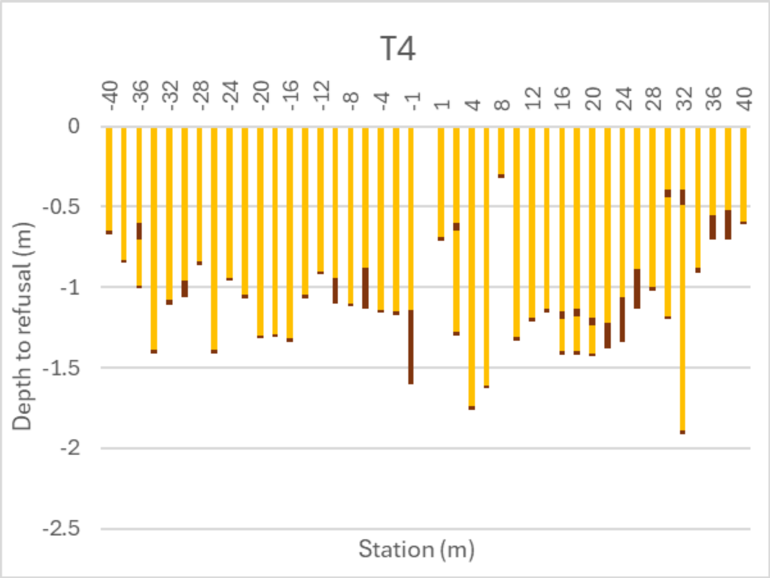
	Upper Baker	**Lower Baker**	**Onahu**	**Significant difference (Kruskal-Wallis)**	**p-value**
Mean WD ratio	4.8	7.5	8.5	Y	<0.001

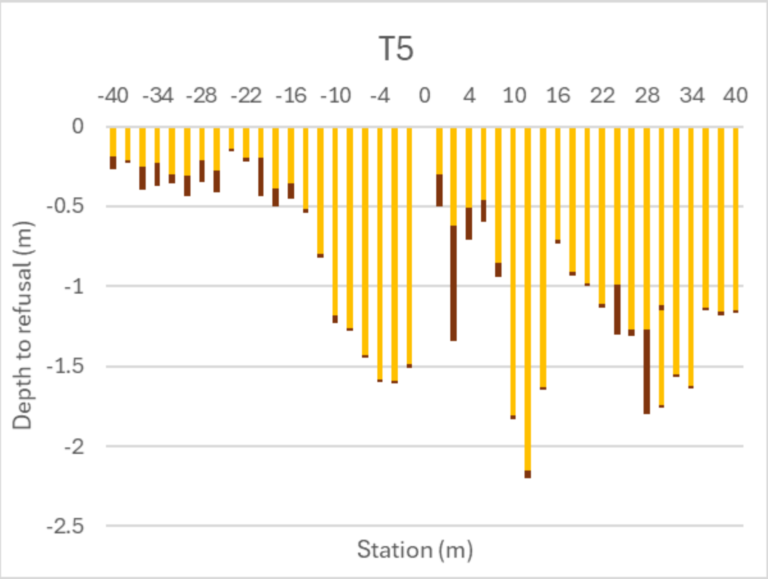
APPENDIX III – FLOODPLAIN DEPTH-TO-REFUSAL

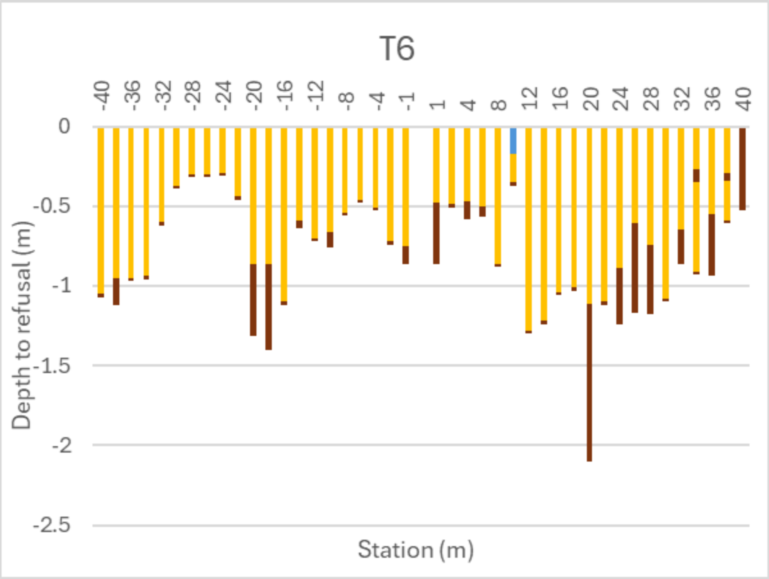


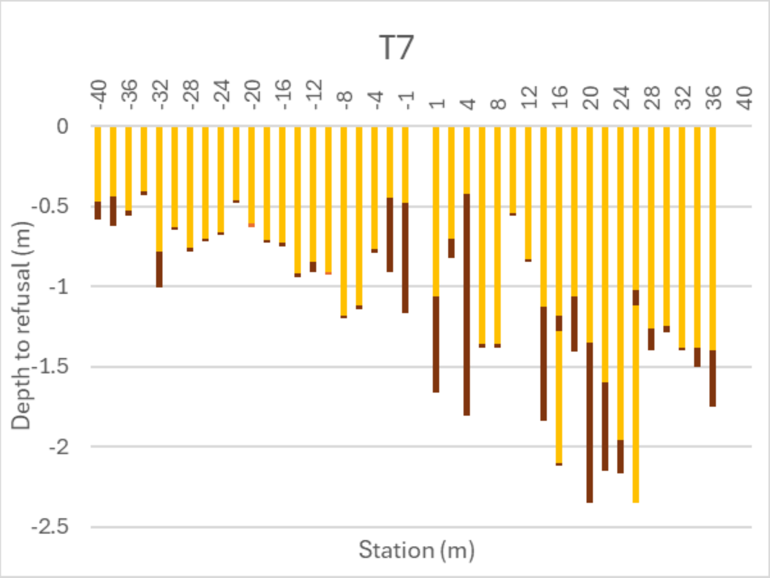


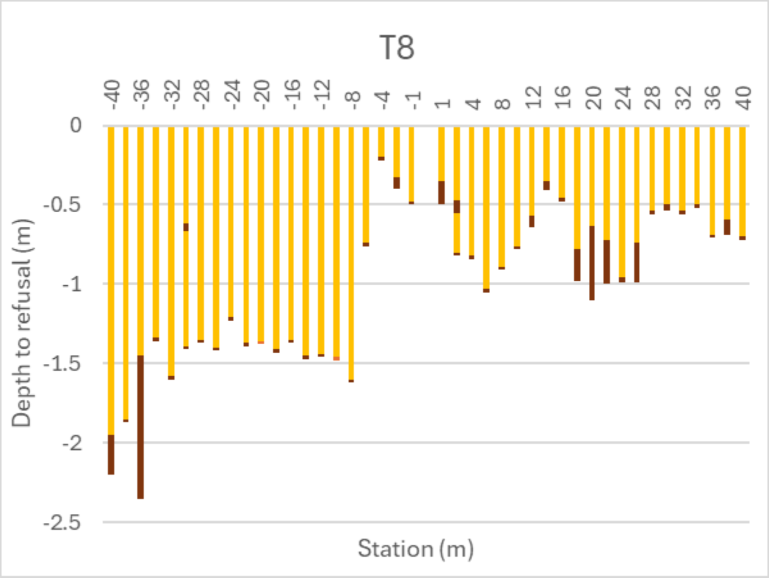


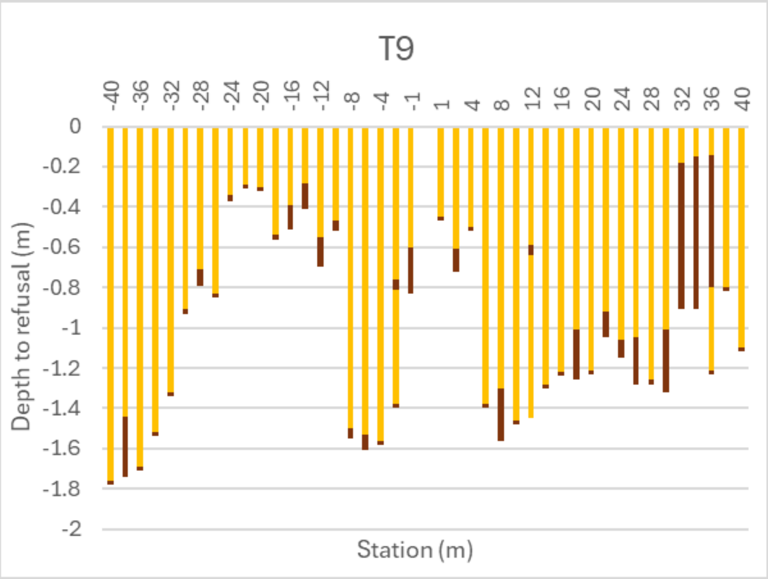


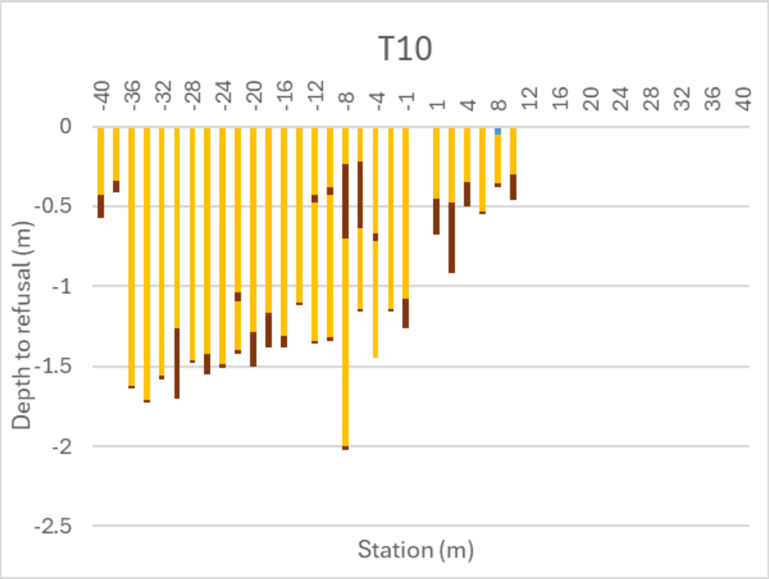

T5
-40 -34 -28 -22 -16 -10 -4 0 4 10 16 22 28 34 40
0
-0.5
-1
-1.5
-2
-2.5
Depth to refusal (m)
Station (m)

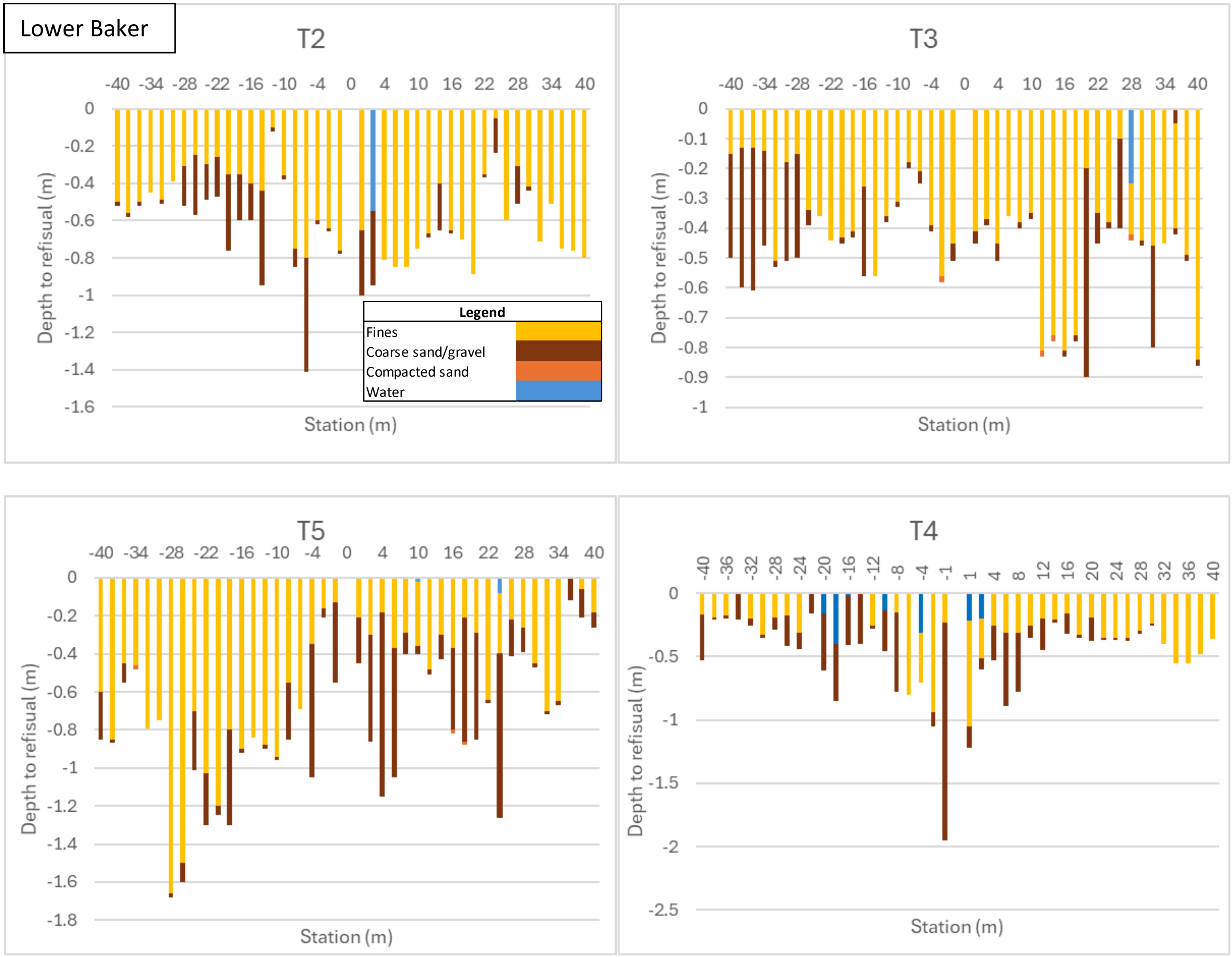

T6
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
0
-0.5
-1
-1.5
-2
-2.5
Depth to refusal (m)
Station (m)

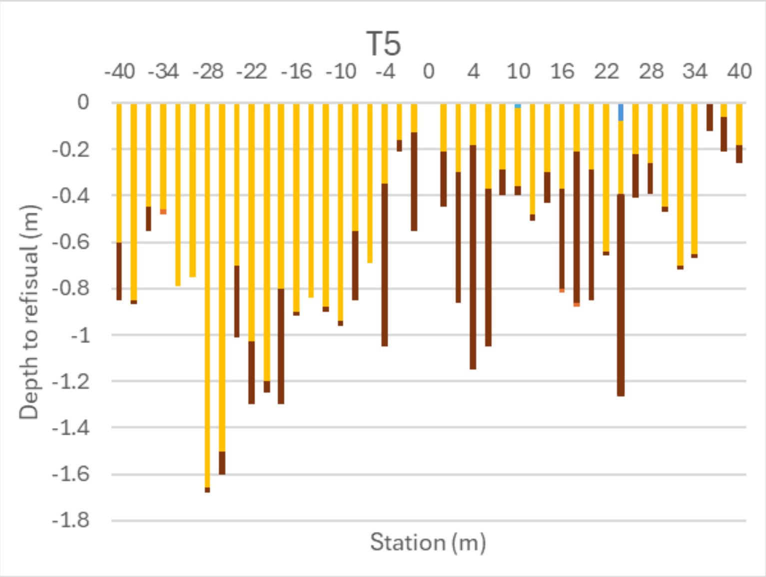

T7
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
0
-0.5
-1
-1.5
-2
-2.5
Depth to refusal (m)
Station (m)

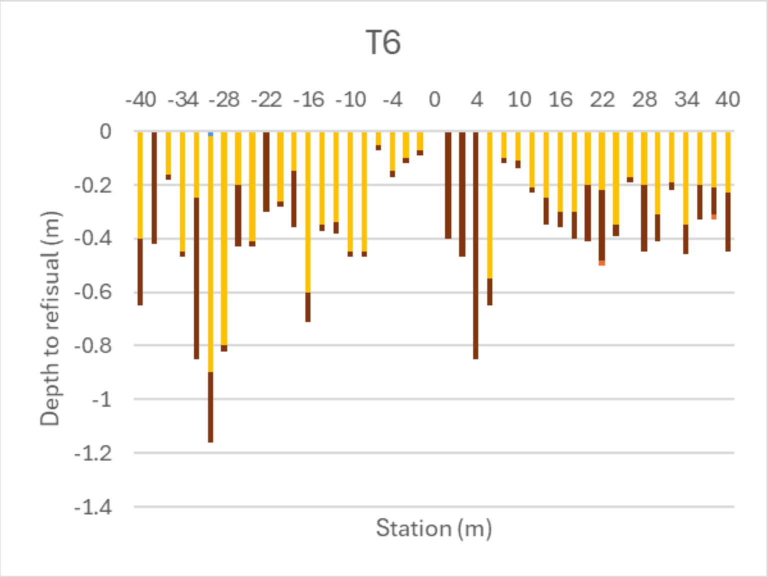

T8
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
0
-0.5
-1
-1.5
-2
-2.5
Depth to refusal (m)
Station (m)

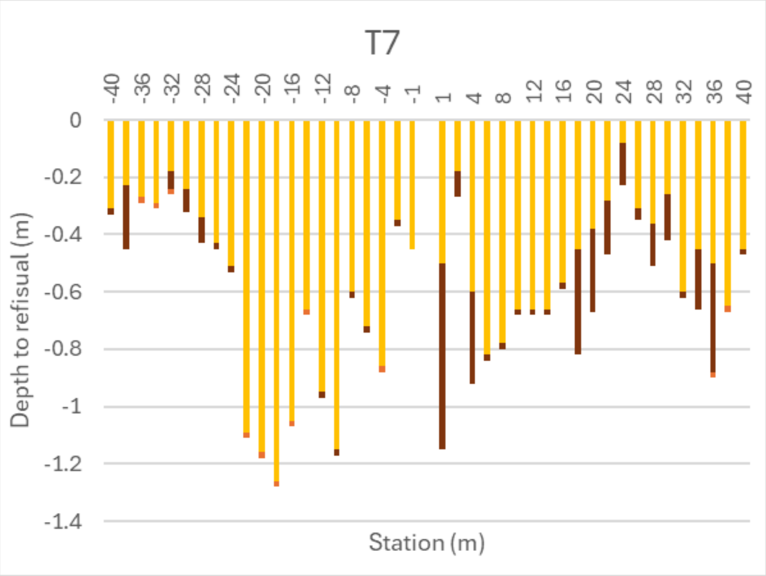

T9
Depth to refusal (m)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
-40
-36
-32
-28
-24
-20
-16
-12
-8
-4
-1
1
4
8
12
16
20
24
28
32
36
40
Station (m)

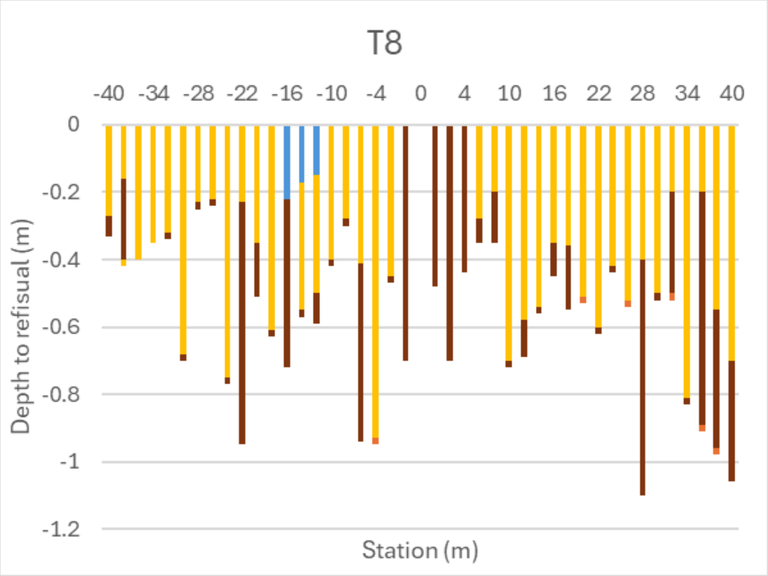

T10
Depth to refusal (m)
0
-0.5
-1
-1.5
-2
-2.5
-40
-36
-32
-28
-24
-20
-16
-12
-8
-4
-1
1
4
8
12
16
20
24
28
32
36
40
Station (m)

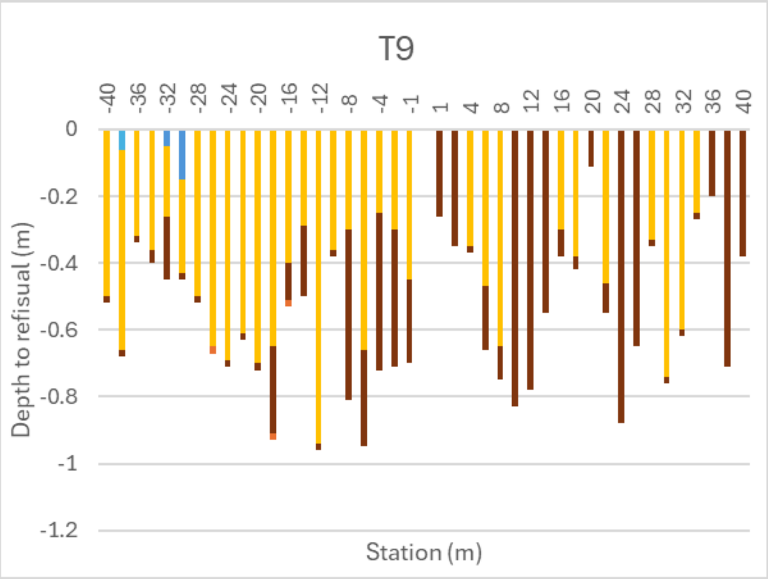

Lower Baker
T2
-40 -34 -28 -22 -16 -10 -4 0 4 10 16 22 28 34 40
0 -0.2 -0.4 -0.6 -0.8 -1 -1.2 -1.4 -1.6
Depth to refisual (m)
Station (m)
Legend
Fines
Coarse sand/gravel
Compacted sand
Water
T3
-40 -34 -28 -22 -16 -10 -4 0 4 10 16 22 28 34 40
0 -0.1 -0.2 -0.3 -0.4 -0.5 -0.6 -0.7 -0.8 -0.9 -1
Depth to refisual (m)
Station (m)
T5
-40 -34 -28 -22 -16 -10 -4 0 4 10 16 22 28 34 40
0 -0.2 -0.4 -0.6 -0.8 -1 -1.2 -1.4 -1.6 -1.8
Depth to refisual (m)
Station (m)
T4
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
0 -0.5 -1 -1.5 -2 -2.5
Depth to refisual (m)
Station (m)

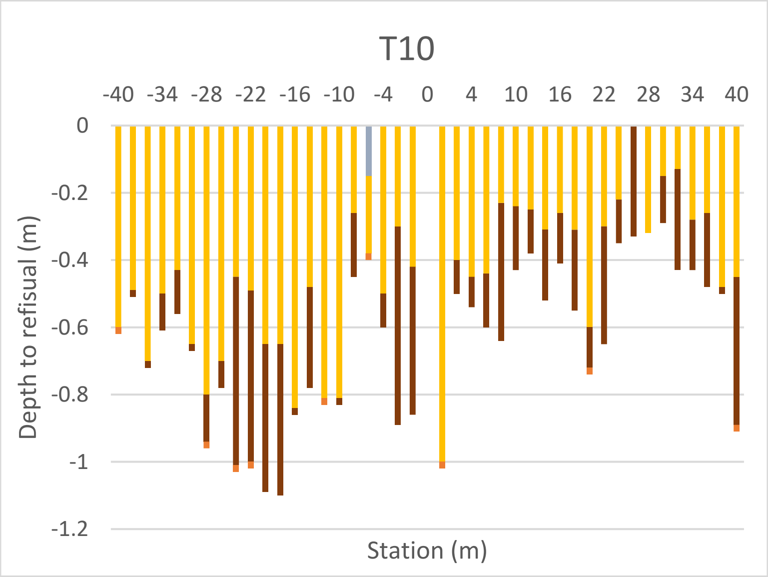

T5
-40 -34 -28 -22 -16 -10 -4 0 4 10 16 22 28 34 40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
Depth to refisual (m)
Station (m)

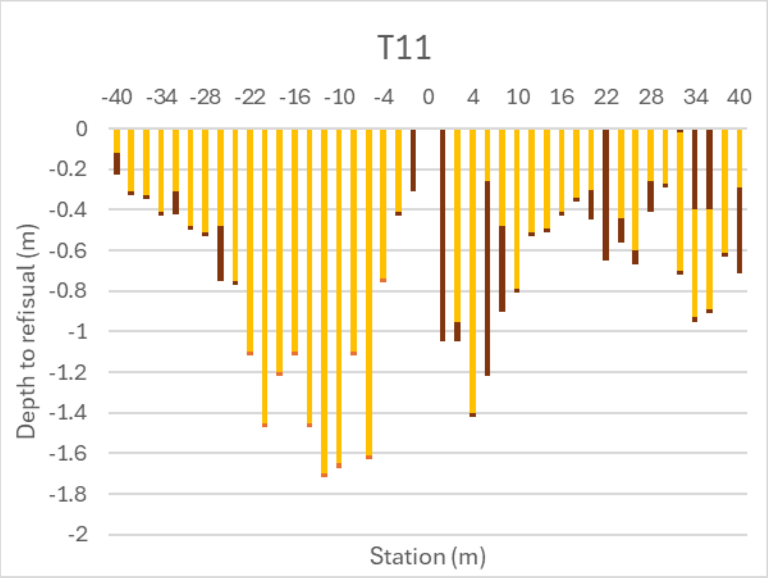

T6
-40 -34 -28 -22 -16 -10 -4 0 4 10 16 22 28 34 40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth to refisual (m)
Station (m)

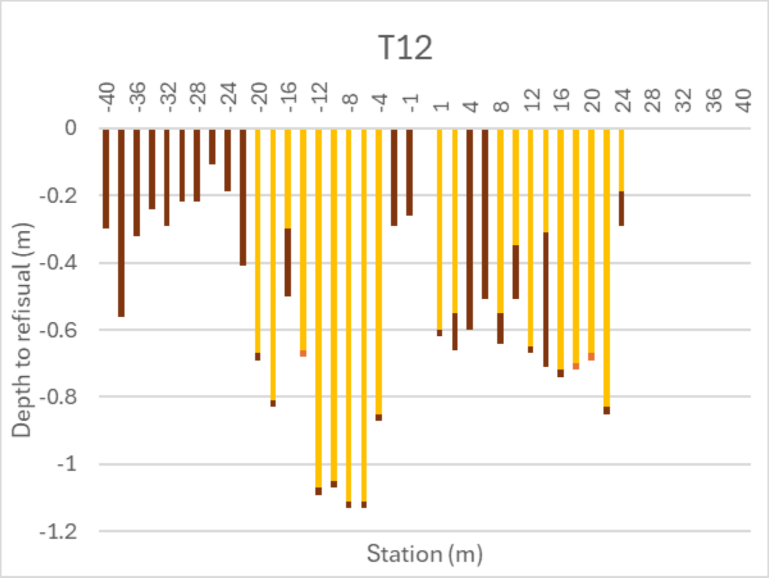

T7
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth to refisual (m)
Station (m)

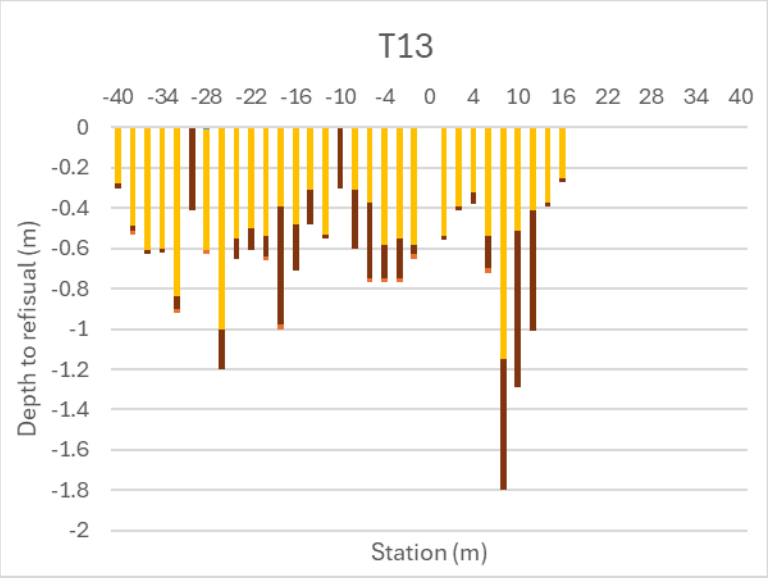

T8
-40 -34 -28 -22 -16 -10 -4 0 4 10 16 22 28 34 40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth to refisual (m)
Station (m)

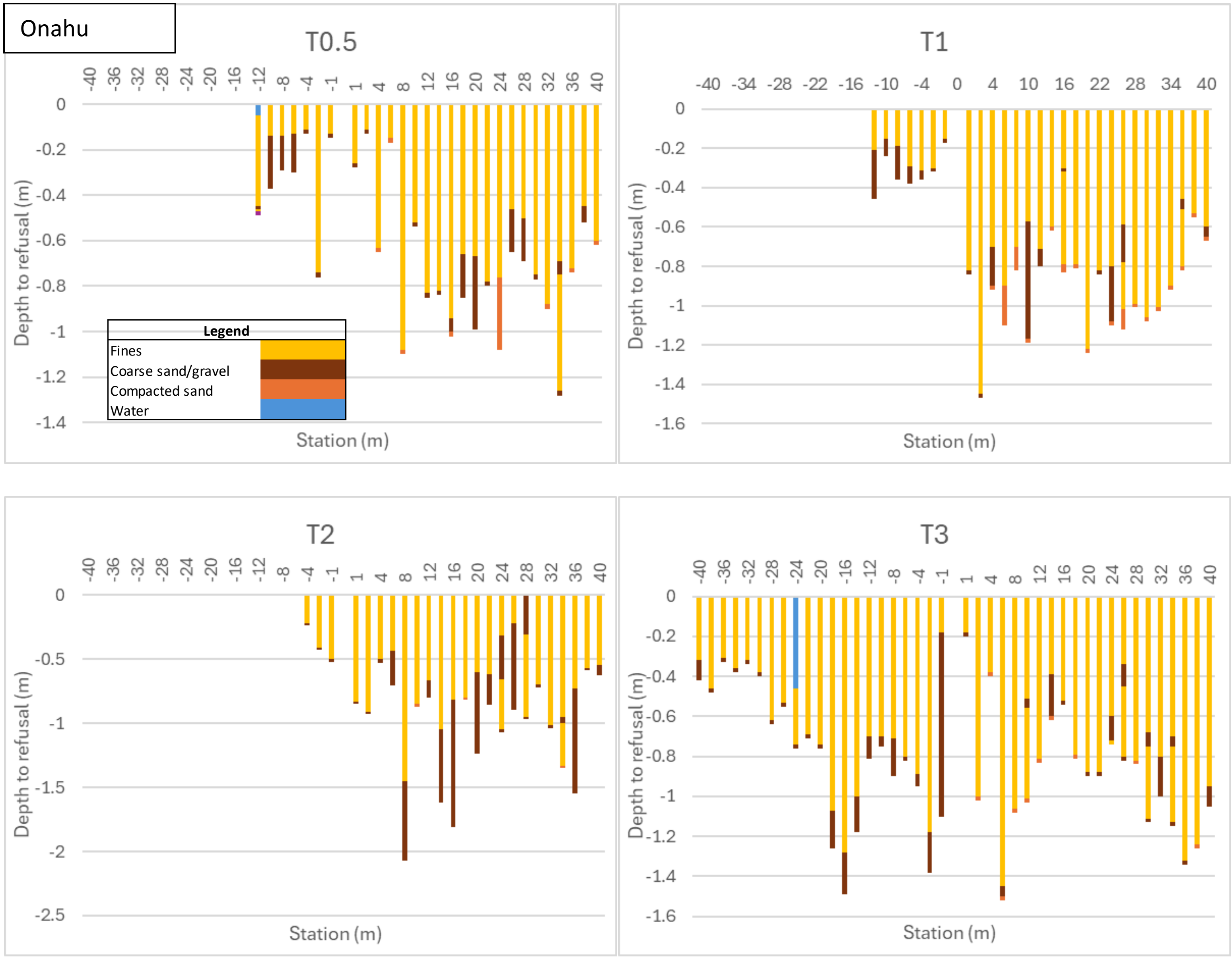

T9
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth to refisual (m)
Station (m)

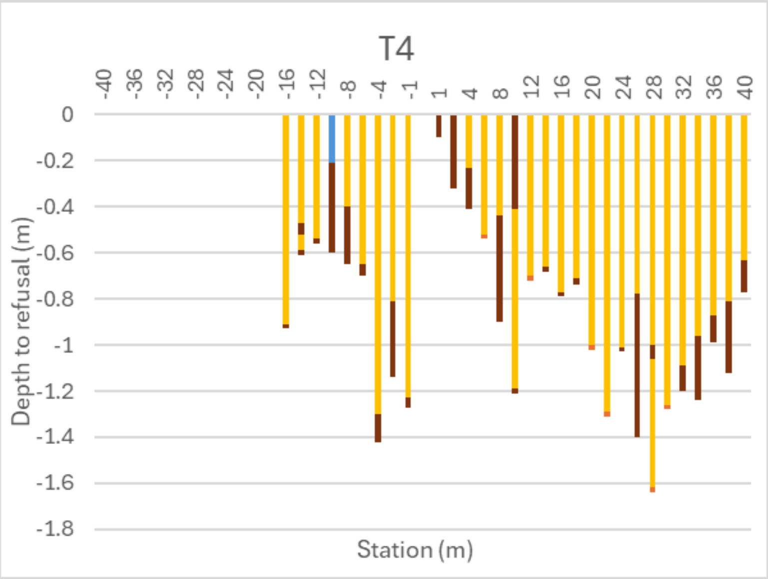

T10
-40 -34 -28 -22 -16 -10 -4 0 4 10 16 22 28 34 40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth to refisual (m)
Station (m)

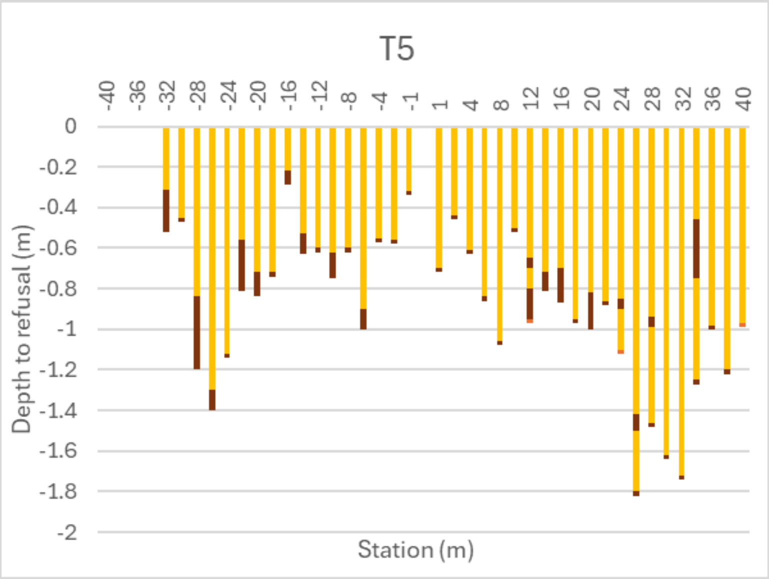

T11
-40 -34 -28 -22 -16 -10 -4 0 4 10 16 22 28 34 40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
Depth to refisual (m)
Station (m)

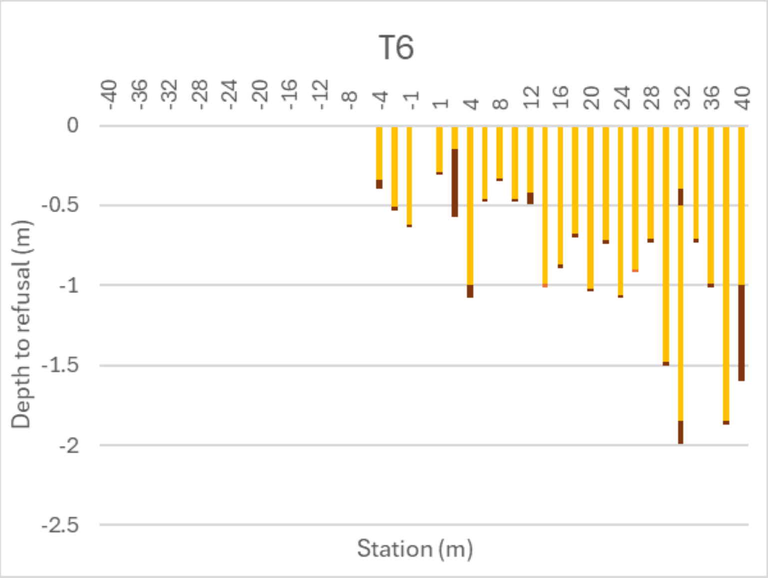

T12
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth to refisual (m)
Station (m)

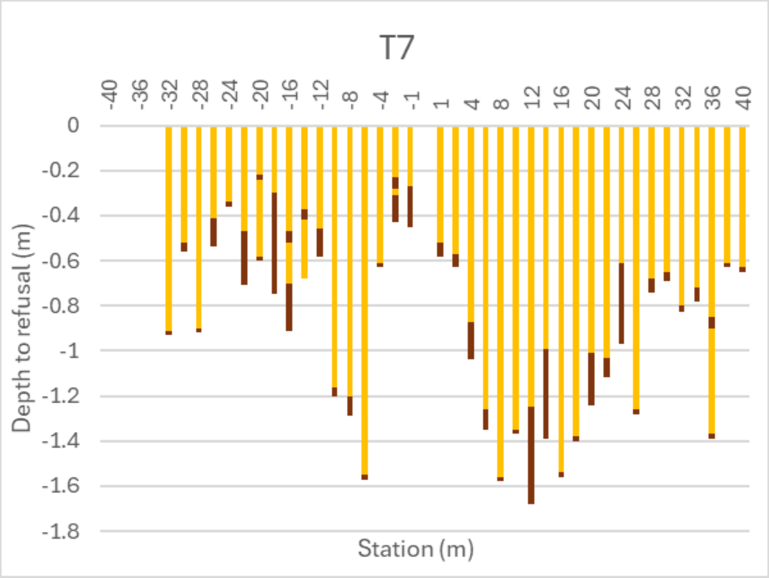

T13
-40
-34
-28
-22
-16
-10
-4
0
4
10
16
22
28
34
40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
Depth to refisual (m)
Station (m)

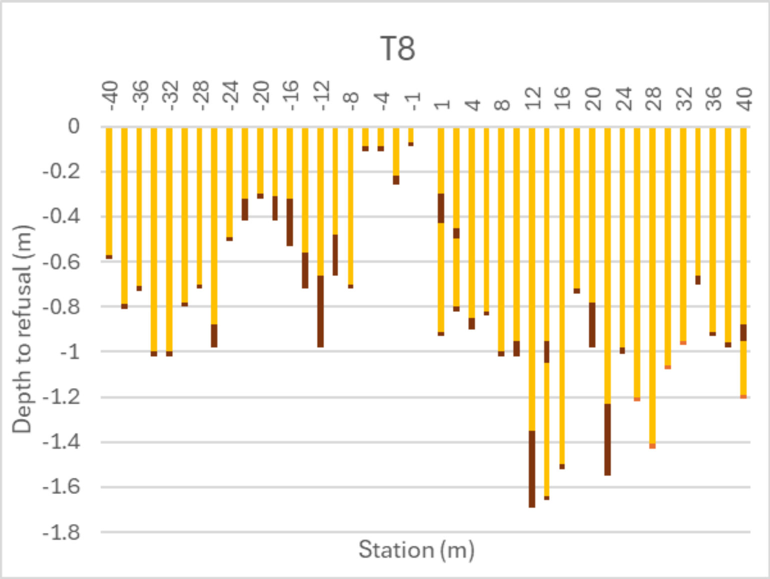

Onahu
T0.5
T1
T2
T3
Depth to refusal (m)
Station (m)
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
-40 -34 -28 -22 -16 -10 -4 0 4 10 16 22 28 34 40
0 -0.2 -0.4 -0.6 -0.8 -1 -1.2 -1.4 -1.6
0 -0.5 -1 -1.5 -2 -2.5
Legend
Fines
Coarse sand/gravel
Compacted sand
Water

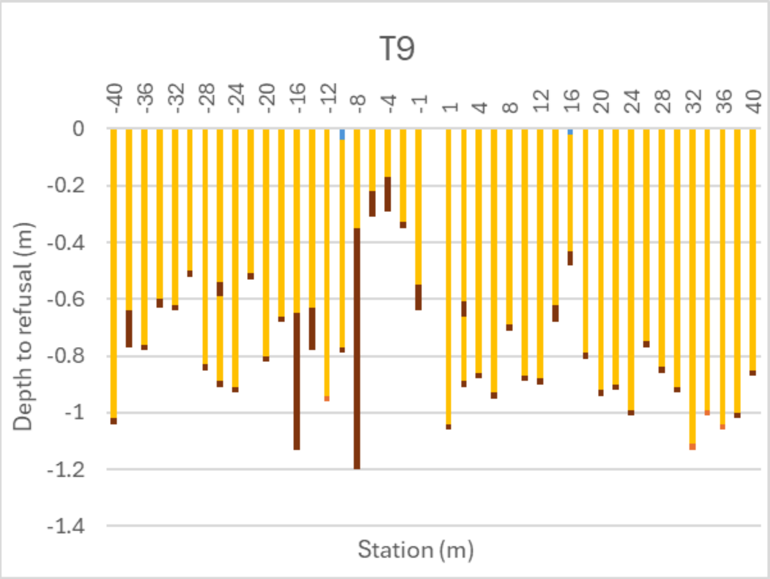

T4
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
Depth to refusal (m)
Station (m)

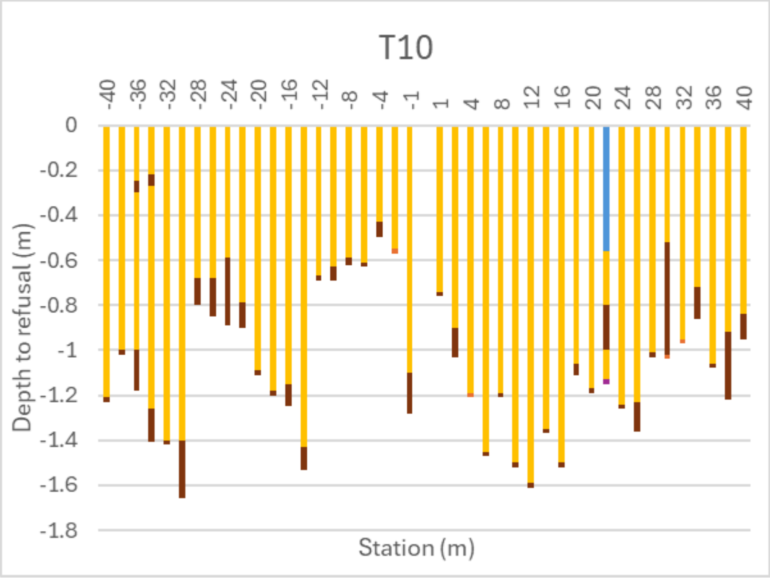

T5
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
Depth to refusal (m)
Station (m)


T6
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
0
-0.5
-1
-1.5
-2
-2.5
Depth to refusal (m)
Station (m)


T7
-40 -36 -32 -28 -24 -20 -16 -12 -8 -4 -1 1 4 8 12 16 20 24 28 32 36 40
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
Depth to refusal (m)
Station (m)


T8
Depth to refusal (m)
Station (m)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-40
-36
-32
-28
-24
-20
-16
-12
-8
-4
-1
1
4
8
12
16
20
24
28
32
36
40


T9
Depth to refusal (m)
Station (m)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-40
-36
-32
-28
-24
-20
-16
-12
-8
-4
-1
1
4
8
12
16
20
24
28
32
36
40


T10
Depth to refusal (m)
Station (m)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-40
-36
-32
-28
-24
-20
-16
-12
-8
-4
-1
1
4
8
12
16
20
24
28
32
36
40

APPENDIX IV – FLOODPLAIN SURFACE COMPLEXITY METRICS

Detailed descriptions of floodplain surface complexity metrics. From Scown et al., 2016

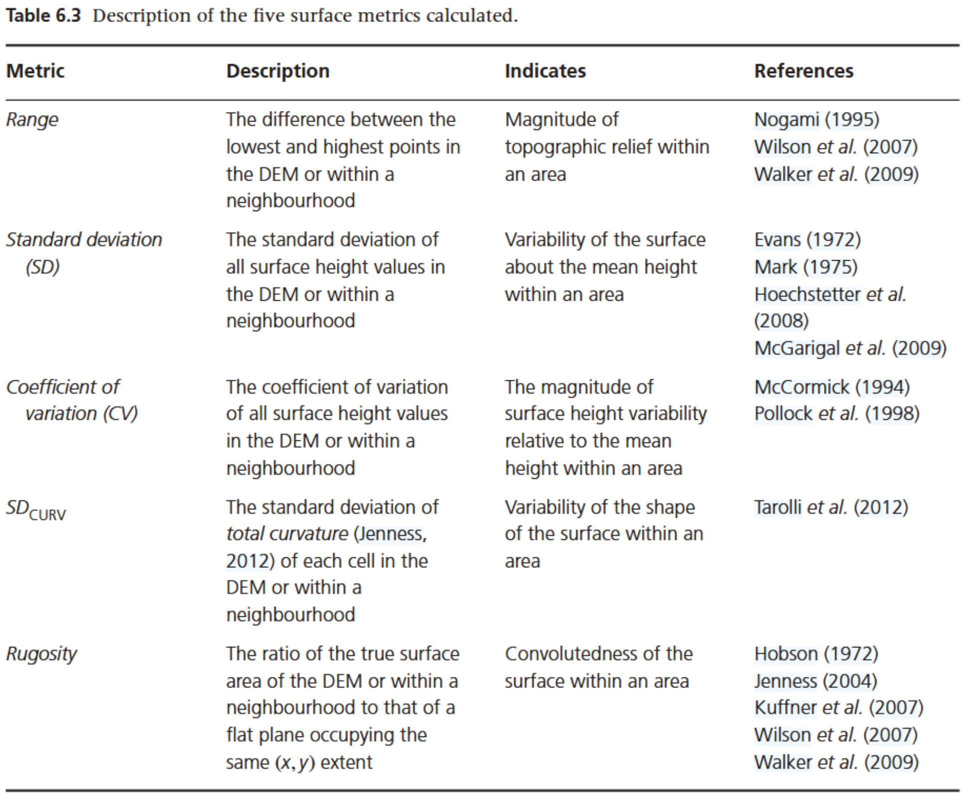


Table 6.3 Description of the five surface metrics calculated.

Metric	Description	Indicates	References
Range	The difference between the lowest and highest points in the DEM or within a neighbourhood	Magnitude of topographic relief within an area	Nogami (1995) Wilson *et al.* (2007) Walker *et al.* (2009)
Standard deviation (SD)	The standard deviation of all surface height values in the DEM or within a neighbourhood	Variability of the surface about the mean height within an area	Evans (1972) Mark (1975) Hoechstetter *et al.* (2008) McGarigal *et al.* (2009)
Coefficient of variation (CV)	The coefficient of variation of all surface height values in the DEM or within a neighbourhood	The magnitude of surface height variability relative to the mean height within an area	McCormick (1994) Pollock *et al.* (1998)
SD_{CURV}	The standard deviation of *total curvature* (Jenness, 2012) of each cell in the DEM or within a neighbourhood	Variability of the shape of the surface within an area	Tarolli *et al.* (2012)
Rugosity	The ratio of the true surface area of the DEM or within a neighbourhood to that of a flat plane occupying the same (x, y) extent	Convolutedness of the surface within an area	Hobson (1972) Jenness (2004) Kuffner *et al.* (2007) Wilson *et al.* (2007) Walker *et al.* (2009)

APPENDIX V – GAGE SITE LOCATIONS

Name	Reach	Northing	Easting	Type
UB_GS1	Upper Baker	4466958.215	426373.2648	gage
UB_GS2	Upper Baker	4466558.459	426177.4607	gage
LB_GS1	Lower Baker	4465034.875	426570.155	gage
LB_GS1	Lower Baker	4465153.025	426455.9095	gage
Onahu_GS1	Onahu	428132.6106	4463415.288	gage
Onahu_GS2	Onahu	428013.1639	4462964.698	gage