

Changing streamflow and sediment dynamics in rivers of the southern Colorado Rocky Mountains, USA

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ABSTRACT

Eco-hydro-geomorphic processes in mountain rivers determine the quantity and quality of water delivered downstream and support important aquatic and riparian ecosystems. In the semi-arid Colorado Rocky Mountains—and across mountain ranges globally—changes to the timing, phase, and amount of precipitation coupled with growing water demand are reducing annual streamflow volumes. Land-use change and increasing fire extent and severity are accelerating delivery of mobile sediment to streams, while new restoration paradigms are emerging to mitigate sediment loading. The 2026 Kirk Bryan field trip is motivated by the scientific question: How do changing environmental and management regimes affect streamflow, sediment storage, and ecosystem services in mountain rivers? We first visit Hotel Gulch, a headwater stream that provides a natural laboratory for understanding how changing climate and precipitation regimes alter groundwater/surface water interactions and streamflow. The second stop, along Trout Creek, shows how beaver modify sediment dynamics in river corridors, which has implications for sediment storage in fluvial systems as well as beaver-related restoration aimed at improving channel-floodplain connectivity. Scaling up estimates of beaver-dam sediment storage across the Rocky Mountains suggests that beaver-driven sediment storage volumes could be similar in magnitude to those currently stored behind human-built dams. The final stop visits the former site of the Lake George Diversion Dam, removed in 2023. We present geomorphic and ecological evidence from this relatively rare example of dam removal in the semi-arid west suggesting that river response to removal is functionally complete after less than three years. Together, our examples illustrate the potential both for detrimental ongoing changes to river corridors as well as for beneficial impacts arising from science-based management practices.

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INTRODUCTION

Mountains are the world's water towers. Water sourced from orographically enhanced rainfall and stored snowpack flows through low-order mountain streams and rivers before being used for human needs in more intensively farmed and populated lowlands (e.g., Immerzeel et al., 2020). In the western United States for example, >45% of the surface drinking water supply originates from National Forest System lands, which are concentrated in mountainous regions but make up only ~20% of the land area (Liu et al., 2022). Along the journey from precipitation to tap, water in mountain rivers shapes landscapes and sustains important aquatic and riparian ecosystems (e.g., Wohl, 2010). The quantity and quality of water delivered downstream, as well as the health of rivers and riverscapes, are heavily influenced by hydrologic and geomorphic processes that respond to environmental changes (e.g., East and Sankey, 2020) as well as direct human impacts (e.g., Comiti, 2012).

The Colorado Rocky Mountains have been identified as one of the most important mountain water towers in North America because they contain plentiful water relative to the low water availability and high demand in the downstream arid lowlands (Immerzeel et al., 2020). Rivers in the semi-arid Colorado Rocky Mountains are, and have been since western settlement, responding to a wide array of stressors and anthropogenic perturbations that have the potential to influence water quantity, quality, and river ecosystem health. Beginning in the nineteenth century, Colorado Rocky Mountain rivers were heavily impacted by beaver extirpation, logging, mining, channel clearing to enable timber floating, and flow diversion/withdrawal (e.g., Wohl, 2001). Extensive, severe wildfires are accelerating sediment delivery to rivers (Moody and Martin, 2001; Ryan et al., 2024) while significant portions of fluvial sediment loads can be trapped behind dams (e.g., Graf et al., 2010; Dethier et al., 2022). Changes to the timing, amount, and phase of precipitation, in line with predictions for climate warming, have reduced average annual streamflow volumes (e.g., Foster et al., 2016; Musselman et al., 2021). These changes to mountain rivers have important downstream consequences. Reduced streamflow and altered sediment loads threaten the viability of ecosystems and water supplies in both the rapidly growing cities of the Colorado Front Range to the east and the famously drought-stricken Colorado River basin to the west (e.g., Schmidt et al., 2023; Salter et al., 2025). Management practices recently developed to mitigate these risks, including beaver reintroduction and mimicry, dam removal, and process-based river restoration (e.g., Wohl et al., 2015; Bellmore et al., 2017; Major et al., 2017; Burgher et al., 2026), also have the potential to alter Colorado Rocky Mountain rivers.

This field trip presents new and ongoing science focused on the question: How do changing environmental and management regimes affect streamflow and sediment dynamics in mountain rivers? The trip is intended to facilitate discussion that (1) consolidates current understanding of how mountain rivers have been affected by past perturbations and (2) charts a path forward

for scientific inquiry that will enable prediction of how rivers will respond to future environmental and management changes, including emerging restoration paradigms.

The trip has three stops (Fig. 1). The first, at Hotel Gulch within Manitou Experimental Forest, focuses on the surface and groundwater hydrology of semi-arid mountain streams in the context of a changing climate. The second stop showcases the influence of beaver dams on mountain-river sediment dynamics along Trout Creek, a tributary to the South Platte River, and facilitates comparison of the relative magnitude of beaver-driven versus human-driven sediment storage in uplands. The third stop, at the former site of the Lake George Diversion Dam on the South Platte River, focuses on sediment dynamics and aquatic ecosystem recovery following dam removal and restoration in semi-arid mountain rivers.

The topics covered on this field trip are a fitting complement to three themes that emerge from Kirk Bryan's body of work. Bryan spent his early career with the U.S. Geological Survey (Sharp, 1993) focusing primarily on water resource problems and their relationship to geology in the desert southwest (Bryan, 1925; Whittlesey, 1951). He made fundamental contributions to understanding how lithology and hydrology interact to shape arid landscapes (Bryan, 1940), especially in areas underlain by thoroughly fractured, coarse-grained granite (Bryan, 1923). In his work on arroyo incision, Bryan (1928) grappled with the relative influence of natural climate forcing and anthropogenic land-use changes on channels and landscapes as well as the implications for reservoir sedimentation and other natural resource issues. The 2026 Kirk Bryan field trip, largely conducted atop the fractured, coarse-grained Pikes Peak batholith, seeks to further understand how geology, hydrology, and human influences interact to affect mountain-river dynamics, ecosystem services, and natural resources.

STUDY AREA

Topography

The field trip takes place in the southern Colorado Front Range, a mountain range within the Southern Rocky Mountains physiographic province (Fenneman, 1946). Regional topography (Fig. 1) is defined by the Rocky Mountain range front rising above the High Plains to the east, Pikes Peak (4302 m) at the southern edge of the field trip area, the Tarryall Mountains (peak elevation 3790 m) at the northwestern edge, and by the drainage network of the South Platte River, which flows northeastward across the study area through a pair of deeply incised canyons. Local topography is characterized by a high-elevation (mean of ~2600 m), relatively low-relief surface (e.g., Epis and Chapin, 1975) punctuated by rocky high points up to ~3000 m and river canyons cutting down to ~2100 m.

The modern topography of the southern Front Range is primarily due to uplift that occurred during the Laramide orogeny ca. 80–40 Ma (Dickinson and Snyder, 1978). After a period of

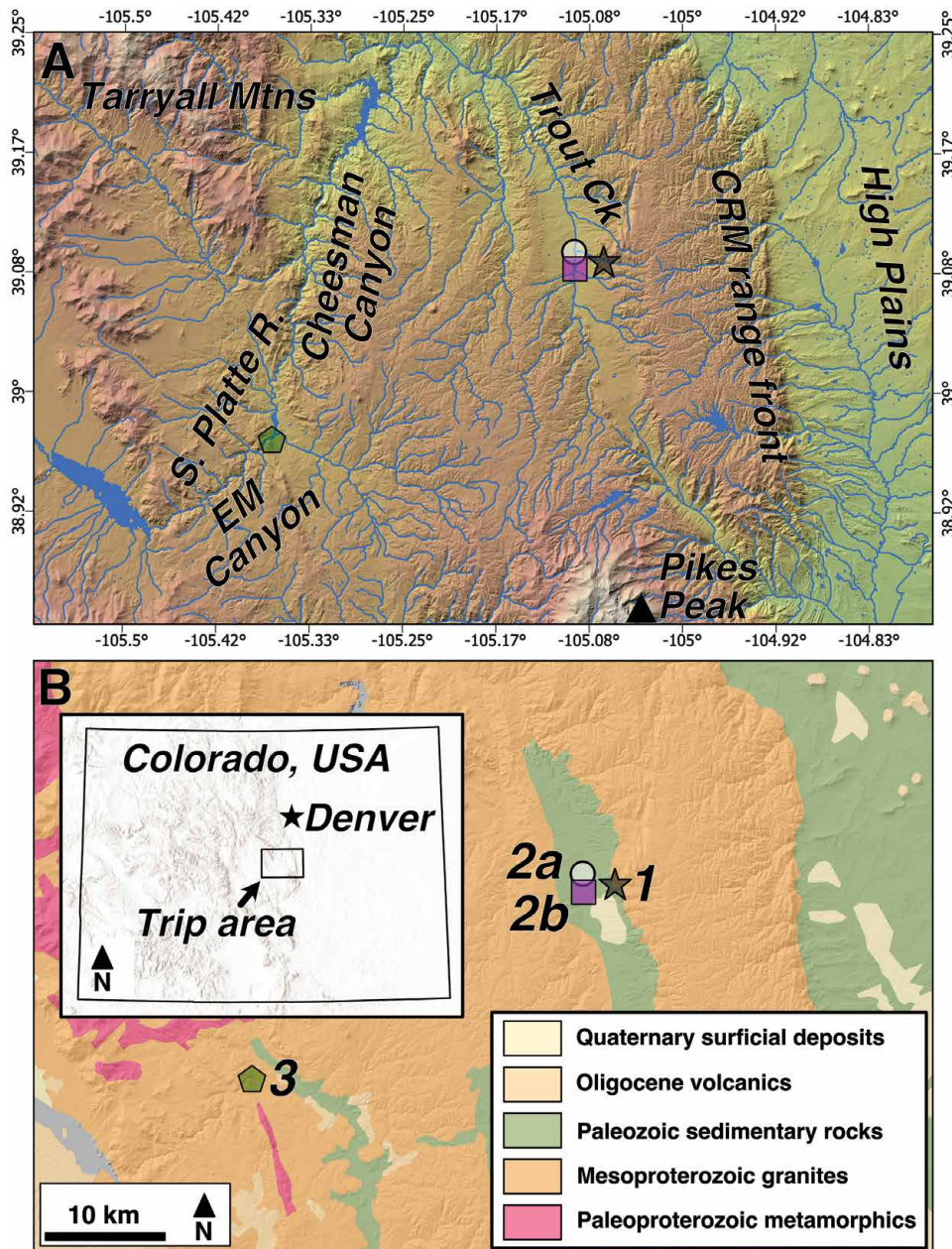


Figure 1. (A) Hillshade of the field trip region derived from USGS 10 m elevation data, colored by elevation, with streamlines from the NHDPlus database. Elevation ranges from ~1800 m on the High Plains to 4302 m at the summit of Pikes Peak. (B) Simplified geologic map with numbered markers showing field trip stops. EM—Eleven Mile; CRM—Colorado Rocky Mountains. Inset in B shows field trip area within the state of Colorado.

postorogenic tectonic quiescence, the field area may have undergone further rock uplift in the Miocene, driven by two related geodynamic processes: the opening of the Rio Grande Rift (Rickerts et al., 2016) and the subduction of the Farallon slab (e.g., Moucha et al., 2008). Those same forces may be responsible for relief production in the southern Front Range over the past ~5 m.y. that has been documented through catchment-averaged erosion rates, river profile analysis, and river incision rates (Leonard, 2002; McMillan et al., 2006; Marder et al., 2025). Marder et al. (2025) argue that southern Front Range rivers are still responding to this geodynamic rock uplift. Their analysis of river profiles reveals knickpoints along Trout Creek and the South Platte River

in Cheesman Canyon that might represent the upstream extent of river response to the most recent pulse of rock uplift. The sites for this field trip, then, are situated in a landscape that is likely undergoing active relief production through transient fluvial incision.

Geology

Most of the field area overlies Mesoproterozoic granites (Fig. 1B). The two dominant granitic units are ca. 1.5–1.4 Ga basement rocks and the ca. 1.1 Ga Pikes Peak batholith (Barker et al., 1975; Fonseca Teixeira et al., 2025) that intruded into the surrounding basement. Both granitic units have substantial textural variability

across space but are generally medium- to coarse-grained biotite granite and quartz monzonite (Wobus and Epis, 1978). The Pikes Peak Granite (PPG) comprises perthitic microcline feldspar (35%–50%), quartz (20%–35%), plagioclase (10%–20%), biotite (2%–7%), and hornblende (0.5%–2%), with accessory fluorite, apatite, zircon, and magnetite (Temple et al., 2007). The other relevant units for this field trip are a suite of Paleozoic sedimentary rocks that underlie the Trout Creek valley: the upper Cambrian Sawatch Sandstone, the lower Ordovician Manitou Limestone, the Mississippian Leadville/Williams Canyon Limestone, and the lower Permian and Pennsylvanian Fountain Sandstone (Temple et al., 2007). Much of the bedrock in the Trout Creek valley is overlain by surficial deposits, including Quaternary gravels on the valley flanks and Quaternary alluvium along Trout Creek and its tributaries (Temple et al., 2007). Stop 1 is located within the PPG, Stop 2 is underlain by alluvium deposited atop the Fountain Sandstone, and Stop 3 is located at the contact between basement granites and the PPG.

Hydroclimate

We describe general hydroclimatic conditions from Manitou Experimental Forest, where data have been collected at varying

levels of continuity since 1936 by entities including the U.S. Forest Service, the National Weather Service, the National Atmospheric Deposition Program (NADP), and the National Center for Atmospheric Research (e.g., Ortega et al., 2014; Frank et al., 2026; Fornwalt et al., 2022; National Atmospheric Deposition Program, 2022). The hydroclimate at Manitou Experimental Forest is also reasonably representative of that at Eleven Mile Canyon given that the sites are only ~25 km apart and differ in elevation by only ~70 m.

The field trip area experiences a cool, semi-arid climate (Fig. 2), with a mean annual temperature of just over 5.5 °C (42 °F) and mean monthly temperatures that range from approximately –2 °C (28 °F) in January to 19 °C (66 °F) in July (Ortega et al., 2014). NADP data, which constitute the most consistent and longest-running record at Manitou Experimental Forest, reveal annual precipitation averaging 368 mm for the period of water years 1979–2025 (Fig. 2B). NADP weekly precipitation totals show that most precipitation is delivered by monsoon-season rainfall in July and August (Figs. 2C and 2D). A typical water year begins with a cool, fairly dry late autumn to winter season followed by a major increase in precipitation from March to May. June anchors a brief early summer dry season that gives

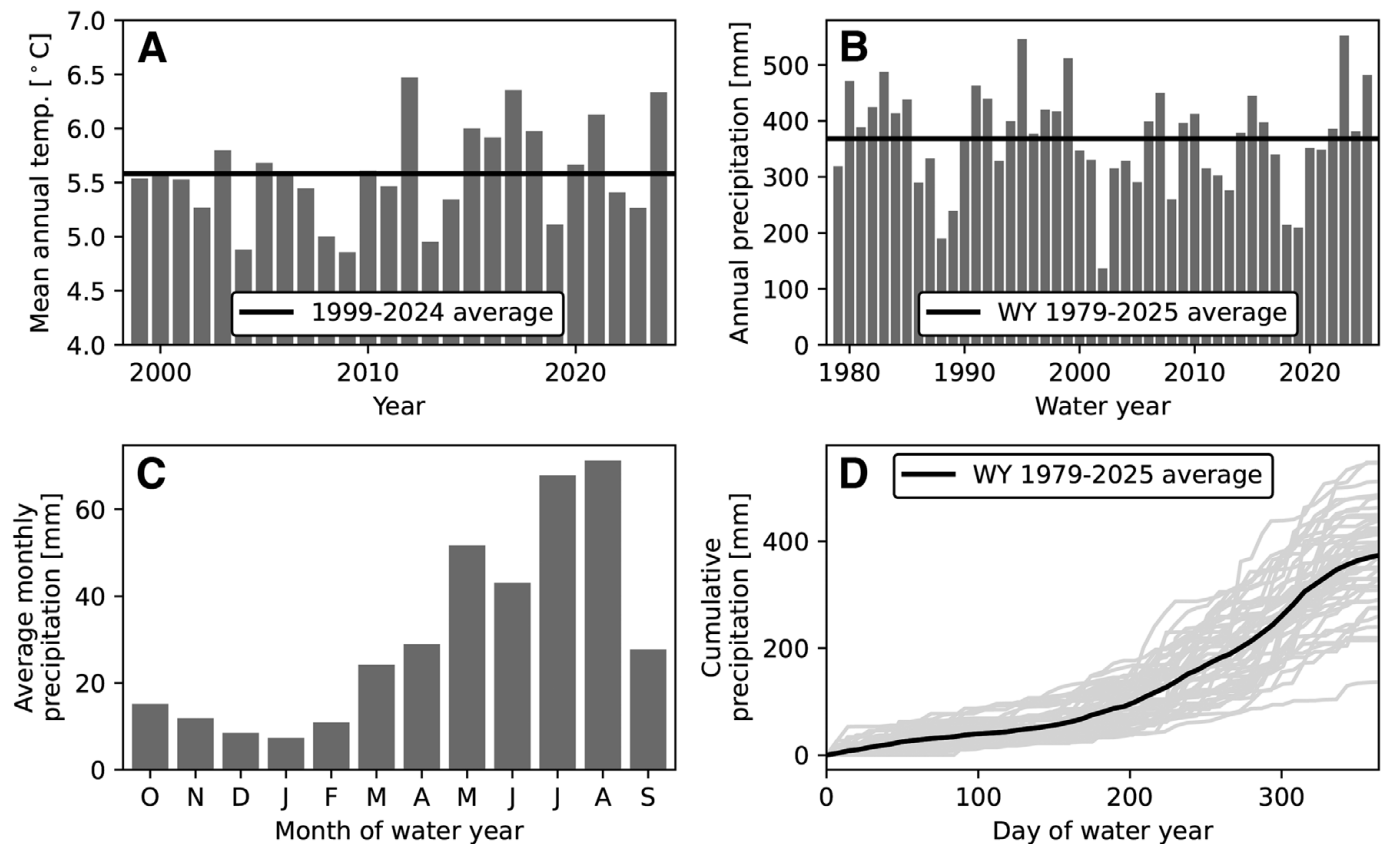


Figure 2. (A) Mean annual temperature [data from Frank et al., 2026]. (B–D) Annual and seasonal precipitation recorded at Manitou Experimental Forest. All precipitation plots are derived from weekly data at NADP site CO-21 (National Atmospheric Deposition Program, 2022). WY—water year.

way to the late-summer monsoon season (July through early September) during which ~30%–50% of annual precipitation falls. The cooler, drier season returns in October. Snow depth measurements indicate that snowstorms occur between October and April, but that most snow is transient and peak snowpack in December through February is both patchy and shallow (Ortega et al., 2014). Soil moisture monitoring records show that the soil is generally dry (averaging 0.1–0.2 m³/m³ within 50 cm of the surface) and receives its most significant pulses of recharge during the summer monsoon season (Ortega et al., 2014). The semi-arid climate, low snowfall, and dry soils of the field area render it potentially sensitive to climate-change-driven increases in air temperature (Fig. 2A) as well as to changes in precipitation phase, amount, and timing (Figs. 2B–2D).

Human Influences

The southern Front Range landscape has experienced a wide variety of human-driven changes that have been documented to affect, or might plausibly affect, river streamflow and sediment dynamics (Wohl, 2001). The rivers of the southern Front Range were likely not heavily influenced by humans before European settlement, except to the extent that the deliberate use of fire might have influenced landscape water and sediment balances (Baker, 2002; Wohl et al., 2017). The mid-1800s saw the widespread extirpation of beaver from Rocky Mountain streams (e.g., Naiman et al., 1988). Beaver removal likely caused many streams in the field trip area, including Trout Creek (Stop 2), to transition from complex, multi-thread riparian wetlands to single-thread, incised channels (Green and Westbrook, 2009; Scamardo et al., 2022). Like most of the southern Colorado Rocky Mountains, most of the field trip region was likely logged during the late nineteenth and early twentieth centuries. Logging continues today but is less widespread. Cattle have grazed in the Trout Creek valley bottom since the late 1800s, which has likely impacted the riparian area and channel form; cattle are currently fenced out of almost all the Trout Creek riparian area. Metal mining, which can increase sediment loads to streams (e.g., Coulthard and Macklin, 2003), began in the late 1800s within a few kilometers of both modern-day Manitou Experimental Forest (Stops 1 and 2) and the mouth of Eleven Mile Canyon (Stop 3) (Burnell, 2015). The Colorado Midland Railway ran on a grade carved into the granite of Eleven Mile Canyon immediately adjacent to the South Platte River from 1887 to 1918; the rails were removed in 1921 (Cafky, 1965). The railroad grade, now a gravel road, constrains the river and floodplain width in many places. Today an extensive network of roads exists near all three field sites on both private and public land. These roads, some of which we will use on this trip, likely drive erosion and sediment supply to streams (e.g., Luce and Black, 1999; Katz et al., 2014) and modify channel form where they intersect streams (e.g., Fairchild et al., 2025).

The most direct human impacts to southern Front Range rivers arise through engineering efforts that alter channel form, streamflow, and sediment fluxes. Both Trout Creek (Stop 2) and

the South Platte River (Stop 3) are dammed in multiple places. The dam impounding Manitou Lake (Stop 2B) likely contributed to downstream sediment starvation and channel incision along Trout Creek. The South Platte dams are used to manage the City of Denver's water supply, decoupling the typical temporal relationships between precipitation and streamflow. Water withdrawals and transboundary diversions further alter spatiotemporal streamflow patterns.

TRIP LOGISTICS

The field trip area is at high elevation, and weather conditions can vary. The trip involves ~4 total miles (6 km) of walking on well-maintained roads and trails. We recommend wearing sturdy, closed-toed shoes and clothing that will provide sun protection, including a hat, and bringing a warm layer and a rain jacket. Water and restrooms will be available at Manitou Experimental Forest on the organized field trip but are not routinely open to the public. There are pit-toilet restrooms available at Manitou Lake and Eleven Mile Canyon.

STOP 1: HOTEL GULCH (–105.070530, 39.091980, NAD83)

Directions

Drive 9 miles (14.5 km) north along Colorado Highway 67 from Woodland Park, Colorado. Turn right at the sign for Manitou Experimental Forest onto County Road 79. Take the second right onto U.S. Forest Service (USFS) Road 347. Bear left to stay on USFS Road 347 and, immediately afterward, park in the dirt area on the left side of the road. Walk south along USFS Road 347, which becomes USFS Road 346 at the first intersection, then turn right to stay on USFS Road 346 after ~0.2 miles (0.3 km). Continue for 1.7 miles (2.7 km). The site is on the right side of the road immediately before the road crosses Hotel Gulch.

Site Description

Hotel Gulch is a small (~7-km²) semi-arid headwater catchment within the Manitou Experimental Forest, managed by the U.S. Forest Service Rocky Mountain Research Station. The Experimental Forest was established in 1936 and covers ~68 km². Hotel Gulch is a tributary to Trout Creek, which flows to the South Platte River. In 2021 and 2022, Warix et al. (2023a) instrumented the upper Hotel Gulch catchment (Fig. 3; ~3 km² drainage area) at eight evenly distributed points along the mainstem to observe groundwater-surface water interactions. Stop 1 is ~1.5 km downstream from their study sites but still showcases the hydrologic dynamics of Hotel Gulch.

Bedrock, Grus, and Groundwater Storage

Upper Hotel Gulch is entirely underlain by the PPG, a coarse-grained biotite-hornblende potassic granite, which can

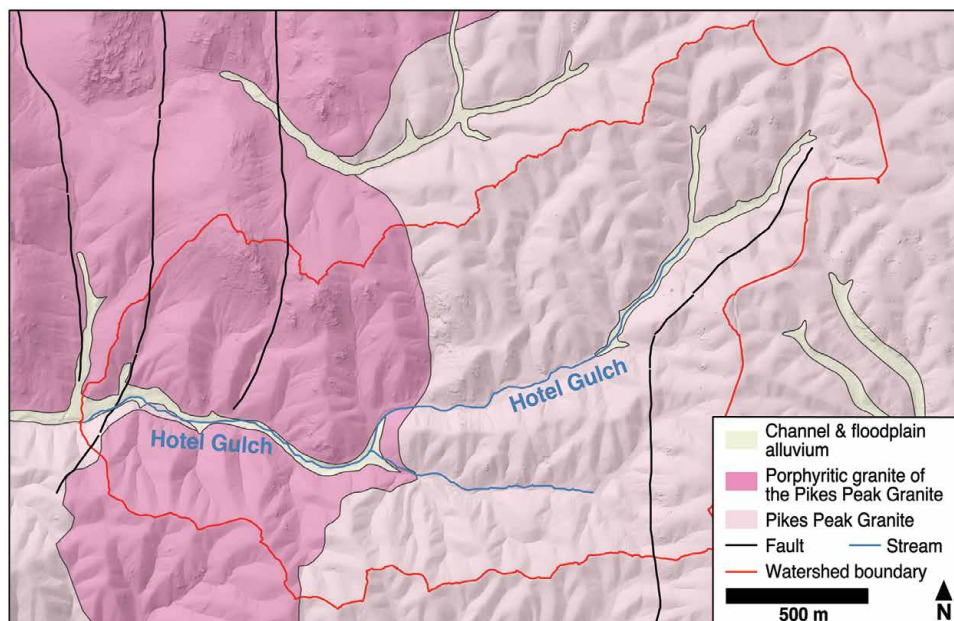


Figure 3. Hillshade of upper Hotel Gulch watershed with geology (Temple et al., 2007) overlain. The field trip stop is located ~1.5 km downstream of the upper watershed outlet. Figure adapted from Warix et al. (2023a).

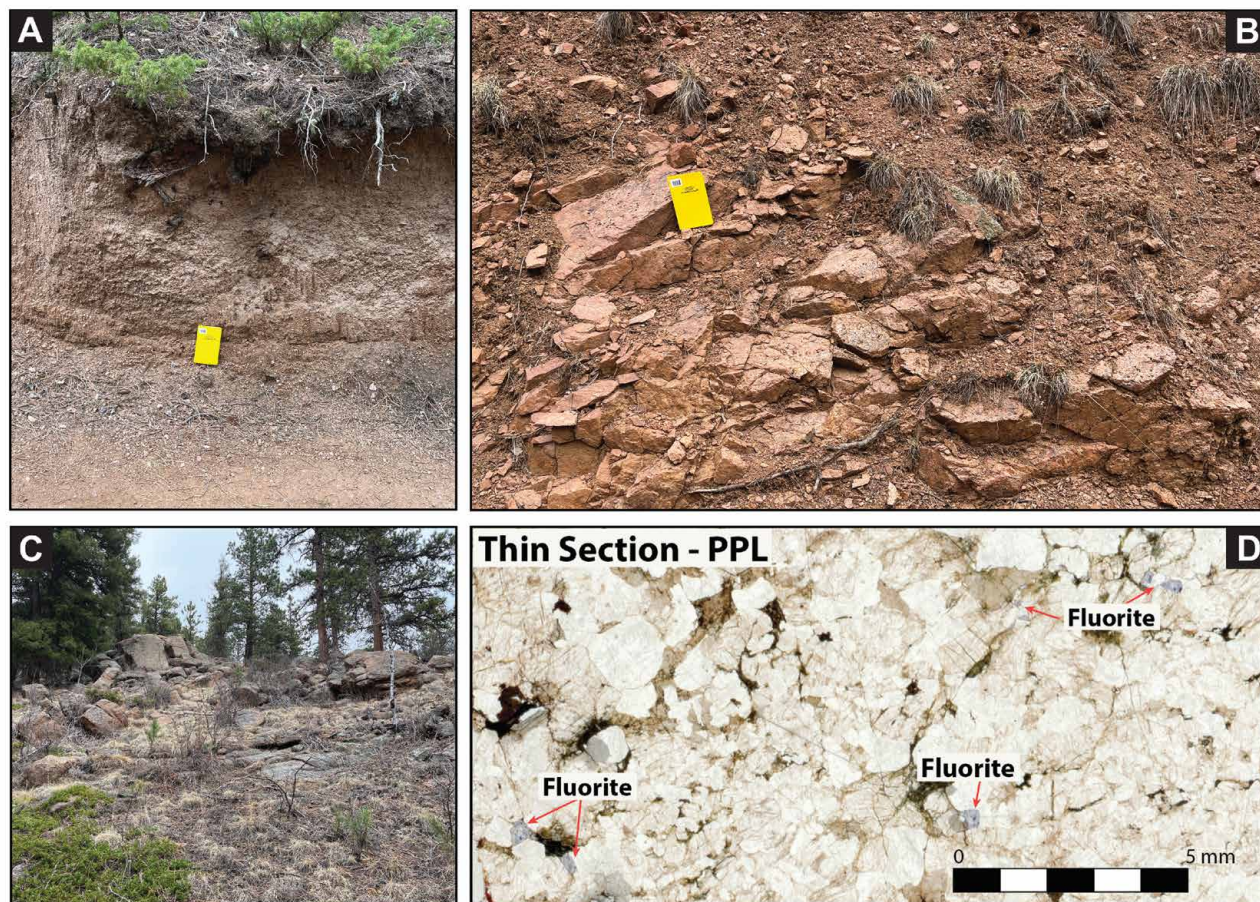


Figure 4. Weathering patterns in the Pikes Peak Granite (PPG) along Hotel Gulch Road (en route to Stop 1): (A) PPG weathering profile in a road cut. (B) Fractured blocks and grus. (C) Spheroidal weathering blocks. (D) PPG in thin section (plane polarized light [PPL]). Fluorite crystals are the light purple grains. Standard 19-cm-tall field book for scale.

be further divided into porphyritic and non-porphyritic members. The PPG hosts shallow and deep groundwater storage that sustains streamflow in the basin (Warix et al., 2023a).

On the walk from the parking area to Stop 1 along Hotel Gulch Road, we can observe outcrops of the PPG (Figs. 4A–4C) that reveal how PPG lithology and weathering dynamics are expressed in this landscape. There are two primary geomorphic expressions of the PPG. One occurs where the granite has disaggregated into grus, or loose granular sediment, which typically fractures along crystal boundaries and microfractures (Fig. 4A, fine grains in Fig. 4B). The weathered grus is generally <10 m thick and is located on hillslopes and in valley bottoms (Wanty et al., 1992). Melting snow and rain infiltrate through the high-porosity grus before recharging deeper groundwater. In valley bottoms where alluvial sediment accumulates, grus further weathers into fine-grained sand, silt, and clay. This material is mapped as channel and floodplain alluvium and can support shallow groundwater storage (Warix et al., 2023a) (Fig. 3). The second geomorphic expression of the PPG is massive bedrock with developed fracture sets (Figs. 4B–4C). Outcrops tend to be spheroidally weathered (Fig. 4C) due to combined chemical and physical weathering concentrated along fractures that tend to be separated by <1 m (Wanty et al., 1992). Fractures are steeply dipping, oriented approximately N45°W and N70°E, with a third set that is nearly horizontal (Wanty et al., 1992) (Figs. 4B–4C). Fractures serve as primary conduits for groundwater flow within the PPG.

Although PPG mineralogy is typical of a granite, average bulk-rock fluorite (CaF_2) content is anomalously high at ~0.35 wt% (Wanty et al., 1992) (Fig. 4D). As meteoric water travels through the bedrock, it dissolves fluorite (among other minerals) and releases fluoride (F^-) (Wanty et al., 1992), enabling the use of fluoride as a natural tracer for groundwater.

Groundwater–Surface Water Connection and Intermittent Streams

Stop 1 gives us a view of Hotel Gulch, an intermittent stream flowing over PPG-derived grus (Fig. 5). Non-perennial streams (intermittent and ephemeral streams combined) make up more than half of the global river network (Datry et al., 2014). In semi-arid regions, the fraction of non-perennial streams is higher at ~80% (Levick et al., 2008). When streams dry seasonally, typically due to a falling water table and increasing evapotranspiration losses (Warix et al., 2023b), they are considered intermittent. In contrast, streams that flow only in response to precipitation events are ephemeral. Perennial streams, such as Trout Creek, flow year-round. Portions of Hotel Gulch are intermittent; the upper reaches have been observed to dry seasonally (Warix et al., 2023a), as have the lower reaches we pass on the walk from the parking area to Stop 1.

Stored groundwater enables portions of Hotel Gulch to flow year-round, as observed by a geochemical signature indicative of groundwater in streamflow during high- and low-flow periods, as well as summer monsoon storms (Warix et al., 2023a,

2024; Bush et al., 2023, 2025). Warix et al. (2023a) used fluoride concentrations as a natural tracer for quantifying groundwater contribution to streamflow in Hotel Gulch. Across all eight instrumented sites distributed along the 2-km-long upper Hotel Gulch main stem, they observed that streamflow originated as groundwater that was stored in the PPG during both high- and low-flow periods; on average, groundwater accounted for >70% of total streamflow in >95% of observations during the April 2021–November 2021 study period (Warix et al., 2023a). However, certain upstream reaches dried during the late summer and early fall despite perennial flow upstream and downstream. Warix et al. (2023a) determined the age of groundwater contributing to streamflow using chlorofluorocarbon (CFC-12) and tritium with a binary mixing model. Mean residence time ranged between 10 and 55 yr throughout the watershed, suggesting that Hotel Gulch is sustained not by recent precipitation, but by water that recharged the PPG fracture system years to decades ago. The range in groundwater residence time was large (45 yr), suggesting spatial and temporal variability in groundwater storage and transport mechanisms within the watershed.

Spatiotemporal variability in groundwater age and streamflow source is due to local topographic and subsurface heterogeneity. Warix et al. (2023a) found that groundwater age was correlated with two landscape properties: hillslope gradient and streambed hydraulic conductivity (K). Sites in the flat upper watershed (slopes <14.5°) had the oldest groundwater (53–55 yr), the lowest streambed K , and the highest area-weighted groundwater contribution to streamflow (Fig. 6). Flatter sites exhibited negligible changes in mean residence time (<2 yr) between June and September 2021. The alluvial fill present throughout Hotel Gulch's upper riparian zone (Fig. 3) is hypothesized to act as a shallow



Figure 5. Looking upstream at Hotel Gulch at Stop 1. Foreground shows the grus on the streambed. Standard 19-cm-tall field book for scale.

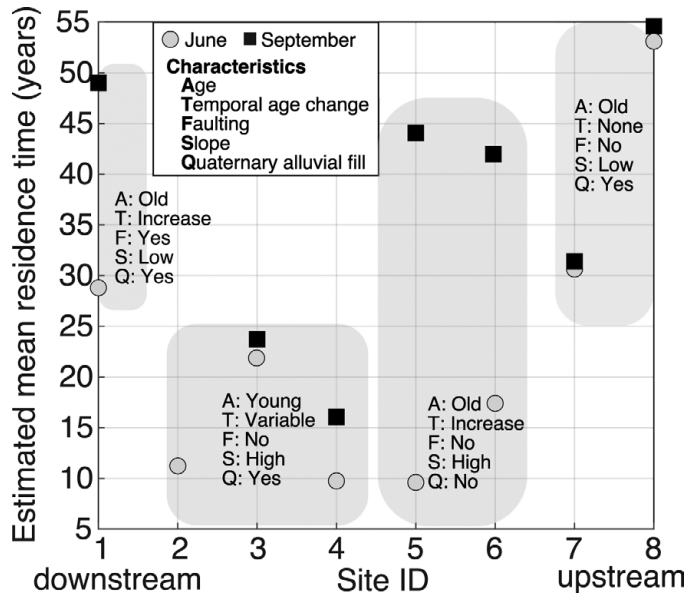


Figure 6. Estimated mean residence time for eight sites in both June (circles) and September (squares) 2021. Gray blocks group sites by relative age, topography, and subsurface structure characteristics. These key characteristics are listed by letter, including groundwater age (A), the temporal age change from June to September (T) 2021, the presence or absence of faulting through the stream (F), relative changes in local slope (i.e., shallow or steep) (S), and the presence or absence of quaternary alluvial fill (Q).

groundwater storage reservoir that can sustain groundwater discharge to streamflow during periods of limited precipitation. Sites in the steepest portion of the catchment (slopes 17–26°) had the youngest groundwater ages (often <20 yr in June), high stream-bed K, and relatively low area-normalized groundwater discharge (Fig. 6). In steeper areas, there were large increases (13–14 yr) in mean groundwater residence time between June and September. This age change is hypothesized to be due to a loss of near-surface interflow primarily sourced by annual precipitation during late summer and fall months, which shifted the dominant streamflow source to older water originating from bedrock fractures. At the steepest sites, the stream dried completely from August 2021 through October 2021. Observation points near N–S–trending faults (Site 1, Fig. 6) close to the upper watershed outlet also exhibited older groundwater, likely reflecting the influence of faults on streamflow sourcing from groundwater (Fig. 3). Overall, flat reaches store water in alluvium that may contribute to streamflow while steep reaches release shallow interflow that drains seasonally and so are the most likely to dry. The reach of Hotel Gulch showcased at Stop 1 is situated in a steep portion of the catchment where relatively little alluvium is stored on the valley floor (Temple et al., 2007), suggesting that the reach we are observing is more dependent on seasonal interflow and therefore more likely to dry than reaches in the less steep, alluvium-mantled (>2 m thick; Warix et al., 2023a) upper valley.

Climate Change Impacts on Semi-Arid Headwater Streams

Streamflow dynamics observed at Hotel Gulch are representative of those occurring in semi-arid regions more broadly. In mountainous locations throughout the western United States, warming temperatures, increased mid-winter ablation, and more frequent rain-on-snow and dust-on-snow events are all altering snowpack magnitude and melt timing, which is expected to decrease groundwater recharge (Siirila-Woodburn et al., 2021; Mote et al., 2018). Projections for the Rocky Mountains suggest that snow water equivalent could decrease by 25% by 2050 (Siirila-Woodburn et al., 2021). Decreasing groundwater recharge has both short- and long-term implications for streamflow persistence given that groundwater supports streamflow throughout the west (Brooks et al., 2025).

In arid and semi-arid regions, climate impacts are forecasted to cause streams to dry more often and for longer (Zipper et al., 2021). As the groundwater table declines, recharging water may be routed to deeper groundwater rather than along shallow interflow flowpaths (Carroll et al., 2024). These changes can cause a net decrease in stream discharge as well as a shift toward a higher relative contribution from deeper groundwater stores (Siirila-Woodburn et al., 2026), thereby causing stream reaches with currently perennial flow to run dry.

Different reaches of Hotel Gulch illustrate different potential responses to aridification (Fig. 7). Currently, in steep areas with thin alluvial fill and higher hydraulic conductivity, streamflow is sourced by seasonal interflow, and there is little to no alluvial storage. In these steep areas, there is a low upstream-area-weighted groundwater discharge in the stream, and groundwater age is young (Fig. 7A). In areas with shallower slopes, thicker alluvial fill, and lower hydraulic conductivity, there is little to no interflow, and the groundwater age does not change seasonally. Groundwater age is relatively older, and alluvial storage sustains high upstream-area-weighted groundwater discharge to streamflow (Fig. 7B). In steep areas, a groundwater table drop that causes stream drying is expected (Fig. 7C). In areas with shallower slopes, the groundwater table may still drop, but alluvial storage and older stored groundwater are hypothesized to sustain streamflow through short-term droughts and enable greater resilience to decreasing recharge (Fig. 7D) (Warix et al., 2023a).

Hotel Gulch serves as a case study that substitutes space for time to develop a broadly applicable conceptual model. Intermittent stream drying patterns have been attributed to variable topography and subsurface structure throughout the west (Godsey and Kirchner, 2014; Warix et al., 2021). Streamflow permanence in semi-arid headwater landscapes is not simply a function of total precipitation: it is controlled by groundwater stored in bedrock fracture networks, hillslope topography, alluvial fill geometry, and subsurface hydraulic conductivity (Fig. 7). Predicting and managing water resources under climate change requires understanding how changes in headwater systems like Hotel Gulch may impact downstream water supplies.

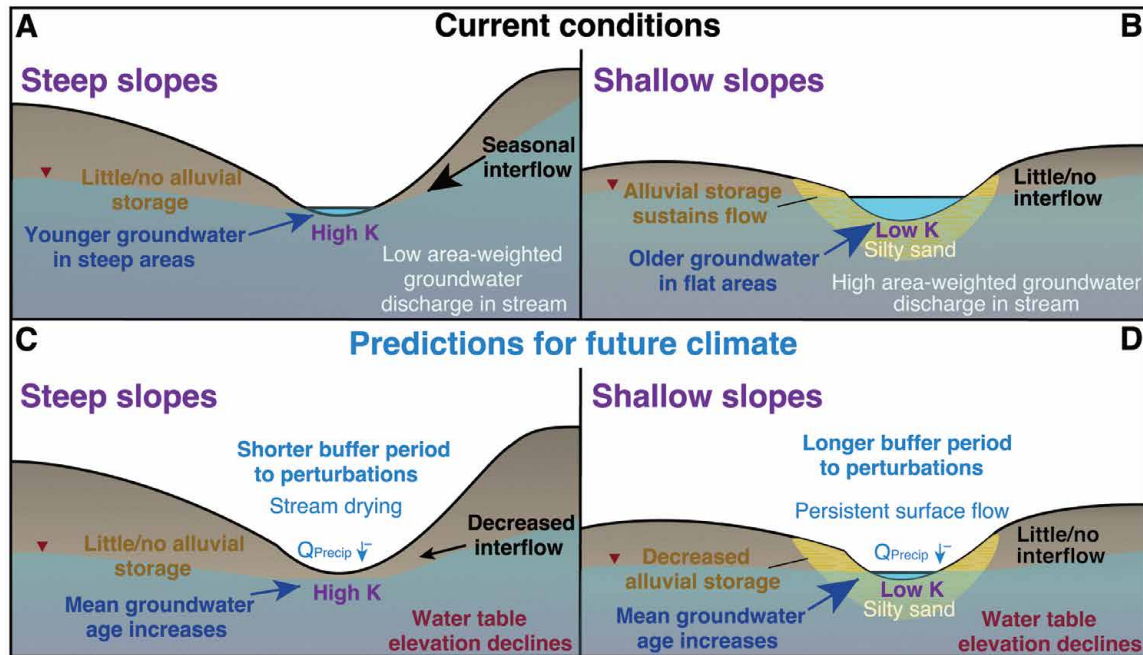


Figure 7. Conceptual model of hypothesized response to future decreased groundwater recharge in flat and steep scenarios in both a current and future setting. Text color is linked to different water sources and is consistent across subplots. In the top panels we show current conditions at Hotel Gulch in steep (A) and shallow slope (B) reaches. The bottom two panels (C and D) show these two geomorphic settings in a future climate scenario. Figure modified from Warix et al. (2023a). K—hydraulic conductivity.

STOP 2A: TROUT CREEK BEAVER DAMS (−105.097054, 39.0984936, NAD83)

Directions

Walk west from the Stop 1 parking area along USFS Road 347. Turn left after ~70 m onto County Road 79 and follow it down to the bridge over Trout Creek before reaching Colorado Highway 67. Stand on the river-right bank of Trout Creek upstream of the bridge.

Background and Study Area

Stop 2A gives a view of an active beaver dam across Trout Creek (Fig. 8). More dams and lodges are visible from nearby vantage points. Beaver modify river corridors (channels and their floodplains) by building dams, which slow flow velocity and promote sediment deposition and storage (e.g., Adamchak et al., 2025; Rees et al., 2024; Dunn et al., 2024; Larsen et al., 2021). Over time, beaver can transform river corridors into multi-thread, physically complex beaver meadows through dam building, canal creation, and modification of the vegetation community (Levine and Meyer, 2014; Polvi and Wohl, 2012). Prior to European colonization and widespread beaver population reductions, river corridors probably stored significantly more sediment and were more physically complex than they are today (Scamardo et al.,

2022; Wohl et al., 2017). Although the importance of beaver in modifying sediment dynamics is increasingly recognized, we still lack field data demonstrating how beaver modify river corridor sediment storage and channel form. Understanding beaver-related sediment dynamics is particularly important as beaver populations rebound and beaver are incorporated into river restoration approaches (Pollock et al., 2014; Nash et al., 2021; Norman et al., 2022). On Trout Creek, beaver pond density has increased over the past 60 years as determined from analysis of aerial imagery, with some reaches that had ~1–2 ponds/km in the 1960s hosting ~10–11 ponds/km by the early 2020s (Rees et al., 2024). Rees et al. (2024) determined beaver pond sedimentation rates in three reaches of Trout Creek to explore the impact of beaver dams on sedimentation over annual to decadal time scales (Fig. 9).

Beaver Pond Sedimentation Rates

Rees (2023) and Rees et al. (2024) used historical and recent aerial imagery and field surveys of sediment thickness in beaver ponds to determine integrated sedimentation rates in ponds of differing ages in three study reaches on Trout Creek upstream and downstream of Stop 2A (Fig. 9). They determined the thickness of pond-deposited sediment by probing deposits until reaching coarser bed material, which they interpreted as the pre-dam sediment surface. Rees et al. (2024) estimated sedimentation rates in ponds of different ages (younger, less persistent versus



Figure 8. View upstream on Trout Creek from Stop 2A showing a channel-spanning beaver dam. The pond is ~40 m wide at its widest point; the upstream channel is ~10 m wide.

older, more persistent ponds) to better understand the impact of beaver on sedimentation rates and sediment storage over annual to decadal time scales. Much of the previous work on beaver pond sedimentation rates has been limited to ponds that have persisted for <5 yr, limiting understanding of the longer-term impacts of beaver on sedimentation rates within river corridors. Although beaver dams and associated ponds can be transient features on the landscape due to dam breaching and beaver abandonment, there is evidence that some ponds can persist 5–10 yr or longer (Rees et al., 2024; Butler and Malanson, 1995).

Sedimentation rates along Trout Creek are highest for young ponds (<5 yr old), particularly for ponds in reach TC02, which is the most incised reach. In reach TC02, tall, eroding terrace banks adjacent to the channel provide a local sediment source (Fig. 9C) that likely contributed to high sedimentation rates (Fig. 10). In older ponds, sedimentation rates are lower, indicating that ponds fill with sediment over time and reach a maximum sediment storage capacity and/or that older beaver dams are abandoned and not maintained, limiting further sediment trapping. In

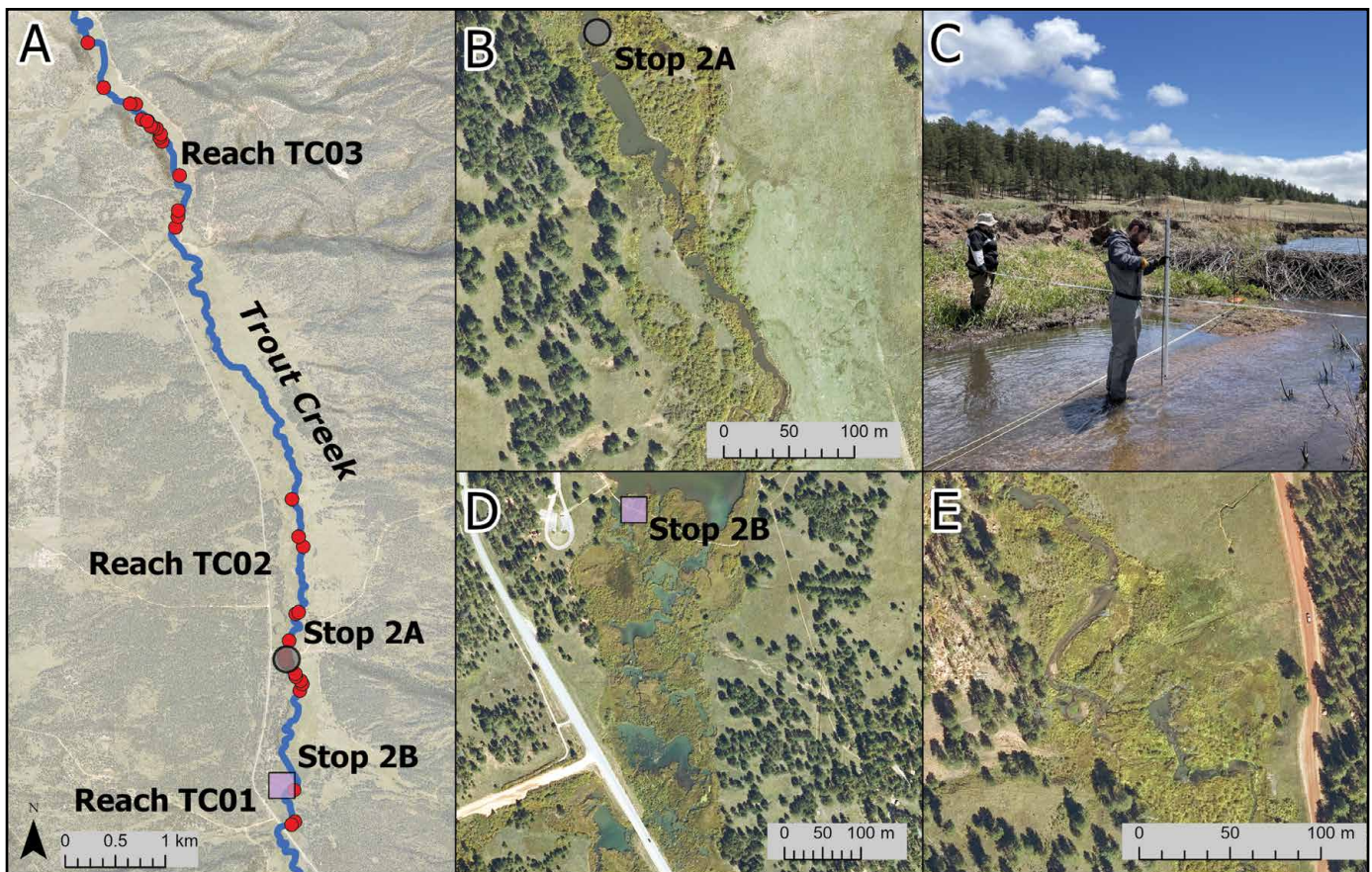


Figure 9. (A) Trout Creek, showing Stops 2A and 2B as well as ponds (red dots) that were measured to determine sedimentation rates in three reaches. Flow direction is to the north. (B) Aerial image of a portion of reach TC02. (C) Measuring pond dimensions in reach TC02, with eroding banks in background of photo. Aerial images of (D) Reach TC01 beaver meadow wetland complex and (E) beaver dams and ponds in reach TC03; aerial images are from the National Agriculture Imagery Program from Fall 2023, downloaded from USGS EarthExplorer, <https://earthexplorer.usgs.gov>.

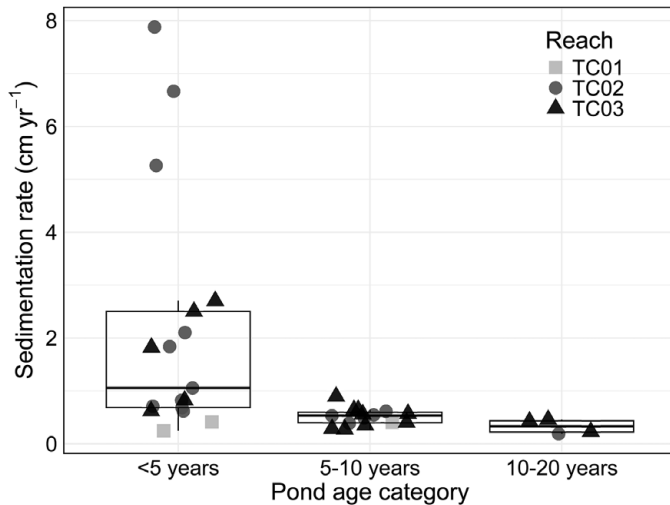


Figure 10. Sedimentation rates in beaver ponds on Trout Creek in reaches TC01, TC02, and TC03 by pond age category determined from aerial imagery. Sedimentation rates shown here were calculated by dividing the average thickness of sediment deposited in beaver ponds by the estimated pond age. Data were previously published in Rees et al. (2024).

addition, pond sediment is likely eroded and later replaced with new, incoming sediment in older ponds as dams breach and are repaired, lowering the overall average sedimentation rate.

Rees et al. (2024) also collected sediment cores from two beaver ponds in Trout Creek and determined sedimentation rates using fallout radionuclides (^7Be : half-life of 53 d and ^{210}Pb : half-life of 22.3 yr) and age-depth models (Landis et al., 2016). In addition to age-depth models from fallout radionuclides in the uppermost portions of the cores, they obtained radiocarbon dates at greater depths. These dating techniques indicated that there is a young “active layer” of sediment that is ~10–20 cm thick and 1–2 yr old, with a deeper, older “storage layer” beneath, as indicated by radiocarbon dates that pre-date the pond construction in aerial photos. For example, one pond in reach TC03 was present in aerial imagery for ~14 yr at the time of sampling, but fine-grained deposits indicating a beaver pond depositional environment were ~1–2 yr old. This indicates cycles of scouring and filling of sediment in the pond over the pond’s lifespan (Rees et al., 2024).

The variation and range in sedimentation rates in beaver ponds, like the one we see from Stop 2A, underscore the need to understand how local factors influence sedimentation rates (e.g., eroding banks in reach TC02 likely contribute to high sedimentation rates). In addition, average sedimentation rates are high in young ponds, but lower overall in older ponds that have likely experienced scouring and re-filling, lowering the integrated sedimentation rate. Low sedimentation rates in older ponds also likely reflect older ponds reaching their maximum potential storage. Understanding sediment dynamics in more persistent ponds has implications for predicting changes to river corridor sediment storage as beaver populations fluctuate due to beaver trapping and removal, population growth, or reintroduction.

STOP 2B: BEAVER MEADOW WETLAND COMPLEX (–105.097471, 39.087146, NAD83)

Directions

After Stop 2A, turn left (south) onto Colorado Highway 67 from Manitou Experimental Forest. Drive 0.6 miles (1 km), then turn left into the Manitou Lake picnic area. After parking at the southern end of the picnic area road, walk S/SE along the footpath that follows the lake shore for ~0.1 miles (0.2 km) until you are overlooking the wetland at the upstream end of Manitou Lake.

Estimating the Time Scale for Beaver Pond Sedimentation to Reconnect Incised Channels to Their Floodplains

Stop 2B gives a view onto a beaver meadow wetland complex immediately upstream of Manitou Lake, an impoundment created by a human-built dam. Beaver-related sedimentation in ponds can drive increased channel-floodplain lateral connectivity, such as that observed here, as sedimentation, channel widening, and avulsions result in multi-thread, patchwork beaver meadows (Pollock et al., 2014; Polvi and Wohl, 2012). On Trout Creek, reach TC02 (upstream and downstream of Stop 2A) is incised into a fluvial terrace, limiting the extent of the riparian zone and floodplain habitat. Rees et al. (2024) used their field dataset on beaver pond sedimentation rates (Fig. 10) to estimate the time required to aggrade the channel in reach TC02 and connect the channel to the abandoned terrace, which would in effect reverse channel incision and yield a well-connected channel and floodplain like we observe at Stop 2B. They estimated the depth of sediment required (D_{infill}) by comparing channel cross-section geometry in reach TC02 to reach TC01, the latter of which is multi-thread and highly connected across the valley bottom. Drawing from the measured distribution of pond ages, a statistical relationship between pond age and sedimentation rate, and information on the fraction of time ponds are inundated based on aerial imagery analyses, they estimated the time needed (T_{infill}) to aggrade the channel by D_{infill} , increasing lateral connectivity with the terrace (Rees et al., 2024). Results indicated that it would take ~100 yr of beaver activity for reach TC02 geometry to become similar to reach TC01 geometry (median estimate = 96 yr; Fig. 11), suggesting that reducing incision with beaver activity may be a relatively long-term process (decades) in relation to typical time scales of restoration activities and monitoring (years).

Comparing Potential Sediment Storage Due to Beaver with Sediment Storage Behind Human-Built Dams

At Stop 2B, we observe water and sediment impounded both by beaver dams and by the human-built dam that impounds Manitou Lake, providing an opportunity to discuss the relative amount of sediment that each type of dam might store. In the Rocky Mountain region, there is increasing concern over water storage capacity in human-built reservoirs as populations increase

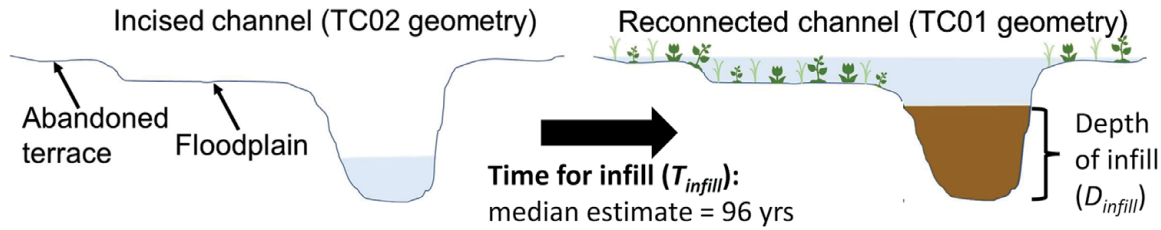


Figure 11. Conceptual figure demonstrating the time needed (T_{infill}) to aggrade the channel by a depth of sediment required (D_{infill}) to modify channel morphology from an incised channel (reach TC02 geometry) to a reconnected channel (reach TC01 geometry). Figure modified from Rees et al. (2024, their figure 7).

and the timing, phase, and quantity of precipitation change under a warming climate (Foster et al., 2016, 2025). Water storage capacity can be reduced due to sedimentation, and thus some river restoration projects include the goal of increasing distributed sediment storage to reduce downstream sediment delivery to reservoirs. Recent work indicates that small human-built dams have reduced sedimentation in large human-built reservoirs farther downstream (Foster et al., 2024), but human-built dams lack the ecosystem benefits of beaver dams and beaver activity (Wohl and Inamdar, 2025). We used modeled beaver dam capacities (number of ponds per kilometer of river) determined with the Beaver Restoration Assessment Tool (Macfarlane et al., 2017) and a compilation of field-based datasets on beaver pond sediment volumes (Scamardo et al., 2025) to estimate how much sediment could be stored in river corridors if beaver were allowed to populate the landscape at their predicted potential

capacity (Fig. 12; Lininger et al., 2025). We compared these estimates with modeled human-built reservoir sediment storage that accounts for upstream sediment contributing area and the impact of a connected dam network on reservoir sedimentation rates (Hurst et al., 2025; Foster et al., 2024, 2025).

The sediment storage comparison between human-built impoundments and beaver ponds (both seen at Stop 2B) for the Rocky Mountain physiographic region demonstrated that if beaver populations were allowed to increase from present levels to reach 100% of their existing dam capacity, sediment storage in beaver ponds could be close to current sediment storage in human-built reservoirs (Fig. 12). If beaver dam capacity was at higher historical levels, reflecting vegetation and land use prior to significant human impacts, sediment storage could be more than the current estimated sediment volume in human-built reservoirs. Longer term, sediment storage in human-built dams will continue to increase until reservoirs are filled (or longer if more dams are built) and could outpace potential beaver-driven storage. There exist other important differences in the temporal dynamics of sediment storage in beaver meadows versus human-built reservoirs. Beaver meadow complexes may have lower overall trapping efficiency, and may therefore be less prone to causing downstream sediment starvation, than human-built reservoirs. Beaver-influenced reaches might reach an equilibrium condition in which, after a period of net sediment accumulation, their time-averaged sediment storage is steady such that sediment is exported downstream at the rate of supply. This condition does not occur in major human-built reservoirs. Our results point to the potential importance of beaver to distributed sediment storage in river corridors and the role beaver could play in reducing sedimentation in downstream reservoirs while also providing ecosystem services that human-built dams do not (Wohl and Inamdar, 2025).

These first-order comparisons over broad spatial extents do not consider watershed- and reach-scale sediment connectivity and disconnectivity that modify sediment storage and yields within river corridors. For example, wildfire could create a significant source of sediment delivered to downstream reservoirs (e.g., East et al., 2025) in watersheds in which beaver capacity could be low, limiting the role of beaver in mediating sediment fluxes. Despite these limitations, the comparison of potential sediment

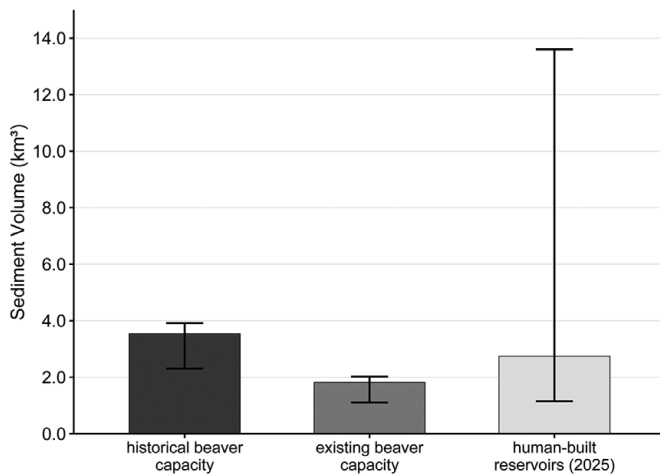


Figure 12. Comparison of sediment volume storage estimates in the Rocky Mountain physiographic region. Error bars on the human-built reservoir storage estimate show the 95% confidence interval for a multiple linear regression model used to predict sediment storage (Foster et al., 2025). Error bars on the historical and existing beaver capacity sediment storage estimates show the 2.5 and 97.5 percentiles from 10,000 Monte Carlo simulation draws (Lininger et al., 2025). Human-built reservoir storage will continue to increase from its present-day value until reservoirs are filled (or longer if more dams are built).



Figure 13. Aerial photograph (© Google Earth, 2020) and field photograph (Lyndsay Saunders, U.S. Forest Service) showing the Lake George Diversion Dam before it was removed. The star indicates the former dam, now the site of the fishing platform from which we will observe the area. Cross-stream lines are the six cross sections where we collected repeat surveys of channel form. Control cross sections are located >2 km upstream (not pictured). The upstream-most cross section is located immediately upstream of, rather than within, the former impoundment. P—parking area.

storage in beaver ponds relative to human-built reservoir sediment storage highlights the potentially significant impact beaver could have on river corridor sediment retention. Together, the research discussed at Stops 2A and 2B demonstrates the important ongoing and potential effects of beaver activities on sediment storage in mountain landscapes, at both local and regional scales.

STOP 3: ELEVEN MILE CANYON (−105.366973, 38.967951, NAD83)

Directions

Exit the Manitou Lake picnic area and turn left onto Colorado Highway 67. After 8 miles (13 km), turn right onto U.S. Highway 24 West. Drive 19.5 miles (31 km), then turn left onto County Road 96. Drive 1 mile (1.6 km) and take the first right turn into the Eleven Mile Canyon Recreation Area parking lot. Walk W/SW along the nature trail that parallels the South Platte River. After ~0.2 miles (0.3 km), you will arrive at a fishing platform constructed of large boulders on the river-right bank.

Background

The former site of the Lake George Diversion Dam (LGDD) is located at the mouth of Eleven Mile Canyon, where the South Platte River exits a narrow bedrock gorge and flows into an alluviated valley (Figs. 1 and 13). Before its removal, the dam (Fig. 13 inset) was the only full obstruction between Eleven Mile Canyon Dam, located ~18 km upstream, and Cheesman Dam, located ~55 km downstream. LGDD was built in 1952 to divert water to supply the city of Colorado Springs. The diversion was abandoned by the 1990s.

Removal of the earthen and concrete dam began in late 2023, by which point the impoundment was almost filled with sediment

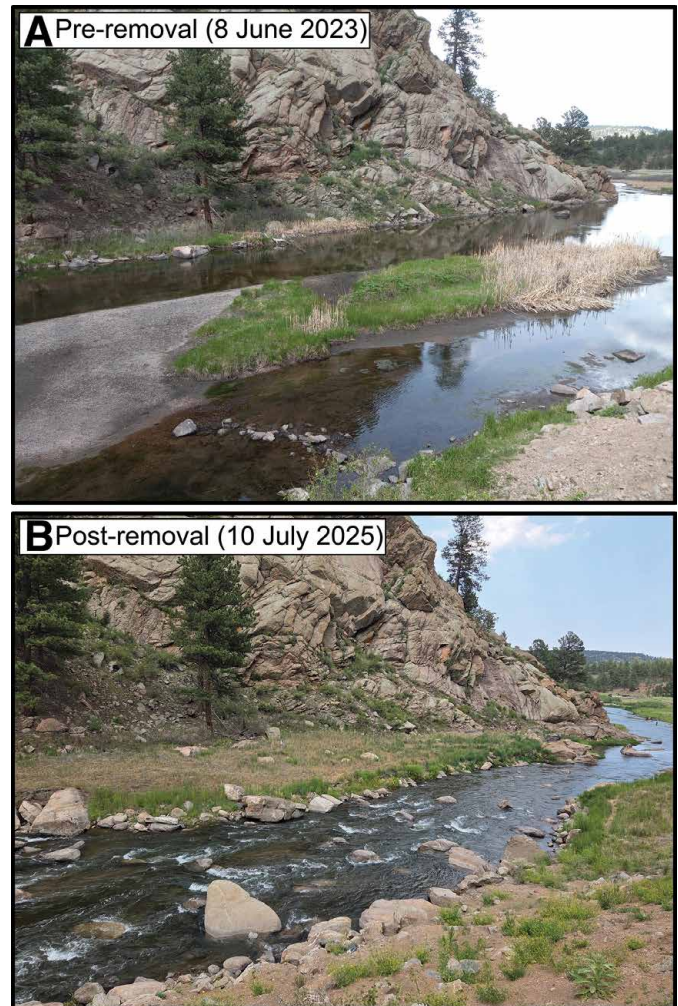


Figure 14. Photographs (by John Korfmacher, U.S. Forest Service) taken looking downstream in the former impoundment.

(Fig. 14A). Because of concerns about sediment impacts on downstream ecosystems and water infrastructure, contractors excavated most of the impounded sediment out of the channel before removal, a practice that is not feasible in most removals (e.g., Collins et al., 2017; East et al., 2018). The removal was accompanied by restoration efforts, including rebuilding channel banks and floodplains (Figs. 14B and 15B) as well as revegetation work. Earth moving for removal and restoration was complete by April 2024.

LGDD represents a case study that has the potential to expand understanding of river response to dam removal. Although removal is becoming a more frequently used management strategy as the dams built in the mid-twentieth-century age into obsolescence (e.g., East and Grant, 2023), most removals are concentrated in water-rich regions. To our knowledge, there have been no dam removals in Colorado documented in published monitoring studies (Bellmore et al., 2017). LGDD, at ~7.3 m tall, is representative of >1000 small dams across the Rocky Mountain region and therefore might serve as an instructive example of how rivers and aquatic ecosystems in mountainous, relatively water-scarce regions respond to dam removal.

Monitoring River Response to Removal of LGDD

We have monitored the LGDD site since 2023, focusing on quantifying geomorphic and ecological responses to dam removal. We are following a before-after, control-impact study design in which we track conditions in the river reaches directly affected by the removal and compare them to measurements

collected in control reaches located >2 km upstream. All pre-removal measurements were collected in July 2023. Following removal and restoration (late 2023 to early 2024), we collected geomorphic measurements in the spring and summer, bracketing typical spring peak flows, and ecological measurements in the summer and autumn following regional sampling standards. This guide presents data through summer 2025.

Geomorphic measurements consisted of channel cross-section GPS surveys to quantify changes in channel shape (Fig. 15). Ecological measurements focused on the abundance and diversity of benthic macroinvertebrates—aquatic animals that live in the streambed, form an important component of the aquatic food web (e.g., Wallace and Webster, 1996), and are sensitive to the quality of channel-bed habitat (e.g., Vinson and Hawkins, 1998).

Geomorphic Response to Dam Removal

Channel adjustment to dam removal was rapid. As a general measure of channel changes over time, we report average elevation change along a cross section ($\overline{\Delta z}$ [m]). Positive $\overline{\Delta z}$ across a time interval indicates net deposition, and negative $\overline{\Delta z}$ indicates net erosion. The control reaches experienced a maximum $\overline{\Delta z}$ of 0.05 ± 0.1 m across any time interval, suggesting that we can attribute observed geomorphic change above that magnitude in the impact reaches to the dam removal and river response.

The summer 2023 to spring 2024 period, which brackets the removal and restoration, is the period during which the channel underwent the most change (Figs. 15 and 16). Change was concentrated in the former impoundment, with the two cross

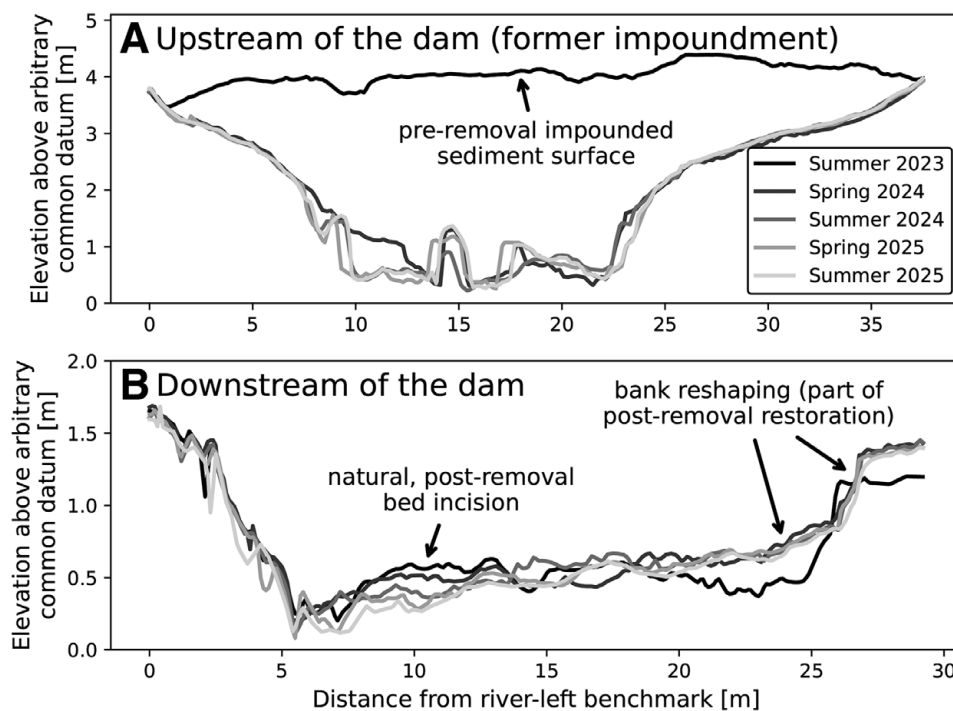


Figure 15. Examples of channel evolution following dam removal. (A) and (B) show results from the studied cross sections that are closest to the former dam.

sections immediately upstream of the former dam seeing mean bed elevation reductions of between 1.5 m and 2 m (Figs. 15A and 16A). Most bed lowering—though likely not all—was accomplished by humans because the removal plan called for as much impounded sediment as possible to be excavated. Slight apparent aggradation at the cross section immediately downstream of the former dam (Figs. 15B and 16B) records another human impact: the reshaping of channel banks during restoration that added elevation on the river-right side. The downstream-most cross section, which was not altered during removal and restoration, experienced modest natural aggradation (Fig. 16B), possibly due to downstream transport of sediment that was impounded behind the dam but not excavated during the removal. Direct human intervention ceased before the spring 2024 survey, such that all observed change after spring 2024 can be attributed to sediment transport processes rather than anthropogenic earth moving.

The spring 2024 to summer 2024 period brackets a month-long spring discharge pulse that was several times the annual average due to prior flow reductions during removal work. Incision continued in portions of the two cross sections immediately upstream of the former dam (e.g., river-left side of Fig. 15A) as well as the two downstream-most cross sections (Fig. 16B). The channel experienced much more muted changes during the summer 2024 to spring 2025 period, during which discharge was below average, with the only potentially detectable change being modest aggradation in the two downstream-most cross sections below the former dam (Fig. 16B). The spring 2025 to summer 2025 interval, which bracketed a spring flow pulse well below the historical average, revealed no detectable change.

Geomorphic data suggest that channel morphology ceased undergoing measurable responses to removal after 2 yr. This is consistent with other studies of small, upland dam removals in wetter regions (e.g., Magilligan et al., 2021). Future removals in semi-arid mountain landscapes will elucidate the extent to which the observed response time scale was driven by unique impoundment excavation and streamflow management conditions, including the lack of any high flow events after spring 2024.

Ecological Response to Dam Removal

The benthic macroinvertebrate community shows rapid and substantial responses to dam removal. We first assess the health of the benthic macroinvertebrate community using the Colorado Multi-Metric Index (MMI), a unitless index that combines multiple measures of macroinvertebrate abundance and diversity. We then use the non-metric multidimensional scaling (NMDS) technique to ask whether benthic macroinvertebrate communities in dam-affected reaches are becoming more like those in control reaches over time. In these analyses, the “upstream” category includes only the two cross sections that were within the former impoundment (upstream M and upstream D); the cross section immediately upstream of the impoundment (upstream U) is excluded.

The control reaches throughout the study period have shown median MMI values indicating that the benthic macroinvertebrate community continuously contained enough abundance and diversity to be considered unimpaired (Fig. 17). Control-reach MMIs likely represent maximum values that dam-impacted reaches could reach. In the former impoundment (“upstream” in Fig.

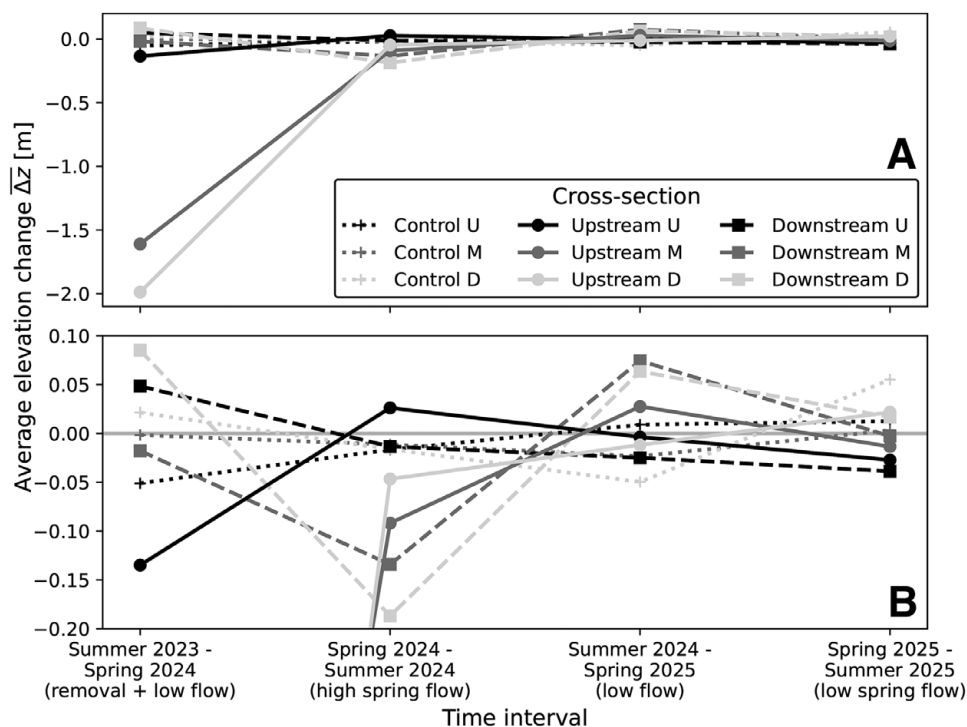


Figure 16. Average elevation change in each studied channel cross section over time. Panel (B) is a zoom-in of panel (A). Error bars have been left off the plot for ease of visualization but are on the order of ± 0.1 m. Lines are visual aids; they are not meant to imply linear change over time. U—upstream, M—middle, D—downstream. Note that cross section Upstream U was located immediately upstream of, rather than within, the impoundment.

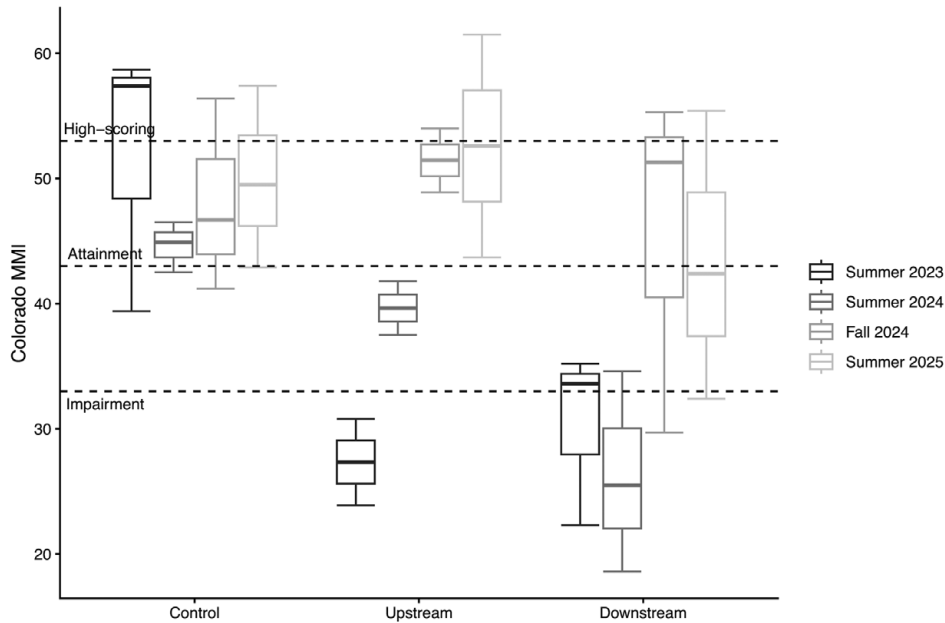


Figure 17. Colorado Multi-Metric Index (MMI) over time in the control reach and the reaches affected by the dam removal (upstream and downstream of the former dam). Dashed lines show thresholds for attainment of aquatic life use.

17), the median MMI before removal (summer 2023) indicated ecological impairment. One year after removal (summer 2024), the median MMI increased above the impairment threshold. By fall 2024, median MMI reached the range shown by the control reaches. It remained there through summer 2025. In the downstream reaches, summer 2024 MMIs were lower than pre-removal MMI values. The downstream reaches then experienced major increases in MMI in fall 2024 with higher MMIs persisting into summer 2025.

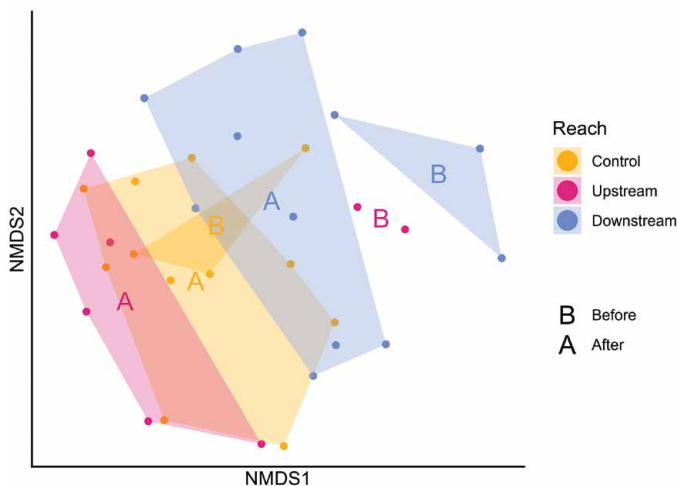


Figure 18. Non-metric multidimensional scaling (NMDS) plot showing how benthic macroinvertebrate community composition changes over time in the control reach and the reaches affected by the dam removal (upstream and downstream of the former dam). Polygons that overlap one another represent samples with similar community composition.

NMDS, a dimensionality reduction technique used in ecology to assess (dis)similarity in community composition (e.g., Fairchild et al., 2025), shows that both the upstream and downstream dam-affected reaches became more like the control reaches over time (Fig. 18). The more similar the communities are in any set of samples, the more the polygon defined by those samples overlaps (Fig. 18). Samples collected before dam removal, in both the upstream and downstream reaches, do not overlap the polygon defined by the pre-removal data from the control reaches. Upstream and downstream samples collected after the removal have substantial overlap with the control samples collected at the same times, indicating that the macroinvertebrate communities in the dam-affected reaches became more like those in the control reaches over time. The upstream reach polygons show more overlap with the control reaches than the downstream reaches do.

Results from LGDD suggest that the benthic macroinvertebrate community recovered from dam removal within 2 yr, a result consistent with recent studies from other regions (e.g., New York State, USA; Dietrich et al., 2025). The recovery is spatially unequal: the former impoundment recovered more quickly and to community composition better approximating the control reaches than the reaches downstream of the former dam did.

Influences on Physical and Ecological Responses to Dam Removal in Semi-Arid Rivers

Field evidence at LGDD suggests that the channel's shape and benthic macroinvertebrate community largely ceased responding to dam removal after ~2 yr, with important differences between how the upstream and downstream reaches responded. From our vantage point at the former dam site, we can observe

how sediment and water management choices made during and after the dam removal, as well as geomorphic context, influenced river response to dam removal.

Management decisions, including reduction of the volume of released sediment (e.g., Grant and Lewis, 2015) as well as hydrograph regulation that concentrated high flow in the months immediately following removal and subsequently kept flows low for the remainder of the study period (e.g., Cannatelli and Curran, 2012; Collins et al., 2024), may have contributed to the short geomorphic and ecological response times. The reduction of sediment supply to the dam-removal reach by a major dam upstream may also have contributed to the rapid response. As a practical matter, these results indicate that the magnitude and timing of post-removal sediment transport and geomorphic change may be more under managers' control in the small, reservoir-studded rivers of semi-arid regions than in wetter landscapes where flow may be less regulated and streamflow is more tightly coupled to precipitation.

Looking up- and downstream from the dam site, we can see key differences in the geomorphic setting of the upstream reach (former impoundment) versus the reach immediately downstream of the dam (Fig. 13) that may help explain differences in observed responses to removal. The upstream reach is relatively steep and narrow with fast flow over a cobble to boulder bed and outcrops of bedrock bordering the active channel (Figs. 13 and 14) and sits within a narrow floodplain constrained by the canyon walls. The channel downstream of the former dam is wider, has a gentler slope and slower flow velocity, and flows over a silt-to gravel-sized bed (Fig. 13). The downstream reach is situated within a wider floodplain as Eleven Mile Canyon opens onto a less confined, alluviated valley.

As soon as the dam was removed, high-velocity flow returned to the upstream reach, exporting most of the sediment that remained after impoundment excavation (Fig. 16A). The newly revealed cobble, boulder, and bedrock bed, with its spatially heterogeneous flow dynamics and substrate characteristics, provided habitat for benthic macroinvertebrates. All sediment transported out of the former impoundment must have entered the downstream reach. Although sediment loading of the downstream reach was much less than it would have been in the absence of impoundment excavation, we documented some net aggradation in the downstream reach during low-flow periods (Fig. 16). Aside from the anomalously large spring 2024 discharge pulse, there may not have been sufficient transport capacity during the study to move sediment that entered the downstream reach after removal due to its lower slope and greater width.

Sediment excavation, regulated flow sequencing, and geomorphic context may help explain why the upstream reach recovered, in ecological terms, more quickly and to a greater extent than the downstream reach even though the geomorphic adjustment time scales were similar between the two. Field observations from the LGDD site provide insight into how river response to potential removal of some of the >1000 small dams in the semi-arid Mountain West might be influenced by

streamflow dynamics, management decisions, and site-specific geomorphology.

CONCLUDING DISCUSSION: ROCKY MOUNTAIN RIVERSCAPES IN TRANSITION

Mountain rivers supply critical water resources and ecosystem services, particularly in arid and semi-arid regions. The stops on this trip have illustrated how changing environmental conditions and management regimes are affecting streamflow and sediment dynamics in the rivers of the southern Colorado Rocky Mountains and potentially other semi-arid regions.

Reduced annual precipitation, lower snowpack, and earlier snowmelt are reducing annual streamflow, increasing the probability that headwater streams like Hotel Gulch become intermittent and increasing the dependence of remaining streamflow on deep groundwater contributions. Beaver ponds and wetland complexes along Trout Creek reveal that beaver ponds may trap sufficient sediment to (1) facilitate reconnection of previously incised channels to their floodplains over century time scales and (2) store as much or more sediment on the landscape than is currently stored behind human-built dams if beaver were to occupy a large portion of their feasible range. Dam removal on the South Platte River led to rapid changes in the physical structure of the river channel and improvements to the benthic macroinvertebrate community, suggesting that dam removal can provide ecological benefits in semi-arid streams with minimal negative impacts.

This trip illustrates how semi-arid mountain rivers respond to individual environmental and management conditions. The great challenge of twenty-first-century river science and management is that many boundary conditions are changing simultaneously. We encourage continued discussion of how the different process dynamics showcased on this trip interact to influence riverscapes and the ecosystems and natural resources they support:

- Hydrologic and geomorphic conceptual and numerical models are calibrated to past climate. What new data and theory are required to build conceptual frameworks that are explicitly designed to incorporate non-stationary hydrologic conditions?
- How will the increasing prevalence of intermittent and/or ephemeral streams impact downstream water quantity and quality?
- How does the increasing prevalence of intermittent and/or ephemeral streams interact with the modern high-severity wildfire regime to change the timing and magnitude of sediment delivery to the perennial river network?
- What are the fundamental constraints imposed by landscape structure (fluvial relief, valley topography) and fluvial sediment loads on watershed-scale, beaver-driven water and sediment storage?
- In an aridifying climate, how will water-management imperatives affect potential geomorphic and ecological response to management interventions like dam removal and restoration?

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