

THESIS

COMPLEX GEOMORPHIC LEGACIES OF DISTURBANCE
IN A DYNAMIC EOLIAN-FLUVIAL CHANNEL NETWORK

Submitted by

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ABSTRACT

COMPLEX GEOMORPHIC LEGACIES OF DISTURBANCE IN A DYNAMIC EOLIAN-FLUVIAL CHANNEL NETWORK

North Sand Creek is a tributary of the North Platte River draining the southern Medicine Bow mountains in the northeastern corner of North Park, Colorado. Its perennial, montane segment upper meets the creek's ephemeral tributary, which flows adjacent to the active dune field of North Sand Hills. Below this confluence, the stream runs alongside inactive, vegetated dunes, then forms a low-slope, sandy alluvial fan, where State Line Ranch diverts North Sand Creek for irrigation. Previous work identified high sediment loading caused by recreational off-highway vehicles (OHVs) on the active dunes, which generates waves of sediment and channel instability that impair State Line Ranch's protected downstream water right. My observations of relict beaver modifications in the stream corridor suggest that channel instability and sediment export may be related to historical beaver extirpation. My objectives in this study were to: (i) compare channel dynamics between the 2019 and 2025 runoff seasons, (ii) map potential sediment sources downstream from the main, highly active dune face on the unnamed tributary and examine potential correlations between stream corridor morphology and the location of these sediment sources, (iii) estimate the upper and lower bounds of potential sediment storage associated with beaver dams based on the location and characteristics of relict beaver dams, (iv) compare the surface area and recent history of sediment deposition and channel change on the alluvial fans of North and East Sand Creeks and adjacent catchments along the eastern side of North Park, and (v) provide guidance for restoration actions in North Sand Creek based on my

results. Repeat cross-section surveys, mapping of relict beaver dams and sand addition points, and collection of high-resolution UAV-derived imagery and surface elevation data were completed during summer 2025. I found that (i) a sediment wave did not occur during 2025, demonstrating interannual variability and annual-scale complex response in sediment transport and storage; (ii) discontinuous sand addition to the perennial mainstem from destabilized dune faces and reworked terrace deposits occurred along only 7.5% of total bank length; (iii) over 300 relict beaver dams potentially created 10,200 – 67,300 m³ of sediment storage at estimated historical density, and local beaver extirpation in the 1970s caused entrenchment, simplification, and loss of attenuation capacity in the stream corridor; (iv) the North Sand Creek alluvial fan is an outlier in estimated volume per drainage area, indicating high historical sediment export; and (v) North Sand Creek has incised 4 m since 2830 yBP, leaving a terrace elevated above the modern valley floor. North Sand Creek's current planform, valley cross-section, and instability are the result of Late Holocene incision, followed by further historic entrenchment and loss of attenuation capacity after beaver extirpation, and exacerbated by OHV introduction of sand to the channel. Restoration practitioners and managers working in North Sand Creek must (i) acknowledge that mass sand export is a long-term process that cannot be stopped, but rather only attenuated; and (ii) target root causes of channel instability by reducing OHV use along the ephemeral tributary and rebuilding lost attenuation capacity through careful use of channel and floodplain structures, and perhaps eventually returning beaver to the landscape. This study provides a novel description of historical beaver modifications to a highly variable eolian-fluvial system and contributes to the body of literature describing complex response across diverse environments and time scales.

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1. INTRODUCTION

This study addresses geomorphic disturbance history, sources of sediment, sediment storage, and associated channel changes along North Sand Creek in northern Colorado, USA. North Sand Creek drains a small basin in the Southern Medicine Bow Mountains on the eastern flank of North Park, a semi-arid intermountain basin (Figure 1). North Sand Creek runs through areas of active and inactive dunes, then joins the Canadian River, a tributary of the North Platte, approximately 4 km downstream of the study area.

1.1 Background

North Sand Creek is primarily a sand-bed channel throughout the study area, although cobble to small boulder size clasts are present in some portions of the streambed. Consequently, this review moves from general channel dynamics to a focus on sand-bed channels. I also review the effects of beavers and OHV use on stream corridors, because beaver modifications along North Sand Creek appear to have strongly influenced sediment dynamics in the past, and off-highway vehicle (OHV) use has influenced sediment dynamics more recently.

Channel form, both planform and cross section, represents the balance between sediment supply and sediment transport capacity in fluvial systems. Schumm (1977) envisioned streams as a continuum from the sediment source zone (erosion > deposition) high in the catchment, through the transport zone (erosion roughly balanced with deposition) to the depositional zone (deposition > erosion) at the downstream end. Each zone has a different balance of sediment supply and transport capacity, and therefore each zone is likely to respond differently to disturbances or changes in the sediment and water regime.

However, this model is based solely on the balance between sediment supply and transport capacity, and channel dynamics are more complicated than that. Multiple adjustments

within a fluvial system – slope, bed roughness, bedform, planform, and cross section - create reaches with distinct sets of processes and thereby distinct forms (Montgomery & Buffington, 1997). A second complication for understanding channel dynamics is the role of living organisms. Riparian vegetation, for example, can substantially increase bank erosional resistance and hydraulic roughness (Griffin et al., 2005; Corenblit et al., 2015). A third complication is that a channel may adjust to changing ratios of discharge and sediment supply through changes in cross-sectional form, bedforms, planform, bed slope, or combinations of these characteristics (Knighton, 1998; Reid & Brierley, 2015) .

Finally, channel adjustment is not necessarily linear in time and space. Schumm's framework of stream complex response (Schumm, 1973; Schumm & Parker, 1973), for example, describes processes occurring discontinuously in time and space. In Schumm and Parker's classic experimental example (Schumm & Parker, 1973), a lowered base level caused incision throughout a miniature drainage, while sediment was deposited in downstream reaches. Without another change in base level, prompted instead by internal stream power thresholds, a second wave of incision propagated through the drainage network, rejuvenating channels, and reworking previously deposited sediments. With a single external disturbance, the experiment produced several cycles of fluvial response. Documentation of complex response in diverse types of channels and in response to myriad external perturbations is now widespread (Petts, 1979a; Gaeuman et al., 2005; Brogan et al., 2019; Major et al., 2019). Studies have documented successive episodes of incision and aggradation in sand-bed channels over diverse scales of time and space (Meade, 1985; Gibson & Shelley, 2020; Grabowski & Wohl, 2021) in response to external perturbations such as floods. Adjustment of bed configuration and channel cross-

sectional form is likely to be fastest in sand-bed systems, which have low bed resistance and highly mobile sediment (Knighton 1998, Figure 5.3).

Little attention has been given to how beaver modifications affect sediment dynamics and channel adjustment in sand-bed channels. Beavers are described as ecosystem engineers because their modifications of stream corridors create resources for a wide variety of other species (Brazier et al., 2021). Beavers build dams to create habitat for themselves, but the dams modify stream corridor processes and forms. Dams are obstructions that reduce flow velocity and enhance surface and subsurface water storage (Hafen et al., 2020; Ronnquist & Westbrook, 2021; Dittbrenner et al., 2022), increase sediment storage (Butler & Malanson, 1995; Dunn et al., 2024), reduce longitudinal stream gradient, enhance stream corridor spatial heterogeneity by promoting multithread channel planform, channel lateral movement, and floodplain wetlands (Stefan & Klein, 2004; Polvi & Wohl, 2013) and promote floodplain and valley-floor aggradation (Westbrook et al., 2011; Kramer et al., 2012). Conversely, when beavers disappear from the stream corridor and dams fall into disrepair, the stream corridor is likely to undergo incision, simplification, drying, and loss of spatial heterogeneity (Green & Westbrook, 2009; Wohl, 2021). As depositional and storage reaches transition to sediment source and transport reaches, downstream portions of the stream may experience increased sediment loads and aggradation.

Recreational off-highway vehicle (OHV) travel is an outdoor activity that has grown in popularity throughout the United States since the 1990s (Marion et al., 2014). While OHV travel may increase access and promote engagement with public conservation lands, heavy OHV use is associated with significant landscape impacts. Within affected catchments, OHV use may modify both hillslope and channel processes. Trail construction and use may increase sediment

yield and runoff generation from hillslopes. OHV trails that cross or run near stream channels erode and destabilize banks, which increases sediment flux into the channel, causes local sediment deposition, and potentially results in downstream propagation of sediment plugs (Marion et al., 2014; Marion et al., 2019). Heavy OHV use in riparian areas is associated with stream channel homogenization, decreased width:depth ratios, and the removal of large wood as OHV recreationalists intentionally modify the riparian landscape to create trails and inadvertently alter the local sediment regime (Fairchild et al., 2025). Higher eolian inputs may also result from OHV use that destabilizes or destroys upland vegetation (Duniway et al., 2019).

1.2 Results from Previous Work at North Sand Creek

Grabowski (2020) studied sequential channel changes along North Sand Creek during the summer of 2019. That year was characterized by substantial snowmelt runoff in both North Sand Creek and an unnamed tributary to the creek that flows along the active dune faces of the North Sand Hills dune field. The unnamed tributary and North Sand Creek below the confluence have numerous channel-spanning logjams that can store sediment upstream from each jam. Grabowski used repeat ground photography and estimated the volume of sand stored in ephemeral terraces deposited along the creeks to evaluate whether each creek experienced a sediment wave during the 2019 runoff season. She also used repeat measurements of logjam sand wedge volume and cross-sectional surveys to examine changes in sand storage associated with logjams over time. Based on these data, Grabowski and Wohl (2021) documented a highly translative sediment wave that was attenuated by logjams along North Sand Creek, with greater than 2 m of vertical channel change associated with individual channel cross-sections (Figure 2). Many cross sections exhibited net incision during the snowmelt runoff period of May to July and net aggradation during August to November (Grabowski and Wohl, 2021). Grabowski also contrasted channel

dynamics along North Sand Creek with those along East Sand Creek, a nearby catchment that drains the East Sand Hills dune field (Figure 1).

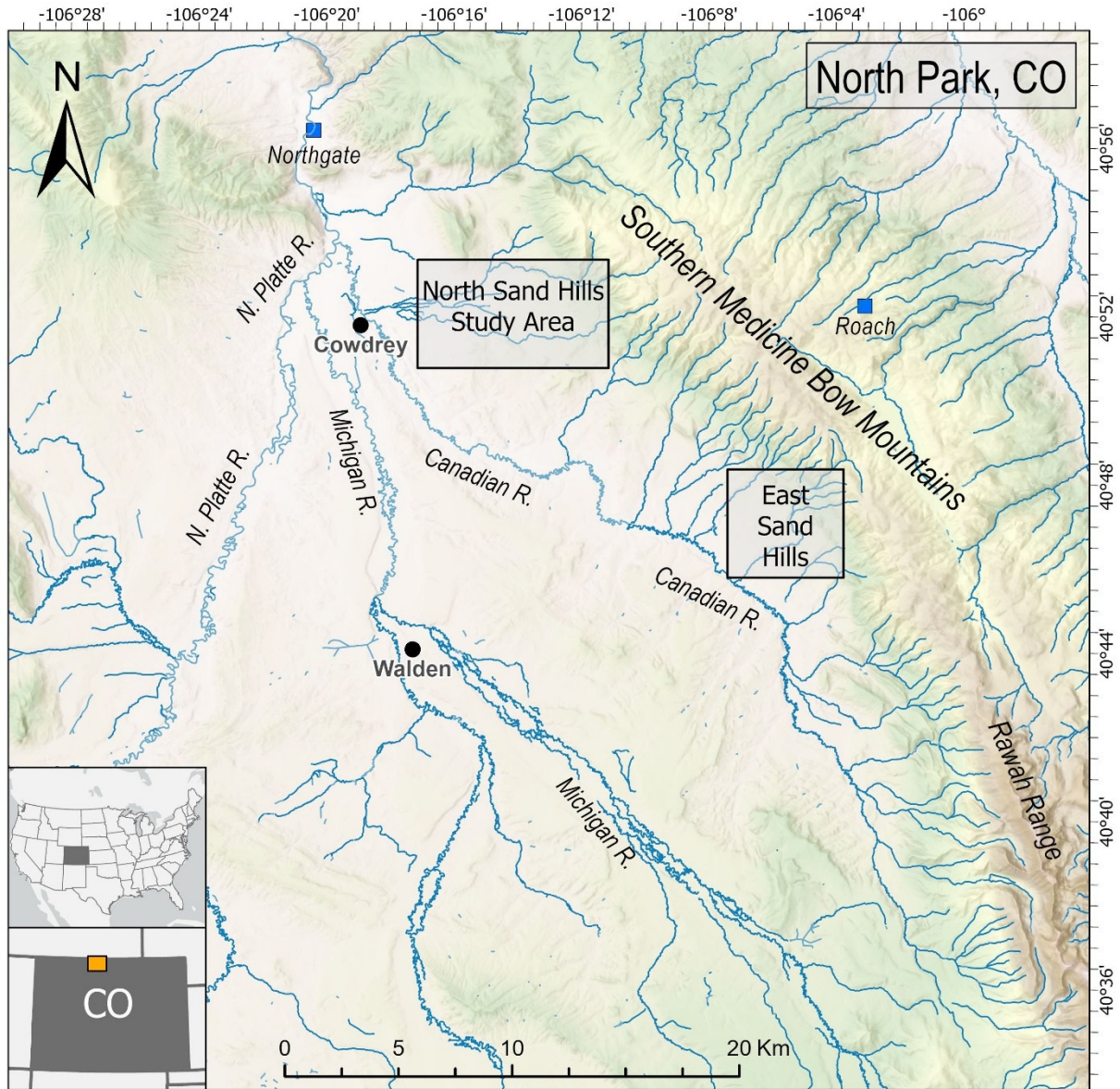


Figure 1. Overview map of North Park basin in North-Central Colorado, with major rivers and towns labelled. Boxes indicate the East Sand Hills active dune field (not studied) and the North Sand Hills dune field and adjacent North Sand Creek (focus of this study). Roach, CO SnoTel Station (USDA, Site 718) and Northgate monitoring location on the North Platte (USGS, 06620000) are shown as blue squares.



Figure 2. From Grabowski (2020). Example of rapid, meter-scale incision over less than two weeks in the ephemeral tributary of North Sand Creek.

Grabowski demonstrated that during years of high flow on the unnamed tributary, both the tributary and North Sand Creek below their confluence exhibit extensive channel adjustment and sand export. I initially expected to see similar patterns of channel change in this study, but the summers of 2024 and 2025 were marked by no flow on the tributary and minimal snowmelt runoff on North Sand Creek. This led to a shift in the emphasis of my work and a focus on longer-term changes in sediment dynamics as inferred from: 1) the presence of abundant, abandoned, and breached beaver dams along North Sand Creek; and 2) the characteristics of the alluvial fan at the confluence of North Sand Creek and the Canadian River.

1.3 Objectives

There are five objectives of this study: (i) compare channel dynamics between the 2019 and 2025 runoff seasons, (ii) map potential sediment sources downstream from the main, active dune face on the unnamed tributary and examine potential correlations between stream corridor morphology and the location of these sediment sources, (iii) estimate the upper and lower bounds of potential sediment storage associated with relict beaver dams based on their location and

characteristics, (iv) compare the surface area and recent history of sediment deposition and channel change on the alluvial fans of North and East Sand Creeks and adjacent catchments along the eastern side of North Park, and (v) provide guidance for restoration actions in North Sand Creek based on my results.

2. STUDY AREA

North Sand Creek is located on the eastern edge of North Park, an intermontane basin in Jackson County, Colorado formed during the Laramide Orogeny (Shroba, 2016). The creek heads in the southern arm of the Medicine Bow Mountains (Figure 1) After descending from the mountains, the perennial North Sand Creek mainstem is joined by an unnamed ephemeral tributary that flows alongside the active sand dunes of the North Sand Hills. Below this confluence, the creek flows approximately 6 km through an area of vegetation-stabilized sand dunes. As the gradient declines, North Sand Creek forms an alluvial fan on the valley floor approaching the confluence with the Canadian River. The alluvial fan is crossed by a series of irrigation ditches that divert flow from North Sand Creek and nearby Crystal Spring and Government Creeks before these streams meet the Canadian River near Cowdrey, CO (Figure 1). Except during years of very high runoff, North Sand Creek does not directly contribute flow to the Canadian River because of irrigation withdrawals and infiltration into the alluvial fan.

2.1 Geology

The headwaters of North Sand Creek in the Medicine Bow Mountains are underlain by Precambrian crystalline basement rocks including ~1.7 Ga granodiorites and quartz monzonites (Tweto, 1979). This bedrock has weathered in place to form a mantle of boulder to pebble sized clasts that cover the hillslopes and floor of North Sand Creek's forested upper drainage (Madole, 1991). At the foot of the Medicine Bow Mountains lies an early Cenozoic reverse fault, and here the creek flows through slopes underlain by occasionally outcropping Triassic, Jurassic, and Cretaceous sedimentary rocks. In order from the edge of the mountains to the valley floor, these

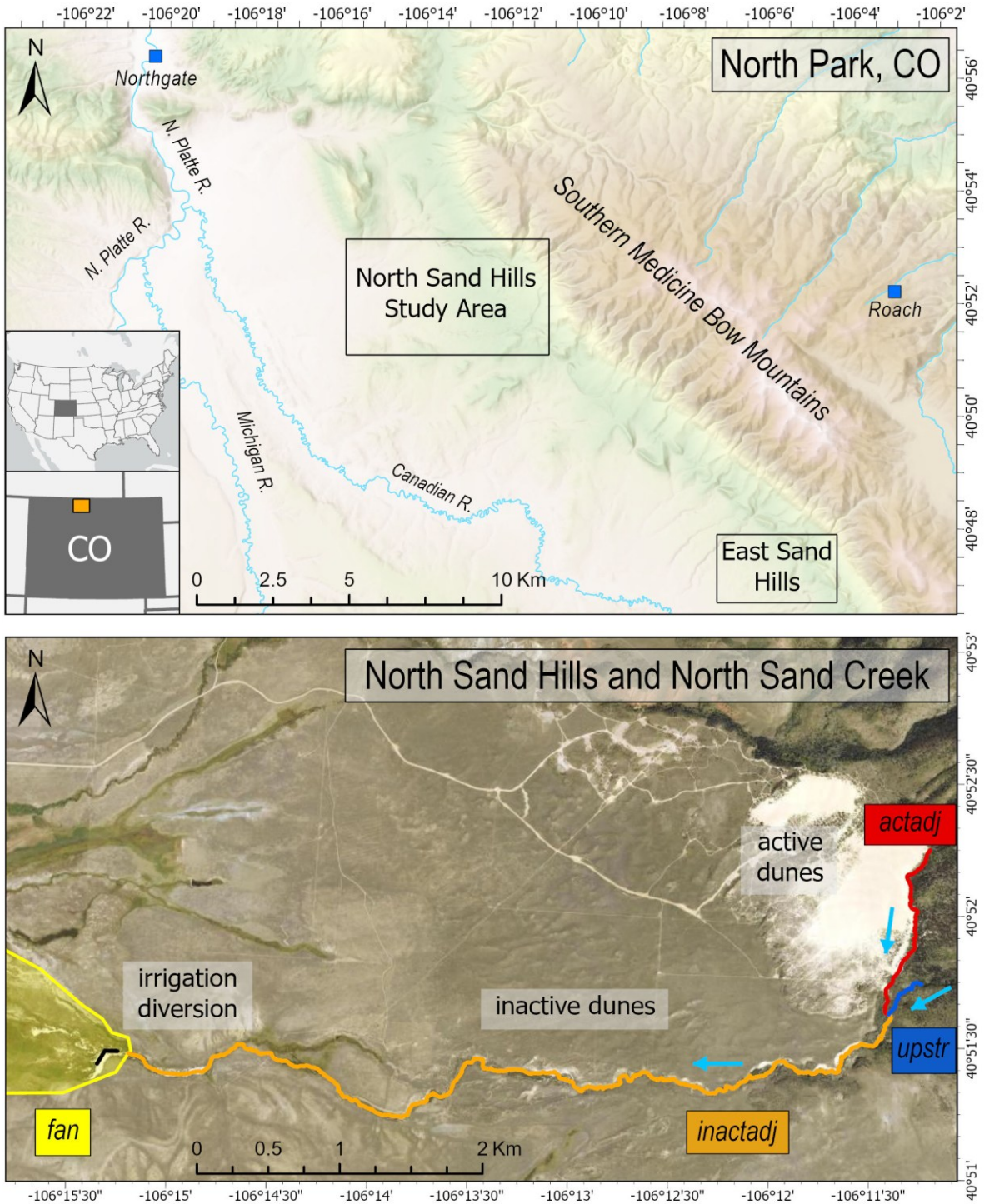


Figure 3. Top: Map of North Park, Colorado. Roach, CO SnoTel Station (USDA, Site 718) and Northgate gauge on the North Platte (USGS, 06620000) are shown as blue squares. North Sand Hills inset = bottom panel area. Bottom: Study area including North Sand Hills and North Sand Creek. Segments labeled in blue (*upstr*), red (*actadj*), orange (*inactadj*) and yellow (*fan*).

are the Triassic redbeds of the Jelm, Chinle, and Chugwater formations; the variegated sediments of the Jurassic Morrison and Sundance formations; the Lower Cretaceous Dakota Sandstone; and the Cretaceous Benton Shale (Tweto, 1979; Madole, 1991).

The mountain ranges along the southeastern flanks of North Park, including the Rawah Range and Never Summer Mountains, were sculpted by valley and alpine glaciers during the glaciations of the Pleistocene, including the best-preserved Pinedale (30-12 ka) and Bull Lake (200-130 ka) glaciations. In contrast, the Medicine Bow Mountains in the northeastern corner of North Park were never glaciated during the Pleistocene due to their relatively low elevation (Madole et al., 1998). This left the mountainous headwater drainage of North Sand Creek unmodified by glacial processes. However, as North Sand Creek flows out of the mountains and enters the valley of North Park, it eventually passes a Pleistocene alluvial terrace interpreted as outwash gravels of pre-Bull Lake age (Madole, 1991). This terrace is relatively widespread along the North Platte and Michigan Rivers, as well as the divide between the Michigan and Canadian Rivers. A younger, lower-elevation set of Pleistocene terraces extensive throughout North Park are interpreted as outwash gravels of Bull Lake and Pinedale age (Madole, 1991). The cobbles and pebbles of granitic composition on the bed and banks of the lower reaches of North Sand Creek are assumed to be reworked from these Pleistocene alluvial terraces.

2.2 Eolian deposits, climate, and vegetation of North Sand Hills

The ephemeral tributary of North Sand Creek runs along the southeastern edge of the North Sand Hills dune field. The active parabolic dunes of the North Sand Hills cover an area of 3.81 km² at an elevation between about 2460 m and 2650 m and migrate slowly to the east and northeast with the prevailing wind direction (Figure 3)Figure 1. Along with the East Sand Hills dune field, which is about 10 kilometers to the southeast along the front of the Medicine Bow

Mountains, the North Sand Hills are the only active sections of a much larger (~86 km²) dormant dune complex that covers much of the northeastern floor of North Park basin (Ahlbrandt & Andrews, 1978). Sand of the North Park dunes is sourced from fluvial sands deposited along the North Platte, Michigan, and Canadian Rivers during the Pleistocene. The sand contains quartz and feldspar grains as well as lithic fragments that indicate metamorphic and igneous origin, suggesting that they are products of glaciofluvial erosion of the basement rocks in the Park Range and Medicine Bow Mountains that surround North Park (Ahlbrandt & Andrews, 1978). Twelve kilometers southeast of the North Sand Hills, the East Sand Hills are another, similarly sized (3.46 km²) active dune field bordered by inactive dunes. The perennial East Sand Creek runs along the East Sand Hills for over one kilometer after descending from the southern Medicine Bow Mountains.

North Park's climate is semi-arid and cold. Daily mean temperatures in Walden, CO range from -8 °C in January to 17 °C in July, and snow cover is usually consistent from October to April (Walden Climate - Weather Spark). The mean annual precipitation for the North Park Basin is 48 cm, but the valley floor receives less precipitation than the surrounding uplands. The 1951-1980 mean annual precipitation in the town of Walden was 28 cm, while the crest of the nearby Park Range received over 127 cm of precipitation (Robson & Glenn, 1996). Average annual precipitation in the North Sand Creek drainage is estimated at 68 cm, mostly as winter snowfall (USGS, 2026).

The long period of snow cover and frequent freezing conditions lead to slow migration of the active dunes. Lenses of snow and frozen, moist sand may collapse as temperatures rise, causing slumping and slope deformation unique to cold-climate dunes (Ahlbrandt & Andrews, 1978). Vegetation stabilizes inactive dunes and anchors the ends of the active parabolic dunes in

the North Sand Hills. Below 2600 m in elevation, vegetation is largely comprised of sagebrush (*Artemisia* spp.) and rabbitbrush (*Ericameria nauseosa*); along riparian corridors and at the mountain front the sagebrush steppe ecosystem transitions to forests composed of aspen (*Populus tremuloides*), limber pine (*Pinus flexilis*), lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), and subalpine fir (*Abies lasiocarpa*) (Ahlbrandt & Andrews, 1978). Willows (*Salix* spp.) and alder (*Alnus* spp.) are also abundant along portions of North Sand Creek.

2.3 North Sand Creek reaches, flow, and management issues

In this study, I divide North Sand Creek into four distinct process segments. The upstream perennial main stem of North Sand Creek (segment abbreviation: *upstr*, for upstream) heads in the Medicine Bow Mountains, flowing through a steep, rocky drainage with subalpine fir, lodgepole, limber pine, ponderosa, and aspen. An ephemeral tributary (*actadj* – active dune adjacent) flows alongside the southeastern edge of the North Sand Hills active dune field for just over one kilometer, then joins the mainstem at an elevation of 2600 meters. The tributary also flows through sections of lodgepole and aspen forest that skirt the dunes. Downstream of the tributary confluence, North Sand Creek flows adjacent to inactive, sagebrush-stabilized dunes for roughly four kilometers (*inactadj* – inactive dune adjacent). In most plots, the tributary confluence (where *actadj* joins *upstr*, and both flow into *inactadj*) is represented as distance or Point 0. Throughout its westward course, the stream is somewhat confined by the dune field to the north and by weathered bedrock outcrops and Pleistocene alluvial terrace remnants to the south (Madole, 1991). At an elevation of 2450 m, North Sand Creek exits confinement, forming an alluvial fan (*fan*) before a nominal junction with the Canadian River. Multiple irrigation structures divert water from North Sand Creek and nearby Crystal Spring and Government

Creeks to hayfields, reducing and (in 2025) entirely blocking flow from reaching the Canadian River.

North Sand Creek's ephemeral tributary (*actadj*) drains a basin of 2.07 km², with a mean elevation of 2868 m. Above the tributary junction at 2600 meters elevation, the forested perennial mainstem incorporates a basin of 3.24 km², with a mean elevation of 3030 meters. At their confluence, the mainstem and tributary drain a basin of 5.31 km² and a mean elevation of 2967 meters (U.S. Geological Survey, 2026b). Most of the contributing area of both the tributary and mainstem is well above the maximum elevation of both the active and inactive dunes. North Sand Creek is ungauged, with no continuous or repeated discharge measurements for the catchment; the nearest USGS gauge is to the northwest on the Platte River at Northgate. However, USGS regional regressions and field observations (Grabowski & Wohl, 2021) indicate that flow in North Sand Creek is strongly seasonal, with peak discharges occurring in June during snowmelt. Predicted average peak discharge for June is estimated at 14.1 cfs (0.4 cms), while discharge recedes to less than 0.5 cfs (0.014 cms) by October (U.S. Geological Survey, 2026b). Strong convective thunderstorms producing heavy, sustained rainfall are unlikely to occur above 2300 m elevation in the Colorado Front Range region (Jarrett, 1990). With an elevation greater than 2300 m for almost its entire length, North Sand Creek is unlikely to experience the flooding associated with these convective thunderstorms. The creek's hydrograph is snowmelt-dominated, with annual discharge magnitude and duration dependent on snowpack depth and melt timing in the Medicine Bow Mountains.

North Sand Hills is managed as an off-highway vehicle (OHV) recreation area by the Bureau of Land Management (BLM), despite the designation of the adjacent forest and riparian zone as a Wilderness Study Area in 1976 (Bureau of Land Management, 2026). OHV use has

occurred on the North Sand Hills since at least the 1990s. Visitation likely increased in the period 2000-2011 and many OHV recreationalists continue to utilize the area. Decades of OHV use have significantly impacted the dune field and adjacent forest and riparian areas. OHV use on the margins of the dunes has contributed to the destruction of dune-stabilizing vegetation, likely increasing eolian transport rates. The BLM addressed these impacts by fencing off some impacted areas to promote revegetation, and while the fenced-off areas regained some vegetation cover by 2020, unfenced areas continued to lose vegetation (Grabowski, 2020). OHV users also frequently rode in the ephemeral tributary of North Sand Creek before BLM land managers fenced off most of the tributary in the summer of 2019. However, part of the upper tributary channel and the adjacent dune slip-faces remain open to OHV use. OHV use on the slip-faces of the adjacent active dunes causes elevated sand loading within the ephemeral tributary via destabilization and slumping, combining with natural eolian transport to bury sections of the upper tributary channel under a thick layer of sand.

When runoff is sufficiently high to activate flow in the *actadj* segment, the sand contributed to the channel by eolian transport and OHV erosion can mobilize as a sediment wave. However, during low runoff years such as 2025, flow may not occur in the tributary, and the sand bed remains immobile. Julia Grabowski observed meter-scale incision and a translating sediment wave in the *actadj* segment of North Sand Creek during the spring and summer of 2019 (Figure 2). She estimated that roughly 9,600 m³ of sand was exported from the *actadj* segment (Grabowski, 2020). Sand exported from the ephemeral tributary during high runoff years, as well as sand potentially sourced from previously deposited sand in the *inactadj* segments, travels through the channel network to reach the low gradient depositional zones at the head of North Sand Creek's alluvial fan. Deposition at the fan head increased after 2011, based on remote

imagery compiled by Grabowski as well as reports from State Line Ranch, which uses its senior water right on North Sand Creek to irrigate hayfields on the creek's fan. State Line Ranch's ability to divert water for irrigation has been impaired by mass sand export that overwhelms the diversion structure. Direct addition of sand by OHV degradation of vegetation on the dune field has likely exacerbated mass sand export to the alluvial fan and State Line's diversion. East Sand Creek, while bordering the East Sand Hills active dune field, did not exhibit meter-scale adjustment or a translating sediment wave in 2019 (Grabowski, 2020).

3. METHODS

3.1 Field Methods

I primarily conducted fieldwork during the 2025 runoff season, starting in late May and ending in early October. Several early site visits in late summer and early fall 2024 provided context for summer 2025 fieldwork.

3.1.1 Cross Sections

Channel surveys were initially designed to assess geomorphic change along the length of the channel, under the assumption that downstream-moving sand waves would create successive aggradation and incision, analogous to those observed by Grabowski in 2019. I established multiple cross sections in each of the four process segments. The location of each cross section was chosen to cover changing geomorphic characteristics (channel width, sediment inputs, vegetation, sediment characteristics), downstream spacing (cumulatively cover most of the channel length), and ease of repeated access. The cross-sectional surveys were designed to observe spatial and temporal differences in channel adjustment. Some cross sections were co-located with time interval cameras pointed at the channel.

At each cross-section site, I determined a feasible location for the cross-section endpoints. Endpoints were located above the elevation of a field-assessed bankfull channel (historical flow markers, change in slope, vegetation) and were either marked with nails hammered into trees/roots, or with wooden stakes or in a few cases rebar planted in soil and reinforced with rebar/metal rods/rocks if necessary. Cross section endpoints were marked with a Jupiter Geode GNSS receiver with sub-meter horizontal accuracy. Cross section locations along North Sand Creek are shown in Figure 4.

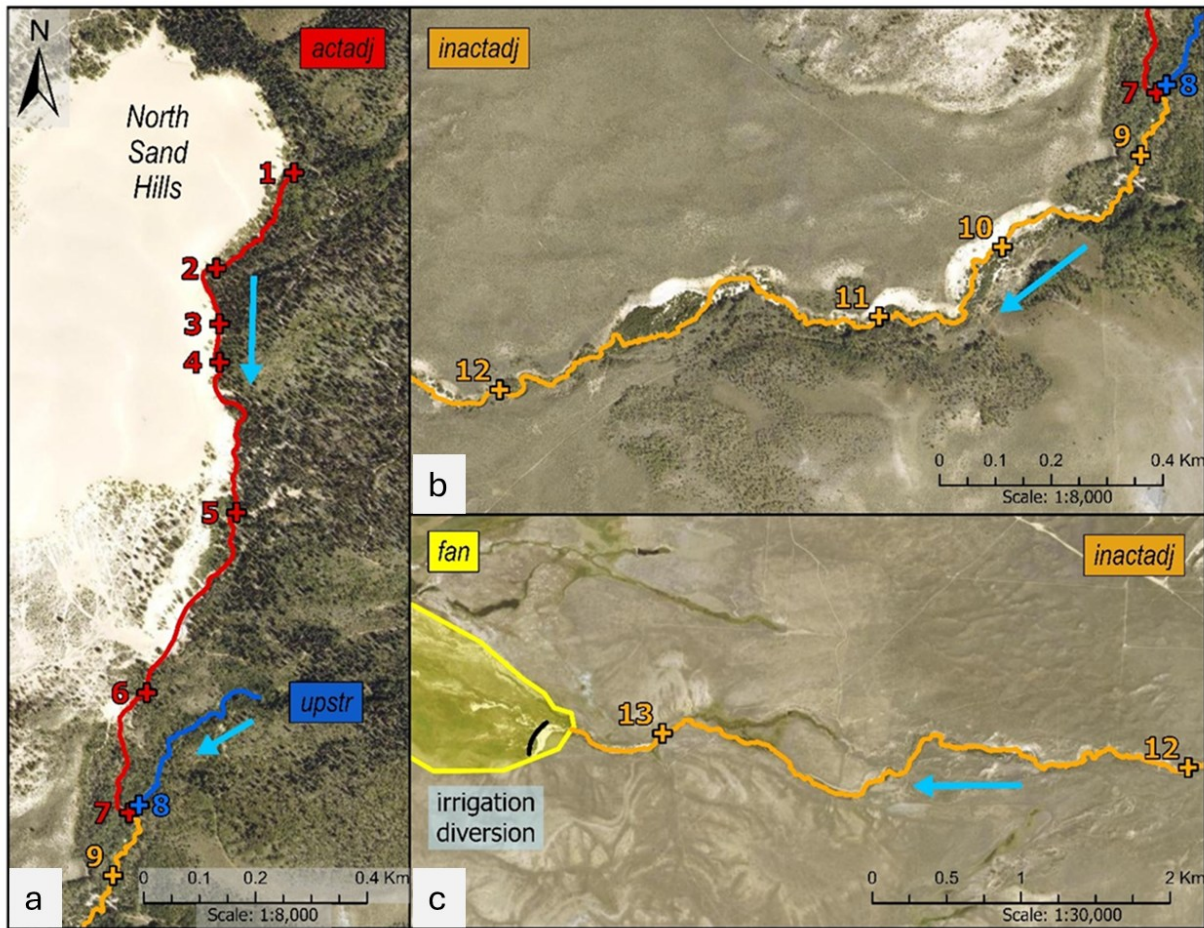


Figure 4. Cross section locations, marked with cross and number in color corresponding to North Sand Creek segment (*upstr* = blue, *actadj* = red, *inactadj* = orange). Flow direction is shown with turquoise arrow. (a) is in 1:8,000 scale, showing *actadj* and *upstr* segments. (b) is also in 1:8,000 scale, showing upper *inactadj* segment from tributary confluence to CS 12. (c) is in 1:30,000 scale, showing the lower *inactadj* segment from CS 12 to the State Line Ranch diversion and NSC *fan*.

Repeat cross section surveys were completed on June 9, June 17, July 2, July 22, and August 5 (upstream cross sections were not resurveyed on July 22). Because of logistical constraints, I used a metric tape and compact extendable stadia rod for cross-section surveys. During each survey, one end of the survey tape was attached to the endpoint stake, stretching the tape to reach the other endpoint, and clipping it in place with a binder clip. At the first cross section of the season, tapes were leveled by eye, and the level position was marked on each stake

by a plastic zip tie tightly affixed to the stake. During subsequent repeat measurements, the tape was fixed at the same position. With consistent placement of tape endpoints, this methodology is intended to measure relative, rather than absolute, changes in bed elevation and channel width/channel geometry. During surveys, I measured height from the bottom of the extended tape to the channel bed surface at standard intervals of 40 cm, with shorter intervals at slope or surface transitions to capture small changes in elevation and longer intervals on particularly wide, flat cross-sections.

After field data collection, data were processed and plotted in *RStudio*. Based on field notes, some repeat cross sections were removed from the dataset due to broken endpoint stakes, endpoint relocation due to bank collapse, or poor leveling.

3.1.2 In-Field Sediment Characterization

Anticipating that a sand wave would translate downstream past each cross-section station, I attempted to document changes in bed material composition over the runoff season. At the time of each repeat cross section, I took a photo of the bed material at the location of the cross section and recorded the size class of the clasts on the stream bed (e.g., sand, pebble, gravel, mixed sand and gravel, pebble veneer over sand). Traditional Wolman pebble counts were not used because they would not provide useful information in sand-bed reaches.

In addition, I measured the depth of sand at each cross section by inserting a tile probe marked with 2 cm increments into the sand until the probe reached a resistant layer. This layer was usually gravel or cobble, but in some locations a clay later was present instead. Where clast sizes larger than sand formed the top layer of bed material, sand depth was recorded as zero. Where pebble or gravel clasts were mixed with sand, sand depth was recorded as the probe depth to a resistant layer. To generate a representative sand thickness at each cross section, I repeated

this sand depth measurement at 3 points – left water edge, approximate thalweg, and right water edge – and averaged the results.

3.1.3 Discharge Measurements

Discharge was measured on May 17, June 2, June 17, July 22, and August 5 at the *upstr* cross section (Figure 4, CS 08). Because the *actadj* tributary contributed no or negligible flow throughout the entire runoff season, I consider discharge measurements at the *upstr* cross section to represent all discharge contributed to the channel by surface flow. I made several additional flow measurements at CS 01 and CS 07 in the *actadj* segment and CS 11 in the *inactadj* segment.

I used a Marsh-McBirney flow meter with sensor attached to a USGS top-set wading rod to measure discharge at cross section 08. After surveying the cross section, I left the tape attached to the cross-section endpoints. Starting at the water's edge, I measured flow depth and velocity at 20% intervals over the width of the water surface. Velocity was measured at 60% of depth, or its closest approximation when flow was shallow. Discharge over each interval was calculated as the product of interval width, depth, and velocity. Later in the season, very shallow and sluggish flow made it difficult to accurately measure flow.

3.1.4 Sand Addition and Knickpoint Survey

While conducting this survey, I walked along the ephemeral tributary from the top of the North Sand Hills dune field to the tributary confluence, then along North Sand Creek to the State Line Ranch diversion. I mapped point sources of direct sand addition to the channel, as well as significant channel knickpoints. The bulk of the survey occurred on June 16 and June 18. Additional reaches in the lower creek were covered on August 6 and September 8.

Using a Jupiter Geode GNSS receiver with sub-meter horizontal accuracy, I mapped point sources along the bank of North Sand Creek where sand directly entered the channel, creating visible sand plumes in the creek or clearly showing evidence of gravitational slumping and erosion. Walking on the bank or in the stream, I recorded a point using the Geode at the beginning and end of zones of sand addition for both the left and right banks of the stream. I categorized the mode of sand addition as either “dune” (slumping from active or inactive dune slipfaces or erosion at the toe of a dune) or “terrace” (fluvial erosion of previously deposited sand terraces). Processing the data in RStudio and ArcGIS Pro, I generated a measured length for each zone of sand addition, then summed the total length of sand addition over 100 m reaches.

I identified knickpoints as sudden changes in bed elevation or a sudden steepening of the bed. Where a knickpoint was visible, I recorded its location with the Geode GNSS, then measured the approximate change in bed elevation using a stadia tape or tile probe and noted the association of the knickpoint with one of the following: large wood, small wood jam, presumed relict beaver dam, living root/tree, boulder/cobble, or no association. Coordinates for each knickpoint were imported into ArcGIS Pro.

3.1.5 Relict Beaver Berm Survey

This survey was intended to systematically map all relict beaver berms visible in the *actadj* and *inactadj* segments of the channel network. Observations of beaver chew, relict berms, and morphology reminiscent of incised beaver meadows in the *inactadj* segment suggested that the stream likely supported a large beaver population in the past. Taking place on September 9, 2025, the relict berm survey began on the *actadj* segment roughly 300 m upstream of the tributary-mainstem confluence and ended 4400 m downstream of the confluence on the *inactadj* segment, covering a total of 4.5 km of stream length.

I identified berms through diagnostic characteristics observable in the modern active channel or on the floodplain. Positively identified berms showed a combination of observed diagnostic characteristics. In-channel diagnostics included: exposure of wood and fine sediment accumulations on both sides of the channel with discernible structure or arrangement analogous to beaver dams; exposed beaver-chewed wood; and changes in channel morphology indicating prior influence of dams and dam failures, such as induced multithread flow or sharp L-bends around raised structures. Floodplain characteristics included: linear growths of multi-stem willows, often present on a raised surface; and a transition from a higher-elevation upstream surface to a lower-elevation surface downstream of the suspected relict berm. Examples of relict beaver berms are shown in Figure 5.

I recorded relict berm locations using a Jupiter Geode GNSS receiver with sub-meter horizontal accuracy. I attempted to record these locations as close to the active channel as possible to facilitate later calculation of downstream spacing. When practical, I measured the distance from the streambed to the crest of the relict berm using a stadia tape. Berm locations were transferred to ArcGIS Pro software. Within ArcGIS Pro, I snapped berm locations to a stream centerline determined from analysis of UAV-generated DEMs and orthomosaic imagery (section 3.2.2).

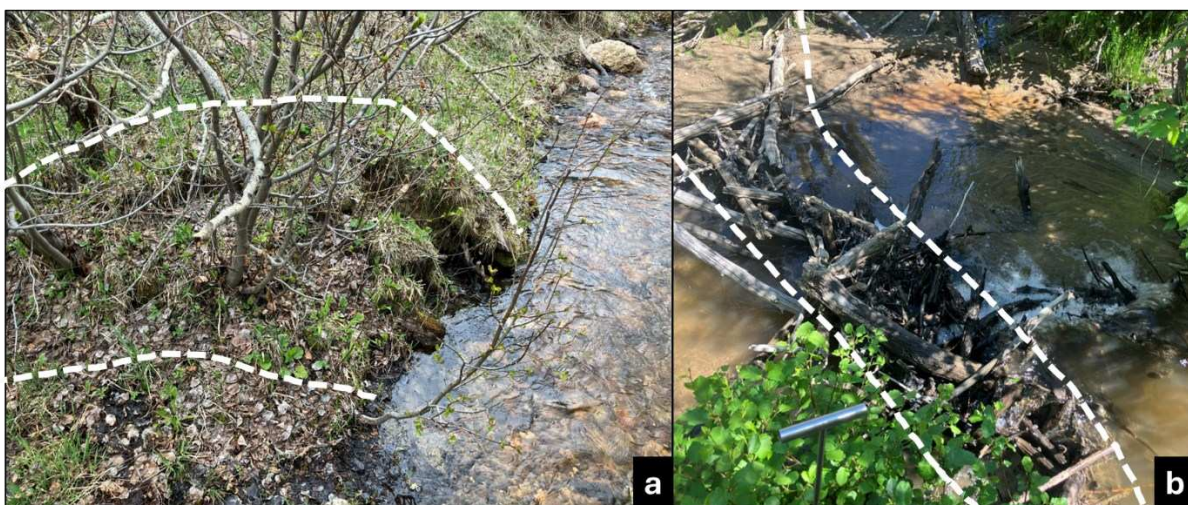


Figure 5. (a) and (b) show examples of relict beaver berms at North Sand Creek. The relict berm in (a) is located at the tributary confluence; it showed a raised linear structure, a transition to a lower downstream floodplain surface, chewed wood, and multistem willow growths on top. The relict berm in (b) is located in the *inactadj* segment; it contained chewed wood in-channel and a raised linear feature to the right of flow.

3.2 Remote Analyses

3.2.1 Historical Aerial Imagery

Historical aerial imagery of North Sand Creek and surrounding areas is available through the U.S. Geological Survey EROS archive (USGS, 2026). I downloaded single frame aerial images covering North Sand Hills, North Sand Creek, and the North Sand Creek alluvial fan from the USGS Earth Explorer website. The aerial images were taken on the following dates: July 7, 1947; August 20, 1953; August 2, 1975; July 12, 1977; and October 22, 1983. I performed a qualitative visual analysis of these images to provide historical context for modern processes. I visually identified beaver modifications (dams, filled ponds) in North Sand Creek and surrounding streams, and visually determined whether freshly deposited alluvial sand was present on the alluvial fan or near the present State Line Ranch diversion. In addition, I visually

determined the presence or absence of OHV trails on the North Sand Hills and qualitatively compared vegetation density on the dune field and in riparian areas.

3.2.2 UAV Imagery and LiDAR

On August 4, 5, and 6, the Colorado State University (CSU) Drone Center conducted unmanned aerial vehicle (UAV) flights over the North Sand Hills and all four segments (*upstr*, *actadj*, *inactadj*, *fan*) of North Sand Creek. Using a fixed-wing Wingtra platform equipped with a high-resolution camera and a Light Detection and Ranging (LiDAR) scanner, the Drone Center captured RGB images and a LiDAR three-dimensional point cloud over the entire study area. Both surveys had a 2-3 cm resolution and were referenced to GNSS ground control points.

Drone Center technicians then processed the raw UAV survey data independent of the author. They produced georeferenced orthomosaic images and a high-resolution Digital Elevation Model (DEM) for the entire study area. The raw imagery, processed orthomosaics, raw point cloud returns, and DEMs were then uploaded to the CSU Geospatial Centroid online storage. I then downloaded the DEMs and orthomosaic imagery.

3.2.3 Valley and Stream Characteristics in ArcGIS Pro

I imported the LiDAR-generated DEMs and orthomosaic imagery into ArcGIS Pro and reprojected both into the UTM Zone 13N coordinate system. I clipped both rasters to an area of interest (AOI) covering the North Sand Creek stream corridor, including the ephemeral tributary, hillslopes immediately adjacent to the stream, and the alluvial fan downstream of the State Line Ranch diversion. During my workflow, I displayed the DEM as a shaded relief map with a Z-factor of 2.0 to emphasize small changes in elevation. Orthomosaic imagery was displayed in true color.

Using the DEM and orthomosaic imagery, I defined a stream centerline/thalweg line for each fluvial process segment of the stream (*upstr*, *actadj*, *inactadj*). I based the streamline on the lowest elevation within the stream corridor. When lowest elevation was unclear due to channel-spanning vegetation or multi-thread flow, I based my delineation on imagery showing flow within the channel or obvious bed material such as imbricated cobbles or ripples. I then generated points at 1-m intervals along each segment's centerline and sampled the DEM at each point, making a longitudinal profile for each segment.

After creating stream centerline features for each segment, I focused analysis on the *inactadj* segment where the majority of the beaver berm survey (section 2.1.5) took place. Using the DEM and the elevation points samples along the *inactadj* centerline, I created a relative elevation model (REM) showing elevation relative to the stream centerline to aid in delineation of the stream valley and bankfull inset. Displayed as a transparent layer over the DEM hillshade, this allowed for confident interpretation of changes in slope and surface elevation in the riparian corridor.

Along the *inactadj* segment, I delineated valley width and bankfull channel width using information from the DEM, REM, and orthomosaic imagery (Figure 6). The valley width corresponds to the area of the terrace surface that is elevated roughly 1 m above the streambed in most reaches. The REM and DEM clearly showed a transition in slope and elevation to an older, abandoned terrace surface or directly to adjacent hillslopes in most locations; where this was unclear, I made a judgment based on transitions from the alder and willow plant communities on the lower terrace surface to xeric sagebrush communities on higher surfaces. The bankfull/inset channel edge was determined via the slope transition from active channel to terrace surface visible in the REM and DEM. In the orthomosaic imagery, this could also be distinguished by

differences in apparent sediment wetness (dark, wet in the channel; bright, dry on terrace) or texture. After delineating the valley area and inset channel area, I measured inset and valley width at 25-m stream distance intervals.

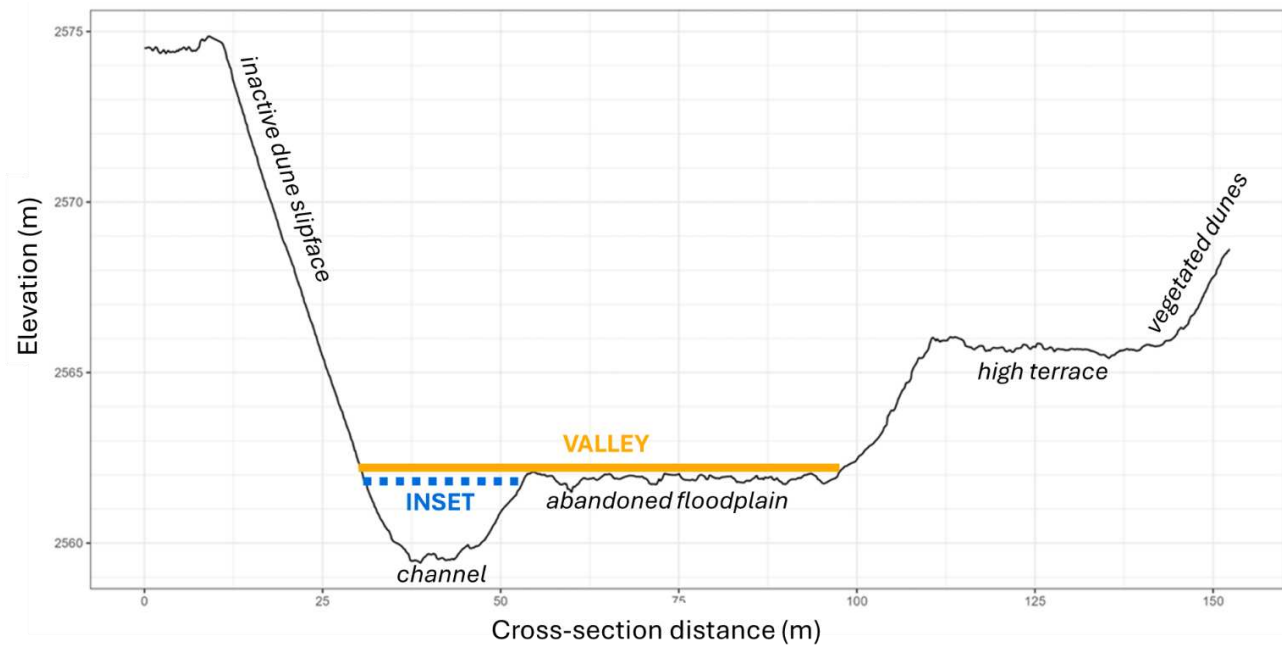


Figure 6. Representative DEM-generated *inactadj* valley cross section, showing the inset active channel, abandoned floodplain, and high terrace. Inset width is shown by blue dashed line; valley width is shown by solid orange line.

At each 25-m interval, I also recorded the primary bed material visible in the August 2025 imagery for the following segment. The high-resolution imagery allowed me to determine if the bed was primarily cobble-boulder, primarily sand, or a mix of both bed materials, with sand partially overlaid over visible larger clasts.

I transferred the ArcGIS tables of valley and inset width and elevation versus stream distance to RStudio for analysis. Splitting the *inactadj* segment into 200-m reaches, I calculated an overall slope and average valley and inset width for each reach. I used the *tidyverse*

(Wickham et al., 2019) set of R packages for analysis, as well as *ggiraph* (Gohel, 2026) and *patchwork* (Petersen, 2025) for visualization.

I used the *emmeans* (Lenth and Paskowski, 2026) and *car* (Fox and Weisberg, 2019) packages in RStudio to test for statistically significant differences in reach characteristics between bed material types (sand, mixed cobble-sand, and cobble-boulder). For valley width, inset width, channel gradient, and inset depth, I created a one-way Anova (Analysis of Variance) model relating each characteristic individually to bed material type. I then conducted a global F-test for significant differences in treatment (in this case, bed material) effects. If the F-test showed evidence of a significant difference in geomorphic characteristics between bed material type, I then calculated the estimated marginal means for each bed material type and calculated Tukey pairwise contrasts between each type. In the results, I report the significance of the global F-test, then significance of individual pairwise contrasts and estimated differences, if applicable. This workflow is summarized in Table 1.

Table 1. One-way Anova models relating reach-scale characteristics to bed material and statistical workflow to test for significant differences between bed material types.

Anova Model		Pairwise Contrasts
slope ~ bed_material	Global F-test for heterogeneity between bed material types	cobble – mixed cobble – sandbed mixed - sandbed
inset_width ~ bed_material		cobble – mixed cobble – sandbed mixed - sandbed
inset_depth ~ bed_material	If evidence for heterogeneity, calculate estimated marginal means	cobble – mixed cobble – sandbed mixed - sandbed
valley_width ~ bed_material		cobble – mixed cobble – sandbed mixed - sandbed

3.2.4 Relict Berm Storage Estimates

I based my estimation of past relict berm sediment storage volume at North Sand Creek on the techniques of Scamardo et al. (2022), outlined in Figure 7. Using modeled estimates of beaver dam spacing along stream corridors generated using the Beaver Restoration Assessment Tool (BRAT; Macfarlane et al., 2017) and regional geomorphic and hydrologic regression curves, Scamardo et al. calculated current and historical beaver dam sediment storage capacity across all Colorado stream networks. Here, I instead use mapped relict berm locations and remotely extracted geomorphic characteristics to estimate past sediment storage behind historical beaver dams at North Sand Creek.

I mapped the locations of relict beaver berms along the *inactadj* segment of North Sand Creek using a Jupiter Geode sub-meter GNSS receiver (section 3.1.5). Relict berms were mapped in the *actadj* and *upstr* segments but were disregarded in this analysis. I transferred the coordinates of the mapped relict berms into ArcGIS pro and assigned each berm a downstream distance from the tributary-mainstem confluence along the remotely derived stream centerline (section 3.2.2). Based on its downstream distance, each berm was assigned a local gradient, bankfull channel width, and valley floor width, calculated as the average of each of these values over the 100 m reach within which the berm was mapped (section 3.2.2). I also calculated the distance from each relict berm upstream to the previous berm.

In the field, I measured the height above the modern streambed of a subset of 30 relict dams. Height values ranged from 60 cm to 200 cm above the stream bed. The mean height above the streambed was 117 cm and the median was 100 cm. This corresponds with observations of Hafen et al. (2020), who surveyed 500 active beaver dams and found that their heights followed a log-normal distribution centered on 1.0 m. Thus, in my estimation of past sediment storage

capacity I use 1.0 m as the assumed mean height of historical beaver dams along North Sand Creek. Two meters is used as a presumed maximum dam height above streambed; Hafen et al. (2020) observed dams 2.2 m tall in their study.

I estimated maximum dammed pond length as dam height divided by the channel gradient. This approximates the actual geometric relationship of channel length = tangent of channel gradient. This approximation is appropriate for low-gradient channels such as North Sand Creek's *inactadj* segment, which at its steepest has a gradient of less than 0.07 m/m. However, maximum dammed pond length in some cases exceeded the upstream distance to the previous berm. If maximum pond length exceeded upstream distance to the previous berm, the upstream distance was used in the calculation of pond volume.

If maximum pond length was less than the upstream distance to the next berm, pond volume was approximated as a right triangular prism ($volume = 0.5 \times W \times H \times L$). If maximum pond length exceeded distance to the upstream berm, pond volume was approximated as a rectangular prism ($volume = W \times H \times L$). This was the calculation used in most cases due to the low gradient of the creek.

The volume of sediment stored behind an active beaver dam is usually less than the total pond volume. If sediment fills the pond to the top of the dam, the dam will no longer store water and therefore may be abandoned by the beaver population. However, North Sand Creek currently experiences rapidly cycling seasonal sand loading due to eolian inputs in the *actadj* tributary (Grabowski, 2020) and sand inputs along the length of the *inactadj* segment. Historical beaver ponds in North Sand Creek could have been filled to the tops of their dams over just one or several runoff seasons. Therefore, the *maximum* sediment storage volume for each berm is defined as the total pond volume (Pollock et al., 2003).

Actual sediment storage volume in active beaver ponds is necessarily less than the maximum volume. The actual or probable storage volume can be estimated using empirically derived formulas, such as those developed by Naiman et al. (1986) for beaver ponds in low-relief, low sediment yield boreal forest; and by Butler & Malanson (1995), for steeper mountain environments including a lake delta. Both empirical formulas rely on measured pond surface area, while Butler and Malanson's also incorporates estimated pond age. These empirical formulas are inappropriate for use in North Sand Creek because of the catchment's high seasonal sediment yield, a lack of recorded age markers on observed relict berms (which are often partially covered or overtopped by sand), and inability to measure pond surface area. I attempted to use the empirical formula of Naiman et al. (1986) in calculating *probable* relict berm storage, inferring surface area from measurements of valley width and slope, but found that these results were often larger than the calculated maximum pond volume. Therefore, I only calculate the maximum sediment storage volume for each dam, and the resulting estimates of total relict storage within the *inactadj* segment represent the upper limit for each scenario outlined below.

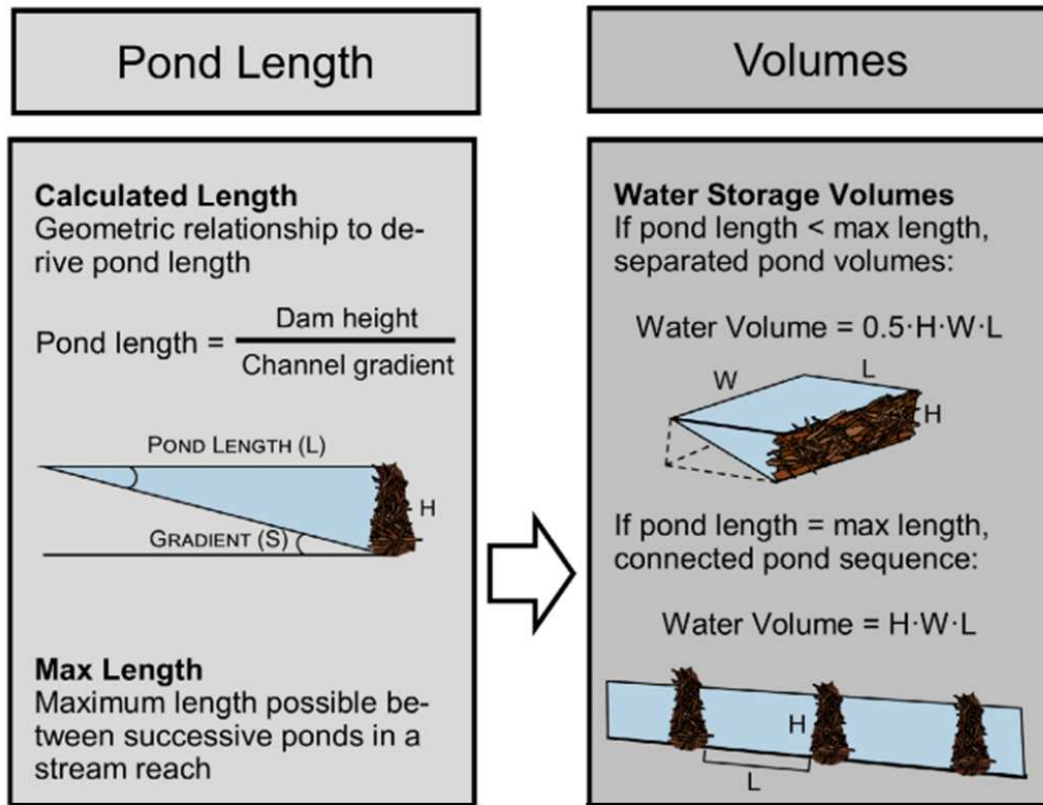


Figure 7. Methodology for calculation of relict berm maximum sediment storage volume, reproduced from Scamardo et al. (2022). Here, the water storage volume corresponds to my calculation of maximum sediment volume.

I calculate maximum relict berm sediment storage along the *inactadj* for four different beaver occupation scenarios to provide a range of past beaver sediment storage estimates. For each scenario, I calculate maximum sediment storage for average berm height of 1 m above the stream bed, and for an average height of 2 m above the stream bed, which would only be possible after many years of aggradation. These scenarios are:

1. **All observed relict dams:** maximum sediment storage volume calculated for all 315 relict dams observed over 4.4 km of stream distance; **71.4 dams/km** density.
2. **50% of observed relict dams:** maximum sediment storage for 50% of observed relict dams; **35.2 dams/km** density. I randomly sampled 50% of the population of observed

beaver berm locations 1000 times to produce 1000 different dam spatial distributions, then calculated maximum sediment storage for each and reported the mean value of all 1000 samples.

3. **Scamardo et al. (2022) historical density estimate:** Using the BRAT beaver habitat suitability model developed by Macfarlane et al., (2017), Scamardo estimated a historical median density of **11.4 dams/km** for streams in the Colorado Rocky Mountain region. Applied to North Sand Creek, this represents a historical scenario in which 16% of observed relict dams were active at any given time. I randomly sampled 16% of the population of observed beaver berm locations 1000 times to produce 1000 different dam spatial distributions, then calculated maximum sediment storage for each and reported the mean value of all 1000 samples.
4. **Scamardo et al. (2022) modern density estimate:** Using the BRAT beaver habitat suitability model developed by Macfarlane et al., (2017), Scamardo estimated a modern median density of **4.0 dams/km** for streams in the Colorado Rocky Mountain region. Applied to North Sand Creek, this represents a potential scenario in which 5.6% of observed relict dams are active at any given time. I randomly sampled 5.6% of the population of observed beaver berm locations 1000 times to produce 1000 different dam spatial distributions, then calculated maximum sediment storage for each and reported the mean value of all 1000 samples.

Scenario 1 represents an absolute maximum, as if all relict berms were filled to the brim at the same time. Based on Scamardo et al.'s (2022) estimate of historical dam density, this is unrealistic, but useful as a representation of total sediment attenuation capacity within the

inactadj segment. Scenarios 3 and 4 represent more realistic beaver occupation densities, with only a fraction of the observed relict berms accumulating sediment at any given time.

3.2.5 Late Holocene Incision and Sediment Export Estimate

During field surveys (sections 3.1.4., 3.1.5.) and remote extraction of valley geomorphic characteristics (sections 3.2.2., 3.2.3.), I observed an extensive terrace 4-5 m above the North Sand Creek channel. In the LiDar-derived DEM of the stream corridor, the terrace is observable as a flat surface along the southern (river left) edge of the modern valley starting 325 m downstream of the *actadj* tributary confluence (106.1914314°W 40.8582849°N) and ending 4200 m downstream of the tributary confluence (106.2250276°W 40.8568592°N). The terrace is well vegetated, primarily with sagebrush but also with some stands of aspen. I refer to the terrace elevated 4-5 m above the channel as t_2 . The modern valley floor, which is disconnected from the active channel by 1 m of incision, is referred to as t_1 .

In the field, I observed two stratigraphic features exposed near the upper limit of the t_2 terrace (Figure 8). First, a dark, finely laminated soil profile (Figure 8a) is exposed south of North Sand Creek, roughly 350 m downstream of the tributary confluence (106.1914262°W, 40.8583023°N). The upper limit of this soil profile is elevated 4 m above the modern stream bed, at an elevation of 2568 m. This hydric soil profile indicates development under ponded conditions. Second, across the stream valley at a similar elevation of 2567 m, (106.1921227°W, 40.8586284°N), an exposure of greyish sand grades into a lens of gravels, which are then overlain by another layer of sand similar in color and texture. The gravel clasts are crystalline, corresponding to the basement rocks exposed at higher elevations in the North Sand Creek perennial catchment rather than the Jurassic sedimentary rocks exposed on the valley floor (Tweto, 1979; Madole, 1991), indicating transport from higher in the catchment.

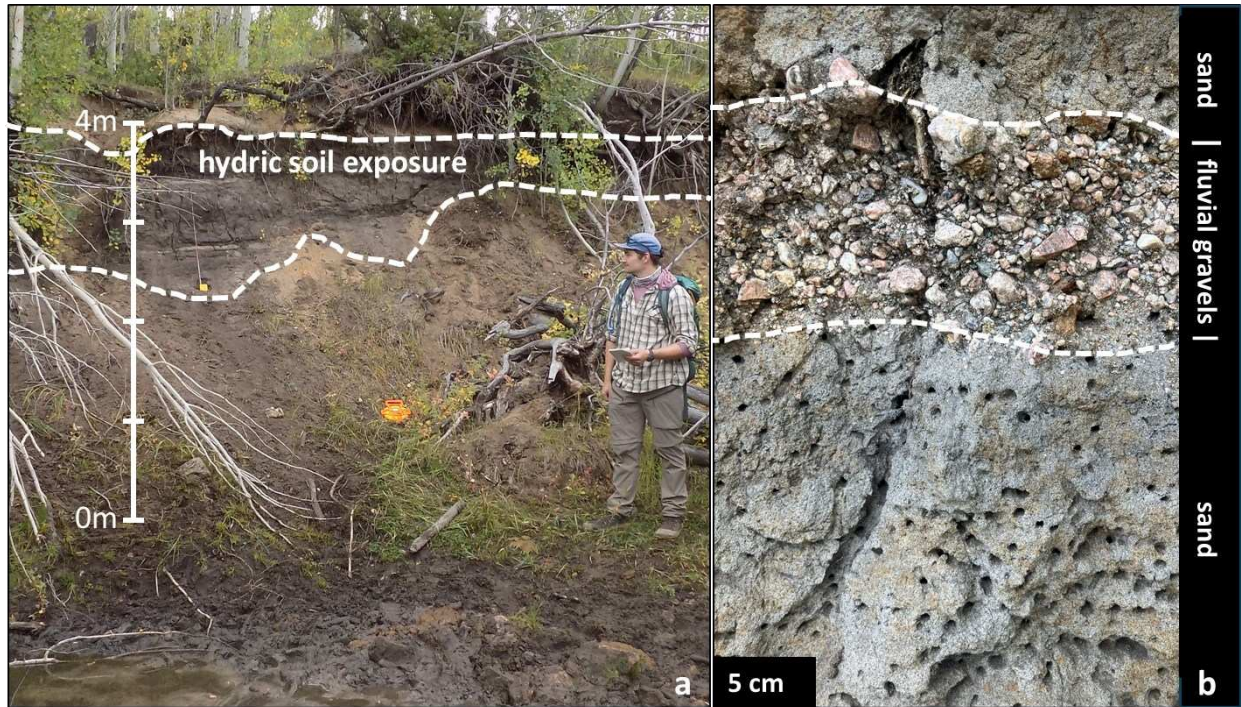


Figure 8. (a) Dark, hydric soil profile exposed 4 m above current *inactadj* channel bed on river left, indicating beaver pond sediment deposition at a higher past valley floor elevation (1 m tape for scale; elevation of 2567.8m ASL also confirmed on DEM). (b) Across the valley on river right at roughly the same elevation (2567.0m ASL), fluvial gravels of crystalline composition bordered above and below by sand indicate a former fluvial channel at a higher past valley floor elevation.

Ahlbrandt and Andrews (1978) also noted the presence of a “peat layer” beneath dormant dune sand in the same location along North Sand Creek (Appendix A). They provide a ^{14}C date of 2830 ± 200 years before present (yBP) for the North Sand Creek hydric soil. Ahlbrandt and Andrews also dated a similar peat layer exposed along East Sand Creek (not visited in this study) to 2110 ± 200 yBP.

I interpret the t_2 surface visible along North Sand Creek as the remnant of a past, higher valley floor. Exposures of fluvial gravels and hydric soil indicate a complex floodplain with both flowing and ponded water. The radiocarbon date from Ahlbrandt and Andrews (1978) constrains

the hydric soil formation to 2830 ± 200 yBP. A period of incision to the modern valley floor elevation (t_1) occurred between the date of soil formation and the present day.

To estimate the sediment volume exported from North Sand Creek during this period of incision, I assume that the ancient valley fill level corresponds to the height of the t_2 surface visible along the southern side of North Sand Creek, and therefore that the volume of sediment exported is equivalent to the prism defined by t_1 , t_2 , and the valley walls. Using the LiDar-derived DEM, I measured the elevation difference between the t_2 and t_1 surface at 50 m intervals from the upstream extent of t_2 (325 m downstream of the *actadj* tributary confluence; 106.1914314°W 40.8582849°N) to its lowest observed extent (4200m downstream of the tributary confluence, 106.2250276°W 40.8568592°N). I then measured the width of the valley floor to the beginning of the steep slope change at the base of the t_2 surface at the same 50 m intervals. I averaged the terrace elevation difference and valley width over 100 m segments. The volume of each 100 m valley segment (representative of the volume of sediment exported to reach the t_1 surface elevation) could then be approximated as a rectangular prism with $volume = W \times H \times L$, where W is the average valley width, H the average elevation difference between t_1 and t_2 , and L 100 m for each segment. Summing the volume of each of these prisms provided an estimate of sediment exported from the *inactadj* segment after 2800 yBP.

3.2.6 North Park Alluvial Fan Characteristics

I calculated order-of-magnitude volume estimates for 10 alluvial fans along the east flank of North Park (Figure 9). Each alluvial fan was observed at the contributing stream's downstream entrance to the main axial drainage valley of the Canadian River. The contributing basins of all 10 alluvial fans were located in the Southern Medicine Bow Mountains and

therefore were underlain by similar lithologies, namely Precambrian crystalline basement rocks in the mountains and Mesozoic sandstones and siltstones at the mountain front (Tweto, 1979).

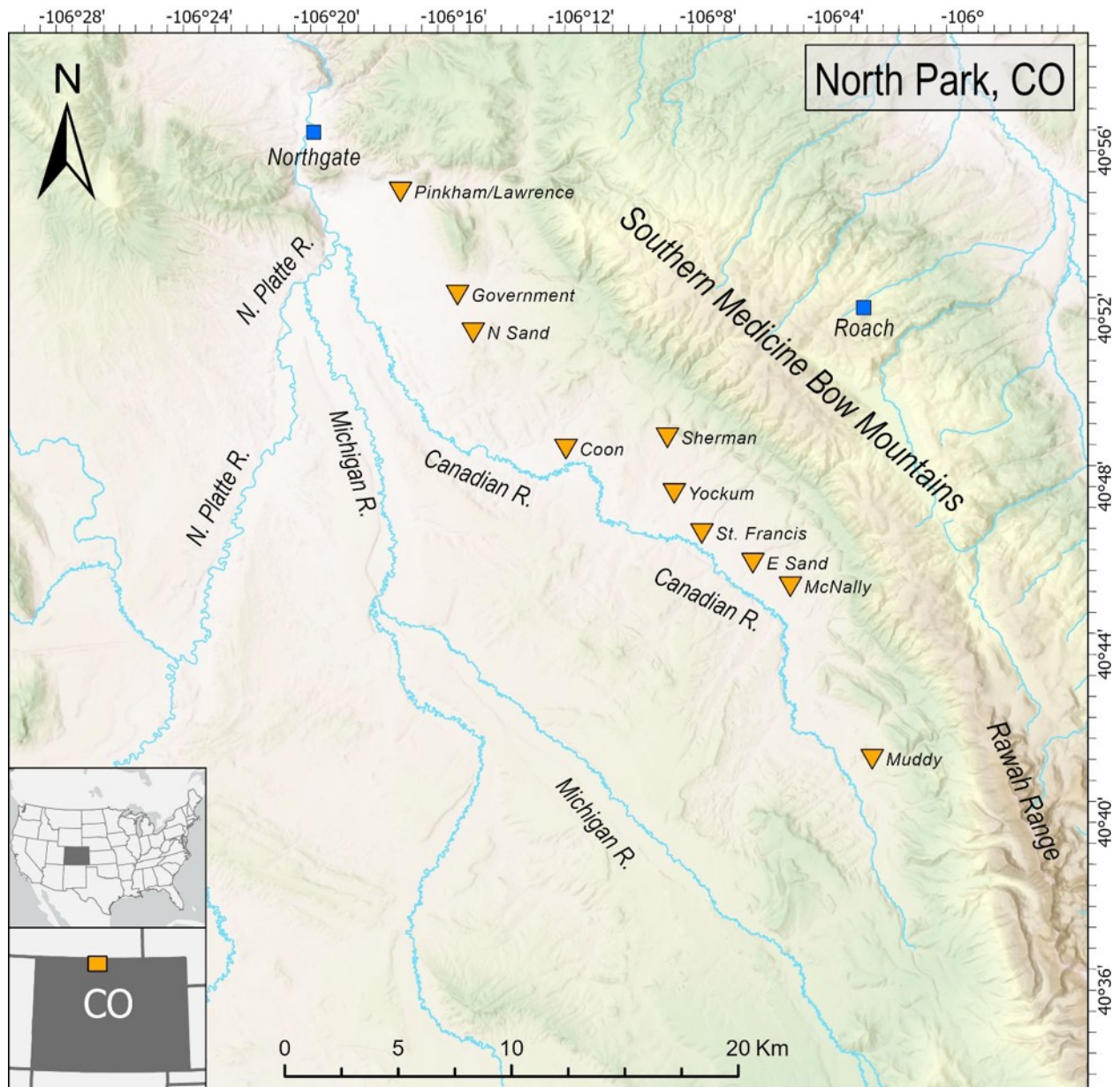


Figure 9. Locations of the 10 alluvial fans on the east flank of North Park (orange inverted triangles). Each fan is labeled with the name of its contributing stream or creek. All fans were observed at the contributing stream's downstream entrance to the main axial drainage valley of the Canadian River.

I used the topographic base map in StreamStats (USGS, 2026) to calculate the length, width, and thickness of each fan. Length was a straight-line, down-fan distance from the head of the fan where lateral confinement by uplands ceased, to the toe of the fan where it impinged on a larger channel. The width was the straight-line, cross-fan distance between either slight topographic high points or adjacent lateral fans associated with another channel. This distance was taken midway down the fan, between the narrow head and the wide toe. The thickness of the fan was approximated as 12 m (one topographic contour interval) for most of the fans. The exceptions were Sherman, North Sand, and Government Creek fans, each of which was assigned a larger estimated thickness, and Muddy Creek, which was assigned a smaller estimated thickness. The rationale was that most of the fans spanned only one contour interval from head to toe, whereas Sherman, North, and Government Creek fans spanned multiple contour intervals, and Muddy Creek was within a single contour interval. Volume was then estimated as the product of length, width, and thickness. Drainage area at the fan head was computed using the StreamStats algorithm. These estimates are highly uncertain and are used only to compare relative volumes of sediment between individual fans.

3.2.7 PlanetScope Imagery Processing

Using Planet Labs commercial satellite imagery, I developed a binary surface classification model to measure annual changes in bare sand surface area on the North Sand Creek *fan* from 2017 to 2025.

The PlanetScope imagery produced by Planet Labs is a near-daily, 3 m resolution surface reflectance satellite product (Planet Labs PBC, 2026). Planet Labs achieves near-daily repeat imagery by using a constellation of small satellites that orbit the Earth every 90 minutes. From 2017 – 2022, Planet Labs used the Dove satellite system equipped with the PS2 telescope that

measures red, green, blue (RGB), and near-infrared (NIR) spectral bands. In 2022, Planet Labs launched the SuperDove satellite fleet equipped with the PBS.SD telescope, which also captures RGB and NIR bands but adds four additional bands. Dove and SuperDove are cross-calibrated using Sentinel-2 satellite imagery, producing a harmonized record that allows direct comparison of surface reflectance images produced by the PS2 and PBS.SD instruments. Here, I use the harmonized four-band surface reflectance (RGB + NIR) Analysis-Ready PlanetScope product, which provides coverage of North Park, Colorado from 2017 to the present.

I registered for a free educational license to access Planet Labs' web application program interface (API). Using the Planet Labs API, I defined an area of interest (AOI) covering the North Sand Creek alluvial fan. I then filtered images containing this AOI to the date range of August 2017 to October 2025, including only cloud-free images at the end of runoff season (late August to late September). I then selected one image for each year from 2017 to 2025 within the August-September range, attempting to match calendar day of year as closely as possible. Within the API, I clipped the images to my area of interest and stacked the four spectral bands to produce a multi-band image for each year, then downloaded each image. Image dates are presented in Table 2.

Once downloaded, I processed the PlanetScope images in RStudio using the spatial analysis packages *terra* (Hijman et al. 2026) and *sf* (Pebesma, 2018). I clipped each image to a smaller AOI including only the observably active section of the North Sand Creek alluvial fan, then applied the scaling factor of 1×10^{-4} included in the PlanetScope metadata to convert the digital surface reflectance values (0 to 1000) to standard surface reflectance (0 to 1.0).

Table 2. PlanetScope images used in North Sand Creek *fan* cover classification model.

<i>PlanetScope Scene ID</i>	<i>Year</i>	<i>Month, Day</i>
20170827_171030_1024_3B	2017	Aug. 27
20180831_172348_100c_3B	2018	Aug. 31
20190826_173147_1008_3B	2019	Aug. 26
20200901_151133_1050_3B	2020	Sep. 1
20210828_170644_35_245c_3B	2021	Aug. 28
20220831_165840_55_241f_3B	2022	Aug. 31
20230831_173829_74_2473_3B	2023	August 31
20240829_171944_60_24c8_3B	2024	August 29
20250820_182142_38_24bd_3B	2025	August 20

For all images, I calculated three reflectance indices intended to facilitate differentiation of bare soil and sand from vegetated ground in the binary classification model. First, I calculated the Normalized Difference Vegetation Index (NDVI), as shown in Myneni et al. (1995):

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

The NDVI serves as an effective measure of leaf density and chlorophyll content; essentially- it is a measure of “greenness.” It contrasts the high red-light absorption and low reflectance caused

by plant chlorophyll to the relatively high NIR reflectance of vegetation. A high ratio of NIR reflectance to red reflectance is characteristic of dense vegetation (Myneni et al., 1995). The use of the NDVI to estimate trends in vegetation cover and productivity is well established, and NDVI is responsive to changing climatic conditions and environmental disturbances (Pettorelli et al., 2005).

However, remote vegetation monitoring relying on NDVI is sensitive to background soil reflectance (Myneni et al., 1995; Rondeaux et al., 1996), which may vary based on location, soil composition, and interactions with vegetation cover denseness. Therefore, I also calculated the Soil Adjusted Vegetation Index (SAVI) as shown in Rodeaux et al. (1996):

$$SAVI = \frac{NIR - Red}{NIR + Red + L} \times (1 + L) \quad (2)$$

Where L represents an adjustment factor to reduce soil noise in vegetation cover measurement. Here, I use a value of $L = 0.5$, which is the optimal adjustment factor value when working with a wide range of vegetation cover densities (Rondeaux et al., 1996) and is used for the calculation of Landsat-derived global SAVI (U.S. Geological Survey, 2026a). I determined that SAVI would likely be useful at North Sand Creek because of the high contrast between vegetation cover in the sparse sagebrush areas and dense riparian zone, as well as the high reflectance of the sandy soil. Finally, I calculated the Visible Atmospheric Resistant Index (VARI), as shown in Gitelson et al. (2002):

$$VARI = \frac{Green - Red}{Green + Red - Blue} \quad (3)$$

The VARI reduces atmospheric effects and addresses the limits of using NIR reflectance to estimate vegetation cover fraction by using only visible light (Gitelson et al., 2002). This index has been used with success in measuring vegetation cover and live fuel moisture in semi-arid shrublands (Roberts et al., 2006; Schneider et al., 2008).

3.2.8 Binary Cover Classification Model

I used the 2017-2025 four-band PlanetScope images of the North Sand Creek alluvial fan with calculated NDVI, SAVI, and VARI indices to create an extreme gradient boosting (*xgboost*) surface classification model with the classes “sand” and “not sand.” Extreme gradient boosting has been used to create multiclass vegetation maps across diverse ecosystems (Heng Zhang et al., 2019) and model changes in plant biomass from long-duration Landsat-8 datasets (O’Connell, Mishra, Alber, & Byrd, 2021). The model was created and tuned in RStudio using the packages *xgboost* (Chen et al., 2026) and *mlr3* (Lang et al., 2019), alongside *sf* (Pebesma, 2018) and *terra* (Hijman et al. 2026) spatial analysis packages.

Groundtruth data for the model were provided by National Agricultural Imagery Program (NAIP) images of North Sand Creek taken at the end of the growing season in the years 2017, 2019, and 2023. Specifically, the NAIP image dates were Aug. 19, 2017, Oct. 3, 2019, and Aug. 31, 2023. The NAIP images were accessed via the USGS National Map Dataset (USGS 2017, 2019, 2023). I consider these images to adequately represent post-runoff depositional conditions on the alluvial fan and close enough in date to the PlanetScope images that they can serve as ground-truth data. For each NAIP image, I generated a set of points at pixel centers in QGIS that adequately covered freshly deposited alluvial sand and the range of vegetated surfaces. I then visually classified the pixels as “sand” or “not sand,” marking mixed pixels or edge cases as “NA.” This produced over 33,000 “not sand” points and over 400 “sand” visually verified

groundtruth points over the three years of NAIP imagery. I then extracted the pixel reflectance and index values for all groundtruth points from the corresponding 2017, 2019, and 2023 PlanetScope images, producing a subset of groundtruthed data on which to train the classification model.

I used the *xgboost* (Chen et al., 2026) and *mlr3* (Lang et al., 2019) R packages to create an extreme gradient boosting (*xgboost*) classification model to differentiate sand cover and vegetation cover on the alluvial fan. The model was trained and tested on the three years of groundtruth data (2017, 2019, and 2023). Groundtruth data were divided into three outer folds, with each of three model iterations using two years for model training and one year for model testing. Two inner folds were used for hyperparameter tuning. No validation dataset was retained so that the training set could capture maximum spatiotemporal variability. Model goodness of fit was assessed using a confusion matrix and the model sensitivity and specificity. I selected the model input features to achieve the greatest possible overall accuracy, basing my initial selections on the spectral reflectance of riparian vegetation, sagebrush and bare sand and revising based on model prediction accuracy.

The finalized model used the blue band, calculated NDVI, and calculated VARI as input features to differentiate between sand and not sand pixels. Relative model feature importance is shown in Figure 10. Reflectance in the blue band is overwhelmingly the most important feature. Model goodness of fit is represented in the output confusion matrix (Table 3). Overall accuracy of the model was 0.9955, with a sensitivity of 0.99 and specificity of 0.75.

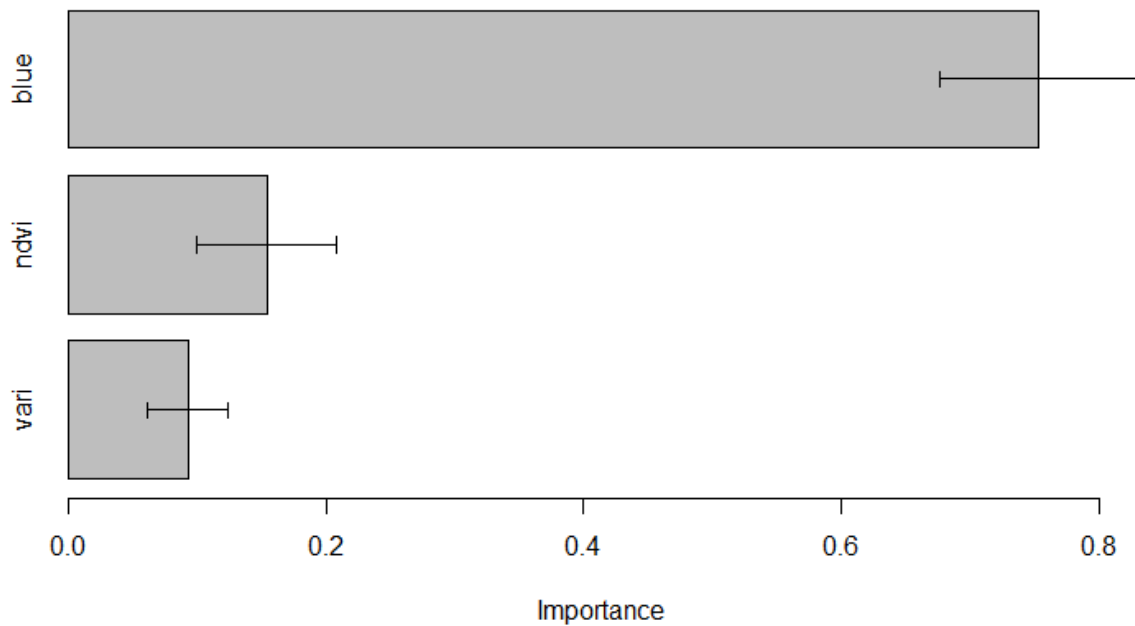


Figure 10. Relative importance of model input features in *xgboost* binary classification model.

After model creation, I used the *xgboost* binary classification model to predict cover class (“sand” or “not sand”) on each of the PlanetScope rasters from 2017 – 2020. This produced one output raster per year showing the model’s predicted binary cover class within the restricted alluvial fan AOI, based on the spectra of each pixel. I then calculated the surface area of sand-classified pixels to produce a modeled 9-year record of post-runoff sand cover on the alluvial fan.

I also created a record of annual cover change by differencing rasters of consecutive years; for example, subtracting the 2018 classified raster from the 2017 classified raster produced a new output raster showing areas of new sand that were deposited during the 2018 runoff season and areas of new or regrown vegetation. I could then calculate the area of new sand and new vegetation for each available pair of years, producing a record of modeled annual deposition and vegetation regrowth for the 2018-2025 runoff seasons.

Table 3. Confusion matrix for finalized *xgboost* model. Sensitivity = 0.99; specificity = 0.75; overall accuracy = 0.995.

TRUE PREDICT	NOT SAND	SAND
NOT SAND	33950	4
SAND	78	324

4. RESULTS AND DISCUSSION

4.1 Seasonal Channel Changes: Results

4.1.1 Summer 2025 Discharge Record

Discharge measurements at cross section 08 in the *upstr* section indicate a highest measured discharge of 0.043 cms (1.52 cfs) on June 2 (Table 4). Flow receded over the remainder of June and early July, reaching a base flow of 0.003 cms (0.11 cfs) by July 22. The discharge record produces a runoff season hydrograph with flow rising throughout May, peaking in early June, declining throughout June and July, and returning to a very low base flow by late July (Figure 11).

Table 4. Measured flow at CS 08 (*upstr*)

<i>Date</i>	<i>cms</i>	<i>cfs</i>
17 May 2025	0.041	1.45
02 June 2025	0.064	2.26
17 June 2025	0.043	1.52
22 July 2025	0.0032	0.11
05 Aug. 2025	0.0031	0.11

I made several additional flow measurements at CS 01 and CS 07 in the *actadj* segment and at CS 11 in the *inactadj*. On May 17, I measured a discharge of 0.002 cms (0.07 cfs) at CS 01 at the head of the North Sand Hills dune field, based on an estimated triangular cross section and a single velocity measurement. This was the only flow observed in the *actadj* tributary during the entire summer and was discontinuous, disappearing below the bed surface roughly 30 m downstream of CS 01 and not reappearing. I did not observe surface flow in the upper *actadj* segment (CS 01 – CS 06) for the remainder of the field season.

At CS 07, I observed a slow trickle of water entering the tributary-mainstem confluence throughout most of the summer. Based on a triangular cross section and a single velocity measurement obtained on June 17, flow at CS 07 was less than 0.0002 cms (0.006 cfs). While negligible, this flow persisted throughout the runoff season. The flow observed at CS 07 in the *actadj* segment began roughly 50 m upstream of the confluence underneath a logjam (interpreted as a relict beaver dam; section 3.1.5.), in an area populated with vegetation adapted to perennially moist environments, including horsetails and sedges. This vegetation community, coupled with observations of flow entering the channel from the nearby banks, suggests groundwater inputs to the channel at CS 07 or hyporheic flow contributed from the perennial mainstem.

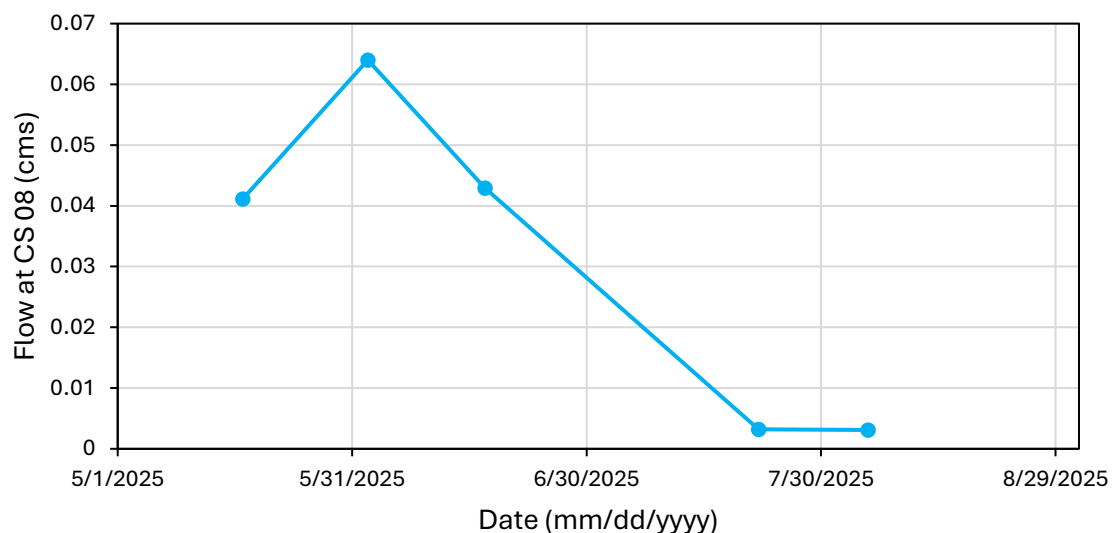


Figure 11. Discharge measurements at CS 08 (*upstr*) during summer 2025. Points represent individual measurements; lines do not indicate a measured rate of change but instead illustrate the general trend.

I measured flow at CS 11 in the *inactadj* segment on June 17 as 0.045 cms (1.6 cfs). Measured discharge at CS 11 agrees well with the measured discharge at CS 08, only differing by 0.002 cms, which is within the margin of error for the survey method. Although flow was

present at CS 11 throughout the runoff season, flow was discontinuous at downstream reaches by July 22. By that date, little to no flow reached CS 13 or the alluvial fan. Some areas of the stream remained wet, indicating potential subsurface flow, but from CS 13 to the alluvial fan the stream became completely dry. Wide, sandy reaches transformed from areas of shallow flow to plains of dry sand where winds produced eolian ripples and obscured the former channel contours.

4.1.2 Cross Section Changes

No continuous flow was observed in the *actadj* ephemeral tributary during the 2025 runoff season. Therefore, no fluvial transport of sand occurred. Repeat cross section surveys in the *actadj* segment (CS 01 – CS 07) showed no observable changes due to fluvial action, nor any measurable sand accumulation within the channel (Figure 12, showing *actadj* cross section surveys). Cross sections 01, 02, and 06 show some evidence of bank collapse and sand addition on the right side of the cross section bordering the active dunes, but channel elevation did not increase due to accumulation. Small differences in channel elevation between cross section dates are within the margin of error for the survey method. Without fluvial transport in the *actadj* ephemeral tributary, meter-scale incision and terracing as observed by Grabowski (2020) did not occur. Bed material remained unchanged throughout the season; all *actadj* cross sections were located in sand bed reaches except CS 04, which had a mixed cobble-sand bed. No sediment wave occurred in the *actadj* tributary during the 2025 runoff season.

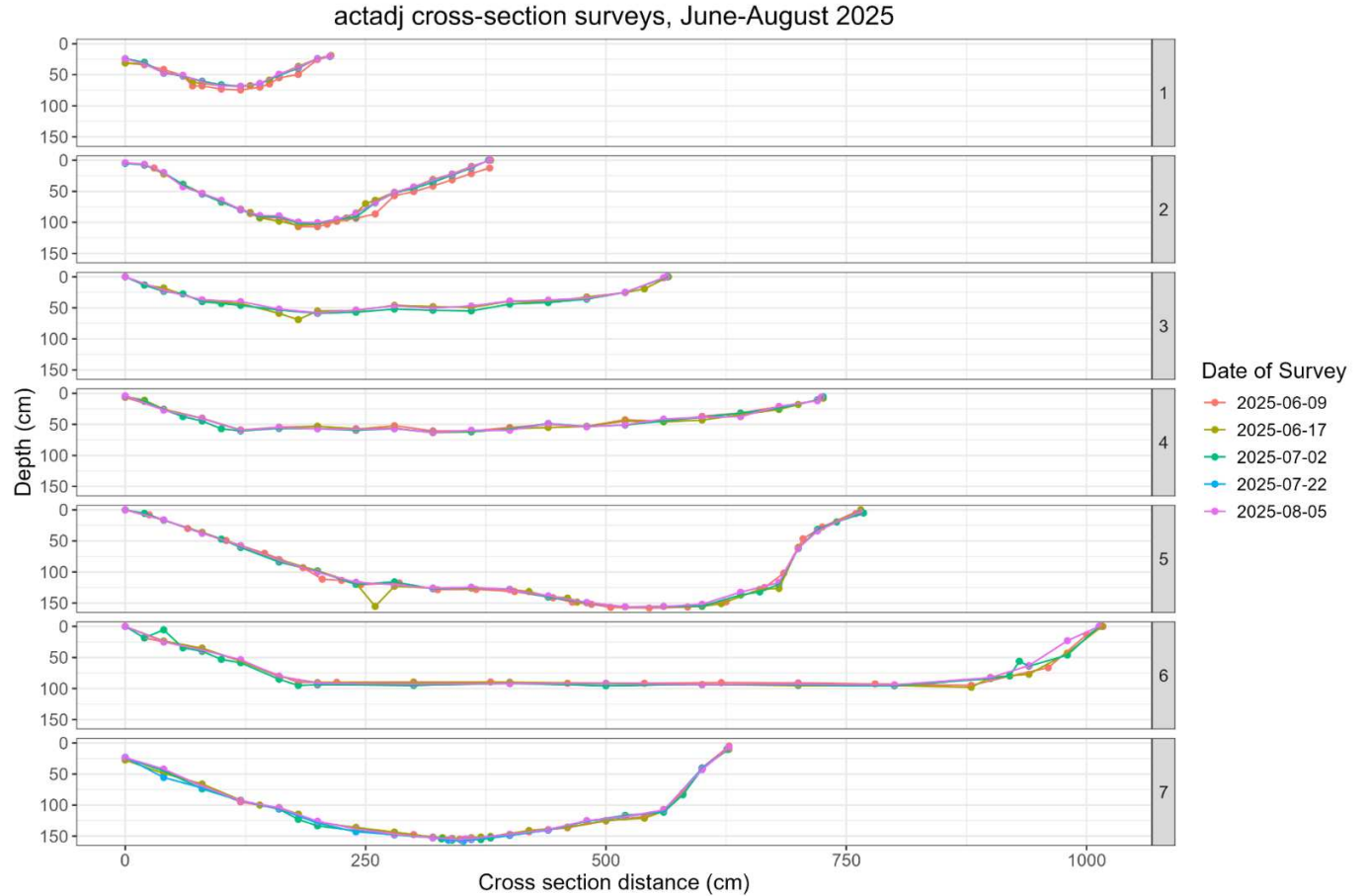


Figure 12. Repeat cross section surveys for CS 01 – CS 07 in the *actadj* segment. Depth indicates stadia distance from leveled tape to the bed surface in cm. Cross section distance is measured from the channel left endpoint. Gray bars show cross section number; colors represent date of survey.

Repeat cross sections at CS 08 showed a stable cobble-boulder cross section. Relatively low discharge did not cause measurable width or depth adjustment in the *upstr* channel. Cross section surveys for CS 08 are presented in Appendix A.

Repeat cross section surveys in the *inactadj* segment (CS 09 – CS 13) show only minor adjustments to channel width and depth (Figure 13). CS 09 and CS 10 show no channel adjustment, with differences in bed elevation attributable to error in my survey method. Apparent decreases in bed elevation on CS 11 after June 9 and on July 22 are respectively attributable to a

broken endpoint stake and minor bank collapse causing endpoint adjustment. Surveys on June 17, July 2, and August 6 show a stable channel cross section at CS 11. At CS 12, the June 9 survey shows a roughly 10 cm lower elevation thalweg than the four following surveys. Between the June 9 and June 17 surveys, bed elevation at CS 12 increased, but the channel cross section remained stable thereafter. At CS 13, some horizontal channel adjustment is apparent in the repeat surveys. From June 9 to August 6, the channel widens by roughly 50 cm via a retreat of the terraced bank on river right. Visual observations of fluvial erosion at this bank confirm horizontal channel adjustment. Changes in bed elevation at CS 13 are within the margin of error for the survey method.

No systematic trends of channel width and depth adjustment were observed throughout the *inactadj* cross sections. No pattern of aggradation, incision, and terracing consistent with a translating sediment wave was observed, and channel cross section adjustments were minor when compared to the meter-scale adjustment observed by Grabowski in the 2019 runoff season.

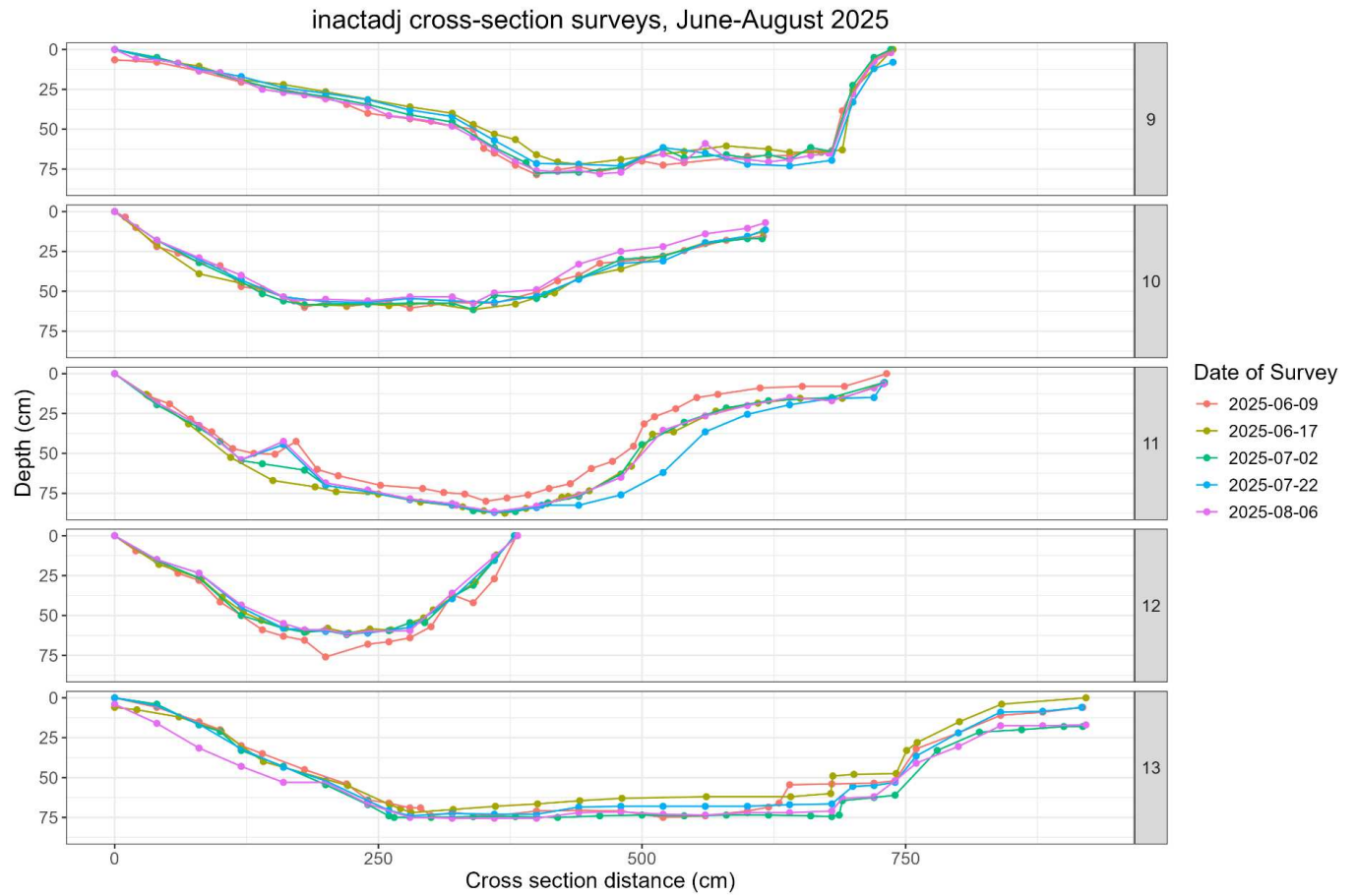


Figure 13. Repeat cross section surveys for CS 09 – CS 13 in the *inactadj* segment. Depth indicates stadia distance from leveled tape to the bed surface in cm. Cross section distance is measured from the channel left endpoint. Gray bars show cross section number; colors represent date of survey.

4.2 Seasonal Channel Changes: Discussion

4.2.1 Comparison of 2019 and 2025 Channel Adjustments

During the 2025 field season, I did not observe the rapid, meter-scale incision throughout the *actadj* ephemeral tributary observed by Julia Grabowski in 2019 (Figure 2), nor did I observe the passage of a translating sediment wave through North Sand Creek. The cross sections I monitored in the *actadj* segment remained stable because no continuous flow occurred, and therefore no fluvial adjustment occurred (Figure 12). Adjustment in the *inactadj* cross sections was minimal (Figure 13), at the scale of centimeters rather than meters, without any visible, systematic trends detectable by the surveying methods used. A pulse of sand causing rapid aggradation followed by incision and terracing – a sediment wave (Gilbert, 1917) – did not propagate downstream. While a sediment wave can operate on an annual scale in North Sand Creek, as in 2019, it is not an annual phenomenon and is dependent on the activation of the ephemeral tributary by sufficient runoff. The volume of antecedent sediment storage in the ephemeral tributary likely influences the magnitude of channel changes throughout the network.

Runoff generation from the catchments of North Sand Creek and its ephemeral tributary is dependent on the volume of winter snowpack and the timing of snow melt in the Medicine Bow Mountains. The Roach, CO SNOTEL (Snow Telemetry Network) station is 12 km east of North Sand Hills (Figure 1). It is not within the catchment of North Sand Creek and is on the eastern side of the Medicine Bow Mountains, separated from North Park by the height-of-land, but it provides regional context for snowpack volume and melt timing. Daily measurements of SWE (snow water equivalent) in Figure 14 show that WY 2025 snowpack at Roach was well below the median depth, compared to a slightly above-median depth during WY 2019 (USDA, 2026). During WY 2019, a late season increase in SWE in May, coupled with a large rainstorm

recorded in Walden, may have caused rapid runoff generation in the ephemeral tributary (Grabowski, 2020).

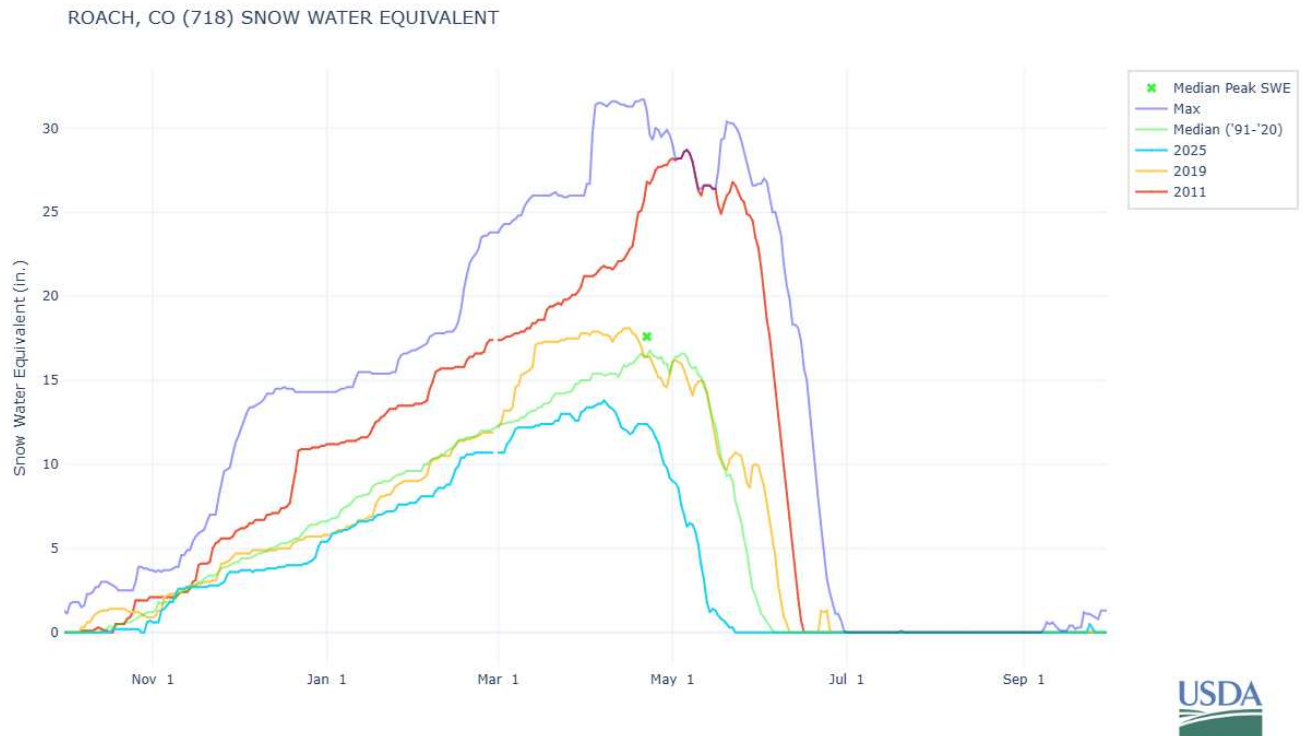


Figure 14. SWE (Snow Water Equivalent) at Roach, CO SNOTEL (Snow Telemetry Network) Site 718 (USDA, 2026). Roach, CO site is 12 km east of North Sand Hills and separated by the Southern Medicine Bow Mountains height-of-land. Blue line shows SWE accumulation during WY (water year) 2025; green line and green X show median and median peak SWE, respectively; yellow line shows WY 2019; red line shows WY 2011; and purple line shows maximum daily SWE over period 1991-2020.

During 2011, the year that State Line Ranch first reported extensive aggradation of sand in their irrigation network on the alluvial fan, early May SWE was the maximum value recorded in the period 1991-2020. SWE dropped precipitously in mid-May 2011, likely generating flashy, intense runoff. Previous years with recorded meter-scale channel adjustment and a sediment wave (2019) or mass sand export (2011) correspond with above-median snowpack and rapid, late season decreases in snowpack. In contrast, WY 2025 saw below median accumulation and

earlier, slower snowmelt. Trends in snowpack elevation may also influence runoff generation at North Sand Creek. The *actadj* ephemeral tributary incorporates a basin that is on average 170 m lower than the basin of the mainstem (USGS, 2026). If lower elevations on the east side of North Park do not receive snow, the ephemeral tributary will be less likely to flow.

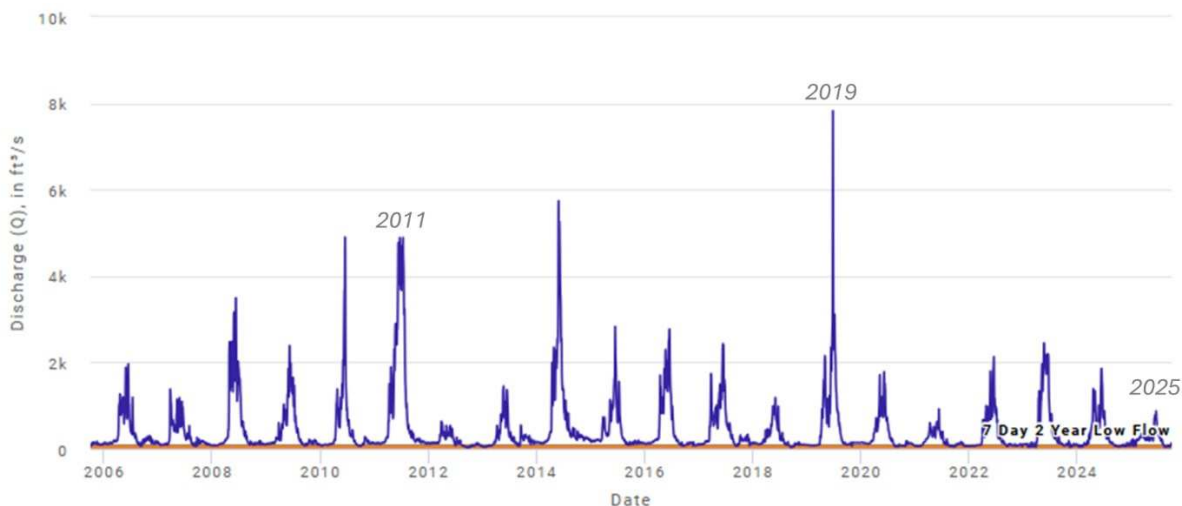


Figure 15. Daily peak streamflow of North Platte River near Northgate CO, USGS monitoring location 06620000 (USGS, 2026). Northgate is 14.5 km northeast of North Sand Hills at the outlet of the North Platte River from North Park. Water years 2011, 2019, and 2025 are labelled.

Daily peak streamflow records at the Northgate USGS gauge on the North Platte River (Figure 15), 14.5 km northeast of the North Sand Hills, represent an integration of runoff from the entire North Park basin (minus abstraction for irrigation and municipal use) and provide context for streamflow in the region. In 2025, flow at Northgate was comparatively low for the 2006-2025 period of record. In comparison, peak annual flow in 2019 exceeded all values on record, likely due to a combination of late season rain and snowfall (Grabowski, 2020), and flow in 2019 was both high and sustained over a long period. Compared to 2019 and 2011, when large channel adjustment and mass sand export were observed, regional runoff generation was lower in

2025. Discharge recorded at the North Sand Creek perennial mainstem in 2025 (Table 4 and Figure 11) was far lower than predicted peak or median values. The highest discharge I measured was 0.064 cms (2.26 cfs) on June 2, and I recorded a minimum baseflow of 0.003 cms (0.11 cfs) on July 22. There is no gauge or consistent discharge record at North Sand Creek, but regional regression equations (USGS StreamStats, 2026) predict an average peak discharge of 0.4 cms (14.1 cfs) and a base flow of 0.014 cms (0.5 cfs).

The runoff generation threshold at which the ephemeral tributary activates is unclear. Longer-duration records of discharge magnitude and timing, as well as correlation with local climatic conditions, are required to predict tributary activation and mass sand mobilization. However, the WY 2025 snowpack was clearly not sufficient to generate surface flow in the ephemeral tributary and mobilize a sand wave. During the relatively dry year of 2025, North Sand Creek and its ephemeral tributary displayed a much different sediment regime than in the relatively wet year of 2019. It is unclear whether a sand wave occurred at North Sand Creek between 2019 and 2025. During field visits to the *actadj* tributary in August 2024, I did not observe flow in the *actadj* tributary or any evidence of recent fluvial activity. Most of the *actadj* segment is sand-bedded, but CS 04 was located in a cobble-boulder run with some sand accumulation between clasts. CS 04 was also 20 m downstream of a BLM-installed fence intended to prevent OHV travel, installed in fall 2019. On the upstream side of the fence, the ephemeral channel was entirely sand-bedded, and OHV-induced dune slumping had created a nearly meter-thick sand deposit. At the fence, this abruptly transitioned to the cobble-boulder surface seen at CS 04. I saw no evidence of fluvial transport through the fence. Other cues, such as accumulation of fallen leaves and small plants growing in the channel, suggest that significant surface flow and incision have not occurred in the *actadj* section since 2019.

4.2.2 Interannual Sediment Regime Variability

The contrast between the sediment wave and widespread instability that occurred in 2019 and the relative lack of channel adjustment throughout North Sand Creek and its tributary during 2025 indicate that the system is interannually dynamic. During years with higher snowmelt runoff, the ephemeral tributary activates, mobilizing the accumulated sand load in the channel and sending a pulse of sand downstream that causes rapid channel adjustment throughout the system. During years with low snowmelt runoff, the ephemeral tributary remains quiescent, and a pulse of sand does not enter the mainstem. Interactions between snowmelt runoff intensity and the volume of sediment stored in the *actadj* channel dictate the magnitude of seasonal geomorphic response.

Research on debris flows in ephemeral and low-order channels provides a conceptual analogue for the annual-scale sediment loading in North Sand Creek. Drainage networks where debris flow sediment inputs are dominant are characterized by long periods with relatively low input, punctuated by short periods or individual events with extremely high sediment input (Miller & Benda, 2000). Debris flow initiation in low-order channels depends on interactions between major sediment-generating events such as wildfires or colluvial landslides, longer-term, lower magnitude sediment addition via soil creep, and the time interval between high magnitude precipitation events (Wohl & Pearthree, 1991; Benda & Dunne, 1997). Sufficient time for accumulation of weathered material or mobile sediment in ephemeral channels is required to create the antecedent conditions for a debris flow, and if a previous high-magnitude event has cleared the sediment supply from the channel, debris flow initiation is less likely for some time after (Wohl & Pearthree, 1991). Debris flow initiation is determined not only by the stochastic occurrence of high magnitude precipitation events, but also by antecedent sediment conditions

within the drainage network. A high rate of sediment flux to a channel and a longer period of sediment accumulation between high magnitude precipitation events increase the probability of debris flow initiation and rapid geomorphic change.

In North Sand Creek, seasonal snowmelt runoff can trigger a translating sand wave originating in the ephemeral tributary (Grabowski, 2020). While the sand wave is different from a debris flow in clast size, velocity, setting, and potential for catastrophic impacts, initiation of the North Sand Creek sand wave may be dependent on similar interactions between sediment addition rate, time of accumulation, and stochastic high flow events. The *actadj* ephemeral channel is located alongside an active dune field and receives natural inputs of sand throughout the year. The primary wind direction and direction of dune migration transport sand eastward toward the ephemeral channel. Eolian transport is highest in autumn when moisture is lowest and winter snowfall does not yet prevent sand grain deflation (Ahlbrandt & Andrews, 1978), but I observed eolian ripples and visible eolian entrainment of sand at various points throughout the summer. Eolian transport is supplemented by slumping of dune faces along wildlife paths and in high-use OHV areas (section 4.3.5). Both visual observations of entire dune slipfaces collapsing under repeated OHV use and documentation in the literature (Marion et al., 2014, 2019; Duniway et al., 2019) demonstrate that OHV use on the dunes and in the ephemeral channel dramatically increase sediment loading. Without annual flows to mobilize sand from the ephemeral channel, sand deposits of greater than one meter thickness entirely obscure the channel where it runs along the dunes (as observed in 2025). Multiple years of accumulation set the stage for the next above-median snowpack or rapid late-season meltout to trigger a sand wave that will propagate channel change and instability throughout the network. While baseline sand inputs from eolian transport and dune slumping could likely provide enough sand

accumulation over multiple years to set the preconditions for a sediment wave, OHV inputs increase the rate of addition, rapidly filling the ephemeral channel even after high runoff years clear out sand deposits. With OHV inputs of sand, sediment waves initiated in the ephemeral tributary are likely to be more frequent and to cause greater geomorphic change downstream. Stochastic high runoff events almost always meet with a large store of sediment in the *actadj* channel, increasing the probability of sand wave initiation, and the higher volume of sand that can be mobilized leads to greater channel adjustment and instability.

4.3 Reach Geomorphic Characteristics & Sand Addition: Results

4.3.1 Gradient

DEM-derived 100 m channel gradient in the *inactadj* segment decreases downstream but is highly variable on the reach scale (Figure 16). Overall stream gradient from the tributary junction to the alluvial fan transition 6275 m downstream is 0.018 m/m, shown as a horizontal dashed line in Figure 16.

The maximum channel gradient of 0.04 m/m occurs in the cobble-boulder run 125 m downstream of the tributary confluence (Figure 16). Short steepened reaches with channel gradient equal to or greater than 0.03 m/m occur at 450, 1100, 1700, 2600, 3100, and 3800 m downstream (Figure 16, orange circles) from the tributary confluence. After 4000 m downstream from the tributary confluence, slope is variable and decreasing as the channel approaches the alluvial fan, but the magnitude of variation decreases.

There are also several reaches of sustained lower gradient, highlighted in blue rectangles in Figure 16. Although there is slope variability within these areas, they have sustained gradients less than 0.01 m/m. Low slope areas from 2000-2500 m, 3200-3700 m, and 4000-4200 m are bounded by upstream and downstream knickpoints.

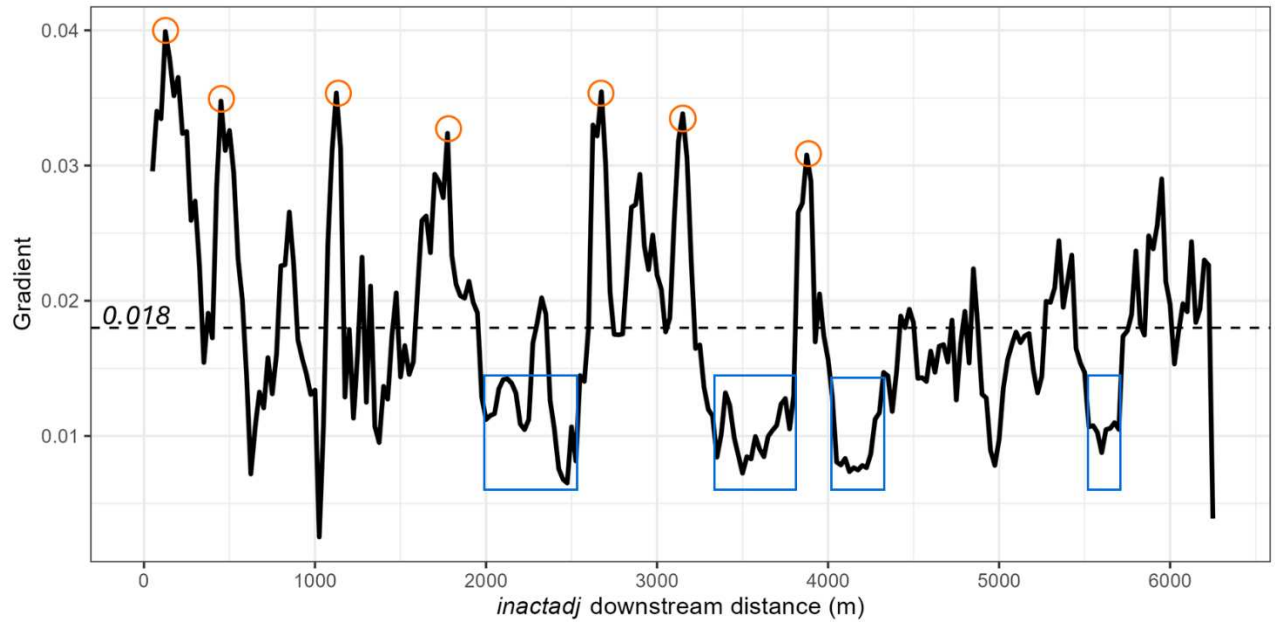


Figure 16. DEM-derived channel gradient (m/m) in the *inactadj* segment. Gradient was calculated over 25-meter intervals, with each point representing the slope of a 100 m reach centered on the point. Orange circles highlight knickpoints with slope greater than 0.03 m/m. Blue rectangles highlight reaches with sustained low slope reaching below 0.01 m/m.

4.3.2 Valley and Inset Characteristics

As described in Methods section 3.2.3, I defined valley width along the North Sand Creek *inactadj* segment as the valley-perpendicular distance between major slope changes on the floodplain abandoned by the modern channel. Similarly, I defined inset width as the channel-perpendicular distance between the steep slope change between the incised modern channel and the abandoned floodplain. Inset width is the maximum width of the surface with which a high flow could plausibly interact. Inset depth is the difference in elevation between the channel and the elevated abandoned floodplain. I remotely measured valley width, inset width, and inset depth along the *inactadj* stream corridor (Figure 17).

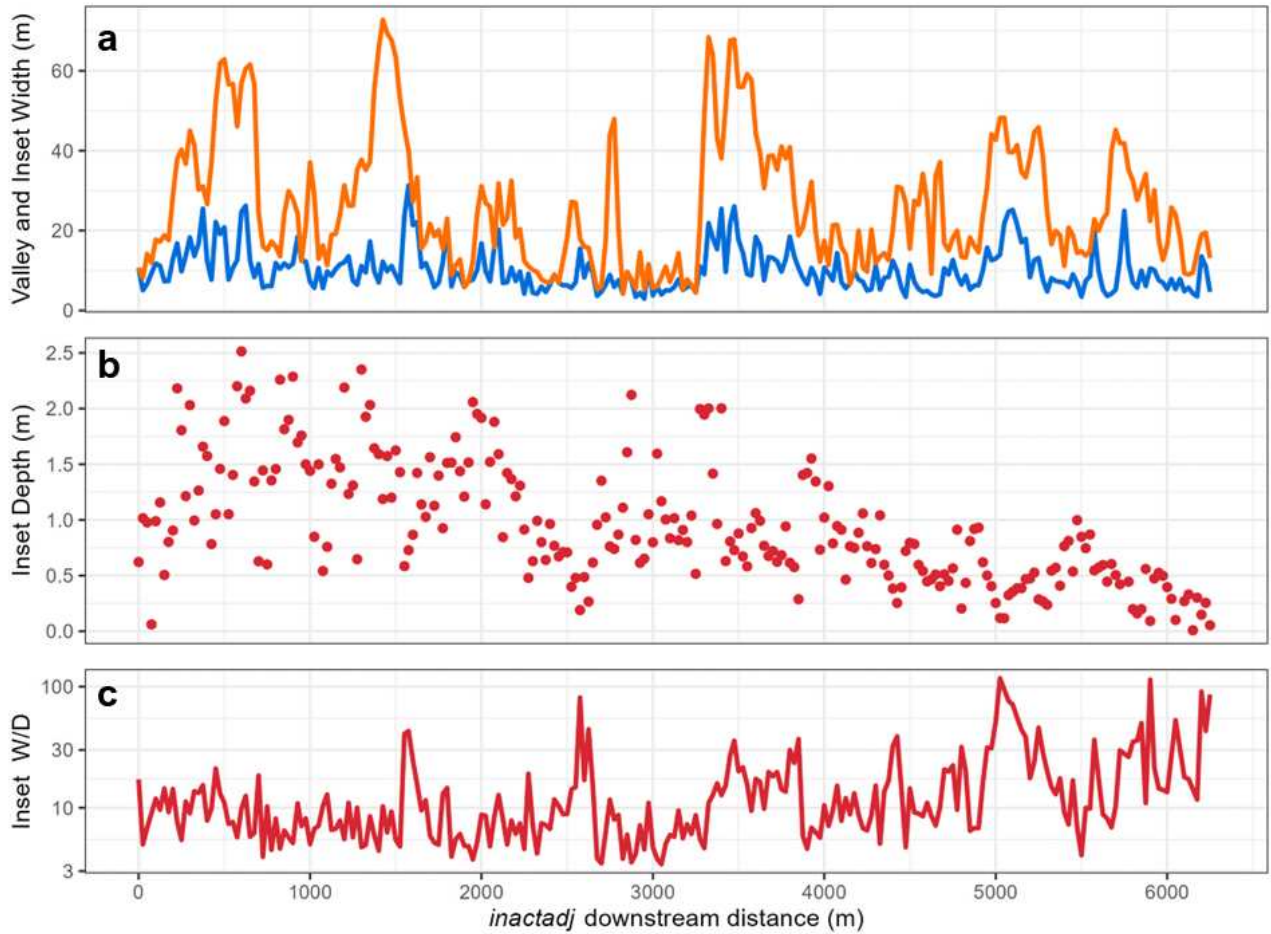


Figure 17. Panel (a) shows *inactadj* valley width (orange) and inset width (blue) plotted against stream distance. Panel (b) shows inset depth, the difference in DEM-derived elevation from the channel to the abandoned floodplain. Panel (c) shows *inactadj* inset width/depth ratio, which does not represent the hydraulic dimensions of the channel but rather the relative entrenchment of the inset channel in the valley context.

Valley width (Figure 17a, orange) is highly variable throughout the *inactadj* segment, with a range from under 5 m wide to 72 m wide. Mean valley width is 26 m. Reach-scale valley width exceeds 40 m in reaches 250-650 m, 1400-1550 m, 32500-3800 m, and 4950-5250 m, with very short sections of valley exceeding 40 m at 2750-2775 m and 5700-5750 m. These areas have a relatively laterally unconfined valley template. In contrast, several reaches have a very laterally confined valley template, with valley widths under 20 m. This includes the uppermost

250 m of the *inactadj* segment, where the stream exits the forest, and a series of highly confined reaches between 1750 and 3200 m. The valley template of North Sand Creek varies along the *inactadj* reach, with several areas of low confinement and wide valley separated by laterally confined, narrow valley reaches.

Inset width (Figure 17a, blue) is also variable throughout the *inactadj* segment but over a more constrained range than valley width, with a minimum width of 3 m and maximum width of 40 m. Mean inset width is 10 m. From 0-3250 m, inset width is less variable than from 3250 – 6275 m. Before 3250 m, inset width is often less than 10 m, and inset width represents a lower proportion of total valley width. After 3250 m, inset width is more variable, frequently exceeding 20 m, and covering higher proportions of total valley width. In reaches with wide valley templates (250-650 m, 1400-1550 m, 325000-3800 m, and 4950 – 5250 m) the active channel inset covers a low proportion of valley width, except between 4950 and 5250 m. There, the active channel inset covers over 50% of total valley width. In areas with a confined valley template (between 1750 and 3200 m; 4000-4400 m), inset width often approaches 100% of total valley width.

I refer to the difference in elevation between the active channel and valley floor as the inset depth. Valley width is inaccessible to the modern active channel along most of the *inactadj* segment due to elevation differences between the inset channel and the valley floor. Inset depth averages 1 m but generally decreases downstream (Figure 17b). Between 2000 and 2500 m, inset depth decreases markedly, leading to an increase in inset width/depth (Figure 17c) without any accompanying large change in inset width. A similar pattern of inset depth-controlled W/D occurs at 3500 m and 5000 m. Downstream increases in the inset width/depth ratio correspond to the downstream decrease of inset depth (Figure 17c).

4.3.3 Long Profile and Bed Material

DEM-derived elevation is plotted against distance downstream from the tributary confluence in Figure 18. Point color represents bed material class (cobble-boulder, mixed cobble-sand, or sand bed). The average gradient for the *inactadj* segment, 0.018 m/m, is shown as a dashed black line.

Between 0 and 4000 m downstream of the tributary confluence, the stream profile alternates between knickpoints and low-slope, concave reaches. Knickpoints are located at 1100, 1700, 2600, 3100, and 3800 m. Between major knickpoints, there are some smaller slope convexities that indicate local steepening; some of these are visible on the plot of stream gradient (Figure 16). After 4000 m downstream, the stream profile is convex.

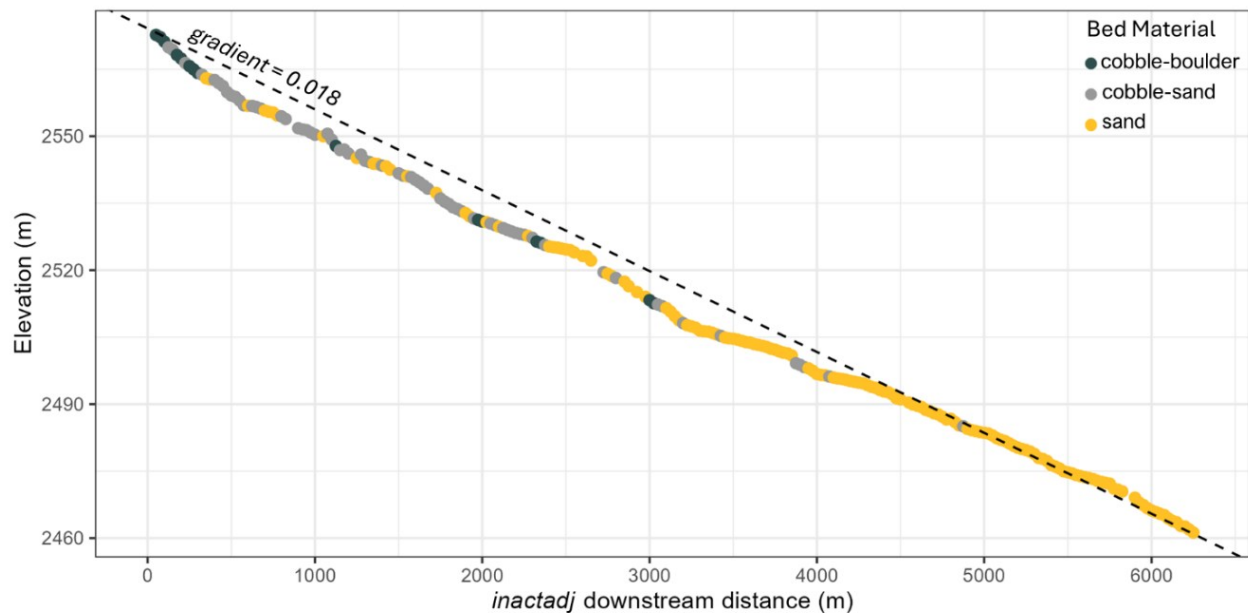


Figure 18. Channel long profile for the *inactadj* segment, with DEM-derived elevation plotted against stream distance at 25 m intervals. Black dashed line is a line with slope = 0.018 m/m, the average gradient of the channel. Colors represent primary bed material (dark grey = cobble-boulder, light grey = mixed cobble and sand, yellow = sand bed).

Bed material varies over the long profile, as shown by the different point colors in Figure 18. From the tributary confluence until 400 m downstream, the stream bed is composed of cobble-boulder substrate; these largest clast sizes correspond to the steepest reaches on the channel. After 500 m and until 3000 m, the stream bed is composed of mixed cobble and sand. In mixed reaches, cobbles are visible, protruding from or surrounded by discontinuous sand layers. In the field, I occasionally observed sand layers overlain by gravel or pebble sized clasts. Mixed reaches are punctuated by short stretches of sand bed or cobble-boulder bed. Transitions to short cobble boulder reaches correspond to profile convexities (knickpoints) at 1100 and 3100 m but also appear in profile concavities.

After 3000 m downstream, the stream transitions to an almost exclusively sand-bed regime, except for cobble-boulder and mixed reaches at the 3100 m and 3800 m knickpoints. The transition to a sand bed corresponds with the transition to a concave-downward stream profile and a decrease in channel slope (also visible in Figure 16). After 6275 m, the last point represented in Figure 18, North Sand Creek transitions into the *fan* segment, where gradient decreases further and the channel is exclusively sand bed. Along the *inactadj* segment, I occasionally observed non-fluvial boulders in the stream or on banks, usually granitic or gneissic, with b-axis measurements exceeding 50 cm. These boulders are too large for fluvial transport under current hydrologic conditions, and I presume that they are sourced from Quaternary terraces in the area as described by Madole (1991).

I estimate that 5.8% (425 m) of the North Sand Creek *inactadj* segment has a cobble-boulder bed, 22.6% (1650 m) has a mixed cobble-sand bed, and 66.4% (4850 m) has a pure sand-bed. The bed material of the remaining 5.8% of the stream length surveyed could not be

determined due to channel spanning vegetation or shadows that prevented a clear view of the channel in the August UAV imagery.

4.3.4 Bed Material vs. Valley and Inset Characteristics

The distributions of channel gradient, inset width, and inset depth for each bed material category are shown in boxplot form in Figure 19. Visual analysis indicates that sand-bed reaches have significantly lower gradient and smaller inset depth than cobble-boulder and mixed-bed reaches, and that inset width does not vary by reach bed material.

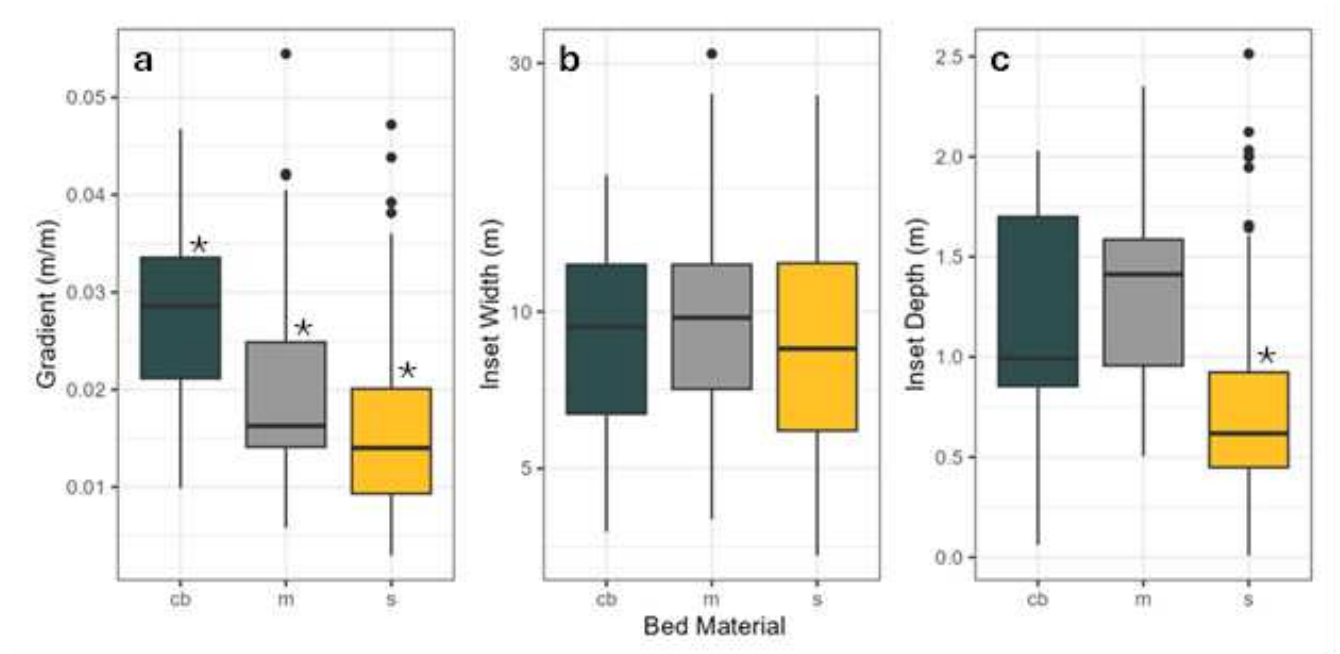


Figure 19. Distribution of gradient (a), inset width (b), and inset depth (c) for points along the *inactadj* segment sampled at 25 m intervals. Data are grouped by observed primary bed material (cb = cobble-boulder, m = mixed cobble and sand, s = sand bed). Median value for each group is shown as a dark line in the center of the box; first and third quartiles by the upper and lower bounds of the box; whiskers represent 1.5 x interquartile range, and outliers are shown as black dots. Stars (*) indicate statistically significant differences.

I also compared inset width, valley width, inset depth, and channel gradient between bed material types using one-way Anova and estimated marginal means. I found no evidence for a significant difference in inset width ($F = 0.72$, $p = 0.49$) or valley width ($F = 2.2$, $p = 0.11$) between bed material types. However, there is evidence for significant differences in channel gradient ($F = 23.7$, $p < 0.001$) and inset depth ($F = 40.8$, $p < 0.001$) between bed material types. Results for F-tests, estimated marginal means, and pairwise contrasts are presented in Table 5.

The estimated marginal means of channel gradient for each bed material type are 0.0264 ± 0.0034 m/m ($p < 0.0001$) for cobble-boulder bed reaches, 0.0203 ± 0.0033 m/m ($p < 0.0001$) for mixed cobble-sand reaches, and 0.0157 ± 0.001 m/m ($p < 0.0001$) for sand-bed reaches. Pairwise comparisons show evidence of significant differences in gradient between cobble-bed and mixed reaches ($p = 0.0047$), cobble-bed and sand reaches ($p < 0.0001$), and cobble-bed and sand reaches ($p < 0.0001$). There are significant differences in reach gradient between cobble-boulder, mixed, and sand-bed reaches. Sand-bed reaches have the lowest estimated mean gradient.

The estimated marginal means of inset depth for each bed material type are 1.21 ± 0.24 m ($p < 0.0001$) for cobble-boulder bed reaches, 1.36 ± 0.12 m ($p < 0.0001$) for mixed cobble-sand reaches, and 0.74 ± 0.077 m ($p < 0.0001$) for sand-bed reaches. Pairwise comparisons show no evidence for significant differences in gradient between cobble-bed and mixed reaches ($p = 0.539$). However, there is evidence for a significant difference in inset depth between cobble-bed and sand reaches ($p = 0.001$), and cobble-bed and sand reaches ($p < 0.0001$). Inset depth is significantly different between cobble-boulder and sand-bed reaches, and between mixed and sand-bed reaches. The distribution of inset depth for cobble-boulder and mixed-bed reaches overlaps (Figure 14c), but the difference in inset depth between them is still significant ($p =$

0.0385). Mixed-bed reaches have the largest mean inset depth at 1.36 m, and on average have a 0.6 m greater inset depth than sand-bed reaches and a 0.15 m greater inset depth than cobble-boulder reaches.

While mixed-bed reaches have significantly lower estimated mean slope than cobble-boulder reaches, two outliers are visible in Figure 19a where mixed-bed reaches have very high slopes. These outliers occur at 125 m and 150 m downstream of the tributary confluence, where small amounts of sand sourced from the mouth of the ephemeral tributary mix with the cobble-boulder runs that are typical for the upper reaches of the *inactadj* segment. Sand-bed reaches have significantly lower estimated mean slope and inset depth than both cobble-boulder and mixed-bed reaches, but slope outliers and inset depth outliers for sand-depth reaches are visible in Figure 19a and 19c, respectively. Sand bed slope outliers (with slope greater than 0.031 m/m) occur at 2625-2650 m and 3125-3150 m. Sand bed inset depth outliers (with inset depth greater than 2.0 m) occur at 600, 1350, 2875, and 3400 m.

Table 5. Results of one-way Anova models, global F-tests for treatment heterogeneity, and pairwise comparisons using estimated marginal means between bed material types. Bold and italic F-values and p-values indicate statistically significant results. In estimated marginal means and pairwise contrasts columns, cb = cobble-boulder, m = mixed-bed, and s = sand-bed.

Anova Model	F-test for heterogeneity	Estimated Marginal Means			Pairwise Contrasts		
slope ~ bed_material	<i>F = 23.7, p << 0.001</i>	cb	0.0264 ± 0.0034 m/m	<i>p < 0.0001</i>	cb-m	0.0061 ± 0.0041	<i>p = 0.0047</i>
		m	0.0203 ± 0.0033 m/m	<i>p < 0.0001</i>	cb-s	0.0107 ± 0.0043	<i>p < 0.0001</i>
		s	0.0157 ± 0.001 m/m	<i>p < 0.0001</i>	m-s	0.0045 ± 0.0043	<i>p < 0.0001</i>
inset_depth ~ bed_material	<i>F = 40.8, p << 0.001</i>	cb	1.21 ± 0.24 m	<i>p < 0.0001</i>	cb-m	-0.146 ± 0.32	<i>p = 0.0385</i>
		m	1.36 ± 0.12 m	<i>p < 0.0001</i>	cb-s	0.473 ± 0.20	<i>p = 0.001</i>
		s	0.74 ± 0.077 m	<i>p < 0.0001</i>	m-s	0.619 ± 0.17	<i>p < 0.0001</i>
inset_width ~ bed_material	F = 0.72, p = 0.49						
valley_width ~ bed_material	F = 2.2, p = 0.11						

4.3.5 *actadj* and *inactadj* Sand Additions

I mapped direct sand additions from the stream bank to the channel along the *actadj* ephemeral tributary and *inactadj* mainstem of North Sand Creek. Mapped reaches are shown in Figure 20.

Along the *actadj* segment, sand addition is nearly continuous where the ephemeral channel runs alongside unvegetated dunes (Figure 20a). Sand addition in the *actadj* segment is almost exclusively linked to dune slipfaces. OHV travel on dunes along the unfenced upper reaches of the *actadj* segment augments eolian and gravitational inputs by destabilizing slipface surfaces and toes, accelerating sand additions (Figure 21a-b). Where OHV travel is heavy, sand deposits in the active channel exceed 1 m in depth, obscuring the underlying cobble-bed observed by Grabowski in 2019. During the 2025 runoff season, sand was not mobilized by fluvial processes in the *actadj* segment. Sand also enters the channel in areas without recent OHV traffic. I observed former OHV tracks brushed or fenced off by BLM land managers that continued to contribute sand via slumping, which was apparently often initiated by moose or other large mammals traversing the steep sand slopes. Furthermore, I observed sand slumping in largely undisturbed areas, as in Figure 21c; this photo was taken in early fall and may represent slumping caused by the freeze and thaw of saturated sand layers in the dunes, as described by Ahlbrandt and Andrews (1978). Figure 21d illustrates incision into sand terraces during prior runoff seasons.

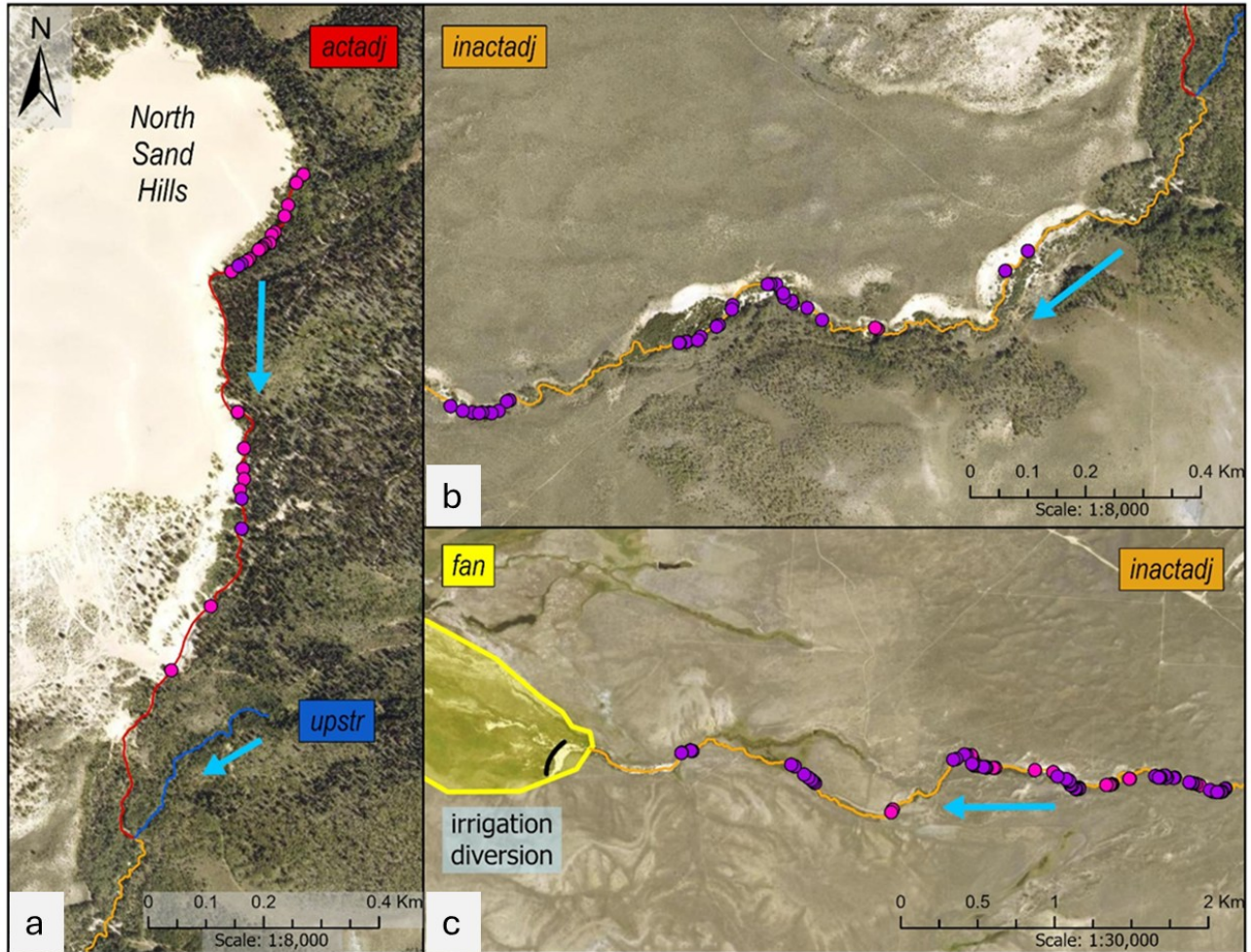


Figure 20. Map of North Sand Creek segments with mapped points of direct sand addition from stream bank to channel. Points are paired, indicating start and end of bank sections with observed direct sand addition. Dark purple indicates addition via reworking of previously deposited sand terraces; light magenta indicates addition from dune slipfaces. The entirety of the *actadj* and *inactadj* segments were surveyed. (a) 1:8,000 scale, showing *actadj* and *upstr* segments. (b) 1:8,000 scale, showing upper *inactadj* segment from tributary confluence to CS 12. (c) 1:30,000 scale, showing the lower *inactadj* segment from CS 12 to the State Line Ranch diversion and NSC *fan*.

Along the *inactadj* segment, most sand addition occurs due to reworking of previously deposited sand terraces (Figure 22a). I surveyed 679 total meters of bank that directly contributed sand to the *inactadj* channel, representing 5.2% of the total surveyed bank length. Terrace addition occurred due to lateral bank erosion in relatively unconfined reaches or on the

outside of meander bends (Figure 22a-b). Past vertical incision contributed to bank undercutting and further sand slumping (Figure 22c). Inactive dunes also contributed sediment directly to the channel; in Figure 20b, the meander bend in the photo interacts with the toe of a partially vegetated dune slipface, destabilizing the surface. In Figure 22d, the stream runs alongside a 200 m long slipface where accumulations of slumping sand along the right bank were apparent in the field. Sand addition to the channel from dune slipfaces occurred over 296 m of bank along the *inactadj* segment, which is 2.3% percent of total length surveyed. 7.5% of the bank along the *inactadj* segment directly contributes sand to the channel.

Figure 23 shows sand addition summed over 100 m reaches along the *inactadj* segment. The reaches with the greatest percentage of bank contributing sand are at 1100-1200 m, 3400-3500 m, and 5500-5600 m. The photo in Figure 22b was taken in the 1100-1200 m reach, where meander bends erode tall sand terraces and slightly destabilize dunes (dune additions here were grouped with terrace erosion, as the effects were simultaneous and inseparable). The photo in Figure 22d was taken between 3400 and 3500 m, where the dune slipface directly contributes to the channel, while Figure 22a shows bank erosion occurring in the 5500-5600 m reach, where the stream meanders through a series of shallow sand terraces.

Based on my survey of sand sources, 92% of the *inactadj* bank does not directly contribute sand to the channel. However, reaches downstream of sand addition sources often displayed active sand transport in the form of bed ripples, antidunes, and migrating sand wedges.



Figure 21. 2025 photos of sand addition along the *actadj* ephemeral channel. (a) OHV tracks on dunes, which mobilizes sand into the ephemeral channel along the forest margins; (b) the ephemeral channel filled with OHV-introduced loose sand; (c) sand slumping occurring without recent OHV traffic; (d) past incision through previously deposited sand. No continuous flow occurred in the *actadj* segment, so sand addition reflects only past fluvial processes and current eolian, gravitational, and OHV-mobilized sand addition.

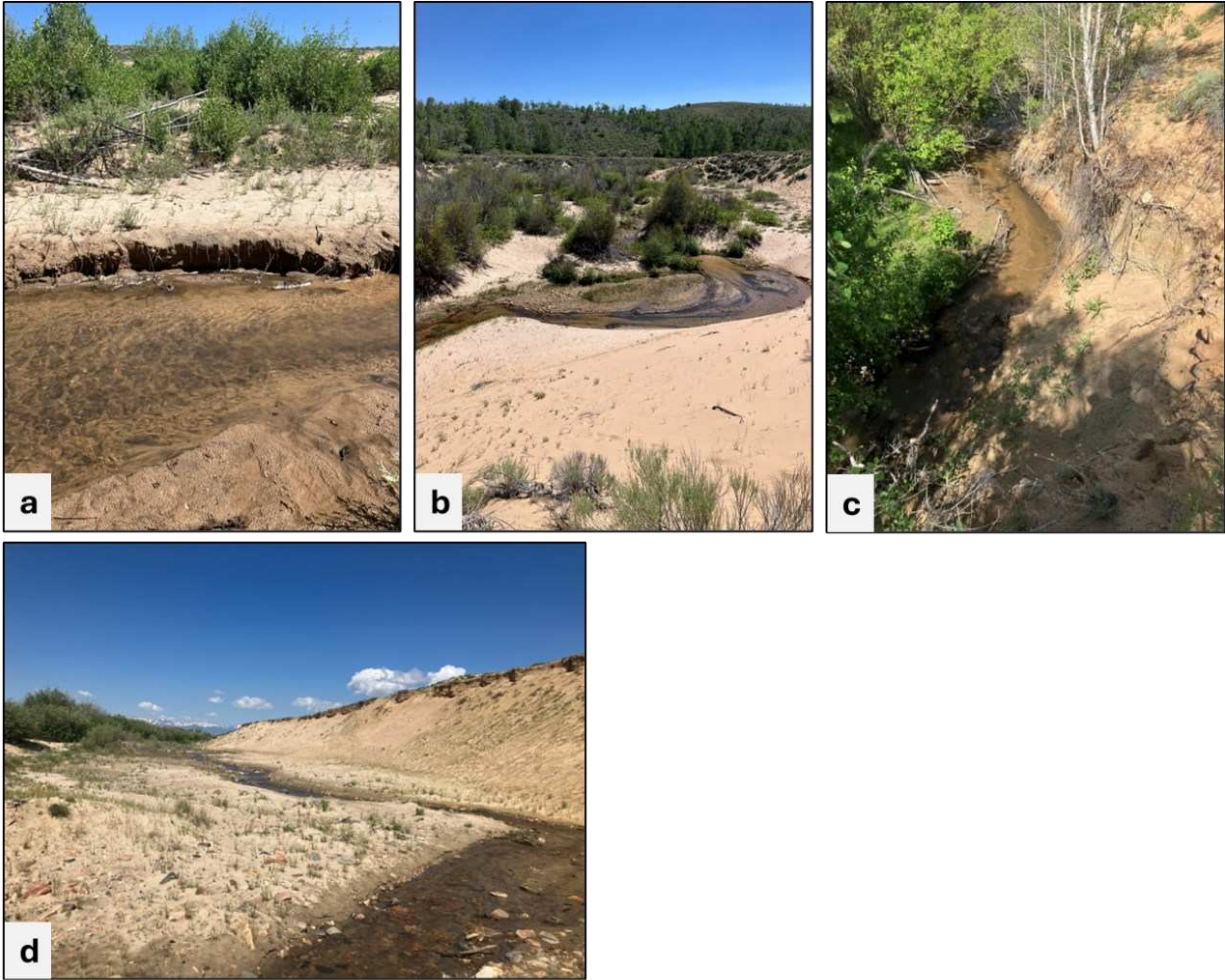


Figure 22. 2025 photos of sand addition to the *inactadj* channel. (a) erosion of partially vegetated sand terraces, flow from right to left; (b) a meander bend around a relict beaver berm destabilizing the toe of a dune slipface, flow left to right; (c) incision along northern margin of the stream and accompanying sand slumping (note turbid water), looking downstream; and (d) both reworking of previously deposited sand terraces and sand addition from partially vegetated dune slipface, looking downstream.

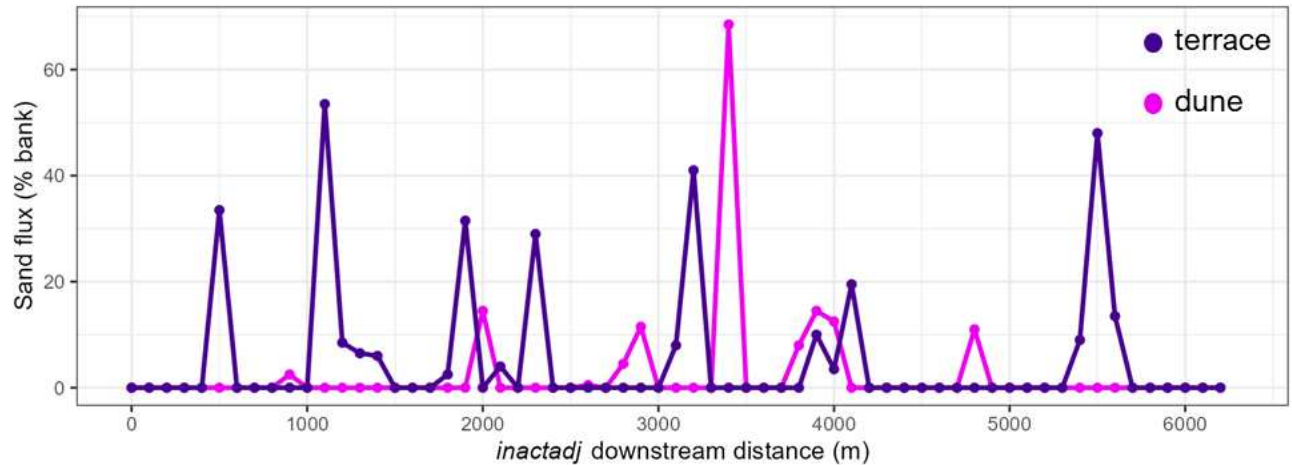


Figure 23. Direct sand addition from streambank to channel along the *inactadj* segment, summed over 100 m reaches. Y axis represents percentage of total bank length (both left and right) within each 200 m segment that adds sand directly to channel. Dark purple represents sand addition by reworking of previously deposited sand terraces; light magenta represents addition from slumping or sliding on dune slipfaces.

4.4 Reach Geomorphic Characteristics & Sand Addition: Discussion

In this section, I will refer to Figure 24, which compiles results from the previous section. Symbols and data in Figure 22 follow Figure 16, 17, 18 and 23. Additional annotations include black vertical dashed lines to indicate major slope breaks, light blue shaded areas to indicate transport/source reaches, and light orange shaded areas to indicate storage reaches. A caption for Figure 24 is included on the page following the figure.

4.4.1 Stream Entrenchment and Disconnection

Field observations during 2025 and DEM-derived measurements of North Sand Creek mainstem below the confluence demonstrate that the fluvially active channel is currently entrenched and disconnected from the wider valley floor. The inset active channel is vertically separated from the valley floor by an average of 1 m of incision. While incision generally

decreases with distance downstream, inset depth is variable and shows a nearly sinusoidal pattern of rapid increase and decrease at transitions between transport and depositional reaches (Figure 22). At major slope breaks, inset depth increases to above 2 m, then decreases afterward, often with a transition from mixed-bed to sand-bed configuration, indicating an aggradational wedge of sand in the channel. Throughout the *inactadj* segment, the inset width is on average 49% of the valley floor width. In reaches where the valley width exceeds 30 m, the inset width covers a much lower proportion of the valley, often staying below 25 m even when the valley width reaches 60-70 m. In areas of relative valley confinement, the inset width may equal the valley width (see 3000 m, Figure 24) because there is no floodplain surface elevated above the channel. North Sand Creek is separated from its valley by an average of 1 m of incision in most reaches, and the stream was only able to access a fraction of the total valley floor in 2025. Growth of young alders (roughly one decade old) in the inset channel and on its steep banks suggests that the incision of the active channel occurred relatively recently, because alders are an early successional species in riparian environments (John Sanderson, Center for Collaborative Conservation, Oct. 2025, pers. comm.). An incised, single thread stream planform hydrologically separated from the floodplain is a common legacy of beaver extirpation (Polvi & Wohl, 2013). I present further evidence of prior beaver habitation, beaver extirpation, and legacy geomorphic effects in Sections 4.5 and 4.6.

During the low flow states observed in 2025, the valley floor was inaccessible to North Sand Creek throughout most of the *inactadj* segment. Incision and confinement systematically decrease after 4000 m, but flow was cut off from the areas of greatest floodplain width (250-750 m, 1250-1500 m, and 3250-3750 m) in the upper reaches of the stream. The inset channel retained narrow, entrenched geometry visible in highly confined reaches through even the widest

valley templates. Alternation between narrow, relatively confined transport reaches and wide, relatively unconfined reaches with extensive floodplains is frequently described with the analogy of “beads on a string” (Stanford et al., 1996; Ward et al., 2002; Stanford et al. 2005; Wohl et al., 2018). In mountainous, high relief river valleys, strings are narrow, relatively steep segments often confined by bedrock separating wider, lower-gradient segments where the river can move laterally. Bead segments are more likely to develop wide floodplains with surface and sub-surface connections to the channel. Beads provide an ecologically important mosaic of aquatic and riparian habitats as flow slows, splits, interacts with vegetation, and mobilizes and deposits sediment on the floodplain (Ward et al., 2002). Spatial heterogeneity on beads facilitates the retention of water, sediment, nutrients, and organic matter over various time scales, providing attenuation capacity that increases the resilience of fluvial systems to disturbance (Wohl et al., 2018). Wide, low gradient beads provide ecological and geomorphic function to fluvial systems. Variation in valley width along North Sand Creek is analogous to the concept of beads and strings, although confinement is induced by dunes and Quaternary terraces instead of bedrock.

In 2025, North Sand Creek had little to no hydrological access to its wider valley areas. Therefore, the capacity of the creek to attenuate fluxes of water or sediment through the *inactadj* segment is reduced. Sediment cannot be deposited on the floodplain, only in transient storage behind wood or in bedforms within the inset channel. Areas of ponded, slowed, or subsurface water that could provide a variety of habitats on the floodplain cannot be formed during high flows. During years of very high sand export from the *actadj* tributary that causes meter-scale aggradation-incision cycles (Grabowski & Wohl, 2021), transient increases in bed elevation may decrease the inset depth, allowing the stream to access the valley floor. Rapid aggradation on annual or sub-annual time scales can increase the incidence of overbank flow and sediment

deposition (Raven et al., 2009). In some areas of the valley floor, extensive areas of bare sand are visible among willows and alders, potentially providing evidence for floodplain deposition from the 2019 sand wave. However, even if the stream can temporarily access the floodplain during aggradation-incision cycles, North Sand Creek is cut off from floodplain ecological and geomorphic function under most other runoff conditions. In-channel logjams provide some sand storage (Grabowski & Wohl, 2021), but lack of floodplain access reduces sediment attenuation capacity and system resilience to disturbance, including annual-scale sediment waves.

4.4.2 Sand Loading, Transport, and Deposition

In Figure 24, I qualitatively classify deposition and transport/source reaches based on longitudinal variations in bed material (Figure 24a), slope (Figure 24b), and inset depth (Figure 24d) observed during the summer of 2025. I interpret reaches with trends of decreasing bed slope, decreasing inset depth, and transition from cobble-boulder and mixed-bed to sand-bed as depositional reaches (orange shading). Decreasing slope indicates lower potential stream power, while decreasing inset depth and transitions to sand-bed reaches indicate vertical aggradation of sand on the stream bed. Conversely, I interpret reaches with increasing or sustained high slope (at least above the average segment slope of 0.018), increasing inset depth, and cobble-boulder or mixed-bed regimes as transport/source reaches (blue shading). Before 4000 m downstream, transport reaches include or are bounded at the upstream edge by a significant slope break (>0.03 m/m). High slope indicates higher potential stream power, while slope breaks may indicate headward erosion through previously deposited bed material.

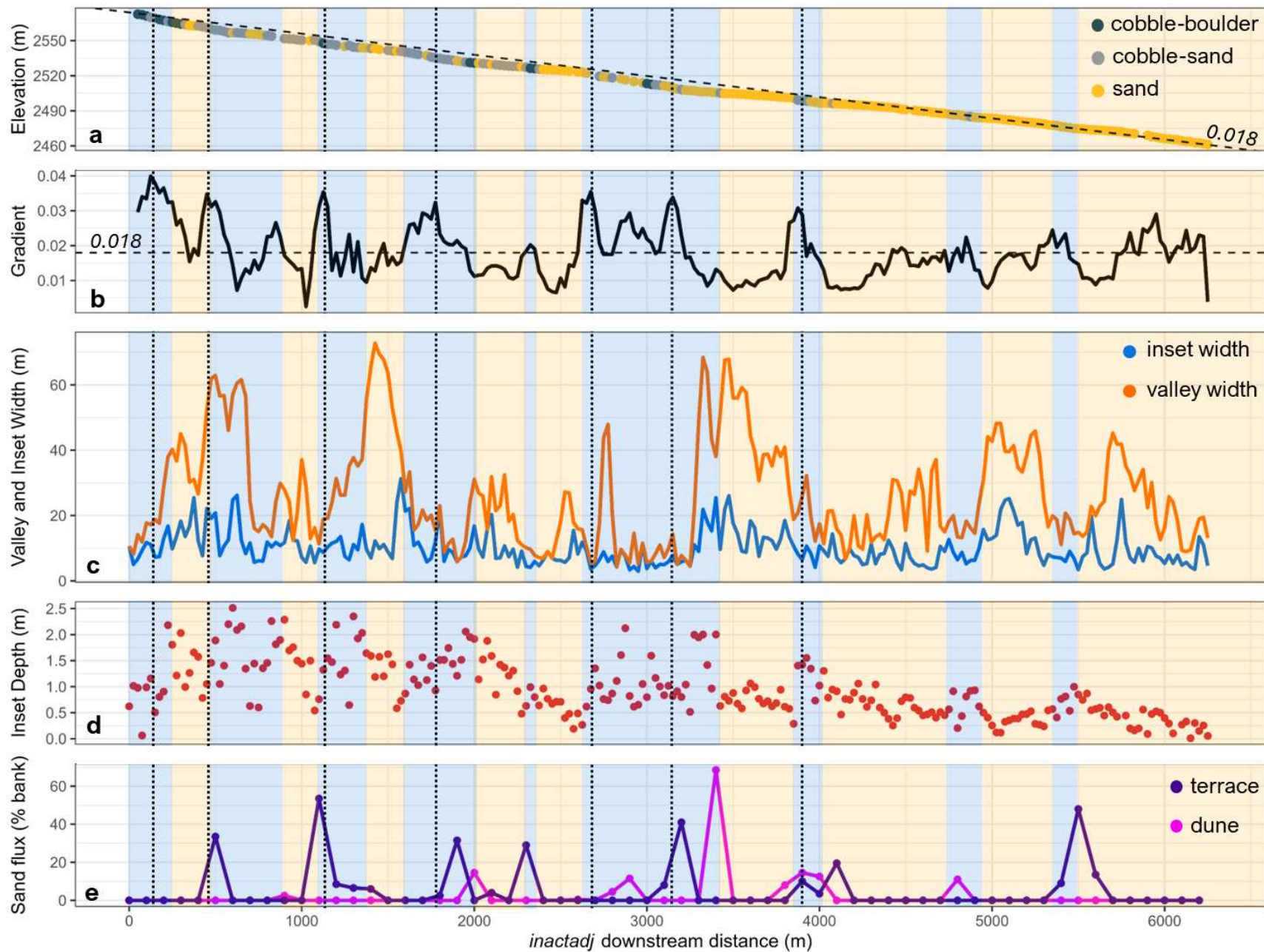


Figure 24. Compilation of geomorphic characteristics for *inactadj* segment. Vertical dashed lines show location of major slope breaks. Blue-shaded areas represent interpreted transport reaches. Orange-shaded areas represent interpreted depositional reaches. (a) shows *inactadj* long profile, with DEM-derived elevation plotted against stream distance at 25 m intervals. Black dashed line is a line with slope = 0.018 m/m, the average gradient of the channel. Point colors represent primary bed material (dark grey = cobble-boulder, light grey = mixed cobble and sand, yellow = sand bed); (b) shows DEM-derived channel gradient (m/m) in the *inactadj* segment. Gradient was calculated over 25-m intervals, with each point representing the slope of a 100 m reach centered on the point; (c) shows *inactadj* valley width (orange) and inset width (blue) plotted against stream distance; (d) shows inset depth, the difference in DEM-derived elevation from the channel to the inaccessible floodplain; (e) shows direct sand addition from streambank to channel along the *inactadj* segment, summed over 100 m reaches. Y axis represents percentage of total bank length (both left and right) within each 200 m segment that adds sand directly to channel. Dark purple represents terrace sand additions and light magenta represents dune sand additions.

High or increasing inset depth suggests ongoing incision of the channel. The presence of a resistant cobble-boulder layer indicates prior mobilization of any overlying sand on the bed, while mixed-bed reaches indicate transport of sand over the resistant cobble layer. Areas of high direct sand contribution to the channel roughly correspond to transport reaches (Figure 24e). Inset width and valley width are highly variable, and cobble-boulder, mixed-bed, and sand-bed reaches do not have significantly different inset or valley widths (Figure 19). During 2025, the active channel was disconnected from the valley floor in most locations because of incision averaging 1 m (Figure 24d), and the narrow, entrenched channel does not interact with the valley floor. Therefore, channel slope, bed material, and reach classification (transport/source or depositional) are disconnected from valley width. However, as the channel shifts from transport-dominated to deposition-dominated after 4000 m downstream, inset depth decreases and inset width increases proportional to valley width, taking up a greater portion of the valley floor than in the transport-dominated reaches upstream (Figure 17, Figure 24c). Upstream of 4000 m, the channel alternates between transport/source and depositional reaches separated by major slope breaks at the upstream end of depositional reaches. Downstream of 4000 m, major slope breaks

cease to appear and long depositional reaches are only punctuated by short transport reaches associated with small increases in slope and inset depth. In addition, after 4000 m, bed material is almost entirely sand, and the long profile has a shallower slope (< 0.18 , the average slope) and becomes slightly convex (Figure 18, Figure 24a).

Tributary activation during high-runoff years routes a pulse of sand from the *actadj* segment to the upper reaches of the *inactadj* segment, as observed by Grabowski (2020). Sand transport proceeds downstream as a sediment wave causing sequential aggradation and incision. Logjams partially attenuate the sediment wave through transient storage of sand, reducing the amplitude of bed elevation changes. Some sand likely reaches the alluvial fan within the same runoff season (section 4.8), but attenuation of the sediment wave suggests that sand is deposited and stored heterogeneously throughout the *inactadj* section. A sediment pulse may take multiple years to fully propagate through drainage networks and can temporarily increase sediment storage in channel bedforms and on the banks (Nicholas et al., 1995; James, 2010). Temporarily stored sediment is then remobilized by later flows, causing a lagged export of sediment after a major sediment pulse. In 2025, the *actadj* ephemeral tributary did not activate, but I observed direct addition of sand to the channel via erosion of fluvial sand terraces and dune slumping where channel meanders undercut dune slipfaces (Figure 23, Figure 24e). I also observed sand transport on the bed and documented a sand-bed regime in reaches throughout the *inactadj* segment (Figure 24a). Fifteen percent of the *inactadj* bank contributes sand to the channel, but this sand addition is likely only a small fraction of the sand contributed by the *actadj* segment during high runoff years. Even in low runoff years following mass sand export, North Sand Creek is probably still working through lagged sand deposits from the sediment wave.

Alternation between steep, deeply incised transport reaches and lower-gradient, less incised, sandy depositional reaches (Figure 24) suggests headward erosion through previously deposited sand wedges coupled with simultaneous downstream deposition. In lower-runoff years following a sediment wave, incision through sand deposits on the bed is initiated by rising flow. Incision proceeds headward as a traveling slope break, leaving an entrenched channel immediately downstream. Entrenchment decreases downstream after a slope break because eroded sand joins a downstream depositional wedge, which increases bed elevation relative to the abandoned valley floor. As sand builds up on the depositional wedge, the slope of the downstream end or toe of the wedge increases.

Eventually, a threshold slope is passed that allows incision through the toe of the wedge, and headward incision begins to proceed through the sand wedge. Incision likely begins upstream, then sequentially initiates downstream as sand wedges reach a threshold slope. After sufficient time, multiple instances of sand wedges with incision occurring at both head and toe create an alternating series of simultaneously operating transport/source and deposition reaches (Figure 24). Transient incision and fill at the transition between transport/source and depositional reaches locally recreate the aggradation-incision fill of the past sand wave. Incision in transport reaches may undercut and destabilize banks, contributing sand to the channel. Likewise, at the transition between steep slope break and low-gradient depositional reach, lateral migration of the channel within the inset may cause terrace or dune erosion (Schumm, 1973; Gran, 2012). Sand passes through depositional and source/transport reaches in sequence and eventually reaches the growing aggradational wedge upstream of the alluvial fan transition, shown by a transition to a convex profile and exclusively sand-bed morphology at 4000 m (Figure 24a). Thus, sand

transport to the alluvial fan continues for multiple years following the passage of a sediment wave.

During 2025, bed elevation change did not occur at a magnitude detectable by my survey methods. Cross sections CS 9 (150 m), CS 10 (525 m), and CS 12 (1875 m) were located well within transport reaches with cobble-boulder or mixed bed material. At such low discharges, mobilization of large clasts and incision through the cobble-boulder layer is impossible. If sand accumulation occurred in these reaches, it may have been transient, filling spaces between cobbles and not causing bed elevation, or simply below the threshold of detection. Cross section CS 11 (925 m) was located within a depositional reach with a mixed bed. No bed elevation changes were detected there, perhaps because the cross section was located on a locally steeper cobble run, or because changes were below the level of detection. Cross section CS 13 (6525 m) was in the depositional transition zone between the *inactadj* segment and the alluvial fan, and adjusted laterally without detectable changes in bed elevation, reflecting the low gradient and constant sand input from the bed and upstream. Over 4.5 km of stream (1875 m – 6525 m) was not monitored cross section adjustment, which includes multiple transitions between transport and deposition reaches. Lack of change in cross sections suggests (a) small changes in bed elevation due to annual sand migration, and (b) that future monitoring should be more spatially extensive, covering the approximately 4000 m transition to sand aggradation, and should employ finer survey methods such as RTK GPS or repeat UAV Lidar to detect centimeter-scale adjustment.

4.4.3 Interannual Complex Response

The process of sand transport described above is analogous to Schumm and Parker's observations of incision and drainage network rejuvenation in an experimental sand-bed system

(Schumm, 1973; Schumm & Parker, 1973) and Patton and Schumm's (1975) description of threshold-initiated erosion in northwestern Colorado gullies. Schumm defines complex response as the progressive adjustment of components within a geomorphic system to one event or period of disturbance. An infrequent event may trigger a series of landscape responses separated in space and time from the initial perturbation (Schumm, 1973). In North Sand Creek, progressive adjustment of the stream via headward incision through depositional sand wedges – resulting in net downstream sand export – is triggered by sand waves originating in the ephemeral tributary. A sand wave occurred in 2019 and likely in 2011, given the near-maximum snowpack, rapid meltout (Figure 12), and mass sand export reported by State Line Ranch that summer (Grabowski, 2020), suggesting that sand waves recur at sub-decadal intervals. The sand wave causes meter-scale adjustment of the bed within a single runoff season, and effects of the sand wave may persist over several years or until the recurrence of another sand wave resets the depositional template.

Schumm and Parker (1973) described rapid drainage evolution and complex response triggered by base level drop in a small-scale experimental season. Since then, complex response has been described in rivers adjusting to upstream reductions to streamflow due to reservoir construction or to fluctuations in sediment supply (Petts, 1979b; Gaeuman et al., 2005), where changes in bed elevation or planform occurred over multiple decades. Cycles of aggradation and incision constituting a complex response proceeded over the course of 15 months in mountain streams where extreme sediment inputs followed the burning of upstream catchments by wildfire (Brogan et al., 2019). After the 1980 eruption of Mt. St. Helens triggered a debris avalanche that buried the fluvial valley below, development of a new drainage system over the next 40 years

followed a complex, non-linear trajectory of lateral and vertical channel adjustment (Major et al., 2019).

North Sand Creek is distinct from these examples of complex response because (i) the cycle of aggradation and incision triggered by a sediment wave (the complex response) propagates through the fluvial system over annual time scales, and (ii) the sediment wave is repeated on sub-decadal scales, resetting the sediment transport template while adjustment to the previous disturbance is ongoing. OHV sediment loading increases the rate of sediment accumulation in the *actadj* tributary, increasing the likelihood of sand wave initiation during high runoff years and thus increasing the frequency of sand wave-induced complex response in the lower reaches, but natural accumulation of sand over several years via eolian and gravitational processes could potentially provide enough sand input to allow sand wave initiation. Complex response triggered by sand waves may have occurred many times over the Quaternary history of North Sand Creek and may represent a long-term adjustment to a past perturbation. A terrace elevated above the valley records approximately 4 m of incision during the late Holocene (sections 4.9, 4.10), and relict beaver modifications of the valley floor suggest that incision of the inset channel was initiated by local beaver extirpation (sections 4.6, 4.7). A logjam-induced knickpoint over 2 m tall in the *actadj* segment also suggests long-term incision or base level drop. Repeated complex response to sand loading on annual scales may be nested within a millennial response to base level drop and decadal responses to beaver extirpation.

4.5 Relict Beaver Berms: Results

4.5.1 Historical Aerial Imagery

I visually examined historical aerial photographs of North Sand Creek and North Sand Hills available through the USGS EROS archive to constrain the timing of beaver dam removal in the study area.

Dammed ponds are not clearly visible in aerial imagery from 1947, even in locations where ponds are visible in later images. This is likely due to lower-resolution photography and non-nadir sun angle. However, strings of beaver ponds are visible in higher-elevation streams in the Medicine Bow Mountains to the north and northeast of the study area, indicating that beaver populations are present in nearby streams.

Aerial imagery from 1977 and 1979 shows beaver ponds at three locations in North Sand Creek (Figure 25). The full extent of these ponds may be obscured by vegetation in the imagery, but all three show areas of open, ponded water extending over the channel and floodplain. Figure 25a shows a pond at the tributary-mainstem junction, with backwatering extending upstream into both the *actadj* and upstr segments. Figure 25b shows two ponds in the *inactadj* segment. The downstream pond extends outward from the channel to cover the heavily vegetated floodplain, while the upstream pond fills a narrower, more confined reach. A valley-spanning dam is visible crossing the upstream end of the upstream (rightward) pond.

A 1983 aerial image (Appendix A) shows that the western pond in Figure 25b is no longer present, but the eastern pond remains full. The presence of the pond in Figure 25a cannot be ascertained due to off-nadir sun angle. The 1983 image also shows evidence of motorized travel on the North Sand Hills, apparent as two-track paths through the partially vegetated active dune margins.

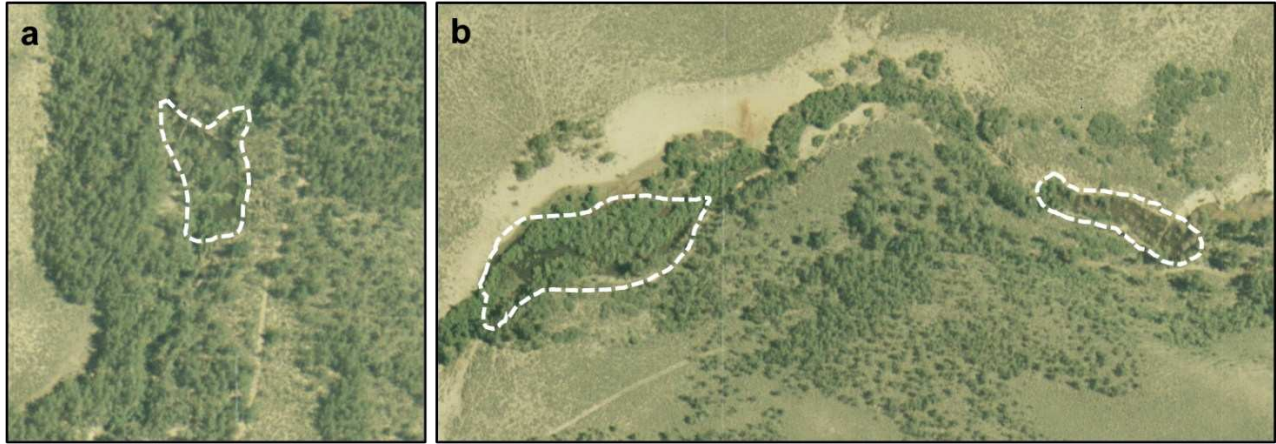


Figure 25. Beaver-dammed ponds visible in 1977 aerial image of North Sand Creek (USGS EROS Archive). Pond in (a) was located at tributary-mainstem junction, at the upstream end of the *inactadj* segment. Ponds in (b) were in the *inactadj* segment between 1000 m and 1600 m downstream of tributary confluence. Downstream ends of pond in (b) correspond with both a mapped relict dam and L-bend stream planform.

4.5.2 Relict Berm Distribution

I observed 8 relict dams in the surveyed reach of the lower *actadj* segment and 307 relict dams in the *inactadj* segment over the 4.4 km of stream surveyed. A presumed relict dam was also observed upstream of CS 08 in the *upstr* segment (not shown in Figure 26). No active dams were observed, and I saw no evidence of recent beaver activity, such as freshly chewed wood. I found beaver-chewed wood throughout the *inactadj* segment, including pieces incorporated in relict berms and stumps in the abandoned floodplain and adjacent stand of poplars, but all observed chew was heavily weathered. Beavers are not currently active in North Sand Creek, but the stream corridor supported a beaver population in the recent past.

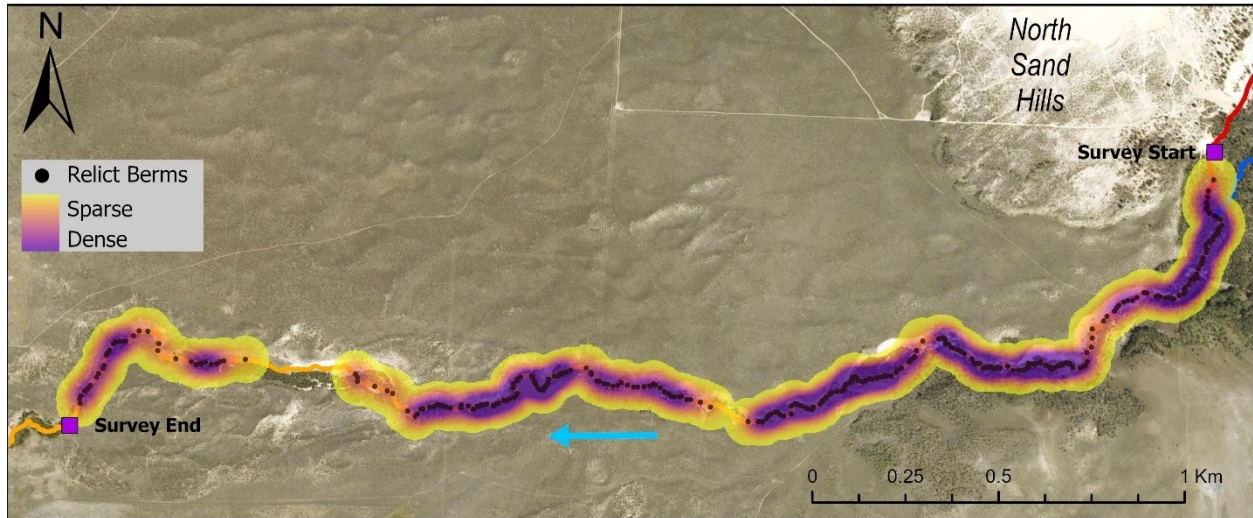


Figure 26. Relative density of surveyed relict beaver dams. Survey started 200 m above *actadj-upstr* confluence and continued for 4.4 km downstream along the *inactadj* segment. 315 relict dams were observed during the survey. Direction of flow shown as blue arrow.

Relict dam density varied over the length of the *inactadj* channel surveyed (Figure 27). The overall relict dam density is 69.7 dams per kilometer, or 7 dams per 100 m. The maximum density of relict dams, 14 dams per 100 m, occurred 200-300 m downstream from the tributary confluence (Figure 27). Very high relict dam densities of 12 dams per 100 m were observed at 900-1000 m, 1400-1600 m, and 2600-2700 m. No relict berms were observed between 3500 and 3700 m downstream of the tributary confluence, and relict dam density decreased downstream. All observed dams were breached and unmaintained. Given the 315 total relict dams along North Sand Creek and the ephemeral tributary, and a total drainage area of 8.99 km² (USGS StreamStats) above the lowest relict dam, the dam to drainage area ratio is 35.0 per km².

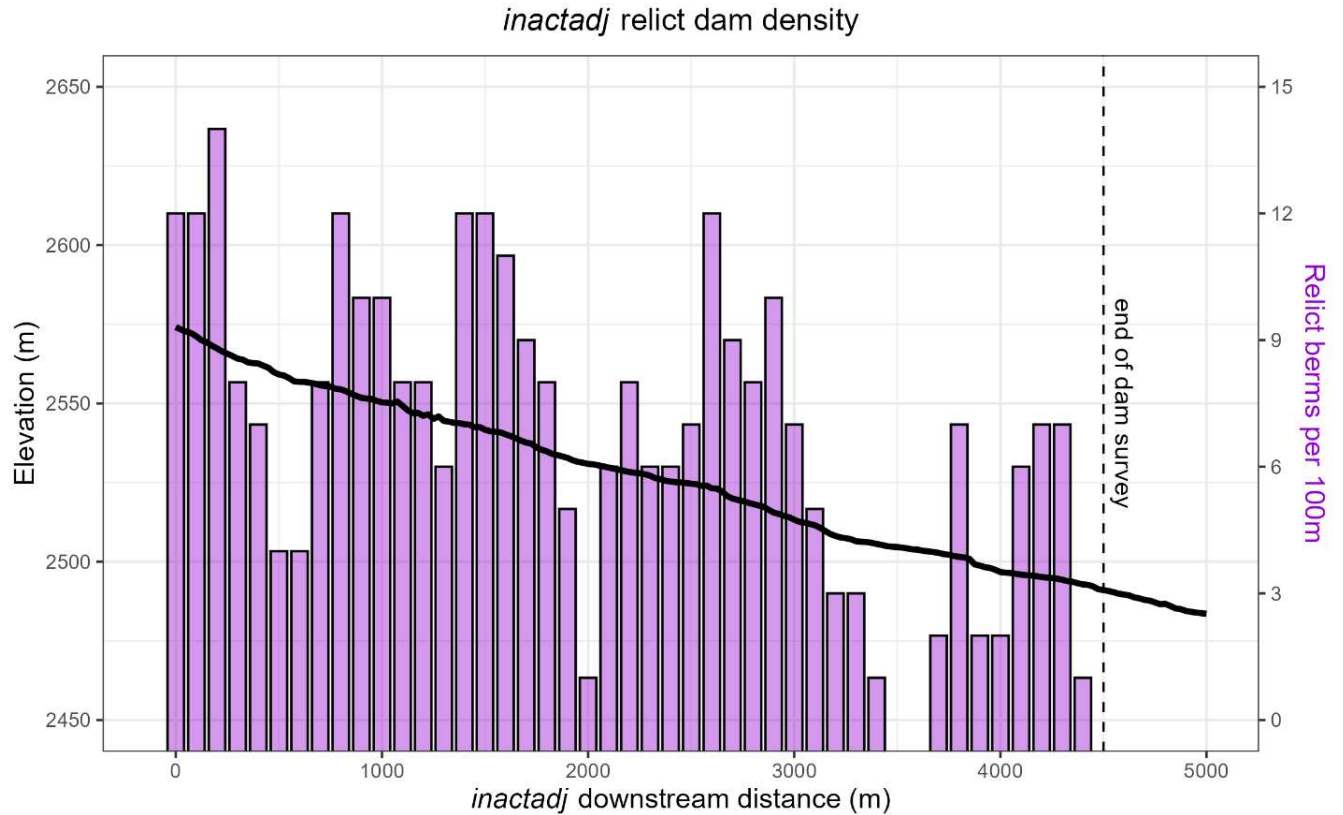


Figure 27. Observed relict berm density in dams per 100 m (purple bars), plotted against *inactadj* long profile (black).

4.5.3 Relict Berm Storage Estimate

Calculated relict beaver dam storage values for all four density scenarios (1: 100% of observed relict dams, 2: 50% of observed relict dams, 3: estimated historical median, and 4: estimated modern median) are presented in Table 6. Estimates of sediment storage are approximate and based only on current valley geometry; these estimates also reflect an absolute maximum storage volume for the simulated dam density, as described in Methods section 3.3.4. Ninety-five percent confidence intervals represent variance in simulated results. All estimates of storage per basin area use a drainage area of 8.99 km², which is the drainage area of the creek at the farthest downstream surveyed beaver dam (USGS StreamStats).

Although the estimated historical median dam density (Scenario 3) is only 16% of the observed relict dam density (Scenario 1), calculated sediment storage and storage per basin area in Scenario 3 is still 48% of calculated sediment storage and storage per basin area in Scenario 1. Estimated sediment storage and sediment storage per basin area in 2 m dam height scenarios is 3-6 times greater than in 1 m dam height scenarios.

Table 6. Compilation of relict sediment storage estimates across four dam density scenarios and two maximum beaver dam height scenarios.

Beaver Dam Scenario		Dam Density (dam/km)	No. of Dams	1 m dam height		2 m dam height	
				Est. sediment storage (m³)	Storage per basin area (m³/km²)	Est. sediment storage (m³)	Storage per basin area (m³/km²)
1	100% observed relict dams	69.7	307	51,200	5,700	184,700	20,500
2	50% observed relict dams	34.8	153	45,300 ± 127	5,000	176,400 ± 488	19,600
3	Est. historical median (Scamardo et al. 2022)	11.4	50	25,500 ± 152	2,800	129,400 ± 786	14,400
4	Est. modern median (Scamardo et al. 2022)	4.0	17	10,400 ± 107	1,200	63,300 ± 638	7,000

4.6 Relict Beaver Berms: Discussion

4.6.1 Historical Beaver Residency

Along the *inactadj* segment, relict dam density is 71.4 dams per kilometer of stream length and, as reported above, 35.9 relict dams per square kilometer of drainage area. Observed relict dam density is nearly seven times the median historical density and nearly eighteen times the median modern density estimated by Scamardo et al. based on habitat suitability in the

Colorado Rockies (2020). It is unlikely that all dams were active and maintained by beavers at the same time, Instead, dams may have been frequently filled by the catchment's high sediment flux (Dunn, 2024) and subsequently abandoned for newly built dams. Surveys of relict dam spacing on the eastern side of Rocky Mountain National Park also provide a comparison for North Sand Creek; on Beaver Brook, relict dams have a density of 18.4 dams/km (7.4 dams/km² drainage area) while on the Upper Poudre relict dam spacing is 6.9 dams/km (10.3 dams/km² drainage area) (E. Wohl, unpublished data, May 2026). North Sand Creek's relict dam density is far higher than at these two sites, likely reflecting a high rate of dam building and abandonment due to historically high seasonal sediment export.

I found no evidence of current beaver activity in North Sand Creek over the duration of this study. However, the results of the relict dam survey demonstrate that North Sand Creek and its riparian areas supported a historical beaver population. Chewed wood found throughout the channel network, in riparian woodlands, and on the hillslopes above the channel provides further evidence of widespread beaver residency and resource use. The ages of the relict beaver dams are unknown, but all dams were breached and unmaintained at the time of the study. Beaver dams can persist undamaged for years after abandonment (Laurel and Wohl, 2019), so the dams were likely not occupied for the last decade or more. In addition, chewed wood found in dams and on the landscape was worn, rounded, and often decomposed, further suggesting that the beaver population has been absent for some time. Without dating beaver dams using isotopic techniques, dendrochronology, or other methods, I cannot constrain the number of beaver dams that may have been active at any given time at North Sand Creek or definitively determine the date at which beaver occupation ceased.

However, analysis of historical aerial imagery allows me to partially constrain the period of local beaver extirpation. As described in Section 4.5, I observed three active beaver ponds in the 1977 aerial image of North Sand Creek with downstream dams and open water covering the active channel and riparian areas. In 1977, a beaver population was either maintaining these dams or had only recently abandoned them. Presence of active beaver ponds in 1983 BLM aerial images of North Sand Creek is difficult to evaluate due to color grading and off-nadir sun angle, but one pond (eastern pond in Figure 25b) no longer covers the floodplain, and the channel deviates around an obstruction at the downstream end of the former pond. The pond in Figure 25a is also no longer visible in 1983, with a sinuous channel now apparent through the canopy gap that once revealed the pond. By 1983, at least two of the beaver dams forming the ponds observed in 1977 had breached. Beaver dams continued to impound water at North Sand Creek until 1977, but by 1983 beavers may have abandoned these dams. The period from 1983 to 2013 was not analyzed; after 2013, beaver dams are not visible in NAIP images of North Sand Creek. The most recent evidence of beaver occupation in North Sand Creek dates to 1977, and beaver extirpation from the middle reaches of the creek can be constrained to the late 1970s or early 1980s.

Beavers may leave or disappear from streams for a variety of reasons. In North America, the commercial fur trade caused massive beaver population decline after European contact and settlement; by the 19th century, beavers were nearly extirpated within much of their historic range due to fur trapping (Naiman et al., 1988). Records from the fur trade and early European accounts of North America suggest that the great majority of streams were once inhabited and modified by beaver (Wohl, 2021). Beavers clearly inhabited North Sand Creek after the heyday of the fur trade, but beavers still face a variety of population pressures that could cause stream

abandonment: competition with cattle, moose, or elk for woody riparian species (Beschta & Ripple, 2009); natural cycles of decreased food availability (Hartman, 1994); or an unsuitable physical template of the due to gradient or confinement (Beier & Barrett, 1987). I frequently observed signs of moose presence and herbivory at North Sand Creek, and cattle have historically browsed (and continue to browse) in the riparian areas of the creek. Currently, large stocks of woody riparian vegetation such as willow and alder are available along the stream, but in the past, competition with ungulates may have reduced the food and building material available to beaver. In addition, the sandy substrate and repeated sediment waves (Grabowski & Wohl, 2021) may have made dam maintenance and population success difficult, but the sheer number of dams along the creek suggests long-term beaver habitation. Beavers are known to inhabit Medano Creek in Great Sand Dunes National Park, which also has a mobile sand supply and seasonal runoff regime (E. Wohl, CSU Geosciences, March 2026, pers. comm.).

Widespread commercial trapping of beavers for furs has ceased in North America, but interactions between beavers and humans have continued to exert significant population pressures on beavers. Beaver dams may cause inundation of agricultural fields, damage to infrastructure such as culverts, levees, and irrigation structures, or damage to timber or fruit trees. Due to these interactions, beavers have historically been regarded as a nuisance in need of control, relocation, or even eradication (Charnley et al., 2020). In rangelands such as North Park where ranching relies on seasonal streamflow for irrigation and cattle often graze in riparian areas, beaver may complicate ranch operations by blocking irrigation infrastructure, flooding hayfields, or impeding cattle passage with ponds, dams, and mud (Charnley et al., 2020). For these reasons, ranchers may feel the need to remove beavers and beaver dams.

This may have occurred at North Sand Creek, where the State Line Ranch diversion at the proximal end of the alluvial fan is used to irrigate hayfields. State Line Ranch submitted irrigation work logs as evidence in a successful petition to include North Sand Creek on Colorado's Section 303d list of sediment-impaired watersheds. Between May 2006 and June 2008, State Line irrigation work logs record at least six beaver dams removed from North Sand Creek by hand or with heavy machinery near the diversion (Ex. 6 in Petition of State Line Ranch to list Sand Creek as impaired for sediment, 2016). In the field, I observed piles of large and small wood pieces elevated above the modern channel along the reach above the irrigation diversion, which may be the remnants of these dams. It is unclear whether the dams pulled out were active or abandoned by beavers. State Line's water right to North Sand Creek was originally appropriated in 1892, and irrigation records show that the diversion was used for flood irrigation of the hayfield since 1952 at the latest (Colorado Department of Water Resources). If State Line Ranch operations destroyed beaver dams in North Sand Creek throughout the 20th century, as occurred in 2006 and 2008, beaver populations in the creek would have suffered loss of suitable habitat, food stores, and protection from predation provided by ponds and lodges. Dam removal to protect the diversion, and potential upstream dam removal to speed transport of water to irrigation infrastructure, likely contributed to beaver extirpation in North Sand Creek.

4.6.2 Post-Beaver Geomorphology

Beavers modify stream corridor process and form across diverse environments, creating distinct geomorphic features and fluxes, and North Sand Creek displays the legacies of both beaver habitation and extirpation. Beavers built dams along North Sand Creek to create habitat and food storage during their period of habitation. The relict dams I observed were visible in both the active channel and as raised features along the valley floor, averaging one meter higher

than the active channel. Dams in the active channel reduce flow velocity and encourage surface and subsurface water storage by directing water onto the floodplain (Hafen et al., 2020, 2024; Ronnquist & Westbrook, 2021; Dittbrenner et al., 2022). Dams also increase sediment storage by detaining sediment in pond backwaters (Butler & Malanson, 1995). In settings with very high sediment flux, dams may be filled to the top with sediment (Dunn et al., 2024). Long-term beaver habitation promotes floodplain and valley floor aggradation (Westbrook et al., 2011; Kramer et al., 2012). Prior to beaver extirpation, beaver dams at North Sand Creek likely spread water and sediment out over the valley floor, connecting the active channel to a wider floodplain.

The fluvial terrace (t_1) elevated 1 m above the floodplain likely represent valley aggradation caused by beaver dam attenuation of water and sediment fluxes. In contrast to the modern single thread planform, beaver dams likely promoted low-gradient multithread channel planforms in reaches with wide valley templates and greater physical and ecological patch heterogeneity (Stefan & Klein, 2004; Polvi & Wohl, 2013). Due to the high mobility of the eolian sand that forms the bulk of North Sand Creek's sediment flux, beaver dams likely induced rapid lateral channel migration and thereby greater riparian heterogeneity. Prior to stream corridor modification for irrigation and beaver dam removal throughout the 20th century, the North Sand Creek stream corridor was more complex and had greater sediment attenuation capacity. Figure 28 illustrates aggradation to the top of a relict berm that created a beaver meadow that was once a patchwork of surface water and vegetation and is now traversed by a narrow, single-thread channel.

The current geomorphic characteristics of the North Sand Creek stream corridor reflect a transition in process and form away from the influence of beavers and beaver dams. In some Colorado stream corridors, the geomorphic effects of beaver dams may persist for up to three

decades after beaver abandonment if dams remain in place, continuing to induce water and sediment storage and geomorphic heterogeneity (Laurel & Wohl, 2019). However, when dams are removed, changes may take place much more quickly. Dam failure or removal can cause severe entrenchment directly downstream and incision through sediment stored behind the dam, causing downstream sediment export (Marston, 1994; Butler & Malanson, 2005). The stream corridor is likely to incise and become entrenched, steeper, and simplified, with less in-channel and floodplain heterogeneity. Flow velocities increase and former depositional and storage reaches created by beaver dams transition to sediment source and transport reaches, leading to increased sediment flux and downstream aggradation (Green et al., 2009). An incised, single thread channel with sharp meanders around obstructions formed by relict dams is a potential legacy condition in valleys that used to have a long-term beaver population (Polvi & Wohl, 2013). The current planform, cross section, and disconnected valley of North Sand Creek were likely caused by reduction or extirpation of the local beaver population.

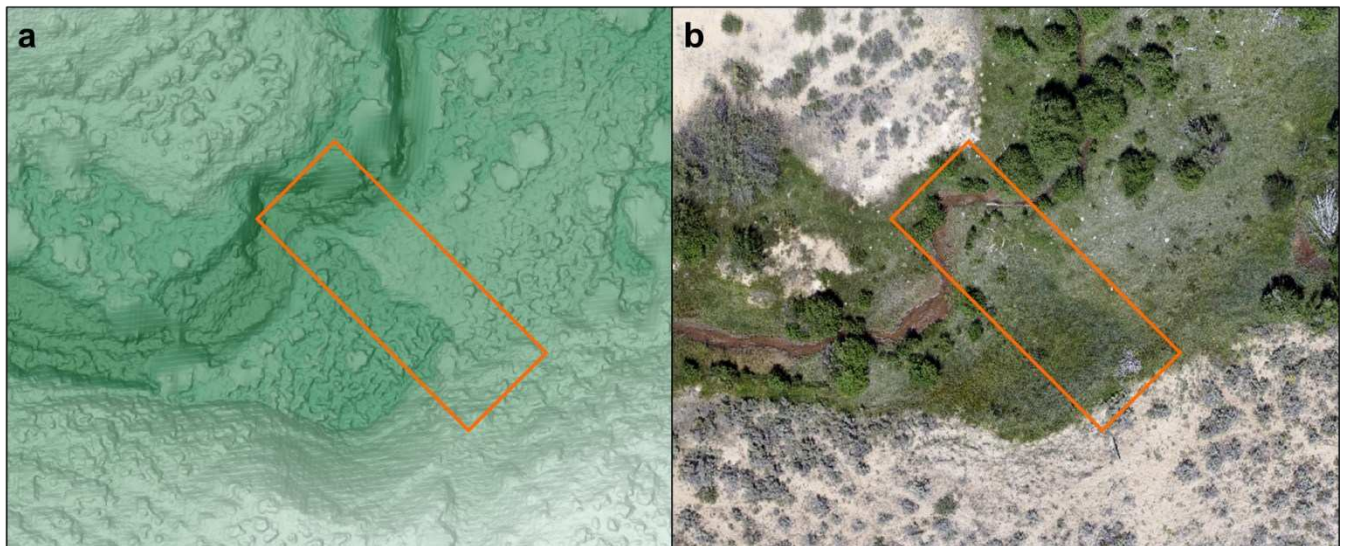


Figure 28. Relict beaver dam observed in DEM (a) and UAV imagery (b) on *inactadj* segment, downstream of relict dam survey (4700 m downstream from point 0). Note transition from higher elevation upstream meadow to lower elevation in (a).

Throughout the *inactadj* segment where relict berms are ubiquitous, the active channel is separated from the valley floor by an average of 1 m of incision (Figure 17b). The creek is almost uniformly single-thread except in very wide and low-gradient reaches, or where heavy vegetation and relict beaver berms induce sharp meanders and flow separation (Kornse & Wohl, 2020), and the stream only has access to a fraction of the possible floodplain width available on the valley floor (Figure 17a). Dammed ponds previously extended well beyond the confines of the current inset channel as late as 1977, as shown in Figure 25. Reaches between 0 and 4000 m downstream of the tributary confluence, where relict beaver dams reach densities of 10-14 per 100 m (Figure 27), were likely a mix of transport and deposition zones where ponds and off-channel flow created temporary and long-term sediment storage. At present, the channel is deeply entrenched and over-steepened with large profile convexities, providing an efficient conduit for downstream sediment transport. Reworking of fluvial terraces directly adds sand to the channel throughout the *inactadj* segment; this may represent continued lateral erosion through sand stored behind relict berms. Downstream reaches have experienced mass sand export and aggradation, as documented by Grabowski (2020). Modern process and form in North Sand Creek are shaped by the legacy of beaver removal, and the system may still be adjusting to this perturbation.

4.6.3 Loss of Attenuation Capacity

The removal of beavers from North Sand Creek likely reduced sediment storage and attenuation capacity. Beaver dams store sediment upstream and promote floodplain aggradation (Butler & Malanson, 2005; Westbrook et al., 2011), and in catchments with very high sediment flux, sediment may fill beaver ponds to the top of dams (Dunn et al., 2024). Lower gradients,

flow velocities, and greater heterogeneity contribute to off-channel deposition in complex beaver-modified reaches.

I provide estimates of sediment storage for a range of North Sand Creek beaver dam scenarios in Table 6. Compilation of relict sediment storage estimates across four dam density scenarios and two maximum beaver dam height scenarios.. Each scenario provides a maximum possible sediment storage behind the given number and height of active beaver dams. Scenario 4-1 assumes that beavers occupy and maintain only 5% of the observed relict dams at any given time and that dams are filled to an average of 1 m depth with sand. This provides an estimated 10,400 m³ of possible sediment storage volume. At the same dam density, but with a greater dam height of 2 m, possible storage capacity increases to 63,300 m³, reflecting a change in pond geometry as water and sediment are stored outside of the modern active channel and expand onto the valley floor. Grabowski (2020) estimated that the *actadj* ephemeral tributary exported roughly 9,600 m³ of sediment during the 2019 runoff season. In the lowest density beaver occupation scenario in Table 6. Compilation of relict sediment storage estimates across four dam density scenarios and two maximum beaver dam height scenarios., beaver dams could likely store the sand volume exported during the 2019 season. Dams that filled or overtopped would likely push water and sediment out of the active channel, promoting floodplain deposition that is not represented in my estimate. In all storage scenarios, including estimated modern and historical dam densities, beaver dam storage volume exceeds Grabowski's estimated 2019 sand export volume.

Dams filled to the brim with sediment are likely to be abandoned by beavers. Dam breaches and high flows that mobilize fine sediment behind dams limit sediment storage time (Levine & Meyer, 2014). Historical beaver dams in North Sand Creek would not capture all sand

transported downstream by a sediment wave comparable to the sediment wave observed during the 2019 runoff season, nor would sediment remain stored indefinitely behind the beaver dams. However, Grabowski (2020) found that logjams in the *actadj* and *inactadj* channel reduced downstream sediment export even as sand was mobilized from upstream storage wedges, not fully stopping but rather attenuating and reducing the amplitude of the sediment wave. The beaver dam scenarios represented in Table 6. Compilation of relict sediment storage estimates across four dam density scenarios and two maximum beaver dam height scenarios. create a cumulative sediment storage volume that is orders of magnitude higher than possible behind logjams alone, and beaver dams are far less permeable than logjams due to construction techniques and incorporation of organic matter (Wohl & Scott, 2017). Beavers also regularly maintain dams and may rapidly rebuild breached or overtopped dams or rapidly relocate and build new dams. A single beaver colony can build dams in a matter of days and may build up to 20 during a single runoff season (E. Wohl, April 2026, pers. comm.).

A healthy, industrious beaver population at North Sand Creek could potentially build enough behind-dam storage volume annually to attenuate the majority of sand exported from the *actadj* tributary. Sediment waves do not occur every year and are dependent on tributary activation, as demonstrated during the 2025 runoff season, so beavers would not face annual mass export of sand. Even a density of 4.0 dams per stream kilometer (17 dams total) in the *inactadj* segment would drastically change the sediment regime of North Sand Creek, likely attenuating high magnitude sediment waves and increasing the stream's sediment storage capacity and access to floodplain roughness and heterogeneity (Westbrook et al., 2011; Wohl & Scott, 2017).

4.7 Alluvial Fan: Results

4.7.1 North Park Alluvial Fans

The contributing catchments of the 10 studied alluvial fans on the east side of North Park vary in size from 12 to 67 km² and have the same lithologies in each catchment (Figure 9. Locations of the 10 alluvial fans on the east flank of North Park (orange inverted triangles). Each fan is labeled with the name of its contributing stream or creek. All fans were observed at the contributing stream's downstream entrance to the main axial drainage valley of the Canadian River. Estimated fan volume is expressed as volume per contributing area to facilitate comparisons between catchments. North Sand Creek has an estimated value of 378,260 m³ fan volume per square kilometer of drainage area. This is an order of magnitude larger than Government Creek (60,590 m³/ha) and two orders of magnitude larger than the other tributary catchment fans, including East Sand Creek (700 m³/ha). Figure 29. Distribution of alluvial fan volume (m³) per drainage area (ha) ratio for alluvial fans on the east side of North Park, Colorado. North Sand Creek is an outlier. Figure 29. Distribution of alluvial fan volume (m³) per drainage area (ha) ratio for alluvial fans on the east side of North Park, Colorado. North Sand Creek is an outlier. Figure 29 illustrates the estimated fan volume/drainage area values.

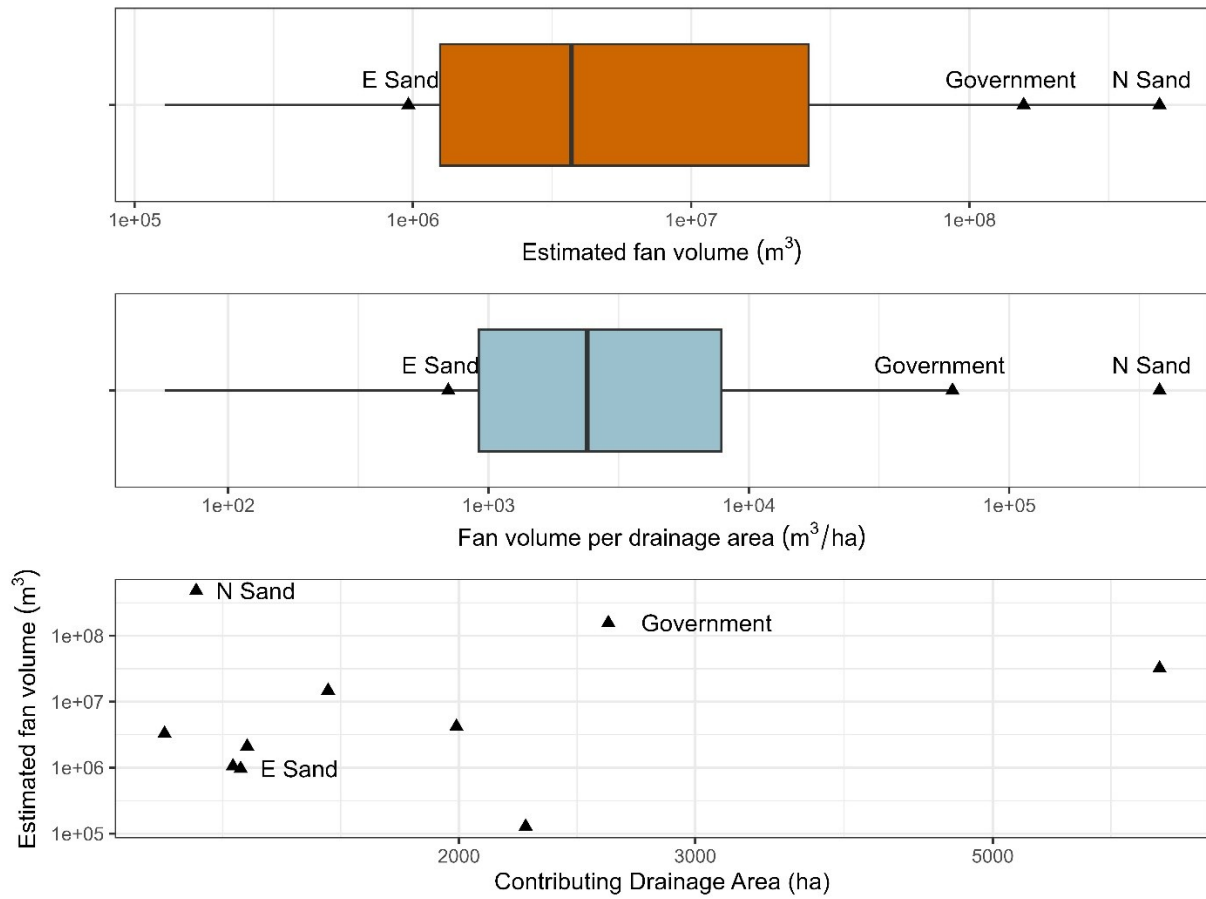


Figure 29. Distribution of alluvial fan volume (m^3) per drainage area (ha) ratio for alluvial fans on the east side of North Park, Colorado. North Sand Creek is an outlier.

4.7.2 Historical Aerial Imagery

I visually analyzed aerial photos of the North Sand Creek alluvial fan area available through the USGS EROS archive, covering the years 1947 through 1977. Aerial photos from 1979 and 1983 were not examined here because they were only available in false color, making visual analysis difficult. Aerial images from July 1947, August 1953, and August 1975 show evidence of fresh alluvial sand deposition near the location of the current State Line Ranch irrigation diversion and hayfield (Figure 30). Sand deposition is extensive in the 1947 and 1953 photos, covering large areas of the hayfield in fan-shaped splays. Deposition is less extensive in the 1975 photo, with smaller, linear areas of deposition that appear to follow irrigation ditches. While I did not quantify alluvial fan sand deposition area in these photographs, the aerial photos demonstrate that in years 1947, 1953, and 1975, North Sand Creek's alluvial fan was active, and sand exported from the creek arrived on the fan.

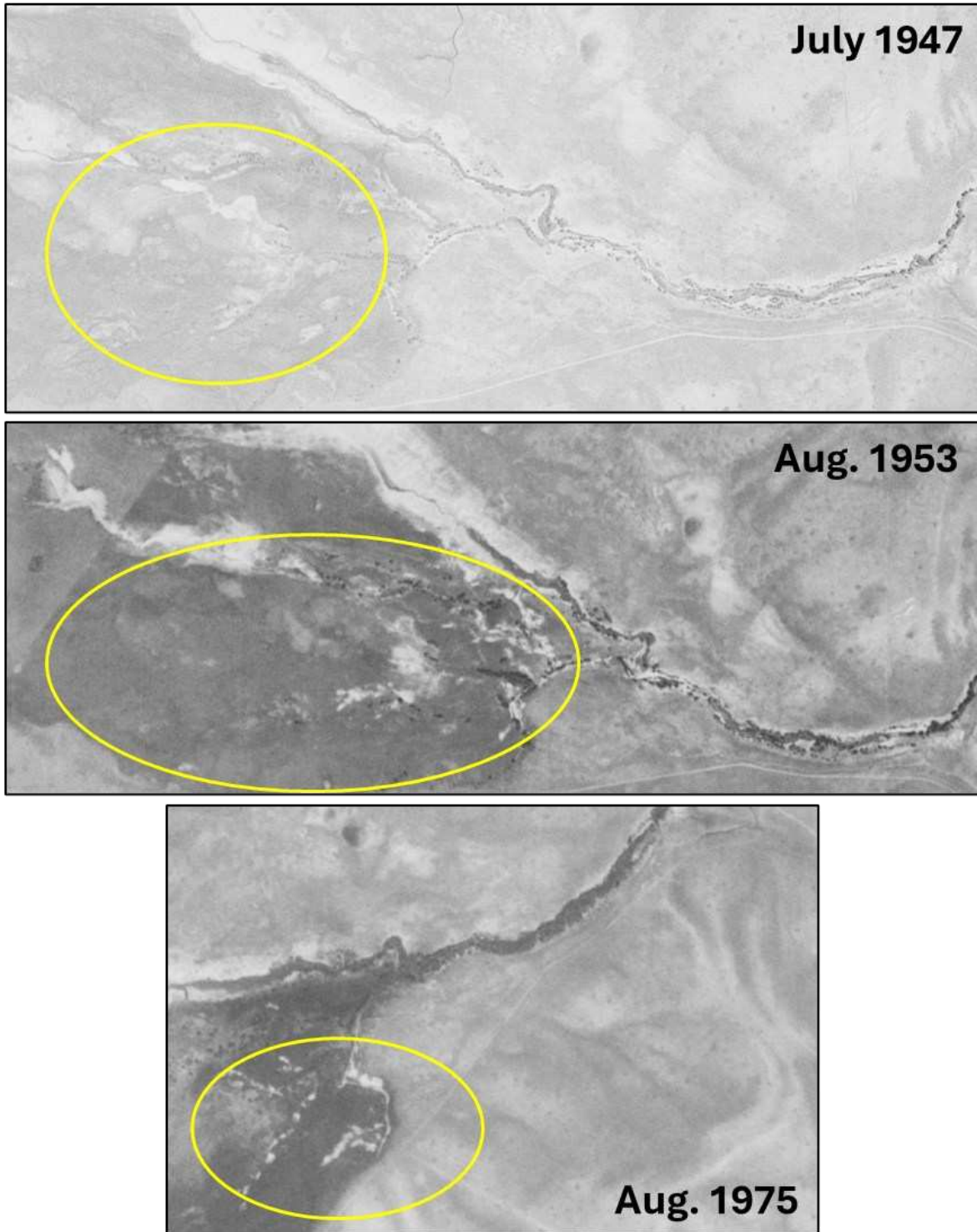


Figure 30. Historical aerial imagery of North Sand Creek alluvial fan, with images from July 1, 1947; August 20, 1953; and August 3, 1975. Yellow ovals highlight areas of sand deposition near the current State Line Ranch irrigation diversion and hay fields.

4.7.3 Alluvial Fan Binary Classification Model

Using an *xgboost* binary classification model, I predicted “vegetation” or “sand” surface cover on PlanetScope images of the North Sand Creek alluvial fan, covering the years 2017-2025.

Surface classification images for each year are presented in Appendix A. The overall accuracy of the model was 0.9955, with a sensitivity of 0.99 and specificity of 0.75. Lower specificity resulted in higher false negative rates, in this case an overclassification of “vegetation” control points as “sand.” Implications of low specificity are addressed in the discussion (section 4.8).

By differencing year-to-year classified rasters, I produced a record of area newly classified as sand during each runoff season from 2018-2025, as well as total classified sand area and total classified vegetation area (

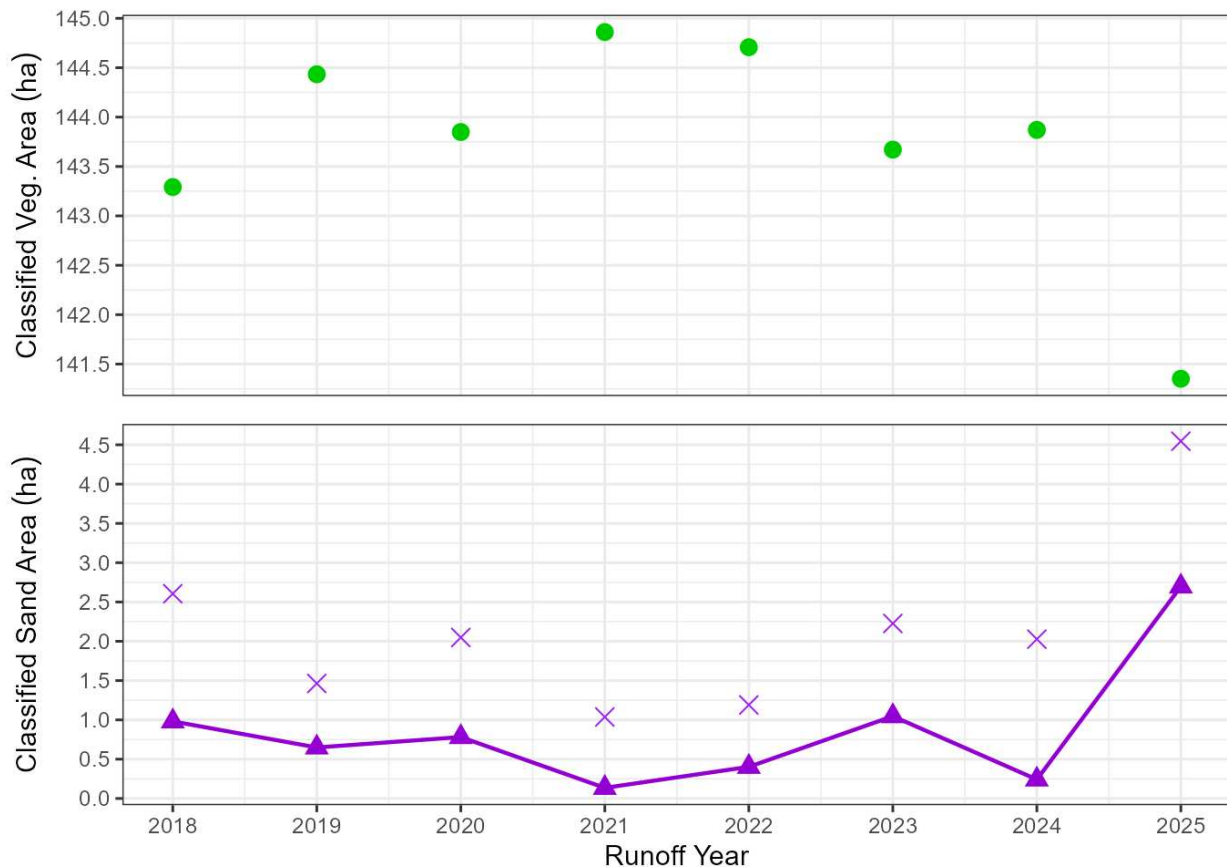


Figure 31). Images showing differences in cover classification on the proximal alluvial fan for the years 2019, 2020, 2022, and 2023-2025 are shown in Figure 32a-f.

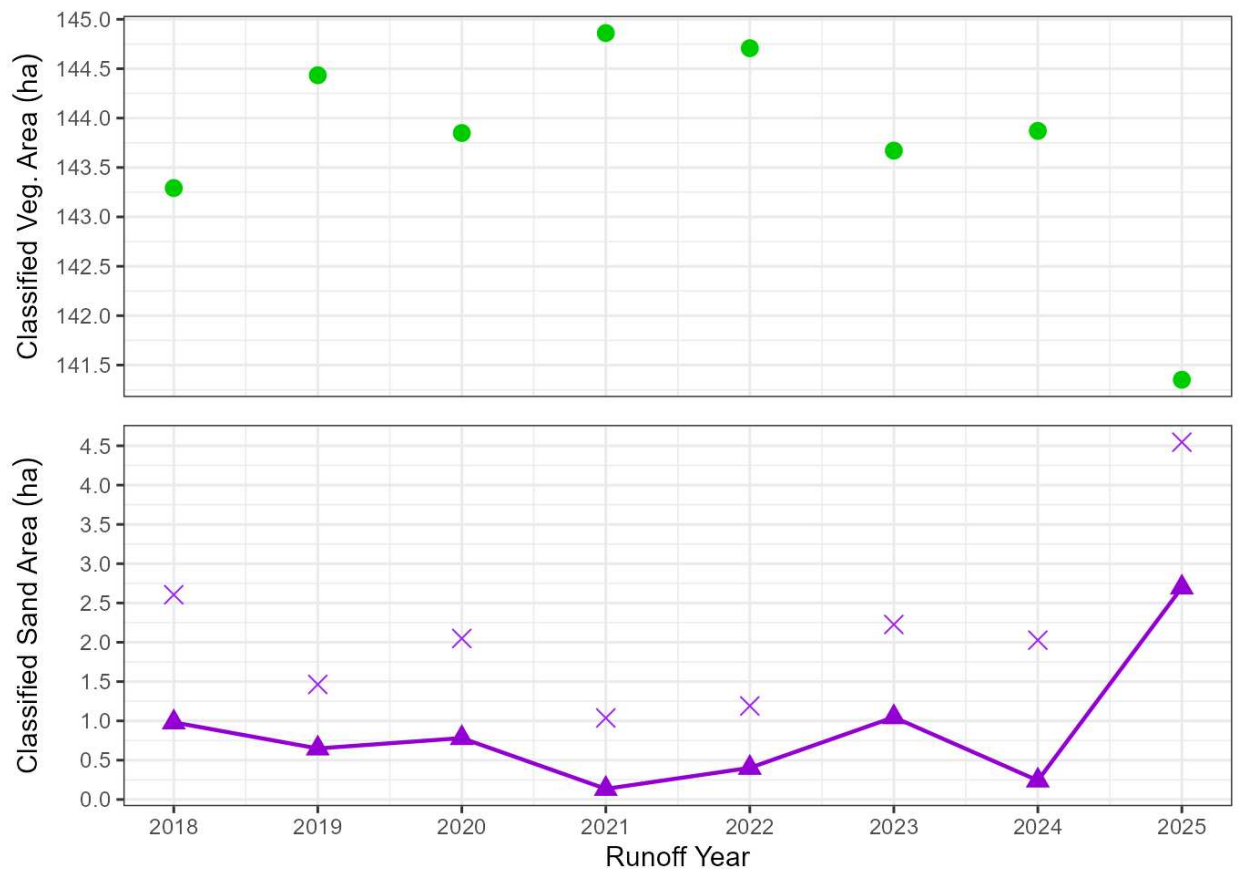


Figure 31 shows year-to year shifts in total classified sand area (purple X). Of note, total classified sand area decreases by over 1 hectare between 2018 and 2019 and between 2020 and 2021. In both pairs of years, new sand classification (purple triangle) also decreased between years. Only 0.14 ha was classified as new sand in 2021, compared to 0.78 ha in 2020. Years with greater new sand classification correspond to years with lower total classified vegetation area (green circles). The years with the greatest new sand classification are 2023 (+1.0 ha) and 2025 (+ 2.7 ha); the 2025 value is more than double any previous year.

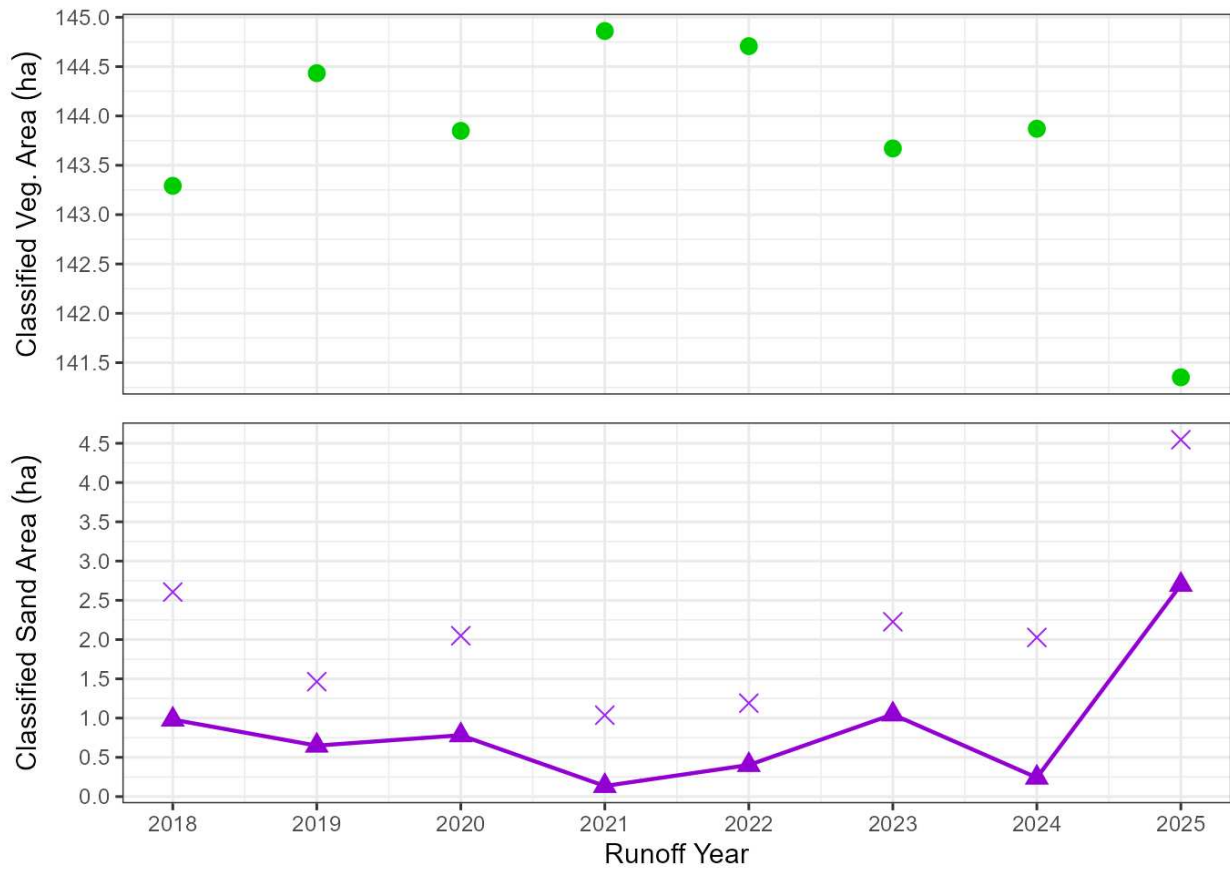


Figure 31. Total area classified as sand (purple X), area of new classified sand (purple triangle), and total area classified as vegetation (green dot) for water years 2018-2025. New sand deposition represents area of patches where surface classification changes from “vegetation” to “sand” on the alluvial fan AOI.

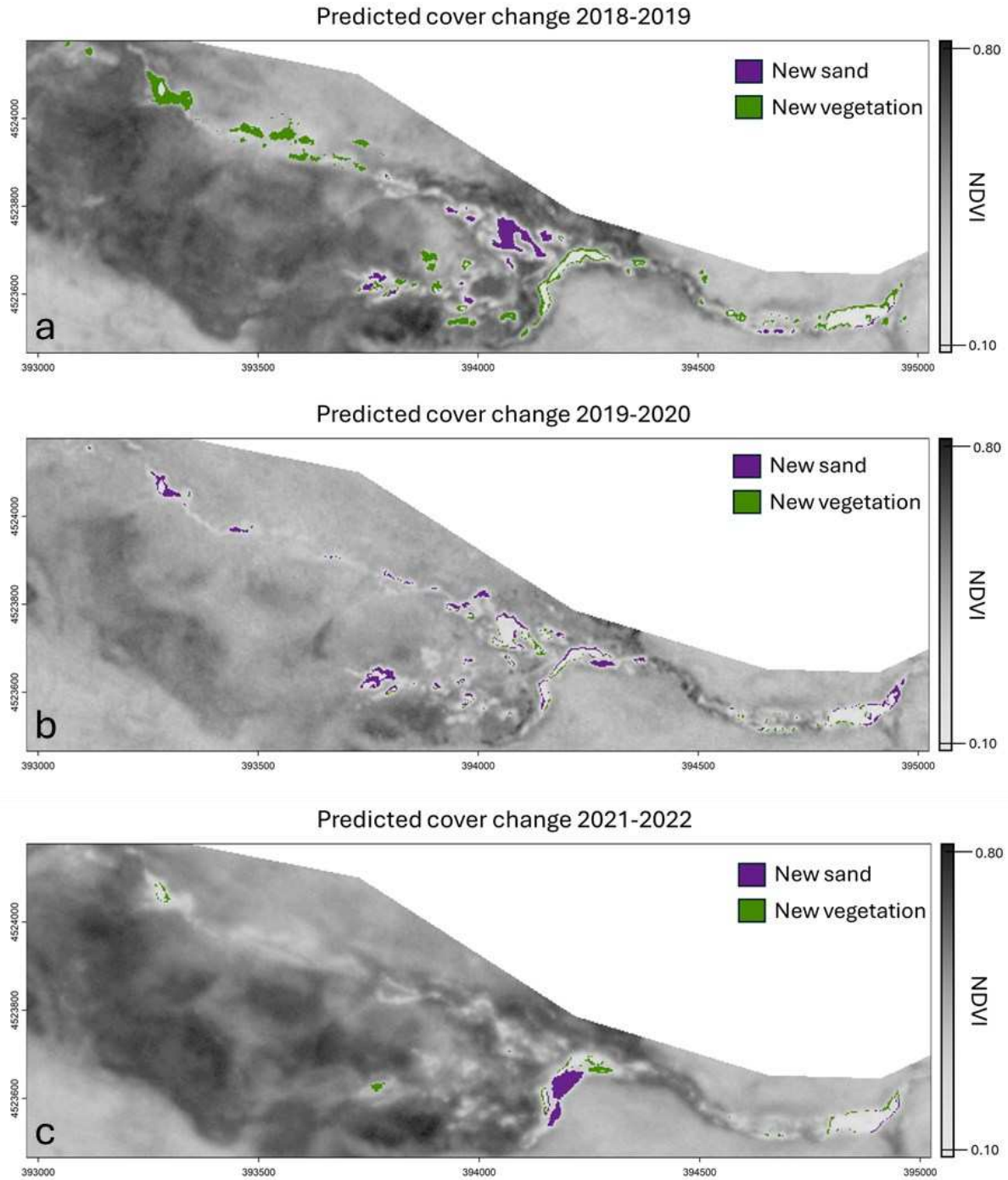


Figure 32a-c. Year-to-year changes in alluvial sand cover and vegetation cover on the upper (proximal) part of the North Sand Creek alluvial fan. Panel a) shows sand deposition from the 2019 runoff year, when Grabowski observed a sediment wave and mass sand export; b) shows deposition during the following year, 2020; c) shows deposition of a large sand area at the State Line Ranch diversion in 2022.

Figure 32a-c shows classified new sand and new vegetation on the proximal part of the alluvial fan near the State Line Ranch irrigation diversion for the year pairs 2018-2019, 2019-2020, and 2021-2022. Areas of new sand and new vegetation represent changes that occurred during the runoff season of the later year. The grayscale basemap shows NDVI (normalized differential vegetation index) values, with darker colors indicating greater values of NDVI. In Figure 30a, the alluvial fan has relatively high values of NDVI, and areas of green indicate that areas that were classified as sand in 2018 have switched to vegetation over the 2019 water year. Areas classified as new sand are distal (downstream) of the State Line diversion. The year 2019 has the fourth-largest modeled increase in sand cover over the 2018-2025 record, at 0.98 ha. New vegetation is mostly visible around the edges of patches of bare sand, which are apparent because of their very low NDVI values, but large patches of new vegetation occur farther down the alluvial fan, distal to sand deposition.

New vegetation and sand classification for the 2020 water year is shown in Figure 32b. In 2020, the model classification shows far less new vegetation, new sand deposition both upstream of and distal to the irrigation diversion, and some areas of new vegetation from 2020 that have been reclassified as sand. New sand totals 0.65 ha. Notably, values of NDVI on the vegetated areas of the fan are much lower than in 2019. Changes from 2020-2021 were minimal and are not included in Figure 28. During the 2022 runoff season, the model classifies 0.4 ha of new sand just upstream of the state line diversion, creating a large sand patch that persists over the next three years (Figure 32c). Little deposition occurs elsewhere, and NDVI is relatively high on the fan.

Figure 302d-f shows classified new sand and new vegetation for the paired years 2022-2023, 2023-2024, and 2024-2025. Figure 32d shows 1.0 ha of new sand, expanding the sand flat

upstream of the irrigation diversion that was created in 2022. Areas of new sand also appear downstream of the diversion. No areas transition from sand to vegetation except for tiny patches at the margins of sand flats. In 2024, the area of both new vegetation and new sand is small. The model classifies only 0.24 ha of new sand in 2024, and new vegetation only appears along the margins of sand patches. NDVI is noticeably high (dark colors) in the hayfield on the western side of the AOI.

Between 2024 and 2025, the model predicts 2.7 ha of new sand on the alluvial fan. Most of the new sand visible in the classified image (Figure 32f) is downstream of the irrigation diversion in a large, connected patch, but there are also small areas of new sand and sand isolated from other sand areas. In previous years, much smaller areas of new sand were classified in this area. New sand is also classified around the margins of existing sand patches. NDVI values on the alluvial fan are noticeably lower in the 2025 image, with areas that were previously very dark (approaching NDVI = 0.8) becoming much lighter (NDVI around 0.1). Water year 2018 showed similar patterns of low NDVI and high classification of new sand (Appendix A).

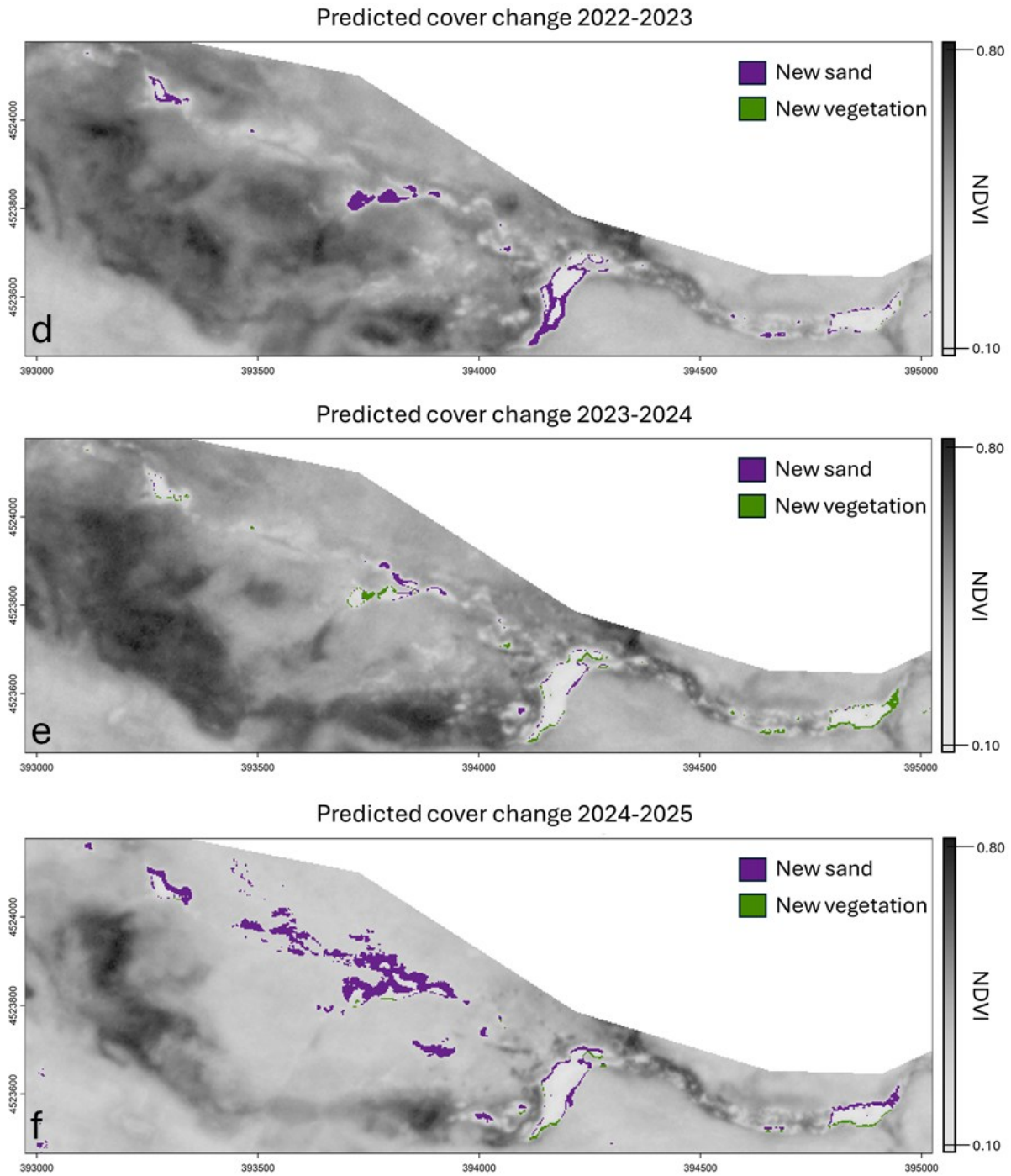


Figure 30d-f. Year-to-year changes in alluvial sand cover and vegetation cover on the upper (proximal) part of the North Sand Creek alluvial fan. Panel d) shows extensive new sand area in 2023; e) shows minimal changes in 2024; e) shows potential mode overclassification of sand during very dry conditions in 2025 – note the much lighter NDVI signal in the grayscale base image.

4.8 Alluvial Fan: Discussion

4.8.1 North Park Alluvial Fans

The North Sand Creek alluvial fan is an outlier in estimated volume and volume per drainage area among other alluvial fans along the east side of North Park. Its large estimated volume and volume per drainage area are likely linked to the catchment's high sediment output and the high mobility of the eolian sand transported by the creek. Alluvial fan planimetric area and volume are directly related to the sediment yield of the upstream catchment (Bull, 1977). The small alluvial fans along the east flank of North Park all formed within the same tectonic setting and are generally located at the downstream end of the drainages as they enter the axial valley of the Canadian River (Figure 9). Their contributing streams all head in the Precambrian crystalline rocks of the Medicine Bow Mountains and flow over Mesozoic sedimentary rocks (Madole, 1991; Tweto, 1979). While most of the streams that create alluvial fans on the valley floor interact with the inactive, vegetated dune field that covers 86 km² of northeastern North Park (including Government Creek), North Sand Creek and East Sand Creek are the only two streams that run directly alongside active dune fields. Of the two, East Sand Creek's volume per drainage area is unremarkable, while North Sand Creek is an outlier (Figure 27).

Because of its ephemeral tributary running alongside the active North Sand Hills dunes, North Sand Creek and its alluvial fan may transport a larger sand load than other streams along the east flank of North Park. Sand-rich alluvial fans may tend towards deposition of sediment via sheetflow, rather than channelized flow. High sand supply can cause an alluvial fan to tend towards laterally extensive, shallow distributaries, rather than a single entrenched channel (Blainey & Pelletier, 2008; Blair & McPherson, 2009; Winsemann et al., 2022). North Sand Creek's relatively high volume and high volume per drainage area of fan deposits reflect the high

volume of eolian-sourced sediment delivered from upstream. In this system, the eolian-fluvial linkage has led to the formation of an unusually large alluvial fan with seasonal sand deposition.

4.8.2 Historical Deposition Context

State Line Ranch reported sand aggradation in their irrigation network on the North Sand Creek alluvial fan beginning in 2011. However, aerial imagery extending as far back as 1947 shows evidence of areas of open sand on the alluvial fan, both at the site of the current diversion and distal (down the fan) from the diversion. Areas of open sand are also visible in aerial images from 1953 and 1975 (Figure 30). While I do not calculate or compare the area of sand that has historically been deposited on the alluvial fan, sand export to the alluvial fan is not an entirely new phenomenon. Sand deposition volume may have increased in 2011, and Grabowski (2020) records channel widening and sand deposition upstream of the alluvial fan after 2011. However, the onset of sand deposition on the alluvial fan cannot be credibly linked to increases in OHV use on North Sand Hills in the 2000s.

4.8.3 Surface Classification Model

The binary surface classification model predicted sand cover with mixed success. Model accuracy was high at 0.99, but specificity was lower at 0.75, indicting a high “false negative” rate. In this model, that meant an overclassification of “vegetation” points as “sand” points. This is not apparent in Figure 32a-e (years 2018-2024), where classification of sand patches seems accurate and relatively consistent with visual analysis. Areas classified as new sand correspond well with sand splays visible in RGB imagery, and areas classified as new vegetation are consistent with regrowth at the edge of sand patches. However, the model’s classification of sand in the 2025 runoff year image (Figure 32f) does not fully correspond to in-field observations of sand deposition. Figure 32f shows sand deposition in small splays downstream of the diversion

and along the edges of previously deposited sand patches; these depositional areas are corroborated by in-field observations (Figure 33), but a large patch classified as newly deposited sand is visible distal to the diversion. I did not observe any flow or alluvial sand deposition in this area during the 2025 runoff season, so the model classification of bare sand does not represent alluvially deposited sand. In the 2017-2025 images, the misclassified area is consistently only sparsely vegetated, with some patches of bare sandy soil visible between sagebrush. This area may correspond to an older sand deposit (see the Aug 1953 aerial image from Figure 28) but it is not classified as sand in any of the other 2017-2025 images.

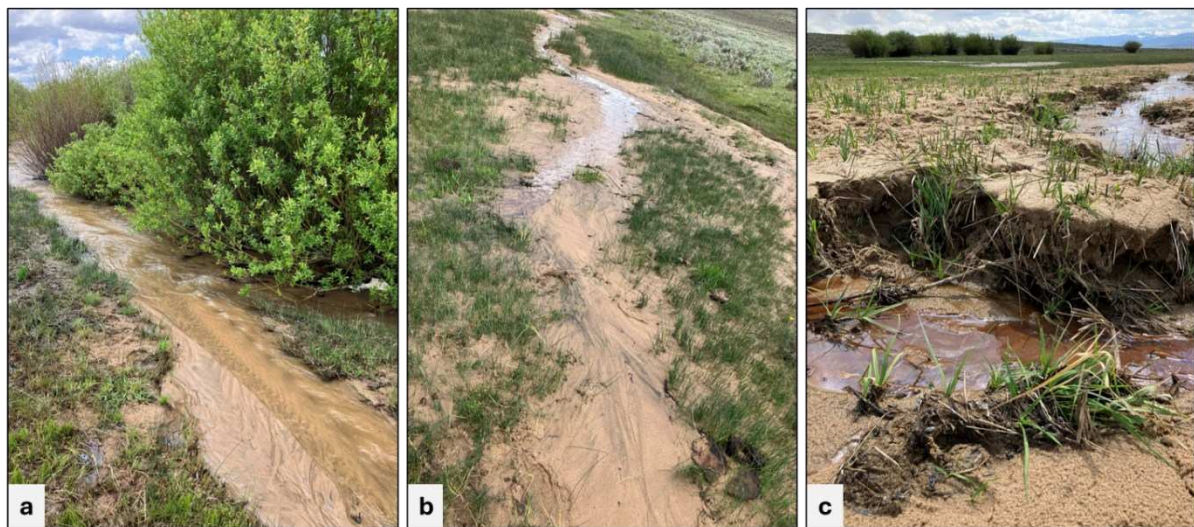


Figure 33. Examples of sand deposition on the North Sand Creek alluvial fan on June 3, 2025. (a) just upstream of the State Line diversion, showing multichannel flow and deposition on the channel margin; (b) and (c) show sand splays deposited downstream of the diversion and (c) also shows fluvial reworking of previously deposited sand.

The classification error likely reflects a lack of cover variety in the groundtruth points sourced from NAIP imagery. I picked vegetation points with clear continuous cover, and sand points with perfectly bare sand. This does not reflect mixed cover classes, as illustrated in Figure

33c, where freshly deposited sand may not fully cover vegetation. I could have included a third “transition” class to cover mixed pixels and reduce overclassification of vegetation as sand. The large area of sand in the 2025 image may also reflect changes in soil and vegetation moisture on the fan. The year 2025 was relatively dry. The NDVI is positively related to antecedent moisture conditions – the NDVI increases when plants are healthy and have greater water content in their leaves (Zhang et al., 2018). Conversely, when plants are stressed, the NDVI may be lower in vegetated or sparsely vegetated areas. This is reflected in Figure 32. The grayscale NDVI image is far lighter overall in 2025 when compared to the other water years, likely indicating that plants on the alluvial fan are water stressed or have even died back during the late summer. Because NDVI is a factor in the binary classification model, reduced NDVI may have caused increased classification of sand areas, or reduced plant leaf area may have caused the same. The model could be refined by adding a factor to represent antecedent moisture conditions, by using imagery with wider spectral and longer temporal coverage such as Sentinel or Landsat imagery, or by employing the linear spectral unmixing techniques that Grabowski (2020) used to produce a record of dune vegetation coverage on the North Sand Hills. Differences in sand classification based on antecedent moisture conditions complicate the comparison of sand deposition between water years, but I interpret the model results below.

Between 2018 and 2019, total sand cover on the *fan* AOI decreased by 1.1 ha, even as new sand deposits totaled 0.65 ha. During the 2020 runoff season, total sand area increased by 0.55 ha and new sand area totaled 0.78 ha. Between 2020 and 2021, total sand area sharply decreased by over 1.0 ha, while sand deposition was relatively low, at 0.14 ha. During the 2019 runoff season, Grabowski (2020) reported mass sand export from the *actadj* tributary totaling 9,600 m³; in comparison to the observed lack of adjustment and sand export in 2025, 2019 was a

year of enormous geomorphic change. However, calculated new sand deposition area on the alluvial fan was not exceptionally high during the 2019 runoff season, and was higher the following year, in 2020. This may reflect a lagged response to *actadj* sand export in the *inactadj* and *fan* segments. Coarse sediment slugs may translate through fluvial systems at a rate of up to 1.5 km per year, but noncohesive fine sediment – such as North Sand Creek’s eolian sand – likely moves faster due to high grain mobility (Nicholas et al., 1995). While the speed of sand slug movement through the *inactadj* segment has not been measured, it is plausible that a sediment wave sourced from the *actadj* segment may take longer than a single year to move through the roughly 6.5 km between the tributary junction and the alluvial fan.

Furthermore, sediment slugs moving through a fluvial system may temporarily increase storage in bank deposits and bedforms, decreasing the magnitude of the sediment downstream, but potentially leading to increased sediment transport over a longer duration due to remobilization of stored sediment (James, 2010). Grabowski (2020) noted that the rate of sediment export from behind logjams decreased with downstream distance in the upper reach of the *inactadj* segment, decreasing the magnitude of channel adjustment. In North Sand Creek, sand temporarily stored in the *inactadj* segment during years of high sand export from the *actadj* segment may be remobilized in the following years as upstream sediment supply decreases. This could lead to elevated sediment export to the alluvial fan in the year following export from the *actadj* channel, as illustrated by the 2019 and 2020 runoff seasons.

However, lower classified sand deposition on the *fan* even during years of high sand export from the *actadj* segment may simply reflect vertical accumulation of sand, instead of increased depositional area. Layers of sand may deposit on patches already classified as sand, increasing the thickness of the sand layer without significantly increasing the area of the sand

patch. High resolution elevation surveys of the alluvial fan (employing techniques such as RTK GNSS surveys or UAV Lidar) repeated over several runoff years and over the course of each runoff season could be used to determine year-to-year vertical accretion in *fan* depositional zones.

The classification of 2.5 ha of new sand area in 2025 does not accurately represent alluvial deposition of sand, but it may indicate interannual variability in the balance between fluvial and eolian processes in the North Sand Creek catchment. I observed shallow flow and fluvial transport of sand on the alluvial fan and wide, sandy reaches through early and mid-June of 2025 (Figure 34a). By early July, flow on the alluvial fan and lower reaches was intermittent, and by July 22, no flow reached the alluvial fan (Figure 34b), likely due to upstream infiltration of declining discharge. Throughout July and August, I observed eolian transport of dry sand on large sand patches. Ripples formed perpendicular to the prior flow direction, and fluvial bedforms were destroyed by eolian transport and deposition. Within two months, fluvial sand transport on the alluvial fan was supplanted by eolian transport.

Eolian processes are known to rework and overprint alluvial fan deposits in arid and semi-arid environments. Sand sheets mobilized by wind may even overwhelm alluvial sedimentation (Blair & McPherson, 2009). I observed the switch to eolian processes and reworking of fluvial deposits on areas that had been fluvially active in 2025, but this may have also occurred in fluvially inactive areas such as the large patch of classified “new sand” in Figure 32f. Eolian transport increases when sediment moisture decreases (Jackson & Nordstrom, 1997). Decreases in seasonal soil moisture in arid and semi-arid climates may cause seasonal dieback of shrubs, which in turn decreases surface roughness and increases the area of open, mobile sediment patches. Sustained growth of perennial vegetation requires multiple years of adequate

moisture, and a single dry season may cause dieback (Draut et al., 2012). On the North Sand Creek alluvial fan, the low moisture conditions of the 2025 runoff season may have caused vegetation dieback, increasing a) the actual and classified area of bare sand; and b) the rate of eolian transport of sand previously deposited by fluvial processes. This likely indicates a shift towards eolian dominance throughout the North Sand Creek system, where dry conditions and vegetation dieback may have increased the rate of eolian deposition in the *actadj* and *inactadj* channels.



Figure 34. Photos of *inactadj* to *fan* transition, showing variability in fluvial and eolian dominance over the 2025 runoff season. Photo (a) was taken on June 3, 2025, and shows wide, shallow flow over a sand bed exceeding 30 m wide; (b) shows the same area from a different angle on July 22, 2025, with no flow, completely dry sand, and ripples perpendicular to fluvial flow direction indicating eolian transport.

4.9 Late Holocene Aggradation & Incision: Results

4.9.1 Evidence for Late Holocene Terrace

I document a remnant terrace along 3875 m length of the North Sand Creek *inactadj* segment, from 325 m downstream of the tributary confluence to 4200 m downstream of the

tributary confluence. The terrace is nearly continuous along the southern (river left) edge of the *inactadj* segment.

This “t₂” terrace is discernible in the field (Figure 35b) but is even more distinct when seen in the DEM and REM displayed in Figure 35a. The t₂ tread lies an average of 3.9 m above the t₁ abandoned floodplain and an average of 4.9 m above the modern active channel. It is vegetated with sagebrush and sparse stands of aspen and limber pine. In contrast, the lower t₁ is heavily vegetated with willow and alder except for areas of bare sand. Alders along the active channel margin and in the active channel are very young, likely less than 20 years old (John Sanderson, Center for Collaborative Conservation, Oct. 2025, pers. comm.). The t₂ has a gradient of 0.02 m/m, which matches the measured gradient of the t₁ abandoned floodplain. Both are slightly steeper than the average gradient of the *inactadj* channel, which is 0.018 m/m.

At 350 m downstream of the tributary confluence, I observed an exposure of a dark-colored soil profile developed in the t₂ tread at the top of the riser between the t₁ and t₂. The local tread is 4 m above the modern stream bed, at an elevation of 2568 m. Fine lamination and dark organic content indicate development under anoxic, subaqueous conditions. Development of a dark, organic-rich soil profile, or histosol, in the semi-arid mountains of Colorado has been observed in filled beaver ponds that transition to beaver meadows (Kornse and Wohl 2020). Paired with evidence of prior beaver habitation, histosols in Colorado are likely to indicate deposition in a former beaver pond. Across the stream valley at a similar elevation of 2567 m, an exposure of greyish sand grades into a lens of gravels, which are then overlain by another layer of sand similar in color and texture. The gravel clasts are crystalline, corresponding to the basement rocks exposed at higher elevations in the North Sand Creek perennial catchment rather

than the Jurassic sedimentary rocks exposed on the valley floor (Tweto, 1979; Madole, 1991), indicating fluvial transport from higher in the catchment.

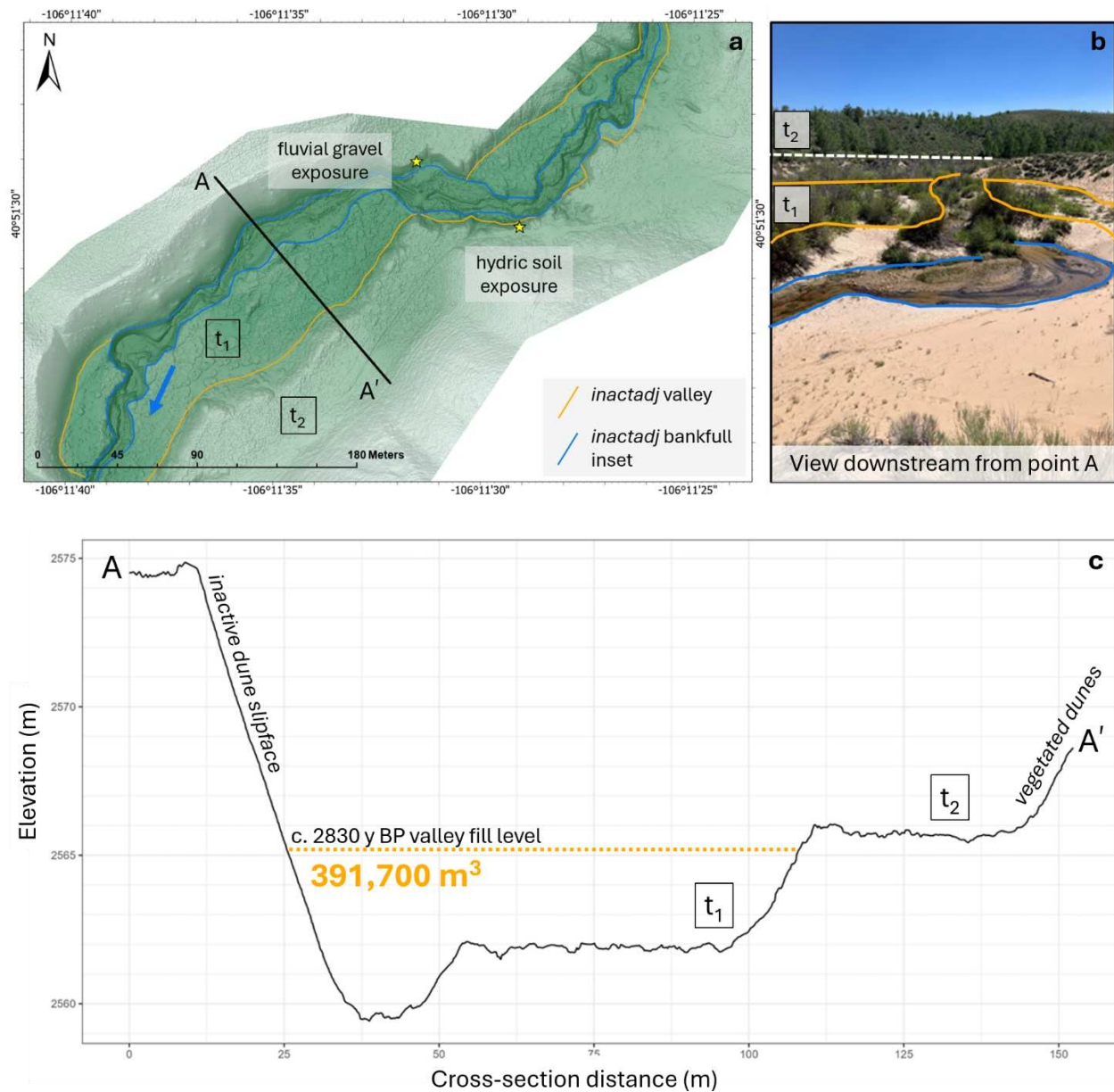


Figure 35. Illustrations of North Sand Creek *inactadj* valley cross section. (a) Delineation of valley width (orange) and inset width (blue), stratigraphic markers (yellow stars), cross section A-A', and labeled t_1 and t_2 surfaces. (b) View downstream from point A, with inset, valley, and surface labels. (c) The elevation profile across A-A', showing bounding dunes, inset channel, abandoned floodplain t_1 , and terrace t_2 elevated 4 m above t_1 .

Ahlbrandt and Andrews (1978) describe a “peat layer” exposed at the edge of the North Sand Hills dune field. The mapped location of their peat layer corresponds to the location of the exposed histosol described above (see Figure 2 from Ahlbrand and Andrews 1978, included in Appendix A). Ahlbrandt and Andrews provide a ^{14}C date of 2830 ± 200 yBP for the hydric soil layer, indicating that deposition under ponded conditions likely ceased at that time.

I interpret the stratigraphic markers, topographic features, and the ^{14}C date as evidence of a 4 m higher valley floor in the North Sand Creek *inactadj* segment 2830 yBP and a period of fluvial incision that followed. Between 2830 yBP and the present, local base level along North Sand Creek dropped by roughly 4 m. The local histosol, indicating deposition under ponded conditions in areas, as well as fluvial gravels of the t_2 deposit, suggests that the circa 2830 yBP valley floor was a mosaic of running and ponded water.

4.9.2 Estimated Late Holocene Sediment Export

Using surface elevations and valley width extracted from the UAV-generated DEM, I estimated the net volume of sediment exported during incision after abandonment of the t_2 . Since 2,830 yBP, over 391,000 cubic meters of sediment were removed from the t_2 and exported downstream. Based upon this, and assuming erosion took place at a steady rate since 2830 ± 200 yBP, a minimum estimate of annual sediment export is $130 - 149 \text{ m}^3/\text{yr}$. Assuming an average sediment density of 2650 kg/m^3 , this is a sediment export rate of $343,000 - 395,000 \text{ kg/yr}$. Averaged over the t_2 valley floor area ($95,000 \text{ m}^2$), this represents a minimum incision rate of $1.4 - 1.6 \text{ mm/yr}$ ($1.4 - 1.6 \text{ m/ka}$) within the North Sand Creek valley.

4.10 Holocene Aggradation & Incision: Discussion

4.10.1 The Past Valley Floor

Roughly 2830 yBP (Ahlbrandt & Andrews, 1978), deposition of organic-rich sediment on the t_2 ceased at the observed organic horizon. Since that time the stream has incised an average of 4 m through valley floor sediment. This period of incision abandoned the t_2 , and then the t_1 floodplain was inhabited by beavers before their extirpation in the later decades of the 20th century. Aggradation of t_1 may have been initiated by sediment and water storage behind beaver dams. The historical presence of beavers and beaver dams in North Sand Creek suggests that the valley floor may once have been wetter, more hydrologically connected to the channel, and more heavily vegetated by riparian plants.

Exposed organic-rich histosols that developed on the t_2 tread suggest that before 2830 yBP, the 4 m higher valley floor may have been similarly inhabited and modified by beavers. I observed a histosol in the t_2 at the upstream end of the terrace (soil shown in Figure 7; location shown in Figure 35a), as well as a similar layer of dark, organic rich soil in the downstream reaches of the *inactadj* segment (Figure 36). In Figure 8, there is greater than 1 m of sediment accumulation represented in the dark histosol layer. In the semi-arid setting of Colorado, organic-rich soils that have formed under anoxic, ponded conditions are very likely to have formed in beaver ponds, especially when evidence such as chewed wood or relict dams also suggests beaver occupation (Kornse & Wohl, 2020). Habitation by beaver may have led to aggradation of sand, gravel fill, and organic rich horizons on the valley floor, forming the t_2 (Westbrook et al., 2011; Polvi & Wohl, 2012). The presence of t_2 suggests an aggradational regime caused by long term beaver habitation during a period of climatic conditions favorable to sediment aggradation and beaver survival before 2830 yBP.



Figure 36. Surficial stratigraphy revealed in cut bank along *inactadj* segment. Section of cut bank shown in photo is approximately 2 m tall.

4.10.2 History of Incision and Sediment Export

The cause of post t_2 incision at North Sand Creek is currently unknown. Fluvial systems may incise for a variety of reasons, such as local base level fall, climatic factors that affect the balance between discharge and sediment supply, or the crossing of internal geomorphic thresholds (Schumm, 1977). In addition to the 2830 ± 200 yBP date for the organic sediment exposed at North Sand Creek, Ahlbrandt and Andrews (1978) also carbon-dated a peat layer exposed along East Sand Creek to 2110 ± 200 years before present. They state that the East Sand Creek peat layer was mostly covered by dune sand and do not mention terraces or incision along

the creek. Visual analysis of the DEM shows evidence of some incision, but no field work was conducted along East Sand Creek. This similar-aged organic sediment in a neighboring drainage may indicate a regional shift in climate or water balance around 2800 – 2100 yBP, or a lagged response to an earlier change.

Records of late Holocene climate change in the Rocky Mountain region do not provide a clear cause for incision or base level drop in North Park but suggest that regional climatic variability increased between 4500 yBP and 2800 yBP. This may have affected runoff, sediment supply, or beaver habitat suitability at North Sand Creek. Insect fossil assemblages preserved in bogs and ponds in the northern Rocky Mountains show that regional summer temperatures were likely warmer than present before 4500 yBP (Elias, 1985), remaining warm until around 3000 yBP, although winter temperatures may have decreased (Elias, 1996). After 3000-2800 yBP, regional temperatures became more variable, oscillating but generally decreasing toward cooler modern conditions (Elias, 1985; Elias, 1996). Pollen and plant macrofossils from the western slope of the Colorado Rocky Mountains indicate that after 4000 yBP the region likely shifted from a summer-dominated precipitation regime to a winter-dominated precipitation regime. Concurrently, the climate became drier between 4000 and 2600 yBP (Fall 1997). Shifts toward a drier, somewhat cooler, and more variable climate in the Colorado Rocky Mountain region between 4500 and 2600 yBP precede the ^{14}C dates of incision at North Sand Creek and East Sand Creek. However, incision could potentially represent a lagged response to changes in the amount and timing of precipitation. Another possibility is that drier conditions and higher climatic variability led beavers to abandon the North Sand Creek drainage around 2830 yBP. In Yellowstone National Park, Wyoming, radiocarbon dating of beaver pond deposits in small drainages show that beaver occupation and damming ceased during periods of severe drought

during the late Holocene (Persico and Meyer, 2009). If discharge is low to ephemeral during periods of drought, beaver may not succeed or may seek more suitable habitat. Beaver abandonment of the drainage during the late Holocene could have initiated a period of incision as beaver dams failed. Further study of late Holocene climate and geomorphology in North Park is required to determine the trigger for North Sand Creek's 4 m incision.

Grabowski's (2020) observation of a translating sediment wave and seasonal aggradation and erosion cycles of meter-scale amplitude suggests that historical incision could have happened very quickly. Grabowski estimated that $9,600 \text{ m}^3$ of sand were exported from the *actadj* ephemeral channel in a single runoff season. This rate of sand export is 65 times higher than the average rate I estimate for incision through the t_2 during the late Holocene. While Grabowski's estimate represents only export from the *actadj* tributary during a wet year, it provides some idea of the speed of the geomorphic change possible in a system with a highly mobile, non-cohesive sediment load. Similarly rapid sediment export and incision have been reported in other semi-arid systems in the southwestern U.S. Along a 55 km reach of the Rio Puerco arroyo in northern New Mexico, downcutting increased arroyo volume by $44.6 \times 10^6 \text{ m}^3$ over 8 years between 1927 and 1935, a change of $5.6 \times 10^6 \text{ m}^3$ per year (Friedman et al., 2015). Incision of up to 30 m has been recorded during decadal arroyo cut and fill cycles in the late 19th and early 20th centuries (Harvey and Pederson, 2011). At Frijoles Canyon in Bandelier National Monument, local rates of incision through unconsolidated gravels during the late Holocene are up to 4 m/ka (Reneau, 2000), exceeding the late Holocene average rate I estimate for North Sand Creek (1.4-1.6 m/ka). Alongside Grabowski's estimate of sand export from the ephemeral tributary of North Sand Creek, these examples suggest that incision of the current valley could have occurred on a decadal or annual time scale.

5. SYNTHESIS

Here, I present a conceptual model of interannual sediment dynamics and long-term disturbance in North Sand Creek, then suggest areas of future study.

5.1 Sediment Dynamics and Geomorphic History

Observed sediment dynamics in North Sand Creek varied considerably between 2019 and 2025. In 2019, Julia Grabowski documented a sand wave that caused meter-scale cycles of aggradation and incision to translate through the *actadj* ephemeral tributary and the upper reaches of the *inactadj* segment. In 2025, runoff generation was not sufficient to trigger a sediment wave in the *actadj* segment, and no cross section adjustment was recorded above the threshold of detection for the survey method used.

North Sand Creek's sediment regime varies interannually based on threshold activation of stored sediment in the *actadj* ephemeral tributary. Sand annually accumulates in the *actadj* ephemeral tributary via natural eolian sand transport, hillslope processes, and OHV-induced sand slumping and bank erosion. During relatively wet years such as 2019, above-median winter snowpack accumulation or rapid meltout creates enough runoff to initiate flow in the *actadj* tributary, mobilizing accumulated sand. The sand propagates downstream as a sediment wave, causing meter-scale aggradation and incision that is attenuated by logjams. Some proportion of sand is deposited on the alluvial fan during the same runoff year, while the rest is stored in bank terraces and bed sediment.

During relatively dry years, such as 2025, runoff is not sufficient to initiate flow or a sand wave in the *actadj* segment. Sand stored there is not mobilized, and accumulation via eolian, hillslope, and OHV processes continues. No pulse of sand enters the perennial mainstem. Instead, sand continues to enter the stream in the *inactadj* section through terrace erosion and

direct addition along partially stabilized dune slipfaces. The magnitude of bank-to-channel sand addition along the *inactadj* segment is small relative to sand loading and export in the *actadj* segment. Sand transport during dry years likely proceeds by headward incision through sand wedges deposited on the bed, occurring simultaneously at the transitions between a series of transport and depositional reaches separated by slope breaks. Sand movement through the channel and export to the alluvial fan continues for years after tributary activation due to remobilization of lagged sand deposits and addition of sand in the *inactadj* segment. As of 2025, the final zone of aggradation begins at roughly 4000 m downstream of the tributary junction, approximately 3.2 km upstream from the State Line irrigation diversion. While the stream has not yet exited confinement and become an alluvial fan at 4000 m, aggradation dominates downstream from that point. The discontinuous zones of erosion and incision observed in 2025, precipitated by sand inputs from a prior sediment wave, are an annual-scale example of Schumm's concept of complex response.

North Sand Creek's sediment regime is interannually variable, with sand waves triggered by runoff conditions that seem to recur on a sub-decadal frequency followed by years of sustained lower-magnitude sand export. Sand export to the alluvial fan is apparent in historical aerial imagery dating to 1947, before extensive OHV use on North Sand Hills. OHV use exacerbates sand loading, sand export, and rapid channel adjustment, but the hydrology and sediment regime of North Sand Creek are inherently variable.

North Sand Creek's interannual hydrologic and geomorphic variability occurs within the context of past disturbances and ongoing geomorphic adjustment to those disturbances. I document 4 m of incision from a paleo-valley floor level (t_2) to the modern valley floor (t_1). Incision left behind a longitudinally extensive terrace visible along the *inactadj* segment. Based

on a ^{14}C -dated hydric soil layer on the upper edge of the t_2 terrace, accumulation of organic matter ceased and incision began around 2830 ± 200 yBP (Ahlbrandt and Andrews, 1978). Using the dimensions of the modern valley, I estimate that a volume of $391,700 \text{ m}^3$ of sediment was exported from the stream corridor between 2830 yBP and the present. Averaged over that timespan, I calculate sediment export rates of $130\text{-}149 \text{ m}^3/\text{year}$, equivalent to $343,000\text{-}395,000 \text{ kg/yr}$. Averaged over the surface area of the excavated valley, this is an average erosion rate of $1.4\text{-}1.6 \text{ mm/yr}$. Erosion may have occurred episodically over this time period or rapidly over a shorter period. The cause of incision is unknown, but may be linked to regional shifts toward a cooler, drier, and more variable climate that occurred between 4500 and 2600 yBP. These shifts could have changed the sediment-water balance in the drainage or caused local beaver extirpation, initiating incision. Observations of the terrace and incised valley volume demonstrate that North Sand Creek has exported large volumes of sediment throughout the Holocene. The stream may not be fully adjusted to the perturbation that caused past incision, keeping sediment export rates high. The North Sand Creek alluvial fan also lends credence to the idea of high sediment export throughout the Holocene; it is an outlier in estimated volume and volume per drainage area when compared to other fans in North Park.

Hydric soil exposures on the t_2 surface indicate deposition of organic sediment under ponded, anoxic conditions. In Colorado mountain streams, organic-rich histosols are most likely to form under beaver ponds on the channel or floodplain. The dark, organic-rich soil exposures I observed suggest that beavers inhabited the valley floor before incision, and that their damming may have contributed to long term aggradation within the valley. After Holocene incision set the modern valley template starting around 2800 years ago, beavers remained on the landscape. I counted 315 relict beaver dams on the t_1 surface and in the inset channel of the *inactadj* segment;

8 relict dams in the lower reaches of the *actadj* segment; observed at least one relict dam in the *upstr* segment; and found many examples of chewed wood in the riparian corridor and surrounding uplands. All dams were abandoned and breached, and I saw no evidence of current beaver habitation. Analysis of historical aerial imagery constrained local beaver extirpation to the late 1970s or early 1980s. Pressures including cattle grazing and dam removal by State Line Ranch to protect irrigation infrastructure may have contributed to beaver population decline throughout the 20th century and eventual local extirpation. I interpret the current planform and valley-cross section as a legacy of beaver occupation and extirpation. Throughout the *inactadj* segment, North Sand Creek is incised, narrow relative to valley width, and hydrologically disconnected from the floodplain. These are common geomorphic legacies of beaver extirpation and dam failure: when beavers leave the landscape, dams eventually fail, causing increases in stream velocity, downstream entrenchment that eventually migrates headward through beaver dam deposits, simplification of river planform, reduction of floodplain complexity, and lowering of the water table (Polvi and Wohl, 2013; Wohl, 2021). My observations of stream planform and valley characteristics align with the typical attributes of post-beaver landscapes.

Over the late 20th century, North Sand Creek lost sources of hydraulic roughness and flow obstruction, heterogeneity, and sites of sediment storage in the channel and disconnected floodplain as beaver were removed from the landscape, reducing the stream's ability to attenuate fluxes of sediment and water and most likely increasing sediment transport and export. Based on the estimated beaver dam density supportable in the Colorado Rocky Mountain region (Scamardo et al., 2024), the historic beaver population could have constructed enough dams to store 62,700 m³ of sediment in the active channel and on the valley floor. Potential beaver dam storage within the active channel alone totals 10,300 m³. If beavers repaired, augmented, and

built new dams each year, storage volume could exceed the export of 9600 m³ of sand from the *actadj* segment recorded by Grabowski in 2019. Without the attenuation potential and storage capacity provided by beaver modifications, North Sand Creek lost the ability to attenuate or absorb sand waves initiated in the *actadj* tributary.

Without beavers, the stream is less resilient and more prone to rapid geomorphic change. Natural hydrologic and sediment regime variability, augmented by OHV-induced sediment accumulation, is the cause of sand wave initiation. However, propagation of meter-scale aggradation and incision and mass sand export to the alluvial fan would likely be reduced or slowed in the presence of beavers and beaver dams.

This study provided millennial, decadal, and interannual annual geomorphic context for observed patterns of channel disequilibrium in North Sand Creek and its ephemeral tributary and contributed to the scant literature on the impact of beaver in highly mobile sand-bed environments. In the recent past, beavers survived and succeeded in North Sand Creek despite highly variable seasonal sediment loading and, over the time of their habitation, built dams at a linear density far higher than any other documented system. This indicates that beavers may adjust the spacing of dams and the rate of dam building based on upstream sediment loading, a concept that requires further investigation in environments with dynamic sediment regimes. Hydric soils exposed on the t₂ surface demonstrate (i) past beaver occupation in the system and (ii) that long term beaver habitation can contribute to multi-meter scale valley aggradation even in seasonally dynamic systems, while the 4 m of incision raises questions about base level drop in the North Park basin. Further investigation of geomorphic and paleoclimatic evidence in the region is required to determine the cause of incision, and whether the trigger was regional or local. Further study and multi-year monitoring of cross section and long profile adjustment with

high resolution survey equipment such as total station, RTK GPS, or repeat UAV Lidar is required to determine the nature and magnitude of geomorphic changes during dry years.

5.2 Management and Restoration

Restoration in degraded streams is undertaken with the aim of returning a process, function, form, ecological service, or human-centered service to a perceived pre-disturbance potential (Shields et al., 2003). However, restoration is often conducted without an understanding of hydrologic, geomorphic, or ecological context (Wohl et al., 2005), or with an approach that over-emphasizes static, form-based techniques do not fully address the causes of geomorphic change (Simon et al., 2007). Beechie et al. (2010) introduced the term “process-based restoration” to describe stream restoration approaches that aim to reestablish biological, physical, and chemical processes at magnitudes and rates needed to form and sustain river and floodplain ecosystems. They provide four principles of process-based restoration (PBR) to guide scientists, managers, and practitioners involved in restoration:

- 1) Target root causes of habitat, ecosystem, and physical system change.*
- 2) Tailor restoration actions to local potential.*
- 3) Match the scale of restoration to the scale of the problem.*
- 4) Be explicit about expected outcomes (to 4, I add: make a plan to monitor outcomes).*

Management and restoration efforts at North Sand Hills intended to reduce downstream aggradation have been underway since at least 2019 (Grabowski, 2020), and implementation of in-channel structural interventions began in fall 2025 and is scheduled to continue in the following years (BIO-Logic, 2025). With acknowledgement of the work already invested in the restoration process, I apply Beechie’s principles of PBR to the thorny problem of restoration at North Sand Creek.

1) *Target root causes of habitat, ecosystem, and physical system change.*

Interventions at North Sand Creek should address the causes of mass sand export and rapid channel adjustment instead of reacting to the symptom. The Bureau of Land Management has installed fencing around most of the *actadj* tributary and around partially vegetated areas on the dunes. This has reduced OHV travel in, across, and adjacent to the ephemeral channel, addressing a *root cause* of sand wave initiation. BLM and future land managers should maintain the current fencing and extend the fence perimeter to include the area where the tributary exits the forest and runs adjacent to the dunes for roughly 150 m. This area is still used for OHV travel, accumulates sand over 1 m deep, and remains a potential sediment source. Outreach to OHV riders by the CSU Center for Collaborative Conservation will increase rider awareness of OHV impacts and deepen manager understanding of factors influencing patterns of OHV use.

Beaver extirpation left the stream without attenuation capacity and caused incision, simplification, and elevated sand transport throughout the stream corridor. Restoration at North Sand Creek must address this historical disturbance while remaining grounded in the geomorphic and ecological context. Addition of wood structures to the active channel addresses the problem of structural starvation (Beardsley, 2024), but I did not observe structural starvation North Sand Creek. Many channel-spanning pieces of large wood and logjams exist, and wood recruitment proceeds through bank erosion and deadfall. The root cause of rapid sediment transfer through the system is lack of sediment retention and storage, not lack of wood, although supplementing existing wood-based roughness in the channel could reduce flow velocity and entrainment of sand. Restoration structures constructed in sand-bed channels often fail through erosion that undermines the structure or erodes the bank around the structure (Shields & Smith, 1992; Shields et al., 1995; Shields et al., 2004; Shields et al., 2006; Shields & Knight, 2005). Thus, structures

in North Sand Creek must be located in areas where banks are relatively cohesive and in-channel sediment storage can be plausibly supplemented by storage on the valley floor. I recommend focusing on areas with low gradient and low inset depth where fluxes of sediment and water could be pushed on to the valley floor with well-placed structures (examples reaches include 3500-3800 m and heavily vegetated areas after 4000 m). In-channel structures should be supplemented with vegetation-racked floodplain structures that could retain overbank deposits.

To effectively trap sediment, human structures require frequent repair and augmentation. Beaver dams are less permeable and retain water and sediment for longer periods than beaver mimicry structures built by humans (Wohl & Inamdar, 2025; Nagle & McNeely, 2026). The ultimate process-based response to beaver extirpation is to promote the reintroduction of beaver to the landscape.

2) Tailor restoration actions to local potential.

North Sand Creek is a naturally dynamic system with a highly mobile sediment load and an interannually variable sediment system driven by snow accumulation and melt. It has also incised 4 m over the past 2830 years and demonstrates high historical rates of sediment export in the size of its alluvial fan. Cessation of sediment export is likely impossible and should not be attempted. Managers and water users must be prepared for continued sediment export, no matter the restoration trajectory.

3) Match the scale of restoration to the scale of the problem.

Restoration scale must match the temporal and spatial scale of incision and channel instability in North Sand Creek. Interannual variability means that the pace of geomorphic change may be rapid (as in 2019) or slow (as in 2025). Managers and practitioners must recognize that rebuilding access to the floodplain could take many years: much of the stream is

separated by over a vertical meter from the valley floor. Furthermore, sand could be remobilized or a sediment wave could move through the system, resetting the template. Restoration actions must proceed on multiple spatial scales at the same time, addressing OHV impacts, riparian function, and land use.

4) *Be explicit about expected outcomes (to 4, I add: make a plan to monitor outcomes)*

Without explicit, realistic outcomes and a plan to monitor response variables, success cannot be evaluated. At North Sand Creek, the “success” conditions are a reduction of OHV-induced sand export from the *actadj* tributary, sediment storage along the *inactadj* tributary, and reduction of mass sediment export to the alluvial *fan* and State Line Ranch’s irrigation infrastructure. I suggest (i) repeat, high precision monitoring bed elevation and sediment depth at representative cross sections in the *actadj* tributary to determine if OHV accumulation declines, (ii) repeat, high precision monitoring of bed elevation and sediment depth at cross sections in depositional zones and behind in-channel and floodplain structures, and (iii) repeat analysis of annual sand deposition extent and depth on the alluvial fan using high resolution satellite or UAV imagery and UAV Lidar.

5.3 Conclusions

- 1) North Sand Creek has incised through 4 m of valley fill since 2830 ± 200 yBP (Ahlbrandt and Andrews, 1978). Histosols exposed on the paleo-valley surface (t_2) indicate long-term beaver habitation and beaver-induced valley aggradation during the Holocene.
- 2) North Sand Creek historically supported a beaver population that built over 315 relict dams in the *inactadj* reach over their period of habitation, at linear densities and dams per drainage area much higher than in published data. Beaver extirpation and dam failure can be constrained to the late 1970s or early 1980s. The stream and valley now show geomorphic

characteristics consistent with beaver extirpation: entrenchment, simplification to a single thread planform, and sharp meanders around relict dams. Beavers can succeed in environments with high, seasonally and interannually variable sediment flux and cause valley aggradation. Beaver extirpation can leave characteristic geomorphic legacies in sandy, highly mobile settings.

- 3) Sand is exported to the alluvial fan even during years of relatively low runoff, and a large alluvial fan volume corresponds to elevated seasonal and interannual sand export.
- 4) North Sand Creek's sediment regime is interannually variable. Sediment dynamics in North Sand Creek varied considerably between 2019 and 2025. During 2019, high runoff initiated a sand wave in the *actadj* tributary, mobilizing stored sand and causing downstream cycles of aggradation and incision. During 2025, continuous flow did not occur in the ephemeral tributary, and flow on the alluvial fan disappeared by mid-July. A sediment wave was not initiated and channel adjustment was nonexistent or negligible, but sand entered the *inactadj* channel through terrace erosion and dune slumping.
- 5) Sand transfer through the *inactadj* segment after a sediment wave may follow a process of headward incision triggered by internal slope thresholds analogous to Schumm's concept of complex response.
- 6) Restoration efforts at North Sand Creek must incorporate the context of Holocene incision, prior beaver habitation and extirpation, and natural hydrologic and geomorphic variability to successfully reestablish processes that will sustain riparian function.

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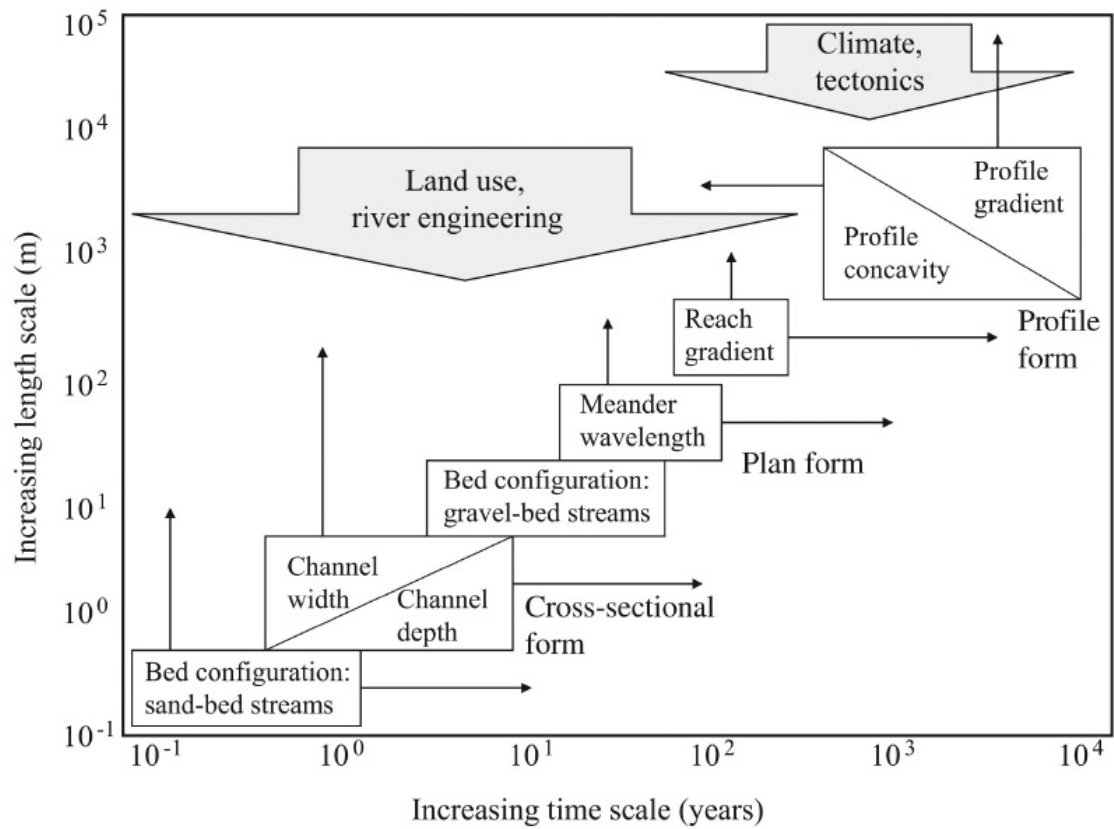
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7. APPENDIX A: SUPPLEMENTAL FIGURES



Supplemental Figure 1. After Knighton 1998, Figure 5.3.

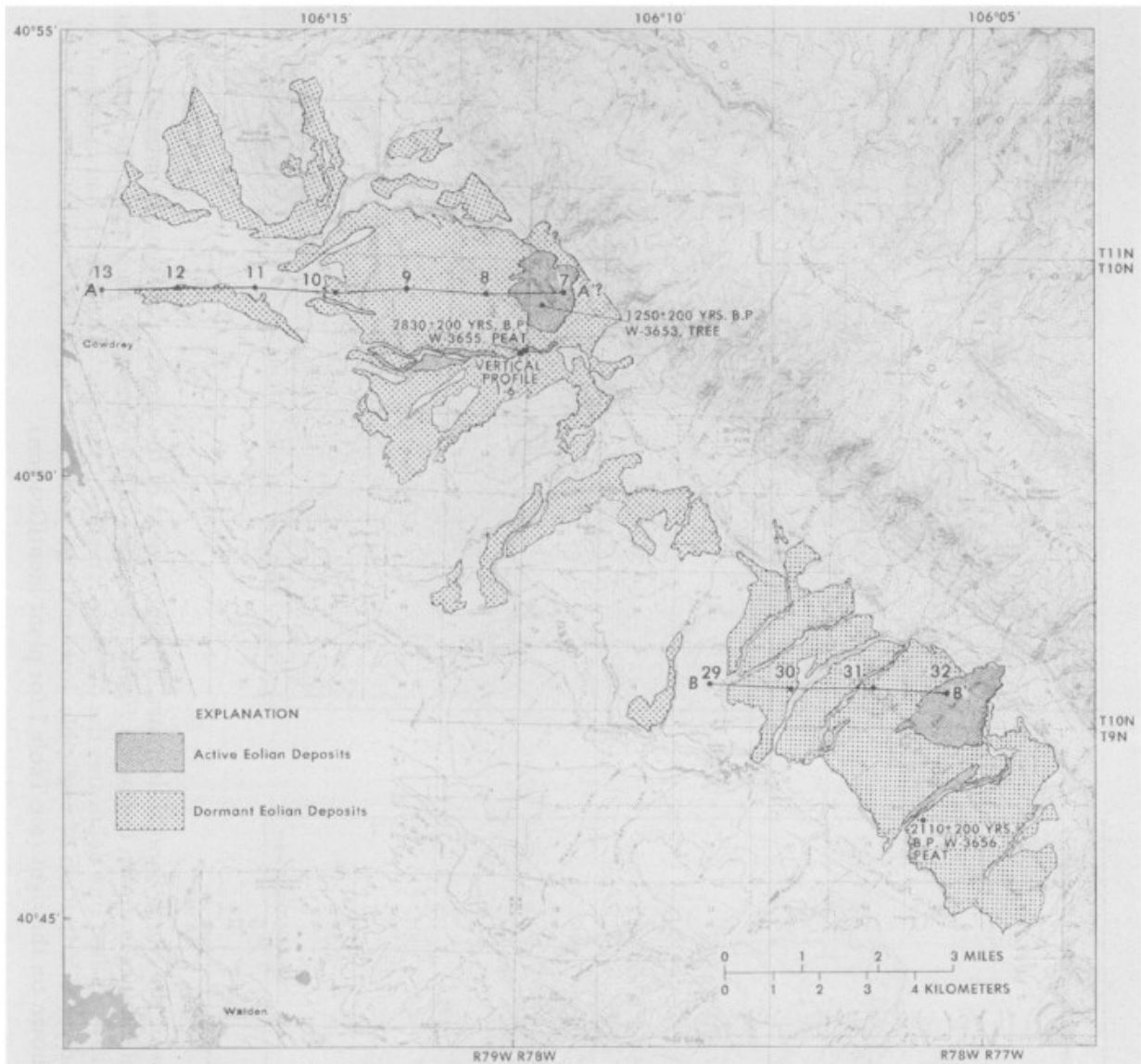


Fig.2. Map of North Park dune field showing active and dormant eolian sand. Dormant eolian sand is based on distribution of the Bangston fine sand (soil 70-AE) as mapped in the preliminary Jackson County soil survey, U.S. Conservation Survey, 1971.

Supplemental Figure 2. From Ahlbrandt and Andrews, 1978. Showing locations of carbon dated hydric soil profiles.

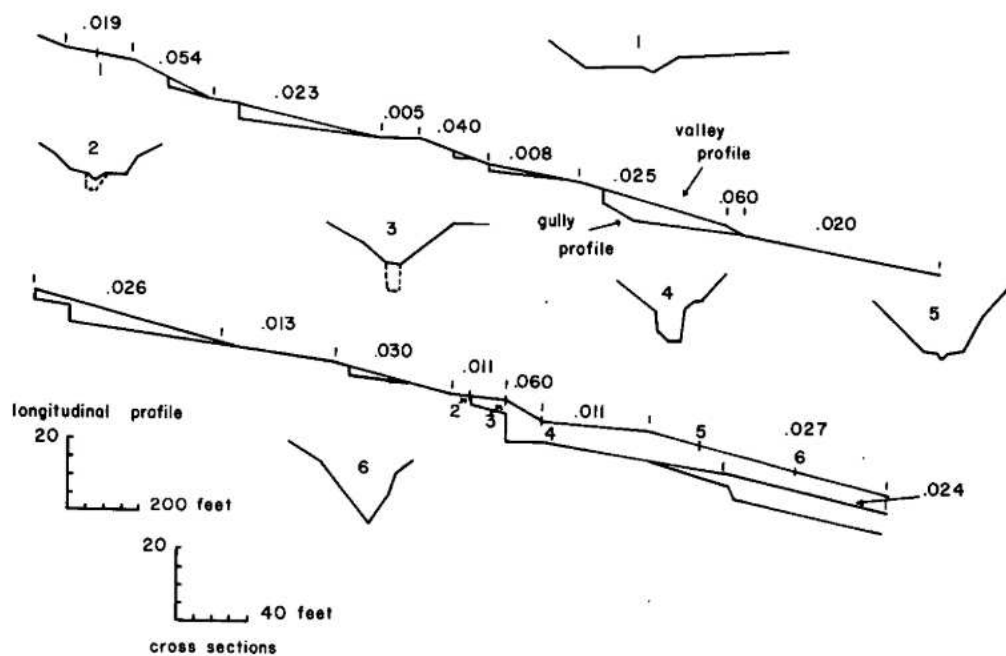
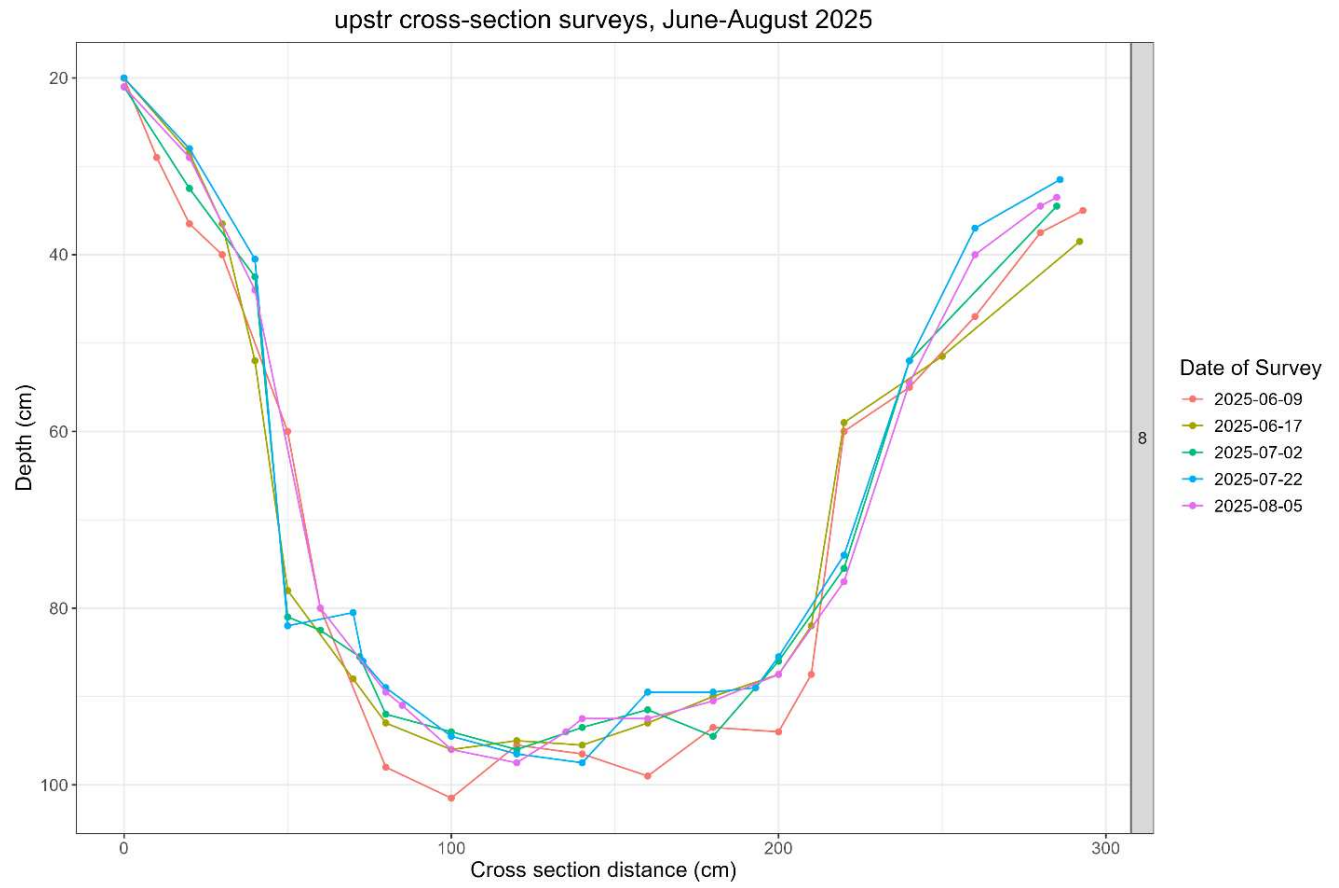
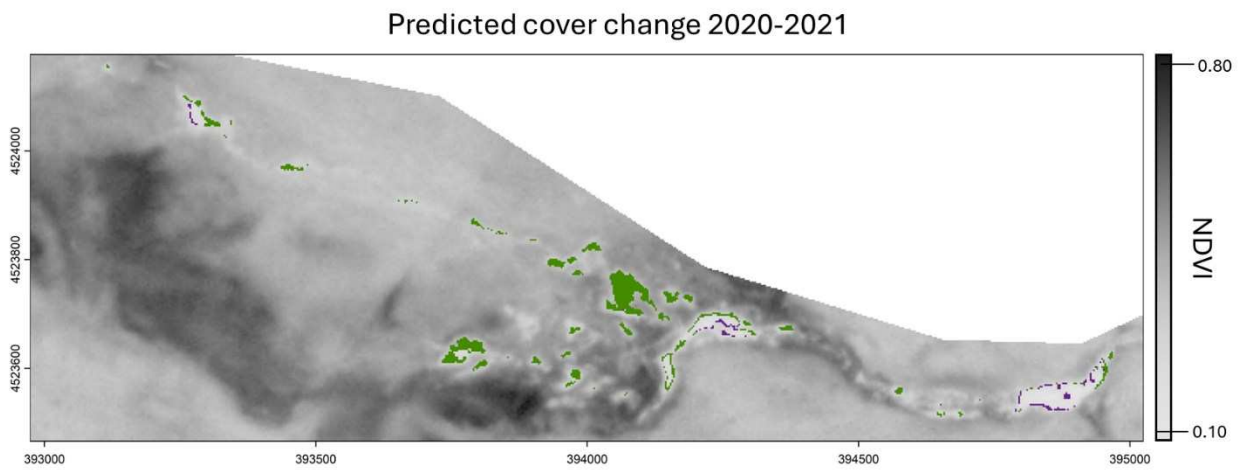
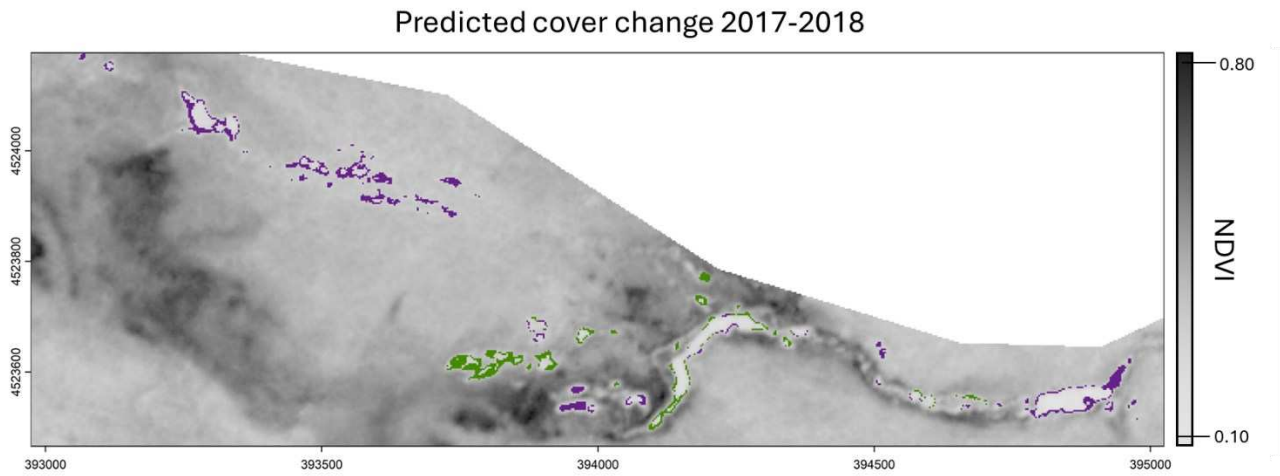


Figure 1. Longitudinal profile and cross sections, Scandard Gulch. Values of valley slope (tan) along surveyed reach are indicated.

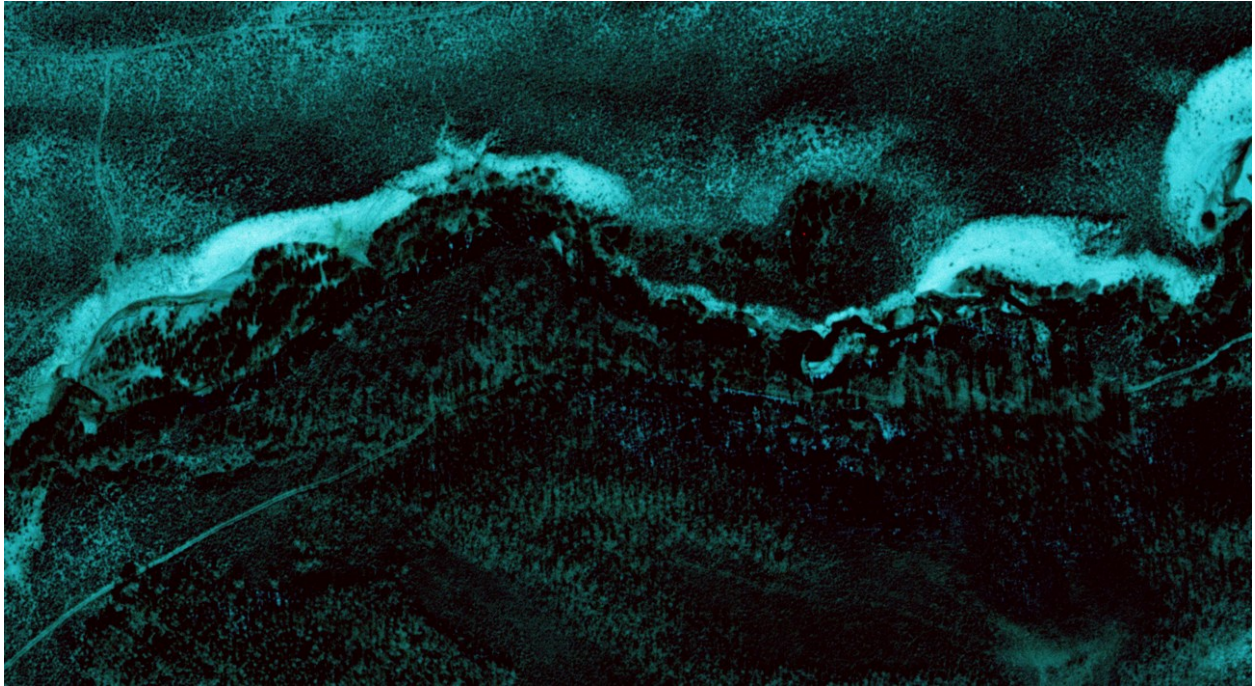
Supplemental Figure 3. From Schumm and Patton, 1975. Gully Erosion in Northwestern Colorado



Supplemental Figure 4. Repeat cross sections at CS 08 in *upstr* segment.



Supplemental Figure 5. Predicted cover change on North Sand Creek alluvial fan.
from *xgboost* binary classification model.



Supplemental Figure 6. 1983 Aerial Image of North Sand Creek, without beaver ponds (USGS EROS Archive)

8. APPENDIX B: DATA

Supplemental Table 1. Monitored cross section locations

CS	Bank Side	Latitude	Longitude	Elevation	Segment	<i>inactadj</i>	stream distance
1	L	40.87081159	-106.1868763	2683.016	actadj	na	
2	L	40.8692529	-106.1884987	2654.326	actadj	na	
3	L	40.8683587	-106.1884152	2646.689	actadj	na	
4	L	40.86773994	-106.1884016	2641.85	actadj	na	
5	L	40.86532175	-106.1879992	2632.133	actadj	na	
6	L	40.86239689	-106.1898549	2615.071	actadj	na	
8	L	40.8605834	-106.1899891	2596.086	upstr	na	
7	L	40.86045732	-106.1901959	2596.736	actadj	na	
9	L	40.85944077	-106.1905196	2589.817	inactadj		153
10	L	40.85793517	-106.1934283	2578.274	inactadj		535
11	L	40.85678313	-106.196026	2572.556	inactadj		917
12	L	40.85552205	-106.2040668	2554.305	inactadj		1871
13	L	40.857146	-106.2459958	2475.712	inactadj		6534

Supplemental Table 2. Relict beaver dam locations

Berm #	Latitude	Longitude	Elevation
1	40.86127809	-106.190238	2604.2
2	40.86102011	-106.190427	2601.5
3	40.86086116	-106.1904389	2599.7
4	40.86072986	-106.1904712	2600.1
5	40.86063441	-106.190462	2599.1
6	40.86057806	-106.190449	2598.8
7	40.86051376	-106.1903389	2596.0
8	40.86043142	-106.1901983	2594.9
9	40.86038098	-106.1900925	2594.0
10	40.86033236	-106.1900076	2594.0
11	40.86018941	-106.189955	2595.4
12	40.86014934	-106.1900276	2595.0
13	40.86013594	-106.1900839	2595.3
14	40.86008907	-106.1900792	2595.7
15	40.86003577	-106.1900683	2595.5
16	40.86002813	-106.1901168	2596.1
17	40.8599568	-106.1901535	2595.2
18	40.8598941	-106.1902335	2594.9
19	40.85983436	-106.1902603	2594.5
20	40.85979849	-106.1903055	2593.6
21	40.85981478	-106.1903448	2592.2
22	40.85981689	-106.1903746	2592.8
23	40.85975304	-106.1903412	2595.8
24	40.85973525	-106.1904914	2593.6
25	40.85967718	-106.1904762	2592.4
26	40.85959984	-106.190431	2591.2
27	40.85952897	-106.1904536	2591.1
28	40.85940442	-106.190546	2590.7

Berm Number	Latitude	Longitude	Elevation
29	40.85933045	-106.1905636	2590.7
30	40.85928499	-106.1905828	2591.3
31	40.85923263	-106.1906082	2591.6
32	40.85913973	-106.1906895	2590.4
33	40.85900957	-106.1907599	2588.6
34	40.85897532	-106.1907472	2588.2
35	40.8589491	-106.1907444	2589.0
36	40.85890896	-106.1907138	2588.5
37	40.85888658	-106.1907787	2588.6
38	40.85890965	-106.1908469	2587.5
39	40.85890321	-106.1908794	2587.4
40	40.85886333	-106.1909443	2588.0
41	40.85874914	-106.1909987	2586.9
42	40.858707	-106.1911051	2587.5
43	40.85863993	-106.1911325	2586.3
44	40.85861614	-106.1911239	2585.7
45	40.85856952	-106.1911363	2585.6
46	40.85853515	-106.1911652	2587.1
47	40.85848179	-106.1912732	2586.1
48	40.85836821	-106.1914641	2585.8
49	40.85840841	-106.1915199	2587.5
50	40.85843233	-106.1916295	2586.5
51	40.85842185	-106.1917284	2585.3
52	40.85844502	-106.1918977	2584.3
53	40.85846	-106.1919688	2586.1
54	40.85844783	-106.1920319	2585.9
55	40.85854474	-106.1923027	2585.5
56	40.85853654	-106.1924118	2585.3
57	40.85842091	-106.1926373	2583.5
58	40.85817882	-106.1926748	2585.1
59	40.85827308	-106.1928584	2584.2
60	40.85831745	-106.1930533	2581.4
61	40.85821707	-106.1932093	2580.7
62	40.85817408	-106.1932827	2580.6
63	40.8580824	-106.1933377	2580.4
64	40.85794356	-106.1935737	2579.8
65	40.85766754	-106.1933374	2581.7
66	40.85764388	-106.1940602	2578.0
67	40.85744575	-106.1940652	2579.6
68	40.8572074	-106.1940743	2578.2
69	40.85705161	-106.1941687	2580.3
70	40.85688026	-106.1941151	2579.5
71	40.85678501	-106.1942593	2577.4
72	40.85673764	-106.1943181	2578.1
73	40.85670211	-106.1944135	2577.2
74	40.85670658	-106.1946452	2576.7
75	40.85678861	-106.194749	2576.4
76	40.85681054	-106.1947593	2576.7
77	40.85681645	-106.1948646	2576.8

Berm Number	Latitude	Longitude	Elevation
78	40.85677426	-106.1949679	2576.4
79	40.85677362	-106.195027	2576.6
80	40.85675571	-106.1950605	2576.4
81	40.85673561	-106.195137	2575.7
82	40.85670594	-106.1952385	2576.4
83	40.85667968	-106.1953124	2576.1
84	40.85668743	-106.1953436	2577.2
85	40.85673016	-106.1954052	2577.2
86	40.85676063	-106.1955174	2574.4
87	40.85684453	-106.1956695	2575.7
88	40.85680255	-106.1956863	2574.6
89	40.8567927	-106.1958047	2574.1
90	40.85678732	-106.1958806	2573.7
91	40.85678828	-106.1959133	2573.8
92	40.8567861	-106.1960627	2572.7
93	40.85671863	-106.1960906	2574.4
94	40.85669051	-106.1961214	2576.2
95	40.85663105	-106.1962066	2576.1
96	40.8566304	-106.19627	2574.9
97	40.8566088	-106.1963739	2574.7
98	40.85662456	-106.1965524	2573.9
99	40.85671291	-106.1967251	2572.4
100	40.85667437	-106.1969595	2571.7
101	40.8566933	-106.1970122	2572.9
102	40.85667584	-106.1971011	2572.7
103	40.85666729	-106.1971673	2573.6
104	40.85669529	-106.1972491	2573.2
105	40.85669816	-106.1973368	2572.7
106	40.85671184	-106.1974448	2573.0
107	40.85665943	-106.1975152	2571.9
108	40.85677179	-106.1976231	2571.6
109	40.8567703	-106.197667	2571.5
110	40.85677686	-106.1977489	2571.0
111	40.85678744	-106.1977742	2570.9
112	40.85688246	-106.1978619	2570.7
113	40.85700496	-106.1981111	2569.3
114	40.85705406	-106.1982059	2569.0
115	40.85709593	-106.1983142	2568.8
116	40.85709738	-106.1983311	2569.4
117	40.85714653	-106.1984767	2570.3
118	40.85716291	-106.19854	2570.1
119	40.85722126	-106.1986076	2568.2
120	40.85723969	-106.198674	2569.6
121	40.85728386	-106.198712	2568.7
122	40.85733142	-106.1987182	2569.2
123	40.85735513	-106.1987632	2568.6
124	40.85737929	-106.1988446	2568.4
125	40.85736275	-106.1989362	2567.8
126	40.85729954	-106.1994469	2567.5

Berm Number	Latitude	Longitude	Elevation
127	40.85706498	-106.1996409	2565.6
128	40.85692059	-106.1997062	2566.1
129	40.85688674	-106.1997337	2566.1
130	40.8568224	-106.1998308	2566.3
131	40.85679287	-106.1998744	2568.2
132	40.85665319	-106.2001241	2569.5
133	40.85660693	-106.2002544	2567.1
134	40.85652297	-106.2002861	2568.5
135	40.85645198	-106.2004369	2565.3
136	40.8564459	-106.2005434	2566.3
137	40.85645282	-106.2006076	2565.1
138	40.85645291	-106.2006667	2564.7
139	40.85641201	-106.2007466	2564.1
140	40.85641553	-106.2007702	2565.2
141	40.85641182	-106.2008774	2564.4
142	40.85639727	-106.200913	2564.3
143	40.85638807	-106.2010438	2564.9
144	40.85637082	-106.2011116	2565.1
145	40.85633473	-106.2011886	2564.8
146	40.85631242	-106.2012883	2565.0
147	40.85629116	-106.2013675	2564.3
148	40.85631073	-106.2015005	2565.8
149	40.85638533	-106.2015733	2565.5
150	40.85642087	-106.2015806	2564.3
151	40.85640237	-106.2016674	2564.2
152	40.85633463	-106.2016856	2563.7
153	40.85631291	-106.2016973	2563.5
154	40.85629014	-106.2017385	2563.7
155	40.85626049	-106.2018065	2562.8
156	40.85623234	-106.2018843	2563.3
157	40.8561548	-106.2019194	2562.2
158	40.856091	-106.201921	2561.8
159	40.85604458	-106.2019973	2562.5
160	40.85606282	-106.202154	2561.8
161	40.85601999	-106.2023063	2560.9
162	40.8559869	-106.2023808	2560.3
163	40.85592151	-106.2024736	2561.3
164	40.85587907	-106.2025193	2561.6
165	40.85582012	-106.2026135	2562.7
166	40.85580113	-106.2026335	2561.8
167	40.85573617	-106.2026778	2560.0
168	40.85566993	-106.2029069	2559.1
169	40.85562284	-106.2029609	2559.3
170	40.85561865	-106.2030536	2558.2
171	40.85564572	-106.2031476	2557.6
172	40.8557093	-106.2032753	2558.4
173	40.85572612	-106.2033766	2558.2
174	40.85571063	-106.2034403	2558.1
175	40.85574997	-106.2034853	2558.5

Berm Number	Latitude	Longitude	Elevation
176	40.85568937	-106.2035912	2558.0
177	40.85549393	-106.2036063	2556.6
178	40.85544341	-106.2038408	2555.7
179	40.85547887	-106.2039458	2555.5
180	40.8555337	-106.2040358	2555.4
181	40.85554219	-106.2041229	2555.3
182	40.85547852	-106.2042547	2555.8
183	40.85544385	-106.2043278	2555.4
184	40.85536784	-106.2044039	2554.0
185	40.85529822	-106.2045112	2552.8
186	40.85530708	-106.2045778	2552.9
187	40.85530901	-106.2046458	2553.2
188	40.85530242	-106.2049725	2554.1
189	40.85565871	-106.206172	2551.9
190	40.85572542	-106.2064941	2551.3
191	40.85579616	-106.2068199	2551.3
192	40.85579113	-106.2069299	2551.6
193	40.85586854	-106.207115	2550.8
194	40.85585493	-106.2071727	2551.2
195	40.85585265	-106.2073403	2551.4
196	40.85587093	-106.2074396	2550.9
197	40.85593509	-106.2075207	2551.4
198	40.85598572	-106.2076702	2551.2
199	40.85607276	-106.2077929	2551.7
200	40.85611961	-106.2079316	2551.8
201	40.85616233	-106.2080021	2551.2
202	40.85612924	-106.2080795	2551.2
203	40.85608521	-106.2083094	2549.7
204	40.85606628	-106.208504	2550.3
205	40.8560749	-106.208641	2548.1
206	40.85613176	-106.2088195	2548.9
207	40.85617757	-106.2090109	2549.8
208	40.85611916	-106.2091339	2549.0
209	40.85608209	-106.2092992	2548.8
210	40.85614009	-106.2094672	2548.5
211	40.85616752	-106.2095834	2548.2
212	40.85621758	-106.209741	2547.5
213	40.85622089	-106.2098118	2547.5
214	40.8563887	-106.209979	2547.4
215	40.85643268	-106.2100019	2547.3
216	40.85653241	-106.2101472	2547.2
217	40.85647004	-106.2106649	2547.7
218	40.85642645	-106.2107651	2547.5
219	40.85642144	-106.2108806	2548.7
220	40.85639936	-106.2108876	2549.4
221	40.85636835	-106.2109706	2548.0
222	40.85637656	-106.2110176	2548.2
223	40.85631367	-106.211049	2549.2
224	40.85632792	-106.2111667	2548.1

Berm Number	Latitude	Longitude	Elevation
225	40.85625718	-106.2113445	2547.6
226	40.85617418	-106.2114074	2545.1
227	40.8560976	-106.2114017	2545.1
228	40.85605121	-106.2114486	2544.7
229	40.85602916	-106.2114807	2545.1
230	40.85597254	-106.2114924	2544.9
231	40.8559865	-106.2115833	2543.4
232	40.85597046	-106.2116492	2543.1
233	40.85603758	-106.211678	2542.8
234	40.85612268	-106.2117322	2542.4
235	40.85615173	-106.2117698	2542.5
236	40.85619938	-106.2118091	2541.7
237	40.85629152	-106.2118678	2541.8
238	40.85629604	-106.2119095	2542.6
239	40.8562679	-106.2122385	2541.5
240	40.85623745	-106.2123353	2541.2
241	40.8562098	-106.2123546	2541.2
242	40.85611649	-106.2124464	2541.6
243	40.85603176	-106.2124689	2541.1
244	40.85589823	-106.212323	2540.3
245	40.85583245	-106.2123609	2540.9
246	40.85579148	-106.2124425	2542.1
247	40.85572752	-106.2125928	2539.9
248	40.85572795	-106.2126735	2538.6
249	40.85571244	-106.2127506	2539.1
250	40.85565143	-106.2129098	2539.3
251	40.85562896	-106.2129926	2537.9
252	40.85560327	-106.2130597	2539.3
253	40.85559301	-106.2131068	2538.8
254	40.85562096	-106.2133125	2539.6
255	40.8555559	-106.2134249	2538.8
256	40.85559826	-106.2134811	2538.5
257	40.85554989	-106.2135117	2539.8
258	40.85555459	-106.2135665	2539.6
259	40.85555783	-106.2136036	2539.3
260	40.85549739	-106.2137001	2539.6
261	40.8555623	-106.2139174	2537.3
262	40.85558907	-106.2141155	2538.0
263	40.85552208	-106.2141397	2536.2
264	40.85551921	-106.214477	2533.8
265	40.85552174	-106.2145997	2534.6
266	40.85555772	-106.2146963	2535.4
267	40.8555462	-106.2147812	2534.8
268	40.85558312	-106.2148904	2537.3
269	40.85555221	-106.2149922	2536.8
270	40.8555266	-106.215123	2534.5
271	40.85548985	-106.2153408	2533.1
272	40.85546563	-106.2153791	2532.9
273	40.85536762	-106.2155068	2531.9

Berm Number	Latitude	Longitude	Elevation
274	40.85531196	-106.215586	2531.0
275	40.85543689	-106.2158349	2530.8
276	40.85583336	-106.2163146	2530.7
277	40.85589	-106.2164711	2529.3
278	40.85602355	-106.2168833	2529.0
279	40.85612029	-106.2174506	2527.7
280	40.85622738	-106.2174227	2527.6
281	40.8563179	-106.2174929	2526.9
282	40.85661775	-106.221021	2524.0
283	40.85658147	-106.2216762	2523.1
284	40.85655653	-106.2218315	2523.2
285	40.85652059	-106.221933	2524.3
286	40.85648346	-106.2220894	2523.3
287	40.85654849	-106.2222891	2523.0
288	40.85649556	-106.2224196	2522.5
289	40.85652619	-106.2224544	2524.0
290	40.85646702	-106.2225944	2522.1
291	40.85653818	-106.222717	2521.0
292	40.85660516	-106.2232166	2519.9
293	40.85680586	-106.223787	2518.8
294	40.85696986	-106.2237603	2518.1
295	40.85726857	-106.224145	2517.6
296	40.85725666	-106.2244091	2517.8
297	40.85714063	-106.2245555	2518.3
298	40.85701704	-106.2248468	2518.1
299	40.85702322	-106.2249103	2518.1
300	40.85701696	-106.2250362	2517.4
301	40.85699511	-106.2251478	2517.4
302	40.85694464	-106.2252057	2517.3
303	40.85678825	-106.2253206	2516.9
304	40.85672638	-106.2253788	2517.0
305	40.8566721	-106.2254476	2517.1
306	40.856424	-106.2254785	2516.9
307	40.8563619	-106.225552	2516.5
308	40.85623221	-106.2256564	2516.1
309	40.85613721	-106.2257349	2515.4
310	40.85594136	-106.2259215	2514.9
311	40.85585665	-106.2260211	2514.8
312	40.85579375	-106.2261108	2515.0
313	40.85569536	-106.2262298	2515.3
314	40.85561811	-106.2262446	2517.5
315	40.85551023	-106.2262546	2516.1

Supplemental Table 3. Repeat cross section surveys for *actadj* segment (CS 01-CS 07).

cs	Date	total_length_cm	distance_cm	depth_cm	start
1	6/9/2025	213	0	31	L
1	6/9/2025	213	20	34	L
1	6/9/2025	213	40	41.5	L
1	6/9/2025	213	60	51.5	L
1	6/9/2025	213	70	68	L
1	6/9/2025	213	80	68	L
1	6/9/2025	213	100	73	L
1	6/9/2025	213	120	74.5	L
1	6/9/2025	213	140	70	L
1	6/9/2025	213	150	65	L
1	6/9/2025	213	160	55	L
1	6/9/2025	213	180	49.5	L
1	6/9/2025	213	200	25.5	L
1	6/9/2025	213	213	20.5	L
2	6/9/2025	379	20	8	L
2	6/9/2025	379	30	12.5	L
2	6/9/2025	379	40	20	L
2	6/9/2025	379	60	39	L
2	6/9/2025	379	80	53	L
2	6/9/2025	379	100	66.5	L
2	6/9/2025	379	120	78.5	L
2	6/9/2025	379	130	86	L
2	6/9/2025	379	140	92.5	L
2	6/9/2025	379	160	92.5	L
2	6/9/2025	379	180	107	L
2	6/9/2025	379	200	107	L
2	6/9/2025	379	210	103	L
2	6/9/2025	379	220	98.5	L
2	6/9/2025	379	240	93.5	L
2	6/9/2025	379	260	86.5	L
2	6/9/2025	379	280	57	L
2	6/9/2025	379	300	50.5	L
2	6/9/2025	379	320	41.5	L
2	6/9/2025	379	340	31.5	L
2	6/9/2025	379	360	21.5	L
2	6/9/2025	379	379	12.5	L
3	6/9/2025	713	0	0	R
3	6/9/2025	713	40	21	R
3	6/9/2025	713	80	41.5	R
3	6/9/2025	713	100	49.5	R
3	6/9/2025	713	120	53.5	R

cs	Date	total_length_cm	distance_cm	depth_cm	start
3	6/9/2025	713	140	52.5	R
3	6/9/2025	713	160	59	R
3	6/9/2025	713	180	70.5	R
3	6/9/2025	713	200	70.5	R
3	6/9/2025	713	240	67.5	R
3	6/9/2025	713	280	64.5	R
3	6/9/2025	713	300	57.5	R
3	6/9/2025	713	320	65	R
3	6/9/2025	713	360	64	R
3	6/9/2025	713	400	61	R
3	6/9/2025	713	440	61.5	R
3	6/9/2025	713	480	62.5	R
3	6/9/2025	713	520	52	R
3	6/9/2025	713	560	45	R
3	6/9/2025	713	580	32	R
3	6/9/2025	713	620	20.5	R
3	6/9/2025	713	660	17	R
3	6/9/2025	713	700	5	R
3	6/9/2025	713	713	0	R
4	6/9/2025	730	0	6.5	R
4	6/9/2025	730	40	26	R
4	6/9/2025	730	80	40.5	R
4	6/9/2025	730	120	59	R
4	6/9/2025	730	160	54.5	R
4	6/9/2025	730	200	53	R
4	6/9/2025	730	240	58	R
4	6/9/2025	730	280	52	R
4	6/9/2025	730	320	60.5	R
4	6/9/2025	730	360	60.5	R
4	6/9/2025	730	400	55	R
4	6/9/2025	730	440	50	R
4	6/9/2025	730	480	53	R
4	6/9/2025	730	520	42.5	R
4	6/9/2025	730	560	45	R
4	6/9/2025	730	600	37	R
4	6/9/2025	730	640	31.5	R
4	6/9/2025	730	680	21.5	R
4	6/9/2025	730	720	11.5	R
5	6/9/2025	765	0	0	R
5	6/9/2025	765	25	8	R
5	6/9/2025	765	65	30	R

5	6/9/2025	765	105	49.5	R
cs	Date	total_length_cm	distance_cm	depth_cm	start
5	6/9/2025	765	145	70	R
5	6/9/2025	765	185	93	R
5	6/9/2025	765	205	111.5	R
5	6/9/2025	765	225	113.5	R
5	6/9/2025	765	245	120.5	R
5	6/9/2025	765	285	117.5	R
5	6/9/2025	765	325	128.5	R
5	6/9/2025	765	365	128	R
5	6/9/2025	765	405	131.5	R
5	6/9/2025	765	445	141.5	R
5	6/9/2025	765	465	148.5	R
5	6/9/2025	765	485	152	R
5	6/9/2025	765	505	157	R
5	6/9/2025	765	545	158	R
5	6/9/2025	765	585	156.5	R
5	6/9/2025	765	625	148	R
5	6/9/2025	765	665	125	R
5	6/9/2025	765	685	102	R
5	6/9/2025	765	705	46.5	R
5	6/9/2025	765	725	27.5	R
5	6/9/2025	765	765	0	R
6	6/9/2025	1017	20	18.5	R
6	6/9/2025	1017	40	25	R
6	6/9/2025	1017	80	35	R
6	6/9/2025	1017	120	56	R
6	6/9/2025	1017	180	90	R
6	6/9/2025	1017	220	90	R
6	6/9/2025	1017	300	89.5	R
6	6/9/2025	1017	380	89.5	R
6	6/9/2025	1017	460	91.5	R
6	6/9/2025	1017	540	91.5	R
6	6/9/2025	1017	620	90.5	R
6	6/9/2025	1017	700	91	R
6	6/9/2025	1017	780	92.5	R
6	6/9/2025	1017	880	95	R
6	6/9/2025	1017	920	80	R
6	6/9/2025	1017	960	66.5	R
6	6/9/2025	1017	1000	13.5	R
6	6/9/2025	1017	1017	0	R
7	6/9/2025	628	0	24	R

7	6/9/2025	628	40	43.5	R
7	6/9/2025	628	80	70	R
cs	Date	total_length_cm	distance_cm	depth_cm	start
7	6/9/2025	628	120	95	R
7	6/9/2025	628	160	106	R
7	6/9/2025	628	200	126.5	R
7	6/9/2025	628	240	137.5	R
7	6/9/2025	628	280	146.5	R
7	6/9/2025	628	300	147.5	R
7	6/9/2025	628	320	153	R
7	6/9/2025	628	340	155	R
7	6/9/2025	628	350	156	R
7	6/9/2025	628	360	153.5	R
7	6/9/2025	628	380	152	R
7	6/9/2025	628	420	143	R
7	6/9/2025	628	460	136.5	R
7	6/9/2025	628	500	125.5	R
7	6/9/2025	628	540	118.5	R
7	6/9/2025	628	560	107	R
7	6/9/2025	628	580	80.5	R
7	6/9/2025	628	600	40	R
7	6/9/2025	628	628	5	R
1	6/17/2025	214	0	31	L
1	6/17/2025	214	20	33	L
1	6/17/2025	214	40	46	L
1	6/17/2025	214	60	51	L
1	6/17/2025	214	70	62	L
1	6/17/2025	214	80	64	L
1	6/17/2025	214	100	67.5	L
1	6/17/2025	214	120	69	L
1	6/17/2025	214	130	67.5	L
1	6/17/2025	214	140	64	L
1	6/17/2025	214	150	58.5	L
1	6/17/2025	214	160	49.5	L
1	6/17/2025	214	180	36.5	L
1	6/17/2025	214	200	24	L
1	6/17/2025	214	214	19	L
2	6/17/2025	382	0	4.5	L
2	6/17/2025	382	20	7	L
2	6/17/2025	382	40	22	L
2	6/17/2025	382	60	38.5	L
2	6/17/2025	382	80	54	L

2	6/17/2025	382	100	67.5	L
2	6/17/2025	382	120	79	L
2	6/17/2025	382	130	84	L
cs	Date	total_length_cm	distance_cm	depth_cm	start
2	6/17/2025	382	140	93	L
2	6/17/2025	382	160	98	L
2	6/17/2025	382	180	105	L
2	6/17/2025	382	200	103	L
2	6/17/2025	382	220	96	L
2	6/17/2025	382	230	93	L
2	6/17/2025	382	240	85	L
2	6/17/2025	382	250	70	L
2	6/17/2025	382	260	64.5	L
2	6/17/2025	382	280	51.5	L
2	6/17/2025	382	300	43	L
2	6/17/2025	382	320	31	L
2	6/17/2025	382	340	22	L
2	6/17/2025	382	360	10	L
2	6/17/2025	382	380	0	L
3	6/17/2025	565	0	0	R
3	6/17/2025	565	20	13	R
3	6/17/2025	565	40	18	R
3	6/17/2025	565	80	39	R
3	6/17/2025	565	120	43	R
3	6/17/2025	565	160	59	R
3	6/17/2025	565	180	69	R
3	6/17/2025	565	200	55	R
3	6/17/2025	565	240	54.5	R
3	6/17/2025	565	280	46	R
3	6/17/2025	565	320	48	R
3	6/17/2025	565	360	49.5	R
3	6/17/2025	565	400	39.5	R
3	6/17/2025	565	440	40.5	R
3	6/17/2025	565	480	32.5	R
3	6/17/2025	565	520	25.5	R
3	6/17/2025	565	540	19.5	
3	6/17/2025	565	565	0	R
4	6/17/2025	726	0	5	R
4	6/17/2025	726	20	11	R
4	6/17/2025	726	40	25.5	R
4	6/17/2025	726	80	40	R
4	6/17/2025	726	120	59	R

4	6/17/2025	726	160	55.5	R
4	6/17/2025	726	200	53	R
4	6/17/2025	726	240	57	R
4	6/17/2025	726	280	56	R
cs	Date	total_length_cm	distance_cm	depth_cm	start
4	6/17/2025	726	360	62	R
4	6/17/2025	726	400	57	R
4	6/17/2025	726	440	55	R
4	6/17/2025	726	480	53.5	R
4	6/17/2025	726	520	44.5	R
4	6/17/2025	726	560	46	R
4	6/17/2025	726	600	43	R
4	6/17/2025	726	640	34.5	R
4	6/17/2025	726	680	26	R
4	6/17/2025	726	700	18	R
4	6/17/2025	726	726	8	R
5	6/17/2025	765	0	0	R
5	6/17/2025	765	40	16.5	R
5	6/17/2025	765	80	36	R
5	6/17/2025	765	120	57.5	R
5	6/17/2025	765	160	80	R
5	6/17/2025	765	200	98	R
5	6/17/2025	765	240	118	R
5	6/17/2025	765	280	123	R
5	6/17/2025	765	320	126	R
5	6/17/2025	765	360	126	R
5	6/17/2025	765	400	128	R
5	6/17/2025	765	420	131.5	R
5	6/17/2025	765	440	139	R
5	6/17/2025	765	460	142	R
5	6/17/2025	765	470	148.5	R
5	6/17/2025	765	480	149.5	R
5	6/17/2025	765	520	156	R
5	6/17/2025	765	260	155.5	R
5	6/17/2025	765	600	155.5	R
5	6/17/2025	765	620	151	R
5	6/17/2025	765	660	128	R
5	6/17/2025	765	680	126.5	R
5	6/17/2025	765	700	60.5	R
5	6/17/2025	765	720	34	R
5	6/17/2025	765	765	0	R
6	6/17/2025	1016	0	0	R

6	6/17/2025	1016	40	23.5	R
6	6/17/2025	1016	80	35	R
6	6/17/2025	1016	120	55.5	R
6	6/17/2025	1016	160	81	R
6	6/17/2025	1016	200	90.5	R
cs	Date	total_length_cm	distance_cm	depth_cm	start
6	6/17/2025	1016	300	90.5	R
6	6/17/2025	1016	400	90	R
6	6/17/2025	1016	500	91.5	R
6	6/17/2025	1016	600	94	R
6	6/17/2025	1016	700	95	R
6	6/17/2025	1016	800	95	R
6	6/17/2025	1016	880	98	R
6	6/17/2025	1016	900	82	R
6	6/17/2025	1016	940	77	R
6	6/17/2025	1016	980	43	R
6	6/17/2025	1016	1016	0	R
7	6/17/2025	628	0	27.5	R
7	6/17/2025	628	40	49	R
7	6/17/2025	628	80	66	R
7	6/17/2025	628	120	92	R
7	6/17/2025	628	140	100	R
7	6/17/2025	628	160	104	R
7	6/17/2025	628	180	114.5	R
7	6/17/2025	628	200	128	R
7	6/17/2025	628	240	136	R
7	6/17/2025	628	280	143.5	R
7	6/17/2025	628	320	151.5	R
7	6/17/2025	628	330	152.5	R
7	6/17/2025	628	340	153.5	R
7	6/17/2025	628	348	155	R
7	6/17/2025	628	360	152.5	R
7	6/17/2025	628	370	151.5	R
7	6/17/2025	628	380	150.5	R
7	6/17/2025	628	420	141	R
7	6/17/2025	628	460	135.5	R
7	6/17/2025	628	500	125	R
7	6/17/2025	628	540	121	R
7	6/17/2025	628	560	110	R
7	6/17/2025	628	600	40.5	R
7	6/17/2025	628	628	10	R
1	7/2/2025	213	0	24	L

1	7/2/2025	213	20	30	L
1	7/2/2025	213	40	47.5	L
1	7/2/2025	213	60	52	L
1	7/2/2025	213	80	60.5	L
1	7/2/2025	213	100	66	L
1	7/2/2025	213	120	68.5	L
cs	Date	total_length_cm	distance_cm	depth_cm	start
1	7/2/2025	213	140	64.5	L
1	7/2/2025	213	160	51	L
1	7/2/2025	213	180	39.5	L
1	7/2/2025	213	200	24	L
1	7/2/2025	213	213	20.5	L
2	7/2/2025	378	0	5	L
2	7/2/2025	378	20	7.5	L
2	7/2/2025	378	40	20	L
2	7/2/2025	378	60	39	L
2	7/2/2025	378	80	54.5	L
2	7/2/2025	378	100	67	L
2	7/2/2025	378	120	80	L
2	7/2/2025	378	140	90.5	L
2	7/2/2025	378	160	91	L
2	7/2/2025	378	180	101.5	L
2	7/2/2025	378	200	102	L
2	7/2/2025	378	220	95	L
2	7/2/2025	378	240	91.5	L
2	7/2/2025	378	260	68.5	L
2	7/2/2025	378	280	52.5	L
2	7/2/2025	378	300	45.5	L
2	7/2/2025	378	320	35.5	L
2	7/2/2025	378	340	24	L
2	7/2/2025	378	360	12.5	L
2	7/2/2025	378	378	0	L
3	7/2/2025	564	0	0	R
3	7/2/2025	564	20	13.5	R
3	7/2/2025	564	40	23.5	R
3	7/2/2025	564	60	27.5	R
3	7/2/2025	564	80	40	R
3	7/2/2025	564	100	43	R
3	7/2/2025	564	120	46	R
3	7/2/2025	564	160	53.5	R
3	7/2/2025	564	200	59	R
3	7/2/2025	564	240	57	R

3	7/2/2025	564	280	52	R
3	7/2/2025	564	320	54	R
3	7/2/2025	564	360	55	R
3	7/2/2025	564	400	44	R
3	7/2/2025	564	440	41.5	R
3	7/2/2025	564	480	36	R
3	7/2/2025	564	520	25	R
cs	Date	total_length_cm	distance_cm	depth_cm	start
3	7/2/2025	564	564	0	R
4	7/2/2025	726	0	5	R
4	7/2/2025	726	20	13	R
4	7/2/2025	726	40	26	R
4	7/2/2025	726	60	37.5	R
4	7/2/2025	726	80	44.5	R
4	7/2/2025	726	100	57	R
4	7/2/2025	726	120	60.5	R
4	7/2/2025	726	160	56.5	R
4	7/2/2025	726	200	57	R
4	7/2/2025	726	240	59.5	R
4	7/2/2025	726	280	57	R
4	7/2/2025	726	320	62.5	R
4	7/2/2025	726	360	61.5	R
4	7/2/2025	726	400	58	R
4	7/2/2025	726	440	48.5	R
4	7/2/2025	726	480	53.5	R
4	7/2/2025	726	520	51	R
4	7/2/2025	726	560	44.5	R
4	7/2/2025	726	600	38.5	R
4	7/2/2025	726	640	32	R
4	7/2/2025	726	680	24	R
4	7/2/2025	726	720	10.5	R
4	7/2/2025	726	726	5.5	R
5	7/2/2025	768	0	0	R
5	7/2/2025	768	20	5.5	R
5	7/2/2025	768	40	16.5	R
5	7/2/2025	768	80	37.5	R
5	7/2/2025	768	100	47	R
5	7/2/2025	768	120	60.5	R
5	7/2/2025	768	160	84	R
5	7/2/2025	768	200	99	R
5	7/2/2025	768	240	120	R
5	7/2/2025	768	280	116	R

5	7/2/2025	768	320	127	R
5	7/2/2025	768	360	125	R
5	7/2/2025	768	400	128	R
5	7/2/2025	768	440	140.5	R
5	7/2/2025	768	480	149.5	R
5	7/2/2025	768	520	156	R
5	7/2/2025	768	560	155.5	R
5	7/2/2025	768	600	155	R
cs	Date	total_length_cm	distance_cm	depth_cm	start
5	7/2/2025	768	640	137	R
5	7/2/2025	768	660	132	R
5	7/2/2025	768	680	119.5	R
5	7/2/2025	768	700	62.5	R
5	7/2/2025	768	720	31.5	R
5	7/2/2025	768	740	19.5	R
5	7/2/2025	768	768	5	R
6	7/2/2025	1013	0	0	R
6	7/2/2025	1013	20	18.5	R
6	7/2/2025	1013	40	5.5	R
6	7/2/2025	1013	60	34.5	R
6	7/2/2025	1013	80	40	R
6	7/2/2025	1013	100	53	R
6	7/2/2025	1013	120	58.5	R
6	7/2/2025	1013	160	85	R
6	7/2/2025	1013	180	95	R
6	7/2/2025	1013	200	94	R
6	7/2/2025	1013	300	95	R
6	7/2/2025	1013	400	92	R
6	7/2/2025	1013	500	95.5	R
6	7/2/2025	1013	600	93.5	R
6	7/2/2025	1013	700	94.5	R
6	7/2/2025	1013	800	95.5	R
6	7/2/2025	1013	900	84	R
6	7/2/2025	1013	920	79.5	R
6	7/2/2025	1013	940	64	R
6	7/2/2025	1013	930	56	R
6	7/2/2025	1013	980	46	R
6	7/2/2025	1013	1013	0	R
7	7/2/2025	626	0	24	L
7	7/2/2025	626	40	45	L
7	7/2/2025	626	80	74	L
7	7/2/2025	626	120	93	L

7	7/2/2025	626	160	106.5	L
7	7/2/2025	626	180	123	L
7	7/2/2025	626	200	133.5	L
7	7/2/2025	626	240	141.5	L
7	7/2/2025	626	280	148	L
7	7/2/2025	626	320	152.5	L
7	7/2/2025	626	329	154.5	L
7	7/2/2025	626	340	156.5	L
7	7/2/2025	626	350	157	L
cs	Date	total_length_cm	distance_cm	depth_cm	start
7	7/2/2025	626	360	155	L
7	7/2/2025	626	370	155.5	L
7	7/2/2025	626	380	153	L
7	7/2/2025	626	400	149	L
7	7/2/2025	626	440	140	L
7	7/2/2025	626	480	126	L
7	7/2/2025	626	520	116.5	L
7	7/2/2025	626	560	111.5	L
7	7/2/2025	626	580	83.5	L
7	7/2/2025	626	600	42	L
7	7/2/2025	626	626	10.5	L
7	7/22/2025	626	0	23	L
7	7/22/2025	626	40	55.5	L
7	7/22/2025	626	80	72.5	L
7	7/22/2025	626	120	93	L
7	7/22/2025	626	160	106	L
7	7/22/2025	626	200	129	L
7	7/22/2025	626	240	143	L
7	7/22/2025	626	280	147.5	L
7	7/22/2025	626	320	152.5	L
7	7/22/2025	626	336	156.5	L
7	7/22/2025	626	352	158	L
7	7/22/2025	626	360	155.5	L
7	7/22/2025	626	400	148.5	L
7	7/22/2025	626	440	140.5	L
7	7/22/2025	626	480	126	L
7	7/22/2025	626	520	119	L
7	7/22/2025	626	560	109	L
7	7/22/2025	626	600	41	L
7	7/22/2025	626	626	10	L
1	8/5/2025	213	0	24.5	L
1	8/5/2025	213	20	32.5	L

1	8/5/2025	213	40	47	L
1	8/5/2025	213	60	51	L
1	8/5/2025	213	80	62	L
1	8/5/2025	213	100	68	L
1	8/5/2025	213	120	68.5	L
1	8/5/2025	213	140	64	L
1	8/5/2025	213	160	49	L
1	8/5/2025	213	180	38	L
1	8/5/2025	213	200	24.5	L
1	8/5/2025	213	213	20	L
cs	Date	total_length_cm	distance_cm	depth_cm	start
2	8/5/2025	379	0	4	L
2	8/5/2025	379	20	6.5	L
2	8/5/2025	379	40	20	L
2	8/5/2025	379	60	42.5	L
2	8/5/2025	379	80	53.5	L
2	8/5/2025	379	100	64.5	L
2	8/5/2025	379	120	79.5	L
2	8/5/2025	379	140	89	L
2	8/5/2025	379	160	89.5	L
2	8/5/2025	379	180	99.5	L
2	8/5/2025	379	200	100.5	L
2	8/5/2025	379	220	95	L
2	8/5/2025	379	240	85.5	L
2	8/5/2025	379	260	68	L
2	8/5/2025	379	280	52	L
2	8/5/2025	379	300	43	L
2	8/5/2025	379	320	32	L
2	8/5/2025	379	340	22.5	L
2	8/5/2025	379	360	11	L
2	8/5/2025	379	379	0	L
3	8/5/2025	563	0	0	R
3	8/5/2025	563	40	22	R
3	8/5/2025	563	80	37	R
3	8/5/2025	563	120	40	R
3	8/5/2025	563	160	52	R
3	8/5/2025	563	200	58	R
3	8/5/2025	563	240	53.5	R
3	8/5/2025	563	280	47	R
3	8/5/2025	563	320	50.5	R
3	8/5/2025	563	360	47	R
3	8/5/2025	563	400	39	R

3	8/5/2025	563	440	37.5	R
3	8/5/2025	563	480	34.5	R
3	8/5/2025	563	520	25	R
3	8/5/2025	563	560	1.5	R
3	8/5/2025	563	563	0	R
4	8/5/2025	724	0	4	R
4	8/5/2025	724	40	27	R
4	8/5/2025	724	80	40.5	R
4	8/5/2025	724	120	59.5	R
4	8/5/2025	724	160	55	R
4	8/5/2025	724	200	57	R
cs	Date	total_length_cm	distance_cm	depth_cm	start
4	8/5/2025	724	240	58	R
4	8/5/2025	724	280	57	R
4	8/5/2025	724	320	63	R
4	8/5/2025	724	360	59.5	R
4	8/5/2025	724	400	59.5	R
4	8/5/2025	724	440	49	R
4	8/5/2025	724	480	54	R
4	8/5/2025	724	520	50.5	R
4	8/5/2025	724	560	41.5	R
4	8/5/2025	724	600	38.5	R
4	8/5/2025	724	640	37.5	R
4	8/5/2025	724	680	21	R
4	8/5/2025	724	720	12	R
4	8/5/2025	724	724	6	R
5	8/5/2025	764	0	0	R
5	8/5/2025	764	40	16	R
5	8/5/2025	764	80	37.5	R
5	8/5/2025	764	120	58	R
5	8/5/2025	764	160	81	R
5	8/5/2025	764	200	100.5	R
5	8/5/2025	764	240	116.5	R
5	8/5/2025	764	280	120.5	R
5	8/5/2025	764	320	126	R
5	8/5/2025	764	360	124.5	R
5	8/5/2025	764	400	128.5	R
5	8/5/2025	764	440	138.5	R
5	8/5/2025	764	480	149	R
5	8/5/2025	764	520	156	R
5	8/5/2025	764	560	155.5	R
5	8/5/2025	764	600	152	R

5	8/5/2025	764	640	132.5	R
5	8/5/2025	764	680	117	R
5	8/5/2025	764	700	62	R
5	8/5/2025	764	720	34	R
5	8/5/2025	764	760	6	R
5	8/5/2025	764	764	4	R
6	8/5/2025	1013	0	0	R
6	8/5/2025	1013	40	25	R
6	8/5/2025	1013	80	38	R
6	8/5/2025	1013	120	53.5	R
6	8/5/2025	1013	160	80	R
6	8/5/2025	1013	200	91.5	R
cs	Date	total_length_cm	distance_cm	depth_cm	start
6	8/5/2025	1013	300	93	R
6	8/5/2025	1013	400	92	R
6	8/5/2025	1013	500	92	R
6	8/5/2025	1013	600	93.5	R
6	8/5/2025	1013	700	93	R
6	8/5/2025	1013	800	94	R
6	8/5/2025	1013	900	82.5	R
6	8/5/2025	1013	940	63	R
6	8/5/2025	1013	980	23	R
6	8/5/2025	1013	1013	0	R
7	8/5/2025	628	0	23.5	L
7	8/5/2025	628	40	42	L
7	8/5/2025	628	80	69.5	L
7	8/5/2025	628	120	93	L
7	8/5/2025	628	160	104.5	L
7	8/5/2025	628	200	126	L
7	8/5/2025	628	240	138.5	L
7	8/5/2025	628	280	147	L
7	8/5/2025	628	320	152.5	L
7	8/5/2025	628	339	154.5	L
7	8/5/2025	628	350	155.5	L
7	8/5/2025	628	354	154.5	L
7	8/5/2025	628	360	154	L
7	8/5/2025	628	400	147	L
7	8/5/2025	628	440	139.5	L
7	8/5/2025	628	480	125	L
7	8/5/2025	628	520	118.5	L
7	8/5/2025	628	560	108	L
7	8/5/2025	628	600	43	L

Supplemental Table 4. Repeat cross section surveys for *upstr* segment (CS 08).

cs	date	total_length_cm	distance_cm	depth_cm
8	6/9/2025	293	0	20
8	6/9/2025	293	10	29
8	6/9/2025	293	20	36.5
8	6/9/2025	293	30	40
8	6/9/2025	293	50	60
8	6/9/2025	293	60	80
8	6/9/2025	293	80	98
8	6/9/2025	293	100	101.5
8	6/9/2025	293	120	95.5
8	6/9/2025	293	140	96.5
8	6/9/2025	293	160	99
8	6/9/2025	293	180	93.5
8	6/9/2025	293	200	94
8	6/9/2025	293	210	87.5
8	6/9/2025	293	220	60
8	6/9/2025	293	240	55
8	6/9/2025	293	260	47
8	6/9/2025	293	280	37.5
8	6/9/2025	293	293	35
8	6/17/2025	292	0	20
8	6/17/2025	292	20	28.5
8	6/17/2025	292	30	36.5
8	6/17/2025	292	40	52
8	6/17/2025	292	60	NA
8	6/17/2025	292	50	78
8	6/17/2025	292	70	88
8	6/17/2025	292	80	93
8	6/17/2025	292	100	96

8	6/17/2025	292	120	95
8	6/17/2025	292	140	95.5
8	6/17/2025	292	160	93
8	6/17/2025	292	180	90
8	6/17/2025	292	200	87.5
8	6/17/2025	292	210	82
8	6/17/2025	292	220	59
8	6/17/2025	292	250	51.5
8	6/17/2025	292	292	38.5
8	7/2/2025	285	0	21
8	7/2/2025	285	20	32.5
8	7/2/2025	285	40	42.5
8	7/2/2025	285	50	81
cs	date	total_length_cm	distance_cm	depth_cm
8	7/2/2025	285	60	82.5
8	7/2/2025	285	72	85.5
8	7/2/2025	285	80	92
8	7/2/2025	285	100	94
8	7/2/2025	285	120	96
8	7/2/2025	285	140	93.5
8	7/2/2025	285	160	91.5
8	7/2/2025	285	180	94.5
8	7/2/2025	285	200	86
8	7/2/2025	285	220	75.5
8	7/2/2025	285	240	52
8	7/2/2025	285	285	34.5
8	7/22/2025	286	0	20
8	7/22/2025	286	20	28
8	7/22/2025	286	40	40.5
8	7/22/2025	286	50	82
8	7/22/2025	286	70	80.5
8	7/22/2025	286	73	86
8	7/22/2025	286	80	89
8	7/22/2025	286	100	94.5
8	7/22/2025	286	120	96.5
8	7/22/2025	286	140	97.5
8	7/22/2025	286	160	89.5
8	7/22/2025	286	180	89.5
8	7/22/2025	286	193	89
8	7/22/2025	286	200	85.5
8	7/22/2025	286	220	74
8	7/22/2025	286	240	52

8	7/22/2025	286	260	37
8	7/22/2025	286	286	31.5
8	8/5/2025	285	0	21
8	8/5/2025	285	20	29
8	8/5/2025	285	40	44
8	8/5/2025	285	60	80
8	8/5/2025	285	80	89.5
8	8/5/2025	285	85	91
8	8/5/2025	285	100	96
8	8/5/2025	285	120	97.5
8	8/5/2025	285	135	94
8	8/5/2025	285	140	92.5
8	8/5/2025	285	160	92.5
8	8/5/2025	285	180	90.5
cs	date	total_length_cm	distance_cm	depth_cm
8	8/5/2025	285	200	87.5
8	8/5/2025	285	220	77
8	8/5/2025	285	240	54.5
8	8/5/2025	285	260	40
8	8/5/2025	285	280	34.5
8	8/5/2025	285	285	33.5

Supplemental Table 5. Repeat cross section surveys for *inactadj* segment (CS 09-CS 13).

cs	date	total_length_cm	distance_cm	depth_cm
9	6/9/2025	738	0	6.5
9	6/9/2025	738	40	8
9	6/9/2025	738	80	13.5
9	6/9/2025	738	120	20.5
9	6/9/2025	738	200	30
9	6/9/2025	738	220	34.5
9	6/9/2025	738	240	40
9	6/9/2025	738	280	43.5
9	6/9/2025	738	320	48
9	6/9/2025	738	340	50
9	6/9/2025	738	350	62
9	6/9/2025	738	360	65
9	6/9/2025	738	380	72.5
9	6/9/2025	738	400	78.5
9	6/9/2025	738	420	75.5
9	6/9/2025	738	440	73.5

9	6/9/2025	738	460	76.5
9	6/9/2025	738	480	74
9	6/9/2025	738	500	70
9	6/9/2025	738	520	72.5
9	6/9/2025	738	540	71
9	6/9/2025	738	600	67
9	6/9/2025	738	620	66.5
9	6/9/2025	738	640	66.5
9	6/9/2025	738	660	63.5
9	6/9/2025	738	680	63.5
9	6/9/2025	738	690	38.5
9	6/9/2025	738	700	25.5
9	6/9/2025	738	720	6.5
9	6/9/2025	738	738	0
cs	date	total_length_cm	distance_cm	depth_cm
10	6/9/2025	615	0	0
10	6/9/2025	615	10	3.5
10	6/9/2025	615	20	10
10	6/9/2025	615	40	22
10	6/9/2025	615	60	26
10	6/9/2025	615	80	32
10	6/9/2025	615	100	34
10	6/9/2025	615	120	47
10	6/9/2025	615	140	49
10	6/9/2025	615	160	53.5
10	6/9/2025	615	180	60
10	6/9/2025	615	200	57
10	6/9/2025	615	220	59.5
10	6/9/2025	615	240	58
10	6/9/2025	615	260	57
10	6/9/2025	615	280	60.5
10	6/9/2025	615	320	57
10	6/9/2025	615	360	57.5
10	6/9/2025	615	400	50.5
10	6/9/2025	615	420	43.5
10	6/9/2025	615	440	40
10	6/9/2025	615	460	32.5
10	6/9/2025	615	500	30
10	6/9/2025	615	540	24.5
10	6/9/2025	615	580	18
10	6/9/2025	615	615	15.5
11	6/9/2025	732	0	0

11	6/9/2025	732	32	14
11	6/9/2025	732	52	19
11	6/9/2025	732	72	28.5
11	6/9/2025	732	92	36.5
11	6/9/2025	732	112	47
11	6/9/2025	732	132	50
11	6/9/2025	732	152	50.5
11	6/9/2025	732	172	42.5
11	6/9/2025	732	192	60
11	6/9/2025	732	212	64
11	6/9/2025	732	252	70
11	6/9/2025	732	292	72
11	6/9/2025	732	312	74.5
11	6/9/2025	732	332	75.5
11	6/9/2025	732	352	80
cs	date	total_length_cm	distance_cm	depth_cm
11	6/9/2025	732	372	78
11	6/9/2025	732	392	76
11	6/9/2025	732	412	72
11	6/9/2025	732	432	69
11	6/9/2025	732	452	59.5
11	6/9/2025	732	472	55
11	6/9/2025	732	492	45.5
11	6/9/2025	732	502	31.5
11	6/9/2025	732	512	27
11	6/9/2025	732	532	22
11	6/9/2025	732	552	15
11	6/9/2025	732	572	13
11	6/9/2025	732	612	9
11	6/9/2025	732	652	8
11	6/9/2025	732	692	8
11	6/9/2025	732	732	0
12	6/9/2025	381	0	0
12	6/9/2025	381	20	9.5
12	6/9/2025	381	40	15
12	6/9/2025	381	60	23.5
12	6/9/2025	381	80	28
12	6/9/2025	381	100	41.5
12	6/9/2025	381	120	50
12	6/9/2025	381	140	59
12	6/9/2025	381	160	63
12	6/9/2025	381	180	65.5

12	6/9/2025	381	200	76
12	6/9/2025	381	240	68
12	6/9/2025	381	260	66.5
12	6/9/2025	381	280	64
12	6/9/2025	381	300	57
12	6/9/2025	381	320	37
12	6/9/2025	381	340	42
12	6/9/2025	381	360	27
12	6/9/2025	381	381	0
13	6/9/2025	918	0	0
13	6/9/2025	918	40	6
13	6/9/2025	918	80	15
13	6/9/2025	918	100	20
13	6/9/2025	918	120	30
13	6/9/2025	918	140	35
13	6/9/2025	918	180	45
cs	date	total_length_cm	distance_cm	depth_cm
13	6/9/2025	918	220	54
13	6/9/2025	918	240	64
13	6/9/2025	918	260	66
13	6/9/2025	918	280	69
13	6/9/2025	918	290	69
13	6/9/2025	918	300	74
13	6/9/2025	918	320	72
13	6/9/2025	918	360	74
13	6/9/2025	918	400	71
13	6/9/2025	918	440	70.5
13	6/9/2025	918	480	71
13	6/9/2025	918	520	75
13	6/9/2025	918	560	74
13	6/9/2025	918	600	71
13	6/9/2025	918	620	68.5
13	6/9/2025	918	630	66
13	6/9/2025	918	640	54.5
13	6/9/2025	918	680	54
13	6/9/2025	918	720	53.5
13	6/9/2025	918	740	52
13	6/9/2025	918	760	32
13	6/9/2025	918	800	22
13	6/9/2025	918	840	11
13	6/9/2025	918	880	9
13	6/9/2025	918	918	6

9	6/17/2025	738	0	0
9	6/17/2025	738	40	6.5
9	6/17/2025	738	80	10.5
9	6/17/2025	738	120	19
9	6/17/2025	738	160	22
9	6/17/2025	738	200	26.5
9	6/17/2025	738	280	36
9	6/17/2025	738	320	40
9	6/17/2025	738	340	47
9	6/17/2025	738	360	53
9	6/17/2025	738	380	56.5
9	6/17/2025	738	400	66
9	6/17/2025	738	420	70.5
9	6/17/2025	738	440	72
9	6/17/2025	738	480	69
9	6/17/2025	738	540	64
9	6/17/2025	738	580	60.5
cs	date	total_length_cm	distance_cm	depth_cm
9	6/17/2025	738	620	62.5
9	6/17/2025	738	640	64.5
9	6/17/2025	738	670	64.5
9	6/17/2025	738	690	63
9	6/17/2025	738	700	25.5
9	6/17/2025	738	738	0
10	6/17/2025	615	0	0
10	6/17/2025	615	40	21
10	6/17/2025	615	80	39
10	6/17/2025	615	120	45
10	6/17/2025	615	140	48.5
10	6/17/2025	615	180	58.5
10	6/17/2025	615	220	59
10	6/17/2025	615	240	58
10	6/17/2025	615	260	59
10	6/17/2025	615	300	57.5
10	6/17/2025	615	340	61.5
10	6/17/2025	615	380	58
10	6/17/2025	615	400	54
10	6/17/2025	615	417	51
10	6/17/2025	615	440	41.5
10	6/17/2025	615	480	36
10	6/17/2025	615	520	28
10	6/17/2025	615	560	19.5

10	6/17/2025	615	600	15.5
10	6/17/2025	615	615	12.5
11	6/17/2025	730	0	0
11	6/17/2025	730	30	13
11	6/17/2025	730	70	31.5
11	6/17/2025	730	110	52.5
11	6/17/2025	730	150	67
11	6/17/2025	730	190	71
11	6/17/2025	730	210	74
11	6/17/2025	730	250	75.5
11	6/17/2025	730	290	80.5
11	6/17/2025	730	330	83.5
11	6/17/2025	730	350	86
11	6/17/2025	730	370	87.5
11	6/17/2025	730	390	84.5
11	6/17/2025	730	410	81.5
11	6/17/2025	730	424	77.5
11	6/17/2025	730	430	77
cs	date	total_length_cm	distance_cm	depth_cm
11	6/17/2025	730	450	73.5
11	6/17/2025	730	490	58
11	6/17/2025	730	510	38
11	6/17/2025	730	530	36.5
11	6/17/2025	730	570	23.5
11	6/17/2025	730	610	18.5
11	6/17/2025	730	650	15.5
11	6/17/2025	730	690	15.5
11	6/17/2025	730	730	6
12	6/17/2025	382	0	0
12	6/17/2025	382	42	18
12	6/17/2025	382	82	27
12	6/17/2025	382	102	38.5
12	6/17/2025	382	122	48
12	6/17/2025	382	139	53
12	6/17/2025	382	162	58
12	6/17/2025	382	182	60
12	6/17/2025	382	202	58
12	6/17/2025	382	222	61
12	6/17/2025	382	242	58.5
12	6/17/2025	382	262	59
12	6/17/2025	382	293	51.5
12	6/17/2025	382	302	46.5

12	6/17/2025	382	342	29
12	6/17/2025	382	362	12
12	6/17/2025	382	382	0
13	6/17/2025	921	0	6
13	6/17/2025	921	21	7.5
13	6/17/2025	921	61	12
13	6/17/2025	921	101	21
13	6/17/2025	921	141	40
13	6/17/2025	921	221	55
13	6/17/2025	921	261	67
13	6/17/2025	921	271	69.5
13	6/17/2025	921	281	72
13	6/17/2025	921	321	70
13	6/17/2025	921	361	68
13	6/17/2025	921	401	66.5
13	6/17/2025	921	441	64.5
13	6/17/2025	921	481	63
13	6/17/2025	921	561	62
13	6/17/2025	921	641	62
cs	date	total_length_cm	distance_cm	depth_cm
13	6/17/2025	921	679	60
13	6/17/2025	921	681	49
13	6/17/2025	921	701	48
13	6/17/2025	921	741	47.5
13	6/17/2025	921	751	33
13	6/17/2025	921	761	28
13	6/17/2025	921	801	15
13	6/17/2025	921	841	4
13	6/17/2025	921	921	0
9	7/2/2025	736	0	0
9	7/2/2025	736	40	5
9	7/2/2025	736	80	12
9	7/2/2025	736	120	19.5
9	7/2/2025	736	160	26
9	7/2/2025	736	200	29.5
9	7/2/2025	736	240	34.5
9	7/2/2025	736	280	41
9	7/2/2025	736	320	45.5
9	7/2/2025	736	360	61.5
9	7/2/2025	736	400	77.5
9	7/2/2025	736	390	71
9	7/2/2025	736	440	77

9	7/2/2025	736	480	74
9	7/2/2025	736	520	62
9	7/2/2025	736	540	68
9	7/2/2025	736	580	66
9	7/2/2025	736	600	68
9	7/2/2025	736	620	66
9	7/2/2025	736	640	69
9	7/2/2025	736	660	61.5
9	7/2/2025	736	680	64
9	7/2/2025	736	700	22.5
9	7/2/2025	736	720	5
9	7/2/2025	736	736	0
10	7/2/2025	614	0	0
10	7/2/2025	614	40	18
10	7/2/2025	614	80	32
10	7/2/2025	614	120	44
10	7/2/2025	614	140	51.5
10	7/2/2025	614	160	56
10	7/2/2025	614	180	58.5
10	7/2/2025	614	200	58
cs	date	total_length_cm	distance_cm	depth_cm
10	7/2/2025	614	240	58
10	7/2/2025	614	280	57.5
10	7/2/2025	614	320	57.5
10	7/2/2025	614	340	61.5
10	7/2/2025	614	360	52.5
10	7/2/2025	614	400	54.5
10	7/2/2025	614	408	52
10	7/2/2025	614	440	42
10	7/2/2025	614	480	30
10	7/2/2025	614	520	28
10	7/2/2025	614	560	20
10	7/2/2025	614	600	17
10	7/2/2025	614	614	17
11	7/2/2025	730	0	0
11	7/2/2025	730	40	19.5
11	7/2/2025	730	80	34
11	7/2/2025	730	100	42.5
11	7/2/2025	730	120	54.5
11	7/2/2025	730	140	56.5
11	7/2/2025	730	180	60.5
11	7/2/2025	730	200	70

11	7/2/2025	730	240	74
11	7/2/2025	730	280	79
11	7/2/2025	730	320	82
11	7/2/2025	730	340	86
11	7/2/2025	730	360	87
11	7/2/2025	730	380	86.5
11	7/2/2025	730	400	83.5
11	7/2/2025	730	411	81
11	7/2/2025	730	440	77
11	7/2/2025	730	480	63
11	7/2/2025	730	500	44.5
11	7/2/2025	730	540	30.5
11	7/2/2025	730	580	21.5
11	7/2/2025	730	620	17
11	7/2/2025	730	680	15
11	7/2/2025	730	730	5.5
12	7/2/2025	379	0	0
12	7/2/2025	379	40	15.5
12	7/2/2025	379	80	26.5
12	7/2/2025	379	120	50
12	7/2/2025	379	160	58
cs	date	total_length_cm	distance_cm	depth_cm
12	7/2/2025	379	180	60.5
12	7/2/2025	379	200	59.5
12	7/2/2025	379	220	62
12	7/2/2025	379	240	60.5
12	7/2/2025	379	260	59.5
12	7/2/2025	379	280	54.5
12	7/2/2025	379	294	54.5
12	7/2/2025	379	320	38.5
12	7/2/2025	379	340	31
12	7/2/2025	379	360	15.5
12	7/2/2025	379	379	0
13	7/2/2025	918	0	0
13	7/2/2025	918	40	4
13	7/2/2025	918	80	17
13	7/2/2025	918	100	21
13	7/2/2025	918	120	33
13	7/2/2025	918	160	43
13	7/2/2025	918	200	54.5
13	7/2/2025	918	240	67
13	7/2/2025	918	260	74

13	7/2/2025	918	265	75
13	7/2/2025	918	300	75
13	7/2/2025	918	340	74.5
13	7/2/2025	918	380	74.5
13	7/2/2025	918	420	75
13	7/2/2025	918	460	74
13	7/2/2025	918	500	73.5
13	7/2/2025	918	540	74
13	7/2/2025	918	580	73.5
13	7/2/2025	918	620	73.5
13	7/2/2025	918	660	74
13	7/2/2025	918	680	74.5
13	7/2/2025	918	687	73.5
13	7/2/2025	918	690	64.5
13	7/2/2025	918	720	62.5
13	7/2/2025	918	740	61
13	7/2/2025	918	780	33
13	7/2/2025	918	820	21.5
13	7/2/2025	918	860	20
13	7/2/2025	918	900	18
13	7/2/2025	918	918	18
9	7/22/2025	738	0	0
cs	date	total_length_cm	distance_cm	depth_cm
9	7/22/2025	738	40	6
9	7/22/2025	738	80	12
9	7/22/2025	738	120	17
9	7/22/2025	738	160	24
9	7/22/2025	738	200	27.5
9	7/22/2025	738	240	31.5
9	7/22/2025	738	280	38
9	7/22/2025	738	320	42
9	7/22/2025	738	360	57
9	7/22/2025	738	400	71.5
9	7/22/2025	738	440	72
9	7/22/2025	738	480	73
9	7/22/2025	738	520	61.5
9	7/22/2025	738	560	65
9	7/22/2025	738	600	72
9	7/22/2025	738	640	73
9	7/22/2025	738	680	69.5
9	7/22/2025	738	700	33
9	7/22/2025	738	720	12

9	7/22/2025	738	738	8
10	7/22/2025	617	0	0
10	7/22/2025	617	40	18
10	7/22/2025	617	80	30
10	7/22/2025	617	120	43
10	7/22/2025	617	160	53.5
10	7/22/2025	617	200	56.5
10	7/22/2025	617	240	57
10	7/22/2025	617	280	54.5
10	7/22/2025	617	320	56
10	7/22/2025	617	360	57
10	7/22/2025	617	400	53
10	7/22/2025	617	440	42.5
10	7/22/2025	617	480	32.5
10	7/22/2025	617	520	31
10	7/22/2025	617	560	19.5
10	7/22/2025	617	600	15.5
10	7/22/2025	617	617	11.5
11	7/22/2025	729	0	0
11	7/22/2025	729	40	18
11	7/22/2025	729	80	32.5
11	7/22/2025	729	120	54
11	7/22/2025	729	160	44.5
cs	date	total_length_cm	distance_cm	depth_cm
11	7/22/2025	729	200	70
11	7/22/2025	729	240	74
11	7/22/2025	729	280	79
11	7/22/2025	729	320	82.5
11	7/22/2025	729	360	87
11	7/22/2025	729	400	84
11	7/22/2025	729	405	82.5
11	7/22/2025	729	440	82.5
11	7/22/2025	729	480	76
11	7/22/2025	729	520	62
11	7/22/2025	729	560	36.5
11	7/22/2025	729	600	25.5
11	7/22/2025	729	640	19.5
11	7/22/2025	729	680	15.5
11	7/22/2025	729	720	15
11	7/22/2025	729	729	6
12	7/22/2025	380	0	0
12	7/22/2025	380	40	15

12	7/22/2025	380	80	23.5
12	7/22/2025	380	120	45
12	7/22/2025	380	160	58
12	7/22/2025	380	200	60
12	7/22/2025	380	240	61
12	7/22/2025	380	280	57.5
12	7/22/2025	380	320	39.5
12	7/22/2025	380	360	15
12	7/22/2025	380	380	0
13	7/22/2025	918	0	0
13	7/22/2025	918	40	5
13	7/22/2025	918	80	16.5
13	7/22/2025	918	120	32
13	7/22/2025	918	160	43.5
13	7/22/2025	918	200	52
13	7/22/2025	918	240	64.5
13	7/22/2025	918	260	70.5
13	7/22/2025	918	280	74
13	7/22/2025	918	320	72.5
13	7/22/2025	918	360	73
13	7/22/2025	918	400	73
13	7/22/2025	918	440	68.5
13	7/22/2025	918	480	68
13	7/22/2025	918	520	68
cs	date	total_length_cm	distance_cm	depth_cm
13	7/22/2025	918	560	68
13	7/22/2025	918	600	68
13	7/22/2025	918	640	67
13	7/22/2025	918	680	66.5
13	7/22/2025	918	700	55.5
13	7/22/2025	918	720	55
13	7/22/2025	918	740	53
13	7/22/2025	918	760	36.5
13	7/22/2025	918	800	22
13	7/22/2025	918	840	9
13	7/22/2025	918	880	8.5
13	7/22/2025	918	917	6
9	8/6/2025	736	0	0
9	8/6/2025	736	20	6
9	8/6/2025	736	40	6.5
9	8/6/2025	736	60	8.5
9	8/6/2025	736	80	13.5

9	8/6/2025	736	100	14.5
9	8/6/2025	736	120	19.5
9	8/6/2025	736	140	25
9	8/6/2025	736	160	27
9	8/6/2025	736	180	28.5
9	8/6/2025	736	200	31
9	8/6/2025	736	220	33.5
9	8/6/2025	736	240	35.5
9	8/6/2025	736	260	41.5
9	8/6/2025	736	280	43
9	8/6/2025	736	300	45
9	8/6/2025	736	320	48
9	8/6/2025	736	340	55
9	8/6/2025	736	360	62.5
9	8/6/2025	736	380	70
9	8/6/2025	736	400	76
9	8/6/2025	736	420	76.5
9	8/6/2025	736	440	76
9	8/6/2025	736	460	78
9	8/6/2025	736	480	77
9	8/6/2025	736	500	68.5
9	8/6/2025	736	520	65.5
9	8/6/2025	736	540	70.5
9	8/6/2025	736	560	59
9	8/6/2025	736	580	68
cs	date	total_length_cm	distance_cm	depth_cm
9	8/6/2025	736	600	69
9	8/6/2025	736	620	70.5
9	8/6/2025	736	640	69
9	8/6/2025	736	660	66.5
9	8/6/2025	736	677	65
9	8/6/2025	736	680	65
9	8/6/2025	736	700	28
9	8/6/2025	736	720	7.5
9	8/6/2025	736	736	2
10	8/6/2025	617	0	0
10	8/6/2025	617	40	18
10	8/6/2025	617	80	29
10	8/6/2025	617	120	40
10	8/6/2025	617	160	53.5
10	8/6/2025	617	170	56
10	8/6/2025	617	200	55

10	8/6/2025	617	240	56
10	8/6/2025	617	280	53.5
10	8/6/2025	617	320	53.5
10	8/6/2025	617	340	57.5
10	8/6/2025	617	360	51
10	8/6/2025	617	400	49
10	8/6/2025	617	440	33
10	8/6/2025	617	480	25
10	8/6/2025	617	520	22
10	8/6/2025	617	560	14
10	8/6/2025	617	600	10.5
10	8/6/2025	617	617	7
11	8/6/2025	729	0	0
11	8/6/2025	729	40	18
11	8/6/2025	729	80	32.5
11	8/6/2025	729	120	54
11	8/6/2025	729	160	42.5
11	8/6/2025	729	200	68.5
11	8/6/2025	729	240	73
11	8/6/2025	729	280	78.5
11	8/6/2025	729	320	81.5
11	8/6/2025	729	324	82.5
11	8/6/2025	729	360	86.5
11	8/6/2025	729	400	83
11	8/6/2025	729	440	76
11	8/6/2025	729	480	65
cs	date	total_length_cm	distance_cm	depth_cm
11	8/6/2025	729	520	35.5
11	8/6/2025	729	560	26.5
11	8/6/2025	729	600	20
11	8/6/2025	729	640	15
11	8/6/2025	729	680	17
11	8/6/2025	729	720	9
11	8/6/2025	729	729	6.5
12	8/6/2025	382	0	0
12	8/6/2025	382	40	15
12	8/6/2025	382	80	23.5
12	8/6/2025	382	120	43.5
12	8/6/2025	382	160	55
12	8/6/2025	382	180	59
12	8/6/2025	382	200	59
12	8/6/2025	382	220	61.5

12	8/6/2025	382	240	60
12	8/6/2025	382	280	59.5
12	8/6/2025	382	320	36
12	8/6/2025	382	360	13
12	8/6/2025	382	382	0
13	8/6/2025	921	0	4
13	8/6/2025	921	40	16
13	8/6/2025	921	80	31.5
13	8/6/2025	921	120	43
13	8/6/2025	921	160	53
13	8/6/2025	921	200	53
13	8/6/2025	921	240	66.5
13	8/6/2025	921	280	75
13	8/6/2025	921	320	75.5
13	8/6/2025	921	360	75.5
13	8/6/2025	921	400	75.5
13	8/6/2025	921	440	72
13	8/6/2025	921	480	71.5
13	8/6/2025	921	520	73
13	8/6/2025	921	560	73.5
13	8/6/2025	921	600	72
13	8/6/2025	921	640	72
13	8/6/2025	921	680	71
13	8/6/2025	921	690	63
13	8/6/2025	921	720	62
13	8/6/2025	921	740	52
13	8/6/2025	921	760	41
cs	date	total_length_cm	distance_cm	depth_cm
13	8/6/2025	921	800	30.5
13	8/6/2025	921	840	17.5
13	8/6/2025	921	880	17.5
13	8/6/2025	921	921	17