# Ackerson Meadow Restoration Design Basis Report

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# Executive Summary

In 2016 a generous gift of land brought the entirety of Ackerson Meadow into public ownership, under the management of Yosemite National Park and Stanislaus National Forest. The 200-acre mid-elevation meadow is important habitat for rare plants and animals including great gray owl and willow flycatcher. Ackerson Meadow contains 84 acres of existing wetlands and 111 acres of former wetland that have been drained by a large erosion gully network. Gully erosion began more than a century ago and was likely triggered by land use including haying, cattle grazing, and road and ditch building. Evidence in the soil and landforms of Ackerson Meadow show that for thousands of years this entire meadow ecosystem was a wetland with no significant erosive channels. Therefore, Yosemite National Park and Stanislaus National Forest have chosen to restore the flat-bottom valley geomorphology of Ackerson Meadow by fully filling the 150,000 cubic yard erosion gully network. Eliminating the gullies will restore hydrologic processes by 1) spreading flood flows across the entire valley, greatly reducing their erosive power, and 2) removing the drain on meadow groundwater, raising the water table. These changes to water flow will prevent further degradation of the existing wetlands and will restore natural hydrologic conditions to an estimated 103 acres of meadow. The restored hydrology will allow dense wetland vegetation to flourish, and the plants will protect the soil from erosion, preventing new gully formation. This self-stabilizing wetland will provide enhanced and expanded habitat for rare wetland-dependent plants and animals and a range of other species that rely on the water, vegetation, and insects that only wetlands can provide during the dry Sierran summer.

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## Introduction

In 2016 Yosemite National Park expanded by 400 acres, its largest increase since 1949, by acquiring the Ackerson Meadow land parcel on the west-central edge of the Park (Figure 1). The parcel contains parts of Ackerson Meadow, South Ackerson Meadow, and forest and upland habitats. Ranging from about 4600 – 4700 feet elevation these meadow additions now make up Yosemite's most extensive mid-elevation meadow system. The site is a top conservation priority due to the presence of rare plant and animal species including slenderstem and yellowlip pansy monkeyflowers, great gray owl, willow flycatcher, pallid bat, and western pond turtle (Stock, 2017). Prior to the 2016 acquisition by the Park, the Ackerson Meaodow complex was mostly private land used for cattle grazing and hay production since the 1870s. Though both Ackerson and South Ackerson meadows are now predominantly within the National Park Service (NPS), smaller portions of each meadow are part of the Forest Service (FS) – Stanislaus National Forest, which administers ongoing cattle grazing leases on these parcels. Nearby Stone Meadow, the third member of the Ackerson Meadow complex, is still privately held outside of the Park and Forest and continues to be used for livestock grazing.

*Figure 1. Overview map of Yosemite National Park showing the general location of the Ackerson Meadow complex.*

The primary purpose of this report is to present the information and rationale underpinning the design for the restoration of wetland ecological function in Main Ackerson and South Ackerson Meadows (collectively called Ackerson Meadow). The ecological restoration goals at Ackerson Meadow are to reestablish the geomorphic landforms, hydrologic processes, and vegetation community that formed and maintained wetlands in areas that are now drained and degraded by human impacts. This report discusses background information on the site conditions, evidence of past ecological function, and historic impacts, to provide context and basis for the proposed design. Details of the restoration design are described here to compliment the drawings and tables presented in a separate document. The restoration design calls for a total of 150,000 cubic yards of eroded gully to be filled in, bringing the land surface back up to the surrounding meadow level. This fill material will be a mixture of soil excavated from the surrounding hillsides and chipped wood and biochar from waste wood within the Park and Forest.

## Site description

Main Ackerson Meadow is a 140-acre valley bottom located on the western edge of Yosemite National Park below a 5.94 square mile watershed (Figure 2). The meadow is positioned in a relatively flat 1.3% southwest-sloping valley along Ackerson Creek's drainage path, which slopes at 5-10% upstream and downstream of the meadow (Figure 3). Two different major rock types are exposed at the surface adjacent to the meadow: unconsolidated glacial till deposits form the low hillsides to the north and west of the meadow, while tonalite, a plutonic rock similar to granite, forms the higher slopes to the south and east (Figure 4). South Ackerson Meadow is a 55-acre valley bottom that slopes west at 1.1% and its entire 3.16 square mile watershed is embedded within tonalite bedrock (Dodge and Calk, 1987). The erosion gully through Ackerson Meadow is up to 14 feet deep and 100 feet wide, cut into cohesive fine-grained alluvium with vertical and collapsing cut banks and block slumps. The thalweg of the main erosion channel through Ackerson Meadow is 11,080 feet long, meandering down a valley length of 8,200 feet, resulting in a sinuosity of 1.35. Numerous tributary gullies branch from the main gully, often terminating in active headcuts (Figure 5).

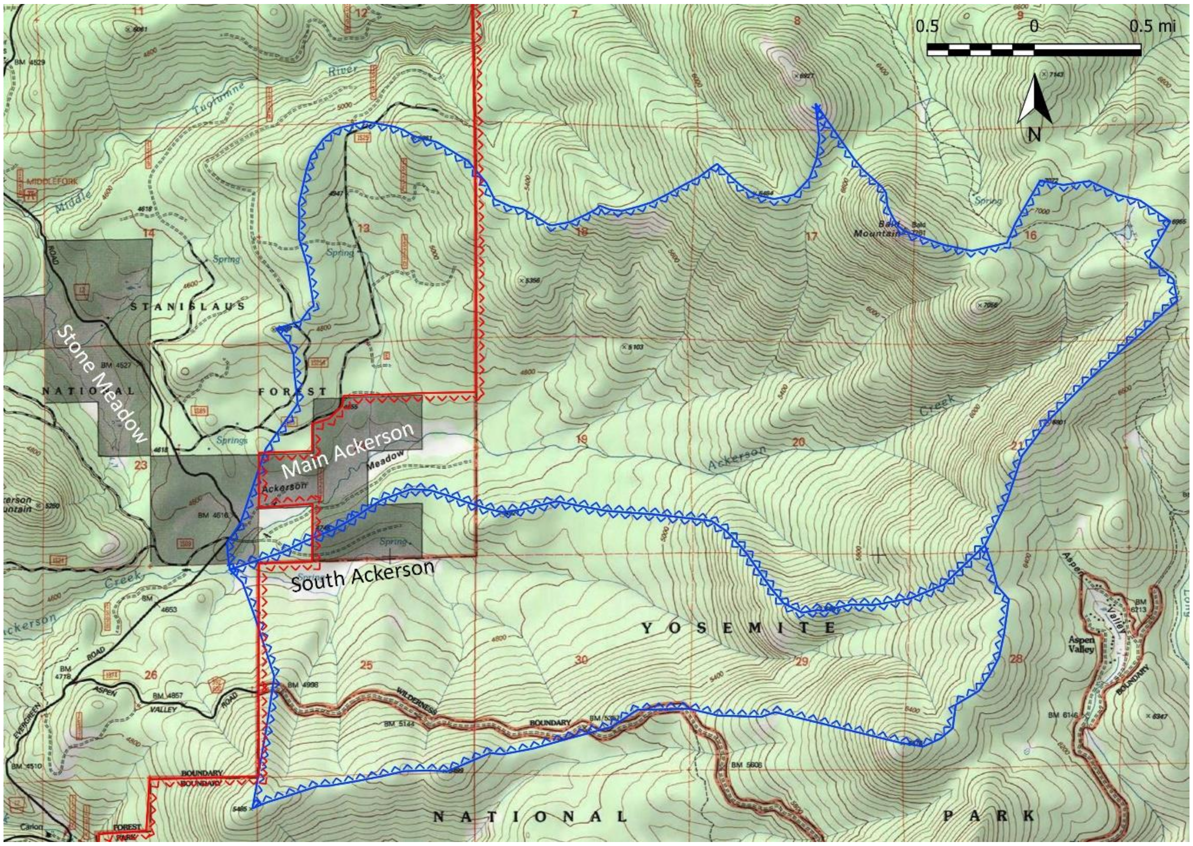

*Figure 2. USGS topographic map from 2001 showing the Yosemite National Park boundary (brown line) including the 2016 acquisition of private lands (shaded grey), and the Forest Service/Park Service MOA administration fence line (red toothed line) covering parts of Ackerson and South Ackerson Meadows. Stone Meadow is still privately held (shaded grey and labelled) outside of the Park and Forest. The watersheds of Ackerson and South Ackerson Meadows are shown as blue-toothed polygons. Bald Mountain, at 7261 ft, is the highest point in the Ackerson Meadow watershed. A regional profile along Ackerson Creek from upstream to downstream of Ackerson Meadow is shown in Figure 3.*

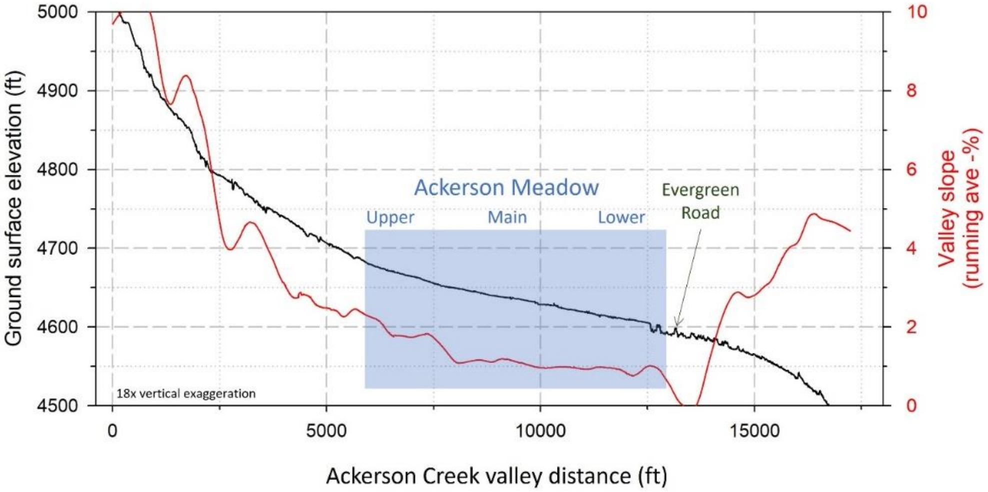

*Figure 3. Regional longitudinal profile of the Ackerson Creek valley showing ground surface elevation (black line) and a running average of the valley slope (red line). The Ackerson Meadow reaches occurs within the blue shaded region upstream of Evergreen Road creek crossing.*

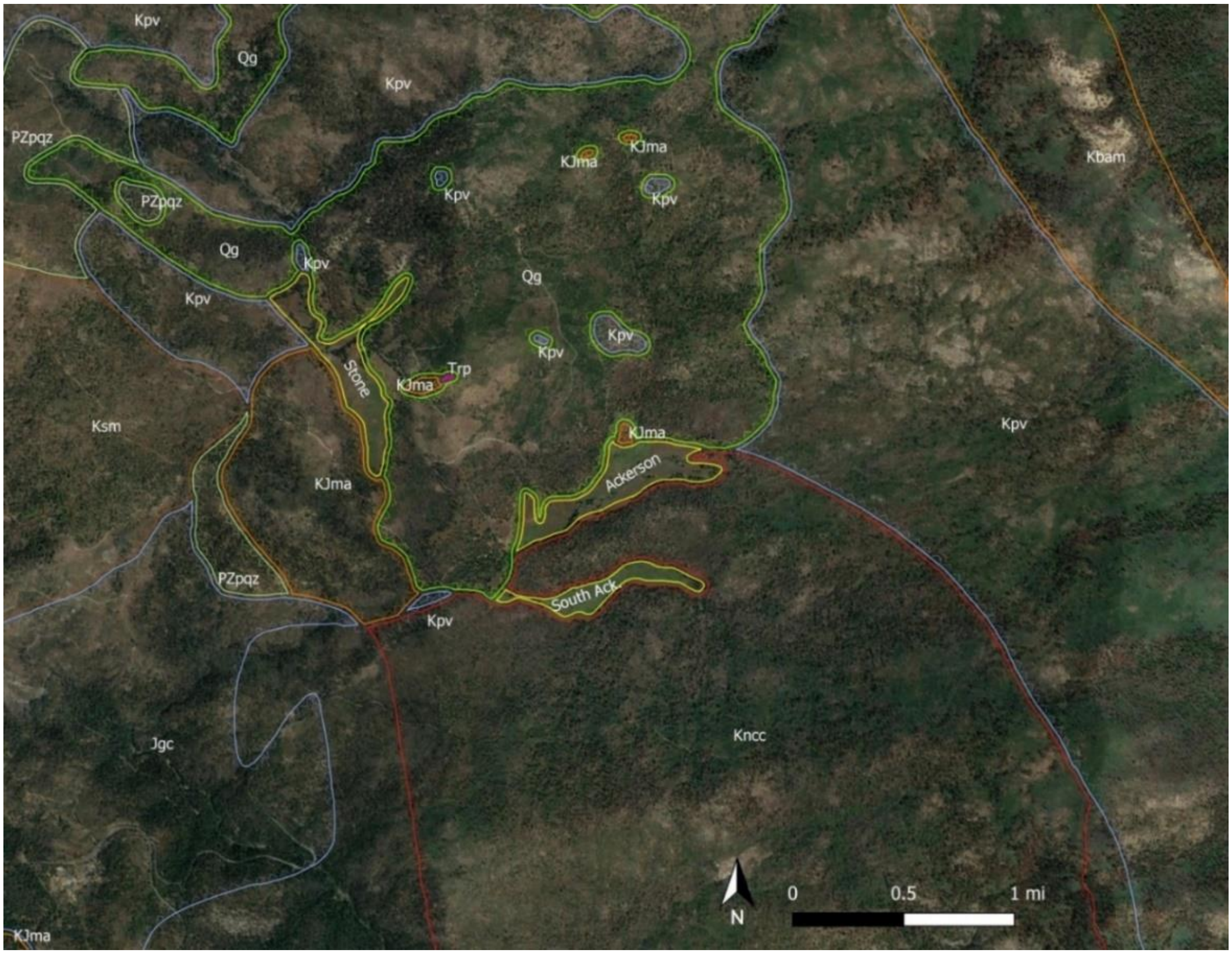

*Figure 4. Surficial geology in the area around Stone, Ackerson, and South Ackerson Meadows, outlined in yellow and mapped as Quaternary (Holocene) alluvium (Qal). Ackerson Meadow is bounded to the north by Quaternary (Pleistocene) glacial deposits (Qg, green outline) and to the south by Cretaceous tonalite of North Crane Creek (Kncc, red outline), a plutonic rock similar to granodiorite. South Ackerson Meadow and its entire watershed are completely embedded within the Kncc and similar Kpv (tonolite of Poopenaut Valley, blue outline) tonolite exposure. Ackerson Meadow's watershed is predominately tonalite (Kpv, Kncc), with glacial deposits (Qg) and Bald Mountain granite (Kbam, orange outline). The southwest side of Stone Meadow abuts a Cretaceous/Jurassic mafic intrusive unit (KJma, orange outline) of gabbro, hornblendite, pyroxenite, and diorite (Dodge and Calk, 1987).*

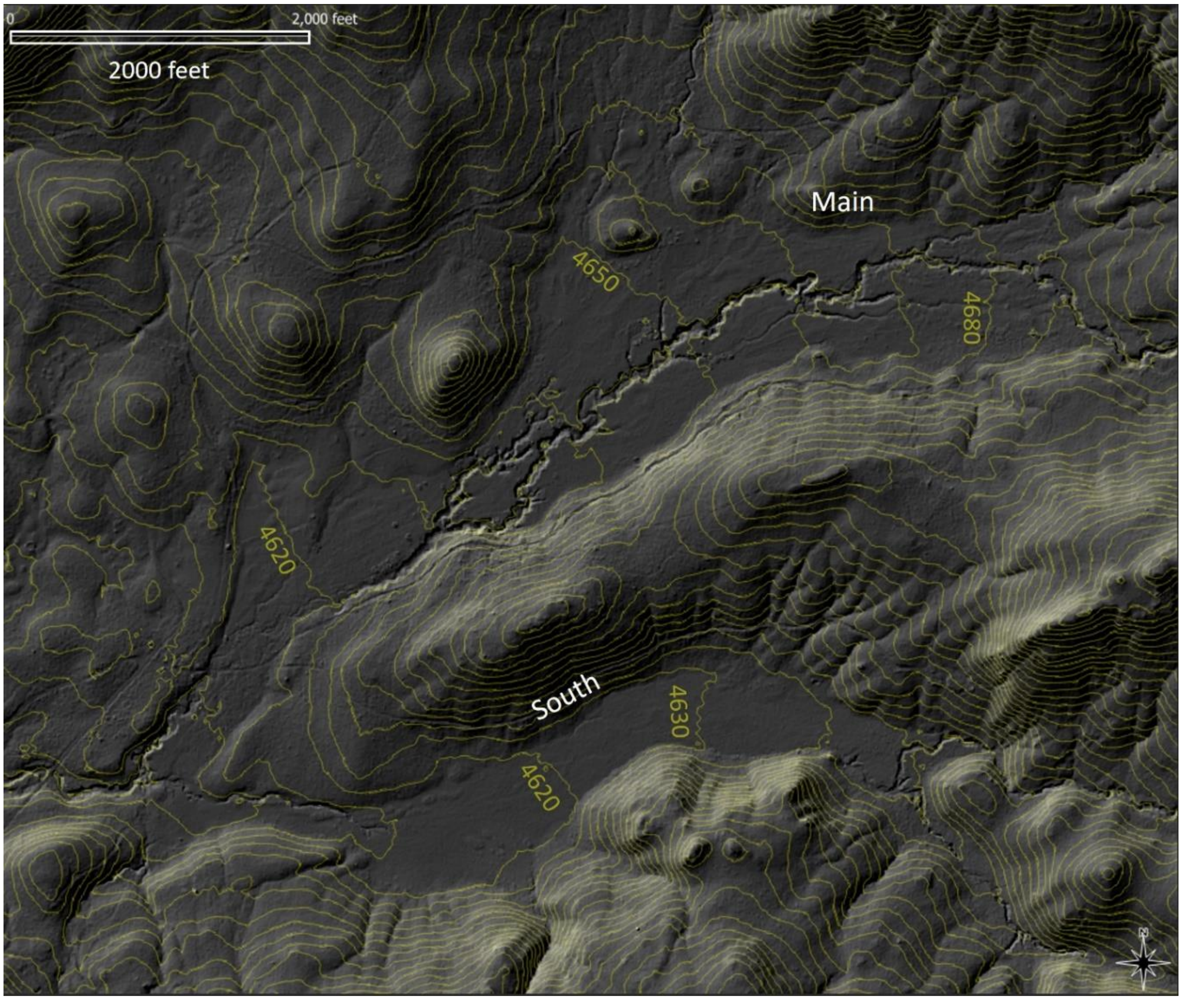

*Figure 5. An overview of the topography of Main and South Ackerson Meadows. The grey hillshade and yellow 10-foot contours are derived from 2013 lidar data. The erosion gully is most apparent in Main Ackerson Meadow above 4620 feet elevation. Note the dendritic branching pattern and numerous headcut-terminated channels of the gully network.*

## Hydrology

The gullies in Ackerson and South Ackerson form topographic troughs within otherwise level cross-section meadows (Figure 10). The gullies receive, confine, and rapidly convey surface water through the meadow. A combination of onsite stream gauging and regional regression modeling was used to estimate the range of flood flows through Main Ackerson and South Ackerson. The combined meadows' flow was estimated to be 194 CFS (range 65 – 577) for 2-year return-interval flood and 2066 CFS (range 852 – 4990) for the 100-year flood (Fong and Avdievitch, 2019).

A 2D HEC-RAS model of the 2- to 100-year flows demonstrates how the gully network in Main Ackerson confines surface water and deprives large portions of the valley fill terrace from flooding (Figure 6). By contrast the model shows that the large central section of South Ackerson floods broadly across its entire valley floor even during the 2-year flow, due to an absence of deep channels. Incised gullies at the upstream and downstream ends of South Ackerson confine flow and prevent flooding at low flows. Only at 25-year flows and higher do significant portions of upper Main Ackerson receive flood flow and meadow inundation is incomplete even in 100-year flows. See Appendix for more HEC-RAS model detail.

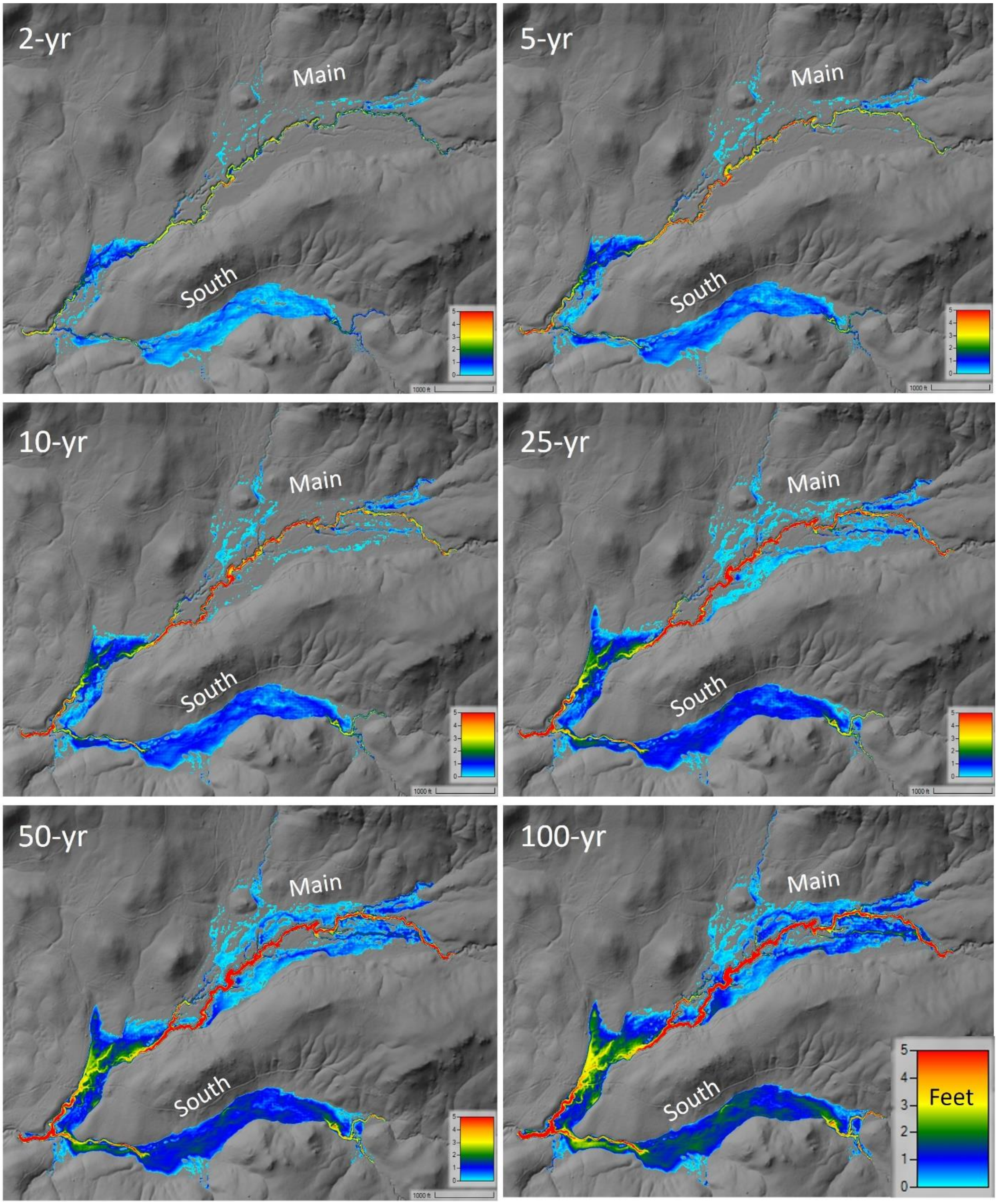

*Figure 6. The modelled flooding extent and water depth for the 2- through 100-yr flow at Ackerson Meadow in its current gullied state. The 2013 lidar topography is shades of grey and the modeled flow depth in feet is represented by colors. Flow direction is from right (east) to left (west). Note that South Ackerson meadow has broadly and evenly distributed flow across its ungullied middle at all flows. In addition, the shallowly gullied downstream Main Ackerson meadow is widely flooded at all flow level. Only at the 25-year flow and higher does significant flooding occur across the upstream section of Main Ackerson.*

In addition to its significant effects on surface flow, the 14-foot-deep gully network in Ackerson Meadow drains groundwater from the surrounding meadow sediments. Draining groundwater into a surface flow channel rapidly dries out the meadow because water moves about 1000 times faster down gradient as surface water over land (1-5 ft/s) than it does as groundwater in soil (1-5 x $10^{-3}$ ft/s) (Loheide *et al.*, 2008; Surfleet *et al.*, 2019). Groundwater drainage is evident in well transect profiles showing an elevated water table at the meadow edges, dropping to 6-10 feet below the surface near erosion gullies (Figure 7).

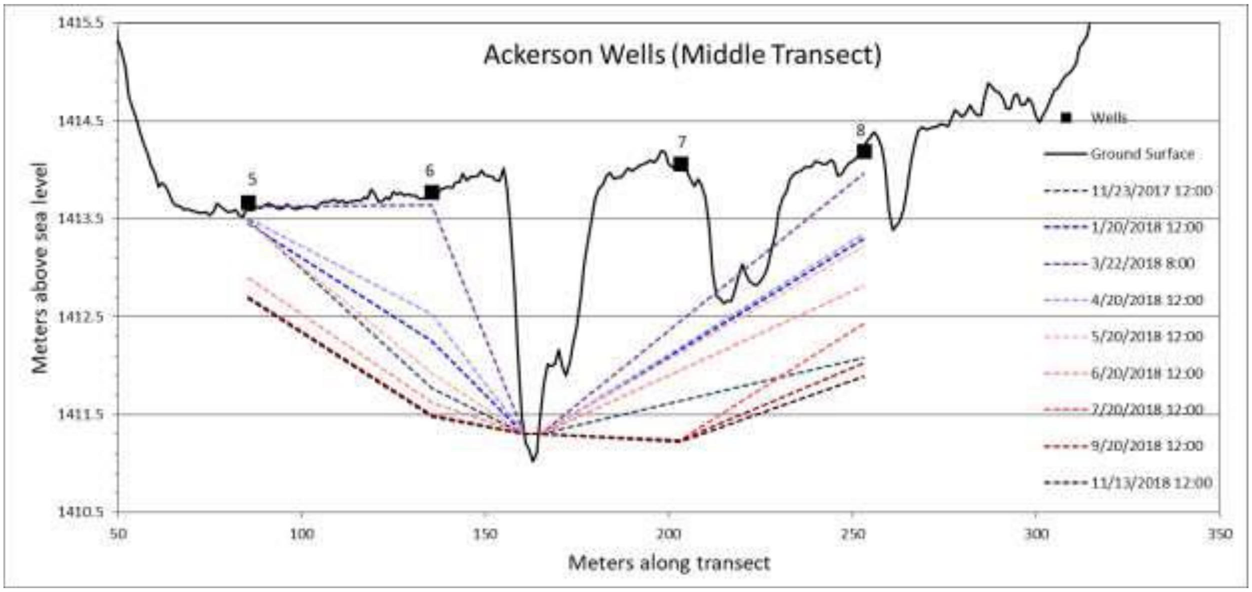

*Figure 7. Cross-section of Main Ackerson showing the groundwater level in monitoring wells for a series of dates. Note that in all measurement periods the water level at the margins of the meadow in wells 5 and 8 is higher than the water level in the main gully, showing that groundwater is draining from the meadow edge towards the gully in the middle. Figure from (Fong and Avdievitch, 2019). **Note that units are in meters**.*

## Geomorphology and soils

Site topography was surveyed to 1-inch horizontal and vertical accuracy using an Emlid RS+ RTK base-rover system in 2019. These data were compared and combined with 2013 and 2019 lidar data to describe Ackerson Meadow's existing topography and geomorphology, and to design the restoration options. The 2013 lidar flight occurred in Nov 2013 during nearly ideal conditions for obtaining high-precision ground topography data: The meadows and surrounding hills were snow-free and vegetation cover was minimal due to a multi-year drought, seasonal senescence, and many areas had recently burned in the Rim Fire (Stavros *et al.*, 2016). The 2019 lidar was flown in Oct 2019 in similarly snow-free and dry-season conditions (Quantum Spatial, 2020). A comparison of the 2013 and 2019 lidar data shows that South Ackerson Meadow vegetation was significantly taller in 2019 and affected ground detection in this densely vegetated section of meadow (Figure 8). No other erroneous differences were detected between the 2013 and 2019 lidar ground surface detection. Actual changes in the ground surface were detected between 2013 and 2019. A section of up to 12-feet of channel incision was identified in the southerly South Inlet Creek, in a reach about 1200 ft upstream of South Ackerson Meadow. About ten 8-foot-tall cut banks in the upstream reach of Main Ackerson experienced significant bank retreat. A road project replaced Evergreen Road's low culverted crossing of Ackerson

Creek with a larger-capacity dual concrete arch span, with the road level approximately 7 feet higher in 2019 than in 2013. Surface elevation models of the restoration options, volume calculations, and design plans and profiles were made using the RTK survey data and the 2013 lidar data because of the superior ground exposure conditions and relatively minor topographical changes noted between 2013 and 2019 within the gully fill zone.

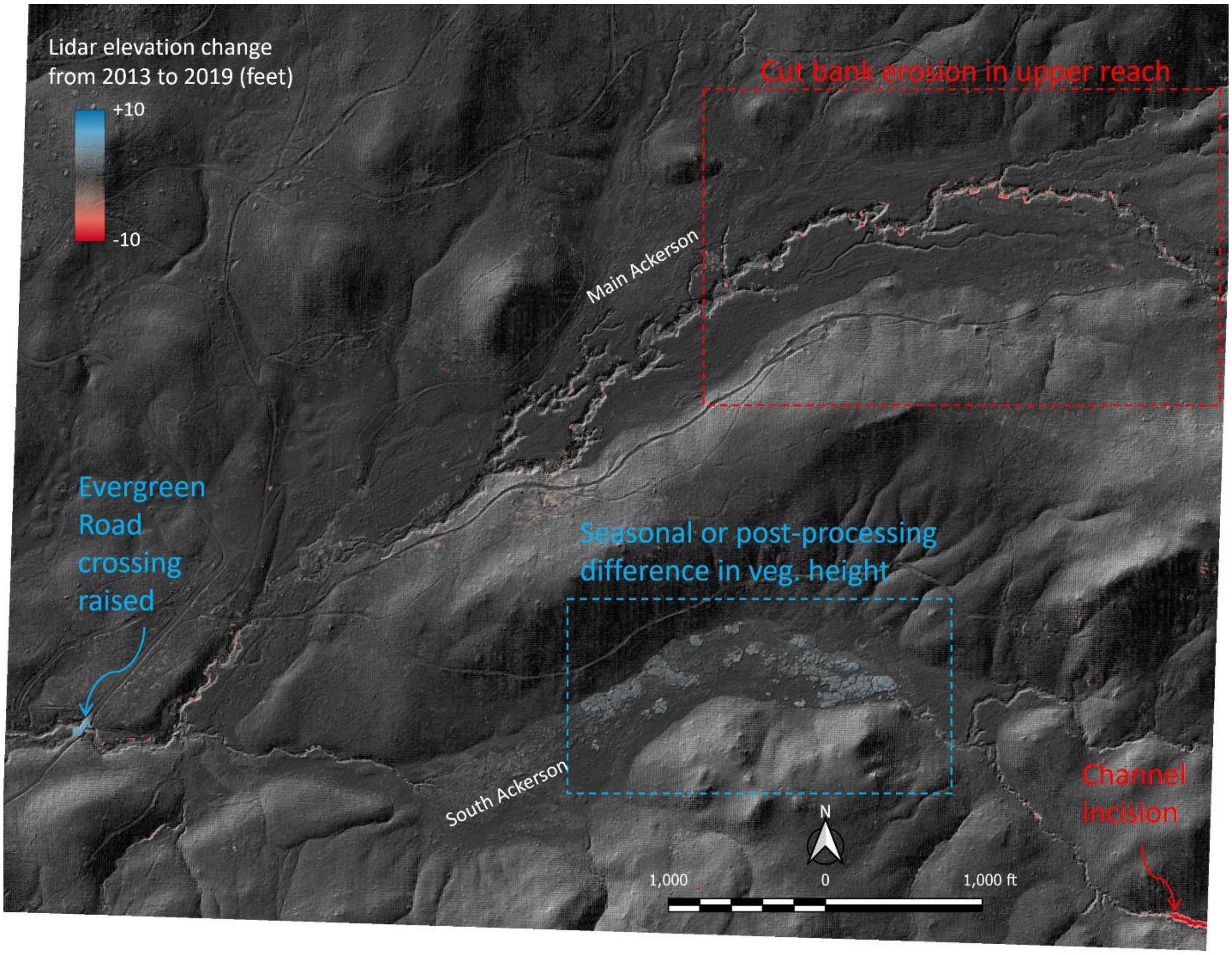

*Figure 8. An analysis of lidar-detected elevation change between the 2013 and 2019 flights. The base grey shaded topography is the 2019 lidar data. Blue shading indicates areas that were higher elevation in 2019, and red shading shows areas of lower 2019 elevation compared to 2013.*

The valleys of Main and South Ackerson meadows are 1-2% sloping planes dissected by an active gully network. The gully network shows evidence of recent formation and expansion rather than being a long-term quasi-stable feature of the landscape. Numerous headcuts and cut banks are eroding from the gully laterally into the shallow-sloping plane of the surrounding meadow sediments. This erosion appears to be a novel process in the geomorphic history of the past ~2,500 years.

The evolution of these fluvial erosion and deposition features is apparent in a comparison of the earliest available air photograph from 1929 and recent imagery and lidar topography from 2013 and 2019. At least eight headcuts evident in 2019 would have been visible and were not present in the earliest aerial photo, from 1929. In addition, the cut banks of the main erosion gully have clearly migrated, increasing channel sinuosity. However, most of the landforms and hydrologic features present today (incised gullies, drainage ditches, and headcuts) were already establish in Ackerson Meadow and can be seen in the earliest available 1929 air photo (Fong and Avdievitch, 2019). Several linear drainage ditches along the meadow surface seen in the 1929 air photo are visible in the modern lidar and air photos and can be seen easily in the field (Figure 9).

Within the gully across from cut banks, inset terraces have formed where fluvial sediments have been deposited as point bars and where earlier less-incised channels have been abandoned. These channel deposits have formed discreet and disconnected inset terraces of wetland vegetation within the gully at various depths below the broader meadow surface. Examples of these terraces forming are visible when comparing the 1929 air photo to the 2019 lidar topography in Ackerson Meadow. Over this 90-year interval the channel has migrated laterally by cut bank erosion and vertically by bed incision. The lateral migration is evident in plan view (Figure 9) and the incision is apparent in cross-section (Figure 10). At the cross-section shown, the former 1929 channel position is now an inset terrace within the gully, 3-4 feet above and 40 feet laterally distant from the current channel bed.

The progression of significant headcut migration and gully network expansion is evident from 1929 to 2013 in nearby Stone Meadow (Figure 11). Stone Meadow is 115 acres and sits outside of the Park and Forest about 1 mile northwest of Ackerson Meadow. The meadow slopes northwest from 4510 feet to 4430 feet elevation over the course of 1 mile (1.5% slope) and lies within a 2.82 square mile watershed that contains glacial deposits to the north and east of the meadow and plutonic rocks to the west and south. Stone Meadow was homesteaded in 1883, within a year of Ackerson Meadow, and similarly grazed since. Given the similarities in the two meadows, it is reasonable to assume that the downstream-to-upstream headcut progression and gully network expansion seen in Stone Meadow is a good analog to the erosion that occurred at Ackerson Meadow. In Ackerson Meadow the earliest photos in 1929 show the gully already extending the full length of the Ackerson Meadow whereas in Stone Meadow the gully had not yet traversed the meadow in 1929.

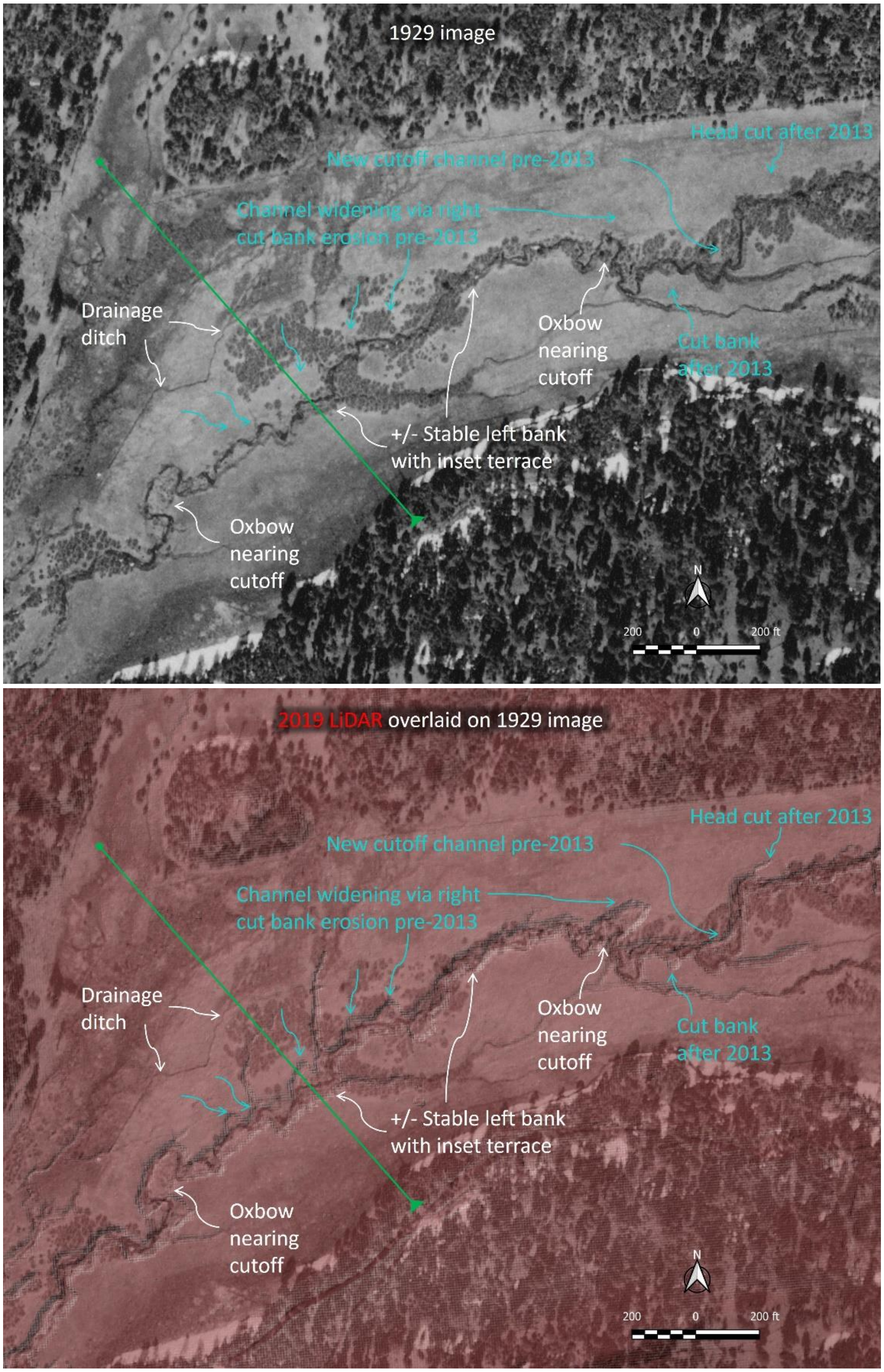

*Figure 9. The 2019 lidar topography (red shading on bottom) overlaid on a 1929 air photo (top) of Ackerson Meadow showing the position of erosion features (blue arrows) that are absent in 1929 but evident in 2019. The white arrows indicate significant geomorphic features evident in both 1929 and 2019. The green line shows the alignment of the cross section in Figure 10. Note that "pre-2013" or "after 2013" references mean that the indicated feature was or was not present in the 2013 lidar data (not shown).*

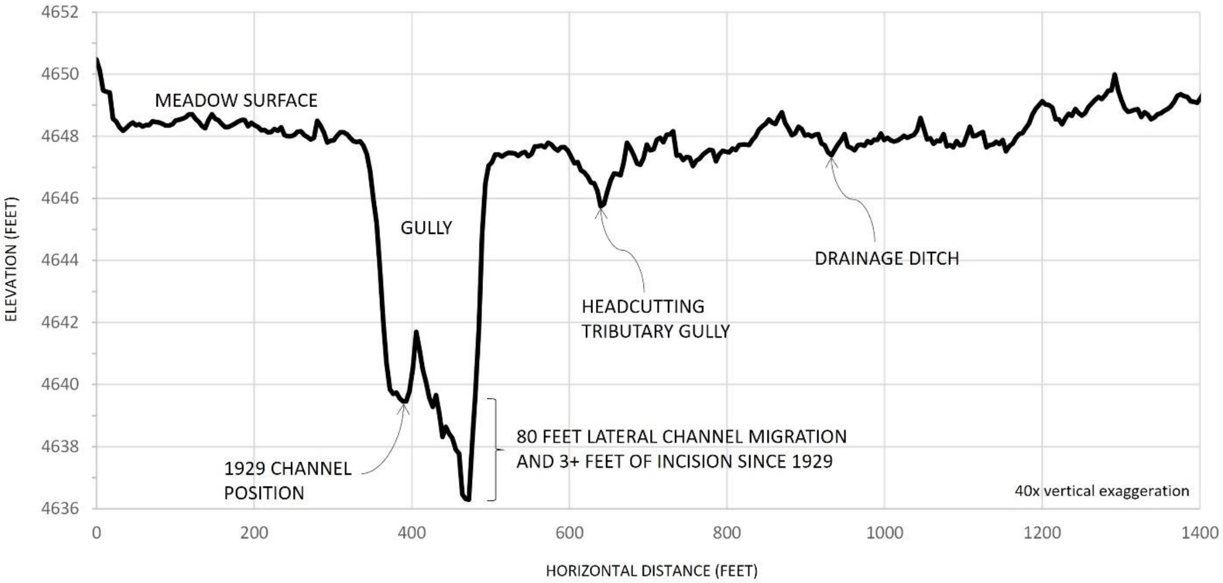

*Figure 10. Cross-section across the Main Ackerson gully showing the level valley width of the 2019 meadow surface dissected by the main gully 11-feet deep, and a headcutting tributary channel 2 feet deep. The cross-section is mapped in plan view in Figure 9. The position of the main channel as seen in the 1929 air photo is indicated. The 1929 channel surface is now an inset terrace more than 3 feet above the current channel elevation, indicating that over a yard of vertical channel incision occurred after 1929. Note the 40x vertical exaggeration.*

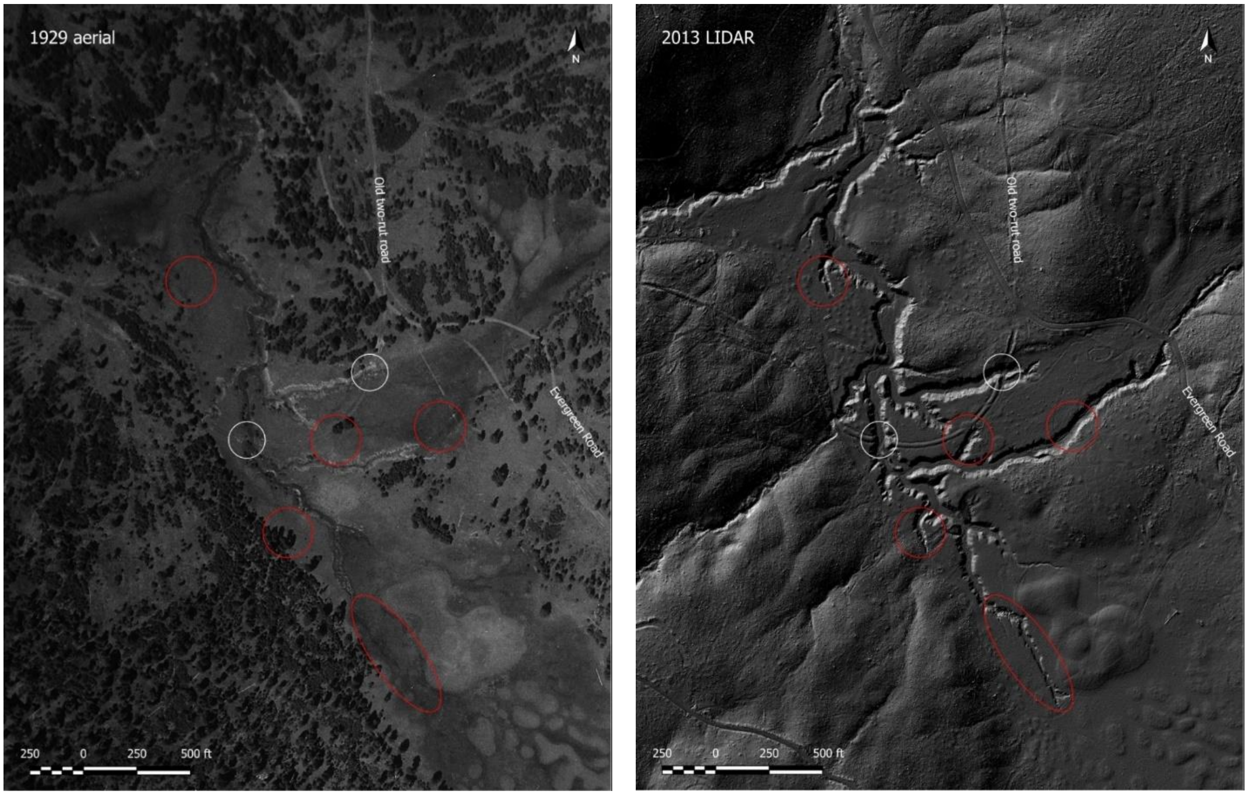

*Figure 11. A 1929 air photo of Stone Meadow (left) and the 2013 lidar elevation model of the same area (right). Red ovals highlight headward erosion that occurred between 1929 and 2013. White ovals show 15-foot-deep impassable gaps in the labelled "old two-rut road' that must have been built prior to 1929, by which time the gully had eroded these locations.*

The rapid headward erosion of headcuts, migration of cut banks, abandonment of channels, and formation of inset terraces since 1929 exemplify the erosional and depositional processes and geomorphic features that are associated with the fluvial environment of gully expansion within the soft sediments of Ackerson Meadow. A landscape with a long prehistory of these fluvial processes including cut bank migration and channel filling, similar in scale to those acting over the past century in Stone and Ackerson Meadows, would include numerous surface geomorphologic and stratigraphic expressions of abandoned channels, point bar deposits, and inset terraces outside of the currently active and unstable gully (Townsend *et al.*, 2019). Instead, the landscape lateral of the gully is a level-in-cross-section meadow surface extending across the valley with <1 foot of local topographic variation. The only deviation from this microtopography is the active erosion gully and associated tributary headcuts; there is no evidence for prehistoric channels anywhere near the size or extent of the current gully.

The upper 3-4 feet of fine-grained organic-rich wetland soil contain lenses and thin layers of coarser deposits indicative of episodic high-energy flood deposits. The surface meadow sediments are underlain by cross-bedded alluvial sands and gravels, likely glacial outwash deposits (Dodge and Calk, 1987).

The surface sediments of Ackerson Meadow are composed of 3-4 feet of very dark brown to black sandy to clayey silt soil. Throughout the meadow these surface soils contain redoximorphic features indicative of saturated wetland soil conditions. Radiocarbon dates from the base of the 3-4 foot deep meadow surface sediments indicates they accumulated over the past ~2,500 years. The age and depth of soil yields a meadow-wide sedimentation rate of about 0.5 mm per year (Fong and Avdievitch, 2019). This equates to approximately 400 cubic yards of externally-supplied sediment distributed across the Main Ackerson Meadow surface area each year.

An independent method of estimating annual sediment delivery to Main Ackerson Meadow yields a similar value. Multiplying a Sierra Nevada range-wide median denudation rate of 0.035 mm per year (Minear and Kondolf, 2009) by the Main Ackerson watershed area of 1,620 ha yields an estimate of 740 cubic yards of sediment eroded per year. Considering that not all sediment eroded from hillsides will be retained in meadow deposits, the estimates of annual watershed erosion (740 cubic yards) and meadow deposition (400 cubic yards) are in close agreement. If as much as 500 cubic yards of hillslope-eroded sediment could be trapped and retained each year within the 150,000-cubic-yard gully, it would take 300 years to refill the gully.

The evidence of accretionary meadow prehistory, including the lack of significant prehistoric erosion channels, followed by novel anthropogenic gully erosion initiated in the last ~150 years is consistent with observations made in similar montane meadows throughout the Sierra (Wood, 1975; Wolf *et al.*, 2015; Wolf, Cooper and Wagner, 2018).

## Vegetation and wetlands

Most of the three-parameter wetlands, areas with wetland hydrology, soils and vegetation, in central and upper Ackerson Meadow are near the meadow edge and are kept wet by toe-slope groundwater discharge (Figure 12). There are several areas where wetland hydrology and vegetation have been lost due to gully drainage, but wetland soil indicators are still present. The middle section of the meadow is drained former wetland, visible on aerial imagery as a tan-brown buffer region of dry vegetation and bare ground adjacent to the erosion gully.

Mature willows occur both in the bottom of the gully and on the banks at the level of the meadow surface, 8 to 10 feet above the channel bed. Because willow seeds require bare moist substrate to germinate, and seedlings need a shallow water table to establish (Gage and Cooper, 2005; Woods and Cooper, 2005), the current dry meadow setting high above the gully bed is a poor establishment surface: bare moist substrate is not deposited this high, and the water table declines too far and too fast for a willow seedling's roots to follow. Therefore, the willows growing on the meadow surface must have established in a hydrogeomorphic setting that received active flood flow and had a shallower water table.

Across more than 100 acres of meadow, the only remaining evidence of former wetland conditions are the level in cross-section geomorphology and fine-grained soils with wetland indicators. These features are remnants of a depositional sheet-flow and groundwater saturated meadow that lacked significant channels. A confined wetland corridor has established within the Ackerson Meadow erosion gully, 3-14 feet below the meadow surface. Groundwater saturates the meadow surfaces along the valley margins. The northern arm of Ackerson Meadow that extends into the glacial till slope receives significant groundwater discharge that supports perennial wetland vegetation and wetland soils. Groundwater also discharges along the south and east edges of Ackerson Meadow. A total of 84.3 acres of existing wetland and 110.6 acres of former wetland were delineated in Ackerson and South Ackerson Meadows. The restoration project will rewet 103.1 acres of these former wetlands, returning them to their functional pre-degradation state (Figure 12).

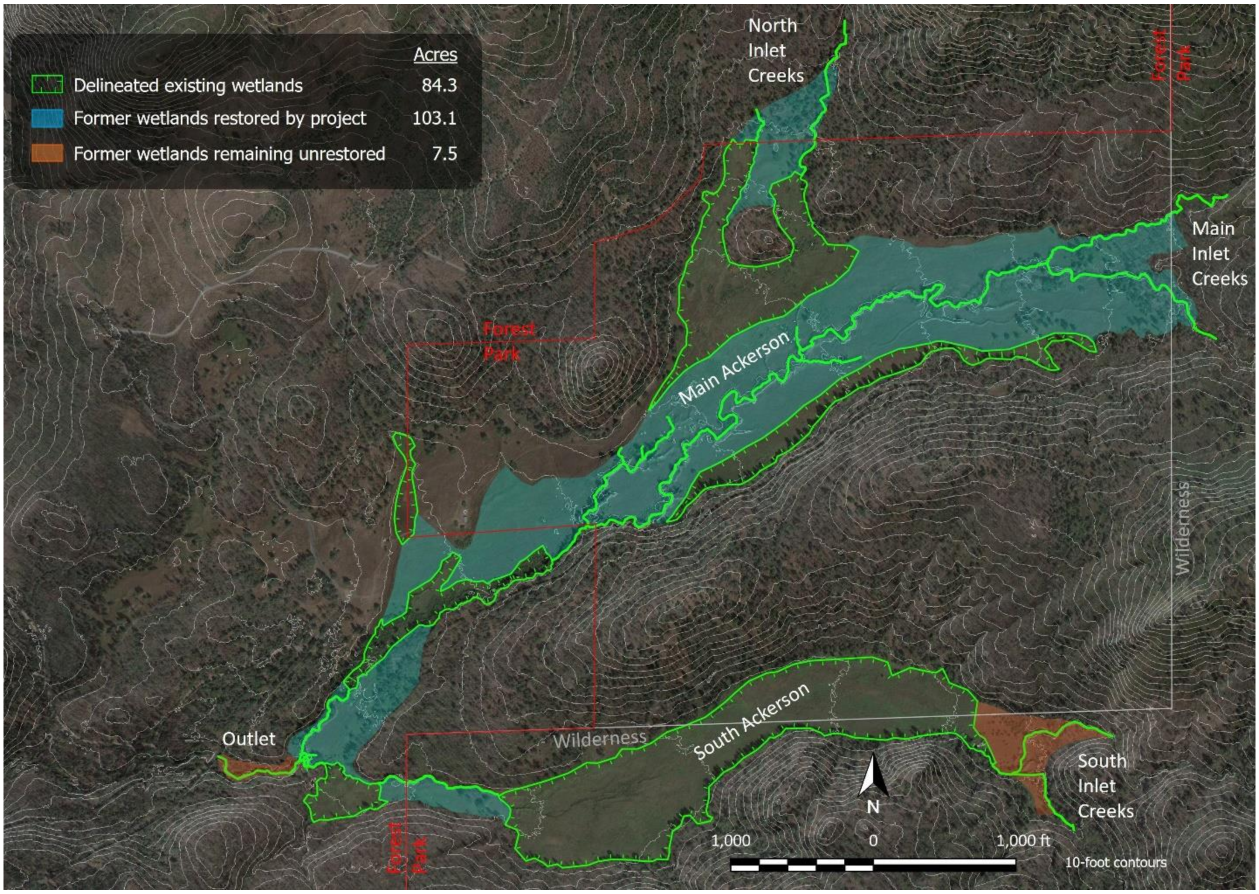

*Figure 12. The delineated existing and former wetlands at Main Ackerson and South Ackerson Meadows, with acreage shown for each type. Groundwater discharge maintains wetland hydrology, vegetation, and soils in the green polygons. The blue-shaded region has been drained and degraded by the erosion gully network but will be rewetted by the restoration project. The orange-shaded region is drained former wetland that will not be restored by this project.*

## Site history

### Human occupation

Abundant evidence of prehistoric human activity, mostly obsidian fragments and bedrock milling features, documents at least 3,000 years of use of Ackerson Meadow prior to the 1850s (Keefe, Kahl and Montague, 1999).

During the historic period, more than half of Ackerson Meadow was privately owned prior to 2016 and had been managed for over a century as a grazing pasture and hay field. In 1850, Joseph Screech built the first road towards Hetch Hetchy past Ackerson Meadow, which was then known variously as Wade's Meadow, Big Meadow and Reservoir Meadow (Hoffmann, 1868). What is now Stone Meadow was known as Buckley Meadow (Paden and Schlichtmann, 1955; Greene, 1987). The earliest land-ownership claim on what would become known as Ackerson Meadow was filed with the State of California in 1857 (Wills, 2020). It is unknown when James F. Ackerson began ranching in the meadow that was to bear his name, but it's clear that he worked or owned the land between 1874 and 1892. After the completion of the wagon road into Yosemite Valley in 1874 Charles Schmidt, of Second Garrotte (just east of present-day Groveland), described that "James Ackerson brought in timothy hay from Ackerson Meadow. He drove his own four horse wagon" (Paden and Schlichtmann, 1955).

Ackerson patented 160 acres in section 24, in what is now Ackerson Meadow, as a homestead in 1882 and another 160 acres in sections 24 and 25 in South Ackerson Meadow in 1884. Irwin J. Buckley homesteaded on 320 acres in what is now Stone Meadow in 1883 and 1884, and Frank E. Horsley patented the 160 acres that lies between the southern downstream end of Ackerson Meadow and the southern upstream end of Stone Meadow (Wills, 2020). If Ackerson complied with the requirement of the Homestead Act to farm his land claim for five years prior to filing his patent, then he was working the meadow by 1877 and probably by 1874 if the report of his hay production is accurate.

Yosemite National Park was created in 1890, and the associated prohibition against all livestock grazing, even on patented land within the Park, was enforced by the US Army cavalry (Greene, 1987). The entirety of the meadow complex composed of Ackerson, South Ackerson, and Stone Meadows was within the original 1890 Park boundary.

Timothy H Carlon, the grandfather of Tim Erickson, the last cattle rancher at Ackerson, bought the meadow in 1892 (Kitzenberger, 2014). By 1895, there were at least six large barns, fencing, and wagon roads within the meadow (Finney, 2012). In 1906, the boundaries of the Park were contracted, returning the three meadows of the Ackerson complex to private ownership and stewardship by the newly-created Forest Service. Stanislaus Forest Reserve was established in 1897, renamed Stanislaus National Forest in 1906, and included the portions of Ackerson Meadow that were neither private nor Park lands. Grazing management on Forest lands in Ackerson Meadow was probably gradual at first and is now permitted under the terms of a grazing lease (Steen, 1975). Livestock trespass into the Yosemite lands of Ackerson Meadow was almost certainly a problem in the early years of the Park and it remains a problem today.

A traveler arriving on Saturday July 4th, 1908 gave a brief description of Ackerson Meadow:

"we rode up to a little scorched-up house in a wide meadow, and were hospitably greeted by a hirsute Irishman who was 'holding down' the ranch for the present owner, the successor of the original Ackerson. Choosing a spot for our camp on the edge of a swampy expanse which afforded good pasturage for the animals, we turned them loose..." (Chase, 1911).

In 1937, Yosemite National Park acquired the "Carl Inn" tract of land containing the southern half of South Ackerson meadow (United States, 1937). This marks the first time when a portion of the meadow complex lay inside the Park while the rest remained in private possession or Forest management. It is reasonable to assume that, prior to 1890, and between 1906 and 1937, all three meadows in the complex were used to graze livestock and/or produce hay. After 1937, grazing and haying in about half of South Ackerson Meadow should have ceased if a border fence was erected and was effective in preventing cattle trespass.

## Beaver introduction

Beaver translocations were conducted in California by the Forest Service from 1934 to 1938, and by the California Department of Fish and Game, aided by Federal funding, from 1940 to 1949 (CDFG, 1963). In April of 1940 the California Department of Fish and Game captured three nuisance beavers, two male and one female, in Merced County and transplanted them to Ackerson Meadow (Hensley, 1946). The beaver dammed Ackerson Creek until at least 1947, but there is no evidence of their activities on a July 28th, 1955 air photo. Both the State of California and Yosemite National Park published narratives of the beaver activity in Ackerson Meadow:

"Another outstanding demonstration is the colony of beaver introduced into Ackerson Creek, Tuolumne County, early in 1940. Only three animals were used to start this experiment. The stream bed was eroded to the degree where the water table had dropped very low and was of practically no value for subirrigation to an adjacent 400 acre meadow along both banks of the stream. The meadow no longer was suitable for livestock and the stream was drying up for a short period in the summer months. By 1944, the beaver had constructed a series of 18 dams down the length of the meadow. The stream was flowing continuously throughout the year, the water table was again normal, and the meadow was restored, furnishing grazing for the livestock. The stored water back of the beaver dams was creating habitat for fishlife and many limits of fish were reported taken by fisherman." (State of California, 1946).

"[The three beaver introduced into Ackerson Meadow] increased rapidly and in 1947 about 20 dams had been built in the meadow area. To our knowledge none has yet entered the park" (McIntyre, 1948).

There is no stratigraphic or geomorphic evidence of prehistoric beaver damming in the meadow sediments or landforms, nor have there been any observations of beaver in Ackerson Meadow since the 1947 report of the introduced population.

## The Golden Rock Ditch

From 1860 to about 1939 a water diversion called the Golden Rock Ditch was operated to supply water to the Ackerson Meadow area and nearby mining districts. The ditch no longer functions as a water diversion due to failure of the inlet dam, decay of wooden flume infrastructure, and collapse of earthen sections along steep hillsides (Keefe, Kahl and Montague, 1999).

“The ditch measures 9 ft in top width, 3 ft in bottom width, 3 ft deep, and is approximately 4.0 miles long within park boundaries. The engineered segment runs from the Middle Tuolumne River at 5,590 ft to approximately 5,440 ft elevation, where it empties into Ackerson Creek. The water was conveyed in Ackerson Creek to Ackerson Meadow at 4,460 ft, where the ditch exits the park. The ditch has an earthen and rock-fill berm along most of its length and, along sharp curves, three- to six-course-high granite rock retaining walls support the ditch. Wooden flumes must have been built over drainages or bedrock, but no such remains were observed. A diversion dam, constructed of concrete and angular rock, is located along the river, and likely functioned as the inlet for the ditch. A date of “June 1939” is carved into the concrete, possibly indicating the last date of repair. ” (Keefe, Kahl and Montague, 1999).

In addition to this written description, the ditch was mapped in 1939, apparently the final year it was in use or maintained (Figure 13). The 1939 map accurately surveyed the alignment of the ditch and definitively shows that the water was discharged to an unnamed creek that enters the north arm of Main Ackerson Meadow (E. F. E., 1939). The creek that conveyed the water is incised where it meets Ackerson Meadow, but it shallows and spreads into unchanneled meadow expanse and does not connect with the existing erosion gully network. The mapped route of the ditch above the meadow is still visible on modern air photos, and the 1939 survey alignment is confirmed to be basically accurate (Figure 14). The ditch above the meadow consisted of two constructed sections totaling 2.41 miles, and two natural drainage reaches of 1.74 miles length, for a total diversion from the Middle Fork Tuolumne to Ackerson Meadow of 4.15 miles.

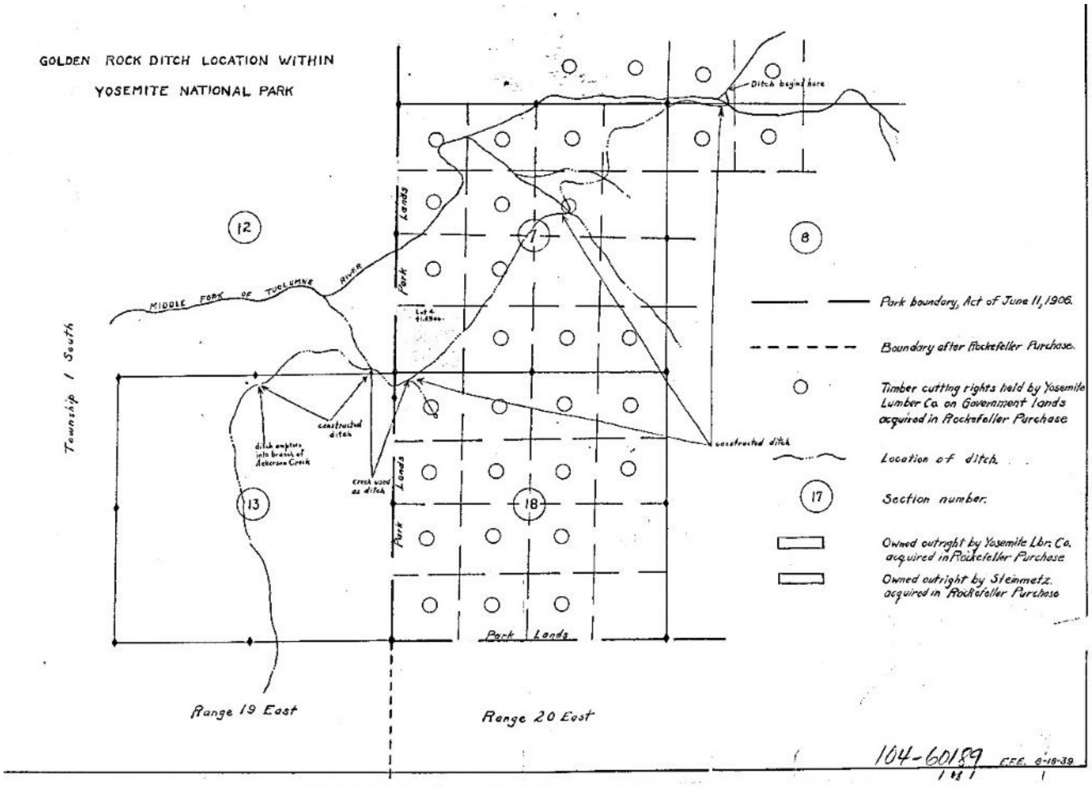

*Figure 13. Map of the Golden Rock Ditch within and adjacent to Yosemite National Park, as surveyed in 1939 (E. F. E., 1939). The arrows indicate constructed section of the ditch and reaches where natural stream courses were used. Note the Public Lands Survey section numbers that correspond to those on the modern USGS topo map shown in Figure 14.*

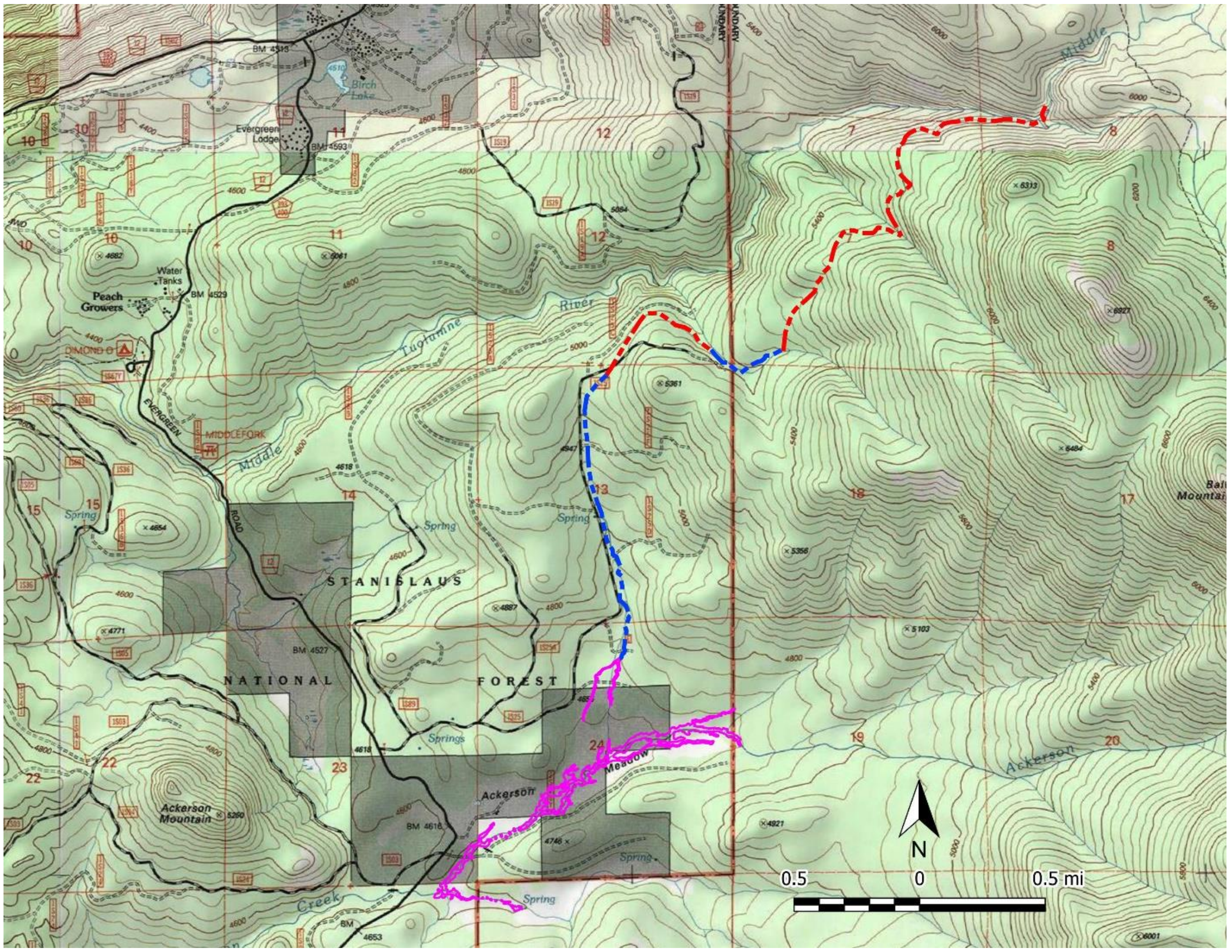

*Figure 14. The alignment of the Golden Rock Ditch from the intake at the Middle Fork Tuolumne River to Ackerson Meadow. The red dashed line indicates constructed ditch, the blue dashed line shows where natural drainage channels were used to convey water, and the pink polygon is the footprint of the proposed gully fill within Ackerson Meadow. The constructed ditch route was visible on aerial photography and matches well with the 1939 map (Figure 13).*

A Tuolumne County booster publication from 1909 describes the flow of the Ackerson Meadow section of the Golden Rock Ditch: “The system consists of 70 miles of main ditch which heads at the middle fork of the Tuolumne river, in the Yosemite National Park, and carries 1,000 miners inches of water” (Union Democrat and Supervisors of Tuolumne County, 1909). The flow estimate of 1,000 miners inches of water is equivalent to 20 cubic feet per second.

A report by the California Department of Water Resources in 1965 investigated repurposing the Golden Rock Ditch for water supply. Rather than re-using the upstream-most section of the Golden Rock Ditch that discharged into Ackerson Meadow, they proposed building a new ditch from a diversion 2.7 miles downstream on the Middle Fork. They called the small concrete dam on the Middle Fork of the Tuolumne River the Mather Diversion, and the ditch from the dam to Ackerson Creek downstream of Ackerson Meadow, the Mather Ditch. The Mather Diversion and Ditch were never built, but the ditch was designed as a concrete trapezoidal channel four feet wide at the base, 14.5 feet wide at the top, and 3.8 feet deep. The capacity of the Mather Ditch was planned to be 150 cubic feet per second, which would have diverted about 25,000 acre-feet of the Middle Fork Tuolumne's estimated average annual discharge of 40,000 acre-feet (CA DWR, 1965).

The design dimensions and minimum slope for the never-built Mather ditch are very similar to the description of the Golden Rock Ditch section above Ackerson Meadow mapped in 1939. The proposed Mather Ditch would have sloped at a constant 0.5% whereas the constructed sections of the Golden Rock Ditch above Ackerson Meadow dropped 440 feet over 12,725 feet, for an average slope of 3.5%. Despite a high average slope, the conveyance capacity of the Golden Rock Ditch would have been constrained by its shallowest-sloping section that drops from 5325 to 5315 feet elevation (10 feet) along a 2,350 foot-long reach, a slope of 0.4%. So, even if the section of the Golden Rock Ditch that emptied into the north arm of Ackerson Meadow carried more than the Tuolumne County estimate from 1909 of 20 CFS, it is unlikely that its capacity exceeded the 150 CFS planned for the concrete Mather Ditch. This amount of water added to the Ackerson Meadow system is less than the estimated 2-year flood event and would not significantly increase erosion potential of flood flows.

Several small ditches are still evident in the meadow downstream of where the Golden Rock Ditch discharged into the north arm of Ackerson. These ditches are visible on the 1929 air photo and are largely unchanged at present as seen on the lidar, air photos, and in the field. They are approximately 1-2 feet deep and wide and serve to capture a small amount of surface or shallow ground water flow. The ditches are positioned on the north side of the main alignment of Ackerson Meadow, below the tributary north arm where the Golden Rock Ditch discharged. This is the only location in the meadow with ditching evident.

## Land use triggers of gully initiation

Two-track automobile routes, more permanent roads, and fence lines are evident across other portions of the meadow, but ditching is only seen between the north arm and main Ackerson valley. Because the ditches do not continue to the ranch house, they were unlikely to have been used to supply water to the operations there. Instead, the ditches terminate at the downstream end of the north arm, indicating that their primary purpose was to intercept some of the flow from the north arm and divert it downstream of the adjacent reach of the main Ackerson valley. Capturing lateral discharge flowing into a valley was a common agricultural practice to create drier conditions on the valley floor (Chimner *et al.*, 2017). The north arm is a groundwater saturated wetland at present, and with the additional flow from the Golden Rock Ditch prior to 1939, the meadow was probably very wet in this location.

Flow augmentation by the Golden Rock Ditch was most likely to have only significantly increased baseflow. The conveyance capacity of the hand-built ditch would have had limited effect on peak flows, which are the most erosive. The lack of a continuous channel connection from the ditch discharge point in the North Lobe of the meadow to the current gully network means the flow would have dispersed across the width of the meadow, greatly reducing its erosive potential. The alignment of the gully network with the main valley axis and the projected flood discharges that greatly exceed the ditch capacity both indicate that the natural flood flows are the primary hydrologic agents of erosion and headcutting in the gully network.

Other potential sources of hydrologic alteration within the watershed include a network of old logging roads, and the logging they facilitated. An examination of the lidar-derived topography of the hillslopes surrounding Ackerson meadow shows no major hillslope failures or road-related erosion features that would indicate large flow concentration or drainage alteration related to these hillslope disturbances.

An old road and the modern Evergreen Road cross Ackerson Meadow at or near its former downstream extent. Incised remnant meadow terraces occur just upstream of the old road crossing, whereas downstream of the crossing there is no evidence of former meadow surfaces or significant downcutting. This old road crossing is located at what appears to be the furthest downstream extent of former meadow (Figure 15).

The gullies in Ackerson Meadow were probably initiated by large flow events moving across disturbed meadow vegetation and soil. Intact dense native wetland sedge sod, like the vegetation present in the wetland expanse in South Ackerson Meadow, is extremely resistant to erosion. Experiments have demonstrated that dense grass and sedges can withstand flow shear stress of greater than 5 pounds per square foot with little to no sediment scour (Ree, 1949; Prosser and Slade, 1994). Removal or significant disturbance of dense vegetation reduces the erosion resistance by a factor of 5-10, resulting in scour at shear stresses of 0.5 – 1.5 pounds per square foot (Prosser, Dietrich and Stevenson, 1995; Tucker *et al.*, 2006).

The Ackerson Meadow HEC-RAS flow model predicts that large flow events produce localized shear stresses of 3-4 pounds per square foot, below the erosion threshold for intact vegetation but higher than disturbed vegetation can resist. Land use impacts to the native vegetation could have shifted the site from being capable of resisting large flow events to being vulnerable to scour and gully initiation.

Once initiated, gullies capture more flow in the next event and can headcut rapidly upstream if shallow soil and vegetation cohesion is compromised (Kirkby and Bracken, 2009). This pattern of expansion is clear in the main gully of Stone Meadow and can be seen in the channels branching from the Main Ackerson gully. The nature of the initial disturbance is uncertain but could have been related to the old road crossing, years of repeated cattle grazing, other land disturbances that have left no trace, or a combination of factors. Intense and poorly regulated grazing initiated gully erosion in similar montane meadows throughout the Sierra (Wood, 1975; Wolf and Cooper, 2016).

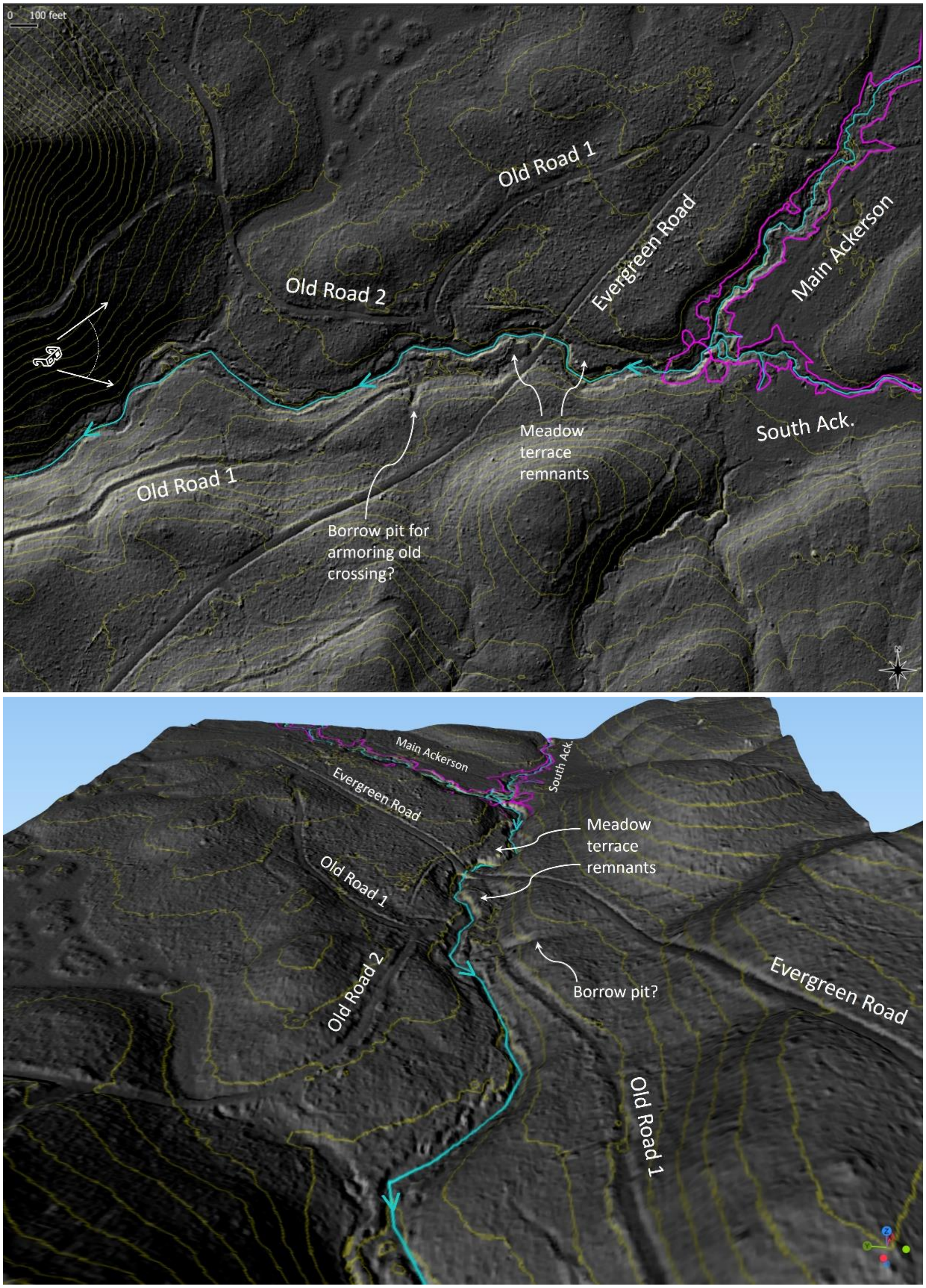

*Figure 15. Lidar topography of the valley reach just downstream of the restoration project, as viewed from straight above (top panel) and from an oblique angle facing east and upstream (bottom panel). The eyeglasses icon with arrows in the top panel indicates the point of view for the bottom panel. The downstream extent of the restoration project fill is outlined in purple and channels are shown in light blue, with flow arrows: right to left in top panel; background to foreground in bottom panel. Yellow lines are 10-foot contours. Note that "Old Road 1" crosses Ackerson Creek downstream of the remnant meadow terraces. The up-valley extension of Old Road 1 crosses Evergreen Road and then Main Ackerson meadow. This meadow crossing is in use and will be armored as part of the restoration.*

## Restoration Design

### Filling the gully to the meadow surface

Due to the human origin of the erosion gully network and its significant impact and continued threat to the valuable wetland resources in Ackerson Meadow, Yosemite National Park and Stanislaus National Forest have decided to restore the interacting ecological and physical processes that formed and maintained the meadow for thousands of years. Several alternatives were considered, and the Park and Forest elected to fully fill the erosion gullies in Ackerson and South Ackerson Meadows. Fully filling the erosion gully network will restore the meadow's pre-disturbance geomorphology, which will then result in a cascading restoration of site hydrologic and ecological process as groundwater tables are elevated, erosive flood energy is spread and dispersed, and dense wetland vegetation becomes established to anchor soil in place.

Alternatives to full-gully fill that were considered but ruled-out included periodically blocking the gully with either machine-built earth plugs or small hand-built wood-and-mud structures.

Earth plugs could be constructed to the meadow surface, raising water tables and dispersing flow much like full gully fill. This alternative was rejected because the design leaves large deep open water ponds upstream of each plug, which present several problems. At high flow, water would fall about 1-foot from the meadow surface and upstream plug into each pond. These spill lips are knickpoints where flow accelerates and erosive force concentrates. In addition, water plunging into a pool can undercut adjacent banks. At low water, the drop from meadow surface to pond level would be even greater, creating more potential for erosion from a late summer or fall thunderstorm-driven flow event. These ponds behind earthen plugs would capture sediment at the measured natural long-term meadow-wide sedimentation rate of ~0.5 mm/yr because flow and associated deposition would occur across the valley width. The upstream-most pond could be expected to receive sediment at a faster rate because it receives a confined flow and sediment load from the upstream channel, but the 50+ in-meadow ponds would fill at approximately the meadow accumulation rate. Given the ponds' kickpoint erosion vulnerability and millennial infill timeframe, it's unlikely the ponds would fill in before another erosion gully network formed. The failure of this alternative to restore meadow geomorphology results in an unstable design and so it was rejected.

Unlike earthen plugs, hand built wood-and-mud beaver dam analogs and post-assisted log structures could not be constructed and maintained at a sufficient height to pond up water to the 8-to-14 foot-depth necessary to spill flow out of the gully and onto the meadow surface. Therefore, the goal of these structures would not be to immediately restore wetland conditions to the dewatered meadow, but rather to accelerate the evolution of the erosion gully into a wider and more-branched channel network. This would involve placing structures to concentrate erosion at cut banks and separate structures that would attempt to capture and retain both externally- and internally-generated sediments to aggrade the channel as it widens. The main problems with this design are the long-term annual maintenance efforts required, the amount of meadow soil erosion caused, and the difficulty of capturing and retaining sediment during high-flow events.

Because sediment capture and retention are challenging and imperfect, generating sediment internally by eroding the gully banks would have the net effect of increasing the gully void volume. Because flow would remain confined within the gully, all external sediment will be delivered into a smaller area than the full meadow width. The gully area is about 1/4th the area of the overall meadow, which would multiply the natural sedimentation rate by 4, from 0.5 mm/yr to 2 mm/yr. Even concentrated, this sedimentation rate is far too slow to fill the gully in a timeframe appropriate for human-maintained structures. Therefore, the outcome of this alternative can only be a broader, lower elevation series of inset meadow terraces developed within the expanded gully.

This alternative was rejected because it fails to restore the degraded ecosystem, it seeks to erode away much of what is left of the meadow and would increase downstream sediment loads because in-stream sediment capture would be imperfect. This alternative could accelerate the evolution of the human-caused gully to a broader inset system similar to the pre-disturbance valley-wide wetland but would still require many decades to centuries of annual maintenance of the dams. This alternative could be feasible in the long term if beaver were to take up permanent residence and maintain dams. There is no geomorphic or stratigraphic evidence that beaver maintained dams in the pre-historic era, and the one human introduction of beaver at the site only persisted for about 10 years.

These two intermittent gully-blockade options were rejected because neither establishes a natural self-sustaining ecosystem in a reasonable maintenance time-frame. Full gully fill was selected as the preferred restoration action because it restores pre-disturbance geomorphology, which will then drive the restoration of the critically interconnected hydrologic and vegetation processes.

Approximately 150,000 cubic yards of material will be required to accomplish full gully fill (Table 1). The fill will be 70% upland soil excavated from cut zones on the nearby hillslopes (Figure 16 and Table 2), and 30% woody organic matter from chipped logs and biochar. A portion of the required wood chips can be generated onsite from trees within the cut and fill zones. Tree surveys of the work zones in and around Ackerson Meadow found an estimated 257 cubic yards of timber per acre of upland cut zone, and about 600 individual trees within the gully fill zones. These onsite trees will provide about 25% of the wood chip volume required, the balance will need to be imported from offsite (Table 3).

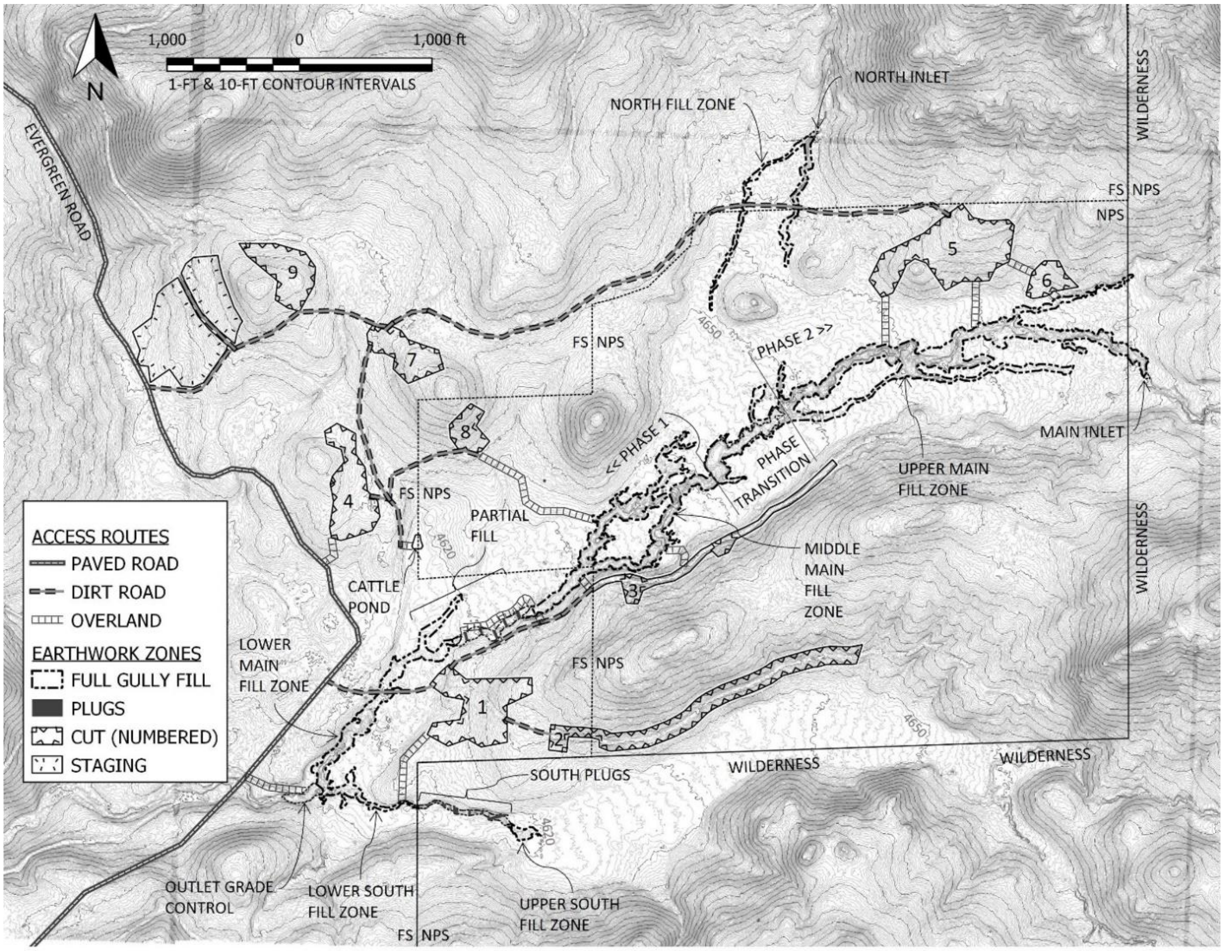

*Figure 16. An overview of the topography and proposed earthwork in Ackerson Meadow. Fully gully fill is indicated for the gullies in Main and South Ackerson, hillslope cut zones are numbered in the order they will be utilized, and access routes from the cut to the fill zones are indicated. The fill itself will serve as the access route up and down the meadow.*

The gully fill will proceed in two subsequent-year phases, starting at the downstream end and working upstream (Figure 16 and Figure 17). Phase 1 will require 76,100 cubic yards of fill and will create 12.7 acres of bare fill area (Table 1). The gully fill will be composed of 70% mineral fill and 30% organic matter in the form of wood chips and/or biochar. The mineral soil will be excavated from cut zones on the surrounding hillslope. The topsoil from these cut zones will be set aside and replaced after excavation and an upland seed mix will be sown into the topsoil (Table 2). The wood chips and/or biochar will be sourced from a combination of onsite trees in the cut and fill zones and imported materials from elsewhere in the Park. Yosemite National Park foresters assessed the timber stands within the cut and fill zones, and their data were used to estimate the volume of wood chips that can be produced from onsite trees felled as part of the excavation and gully fill operations (Table 3). The average wood volume per tree surveyed in the cut zones was 0.53 cubic yards solid wood per tree due to a high proportion of small-diameter trees. Trees counted in the fill zones focused on larger individuals, so were estimated to be about twice as large: 1 cubic yard of solid wood per tree. Trees imported to the project for chipping will be supplied by a fuels-thinning project. Consequently, we used the full-stand estimate of 0.53 cubic yards per tree to estimate the import tree count to account for an expected high proportion of small-diameter trees.

The downstream end of Phase 1 will be a rock-arch-rapids grade control structure designed to convey a flood flow of 2,000 CFS, the probable 100-year flood for Main and South Ackerson Meadows combined. The upstream end of Phase 1 will be a temporary level-fill transition at 4641 feet elevation tapering out into the remaining upstream gully (Figure 17). Phase 1 will also include filling the gully in South Ackerson Meadow. Two sections of gully in Phase 1 will only be partially filled to protect wildlife habitat: A reach of South Ackerson Meadow left as plugs with ponds for Western pond turtles, and a reach of partial fill in Main Ackerson with dense willows that harbor willow flycatcher. During the first phase a pond will be dug in the location of a previous ranch pond to provide water access to cattle away from the Main Ackerson fill, in hopes of reducing grazing impacts to the newly restored wetlands (Figure 16).

Phase 2 the following year will bring the level fill transition up to meadow surface and completely fill the remaining upstream Main gully as well as two small disconnected gullies in the north arm of Ackerson Meadow. In total, Phase 2 will require 73,220 cubic yards of fill and will create 16.14 acres of bare fill. Bare fill will be protected from surface flow erosion using erosion blanket, coir wattles, and live vegetation. The small 1-foot deep linear ditches south of the north arm will be plugged by hand crews to prevent drainage and potential erosion.

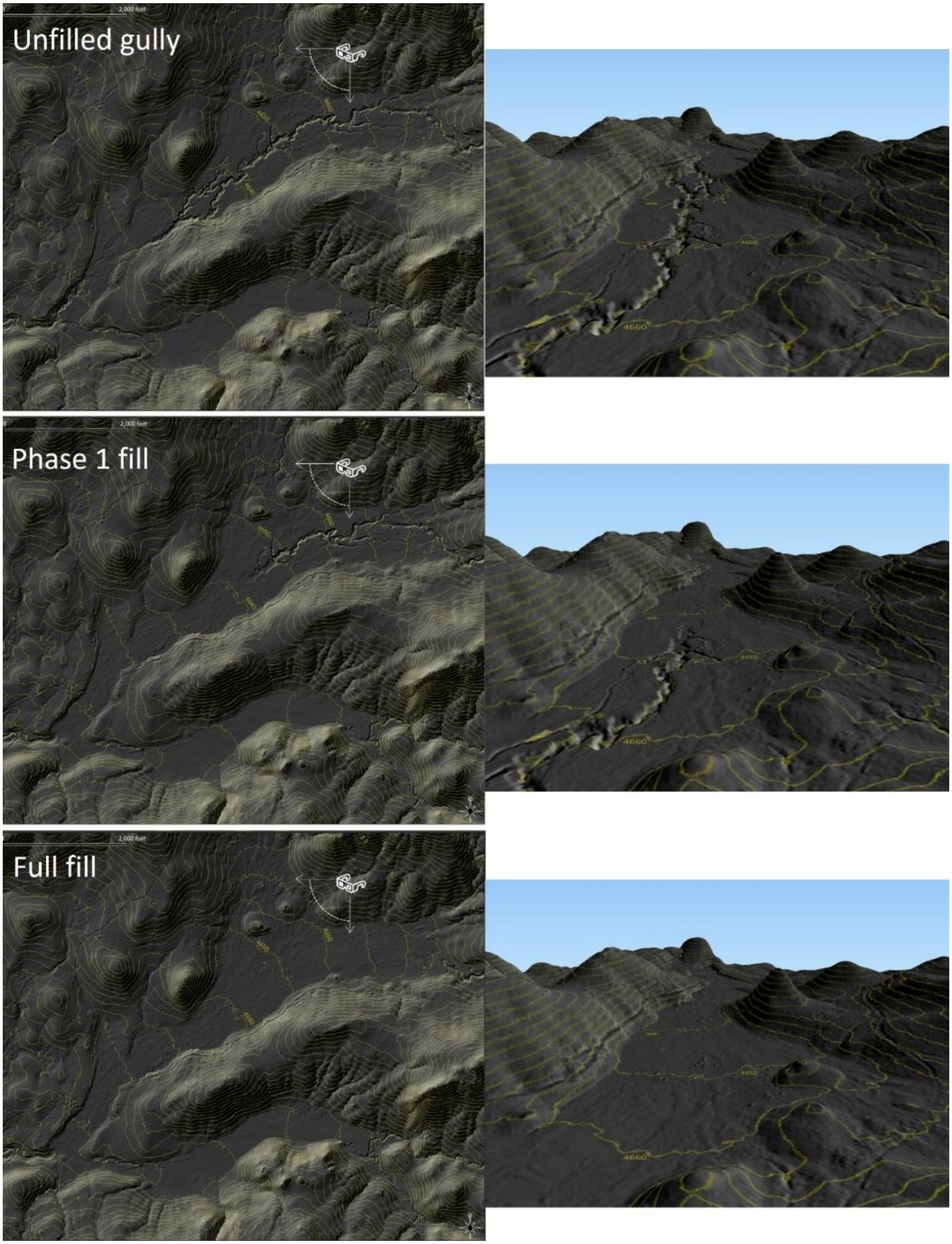

*Figure 17. Hillshade images from LiDAR elevation data showing the current unfilled gully landscape, the propoased Phase 1 landscape, and the final full fill valley floor of Ackerson Meadow. Images on the left show a straight down view, while images on the right are oblique views looking down-valley from the location indicated by the glasses in the left images. Yellow lines are 10-foot contour intervals.*

*Table 1. Estimated fill requirements for the gully fill at Ackerson Meadow, broken out by Phase and Fill Zone, and by mineral soil and wood chip/biochar fractions. ^ = Phase Transition acres are excluded from the Phase 1 subtotal because the final fill surface will be graded, blanketed, and planted as part of the Upper Main fill zone in Phase 2.*

| Fill Zone | Acres | Fill volume ($yd^3$), composed of: | 70% excavated mineral soil ($yd^3$) | 30% wood chips/biochar ($yd^3$) |
|---|---|---|---|---|
| Phase 1 | | | | |
| Upper South | 0.333 | -685 | -480 | -206 |
| South Plugs | 0.203 | -680 | -476 | -204 |
| Lower South | 0.833 | -1995 | -1397 | -599 |
| Outlet (*side berms only) | 0.157 | -254 | -178 | -76 |
| Lower Main | 3.975 | -14309 | -10016 | -4293 |
| Partial Fill | 0.197 | -302 | -211 | -91 |
| Middle Main | 6.984 | -44736 | -31315 | -13421 |
| Phase Transition | 1.851^ | -13145 | -9202 | -3944 |
| Phase 1 subtotal | 12.683 | -76106 | -53274 | -22832 |
| | | | | |
| Phase 2 | | | | |
| Upper Main | 14.198 | -69698 | -48789 | -20909 |
| North | 1.498 | -3522 | -2465 | -1057 |
| Phase 2 subtotal | 15.696 | -73220 | -51254 | -21966 |
| | | | | |
| TOTAL | 28.378 | -149326 | -104528 | -44798 |

*Table 2. Estimated topsoil salvage, mineral soil excavation, and area of the 9 proposed cut zones, presented in likely order of use. Phase 1 of the project would require using cut zones 1-4, and Phase 2 would use zones 4-7, with zones 8 and 9 as reserve.*

| Cut zone | Topsoil salvage ($yd^3$) | Excavated mineral soil ($yd^3$) | Cummulative cut ($yd^3$) | Acres | Cummulative acres | Soil test pit notes |
|---|---|---|---|---|---|---|
| 1 | 10116 | +22521 | +22521 | 6.270 | 6.270 | Surface to 8 ft: Sandy loam w/ sparse cobbles; 8+ ft: Bedrock. |
| 2 | 11967 | +20828 | +43349 | 7.418 | 13.688 | Surface to 8+ ft: Sandy clay loam w/ sparse boulders. |
| 3 | 5230 | +2877 | +46226 | 3.242 | 16.930 | No soil data; similar setting to zones 1 and 2. |
| 4 | 7759 | +17022 | +63248 | 4.810 | 21.740 | Surface to 8+ ft: Sandy loam w/ sparse cobbles and boulders. |
| 5 | 14304 | +34338 | +97586 | 8.866 | 30.606 | Surface to 6-8+ ft: Sandy clay loam w/ sparse cobbles. |
| 6 | 2485 | +4617 | +102203 | 1.540 | 32.146 | No soil data; similar setting to zone 5. |
| 7 | 4871 | +10221 | +112424 | 3.019 | 35.165 | Surface to 6-8+ ft: Sandy loam w/ sparse cobbles. |
| 8 | 2613 | +4924 | +117348 | 1.620 | 36.785 | Surface to 6-8+ ft: Sandy loam w/ abundant boulders. |
| 9 | 5833 | +12787 | +130135 | 3.615 | 40.400 | Surface to 6-8+ ft: Sandy loam w/ abundant cobbles and boulders. |

*Table 3. Accounting of the estimated onsite and offsite wood needed to generate the wood chip portion of the gully fill. † = Fill zone total includes 0.365 acres of gully cleared for the rock arch rapids, which will be filled with rock, not standard fill. * = The offsite tree count requirement is based on the Ackerson Meadow timber cruise average of 0.527 $yd^3$ of solid wood per tree.*

| Onsite wood in cut zones, by zone | Acres | Tree count | Volume of solid wood ($yd^3$) | As wood chips, loose ($yd^3$) | As wood chips, placed volume in fill ($yd^3$) |
|---|---|---|---|---|---|
| 1 | 6.270 | 3049 | 1607 | 3214 | +2009 |
| 2 | 7.418 | 3607 | 1901 | 3802 | +2376 |
| 3 | 3.242 | 1576 | 831 | 1662 | +1038 |
| 4 | 4.810 | 2339 | 1233 | 2465 | +1541 |
| Phase 1 (Cut 1-4) subtotal | 21.740 | 10570 | 5571 | 11142 | +6964 |
| | | | | | |
| 5 | 8.866 | 4311 | 2272 | 4544 | +2840 |
| 6 | 1.540 | 749 | 395 | 789 | +493 |
| 7 | 3.019 | 1468 | 774 | 1547 | +967 |
| Phase 2 (Cut 5-7) subtotal | 13.426 | 6528 | 3440 | 6881 | +4301 |
| | | | | | |
| CUT ZONES 1-7 TOTAL | 35.165 | 17098 | 9012 | 18023 | +11264 |
| | | | | | |
| Reserve cut zones if needed | | | | | |
| 8 | 1.620 | 788 | 416 | 833 | +520 |
| 9 | 3.615 | 1758 | 929 | 1858 | +1161 |
| | | | | | |
| Onsite wood in fill zones, by phase | | | | | |
| 1 | 14.899 | 490 | 490 | 980 | +613 |
| 2 | 13.845 | 136 | 136 | 272 | +170 |
| FILL ZONE TOTAL | 28.743† | 626 | 626 | 1252 | +783 |
| | | | | | |
| All onsite wood | | | | | |
| Phase 1: Cut 1-4, Fill 1 | 36.638 | 11060 | 6061 | 12122 | +7576 |
| Phase 2: Cut 5-7, Fill 2 | 27.270 | 6664 | 3576 | 7153 | +4471 |
| ONSITE TOTAL | 63.908 | 17724 | 9638 | 19275 | +12047 |
| | | | | | |
| Offsite wood imports required, by phase | | | | | |
| 1 | | 23156* | 12204 | 24409 | +15255 |
| 2 | | 26556* | 13996 | 27993 | +17495 |
| OFFSITE TOTAL | | 49712 | 26201 | 52401 | +32751 |
| | | | | | |
| Project GRAND TOTAL | | **67436** | **35838** | **71676** | **44798** |

## Revegetation and grazing

Revegetation will be achieved by placing salvaged wetland sod and willow root balls in the most erosion-prone downstream reach, transplanting nursery seedlings into less erosion-prone areas protected with erosion blanket, and by seeding in the least erosion-prone areas with a mix of native wetland seeds.

The nursery plantings will be the dominant wetland species of sedges and rushes onsite: *Scirpus microcarpus*, *Carex nebrascensis, Juncus balticus,* and *Juncus dubius*. These species are critical because they grow rapidly below ground, forming a dense network of roots and rhizomes that bind and protect the soil surface. The broadcast seed palette should include the nursery-grown species as well as *Glyceria elata*, *Cinna latifolia*, *Deschampsia cespitosa*, and *Calamagrostis canadensis*.

Rapid and complete establishment of dense vegetation on all bare fill areas is essential as long-term protection against erosion and re-formation of an expanding gully network. Although some remnant wetland plants and seeds may be present in the dewatered meadow soil, this area has been impacted for more than a century, so natural plant recovery is likely to be slow. Seed should be broadcast across the rewetted meadow surface areas as well. Sedge planting typically require 4-5 years of growth to attain natural density (Cooper *et al.*, 2017).

Because the formation and maintenance of a dense plant community is critical to stabilizing the meadow soil, managing grazing on the Forest Service grazing allotment is critical to project success. Cattle will be excluded from the meadow entirely during the 2 years of project construction. For at least three more years, a temporary exclusion fence will keep cattle off the filled and planted sections of the meadow. If, after three years of cattle exclusion, the transplants have not achieved natural density, the exclusion can be extended on a per-year basis (Stanislaus National Forest Grazing Permit 16-54-11D).

The majority of restored acres will be within Yosemite National Park, and as part of the acquisition of Ackerson Meadow, the Forest Service and Park swapped land to consolidate grazing and minimize the likelihood of cattle trespass into the Park. A barbed wire boundary fence exists between the Park and Forest to keep cattle out, and the entire fence line will be cleared of hazard trees that could fall across the fence. This should facilitate fence maintenance, which will be the responsibility of the cattle rancher. In addition, a cattle pond is being constructed away from the restoration fill and planting area to provide access to water so that cattle have a drinking source other than the restored wet meadow.

In addition to this grazing infrastructure, a grazing monitoring and management plan is being established and linked to the grazing permit. This plan will set thresholds of impact that would trigger management actions such as removing cattle from the meadow to allow plant recovery and soil stabilization to prevent the reformation of a gully network.

## Flow modeling and grade control

Using the 2D flow modeling program HEC-RAS 6.3.1, the flow depth and shear stress across the full-filled gully topography were calculated for flows up to the estimated 100-yr flood event at Ackerson Meadow (See Appendix for more detail). The flow estimates were derived from a combination of direct gauging of Ackerson Creek and regional regression equations (Fong and Avdievitch, 2019). On a restored landscape with the gully filled in, the modelled flood flow disperses across the valley width, inundating the entire meadow with 1-3+ feet of water depth (Figure 18). The deepest modelled flows occur in the downstream southwest end of the meadow where the valley is the narrowest and where Main Ackerson and South Ackerson converge. Even at the lowest modelled 2-yr recurrence interval flood, the entire valley width receives flow.

The flow-dispersal effect of full gully fill is particularly well-demonstrated when modelling the flood flows across the partially-filled Phase 1 landscape. After Phase 1, the upstream reach of gully will remain unfilled, while the downstream reach is fully filled. The hydrologic effect of this transition from unfilled to full-filled gully is that flow immediately disperses upon reaching the Phase 1 filled reach (Figure 19).

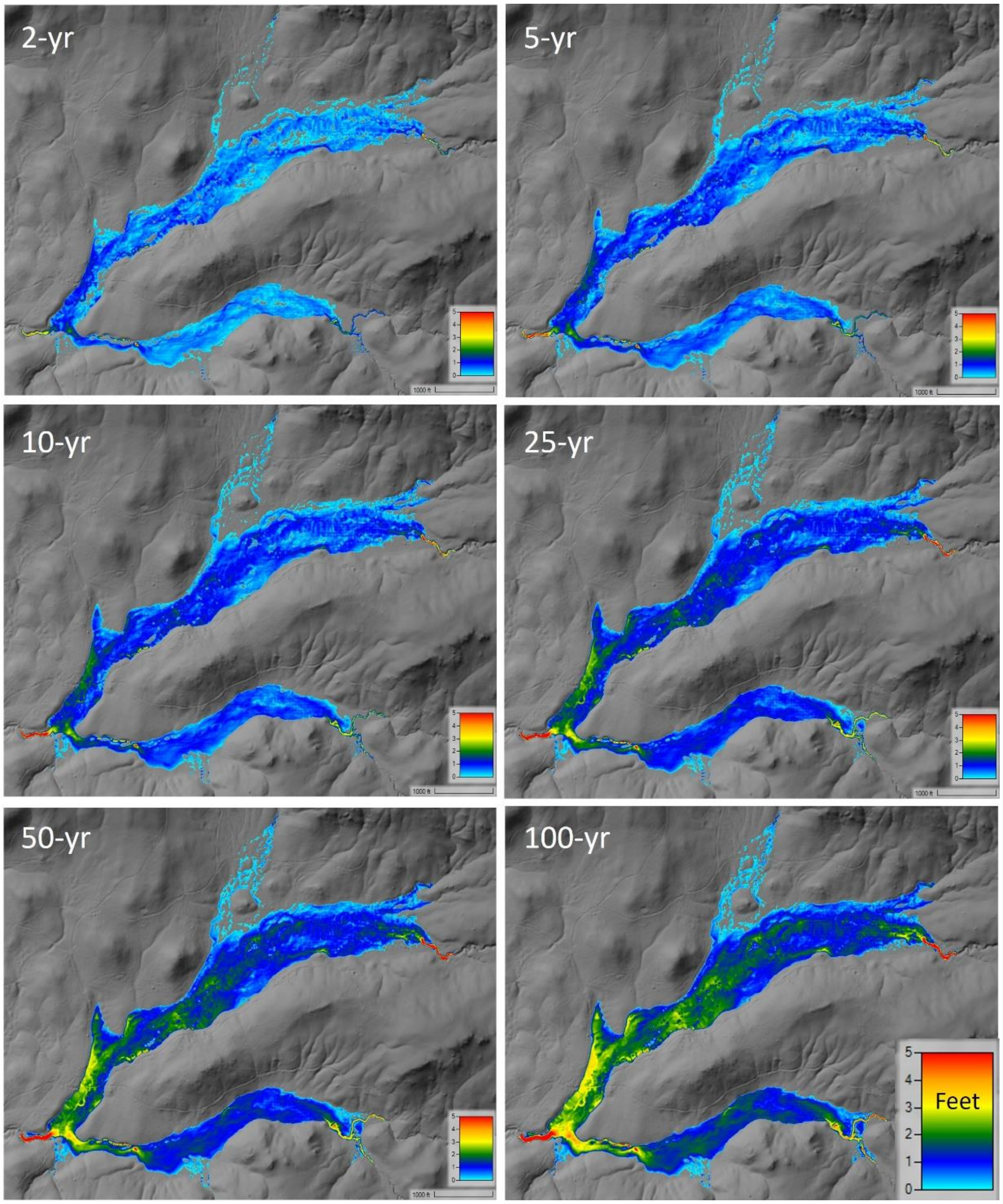

*Figure 18. The modelled flooding extent and water depth for the 2- through 100-yr flow at Ackerson Meadow in the proposed full gully filled state. The lidar topography is shades of grey and the modeled flow depth in feet is represented by colors. Note that meadow-wide flooding occurs across the entire width and length of Ackerson Meadow during the 2-year flood.*

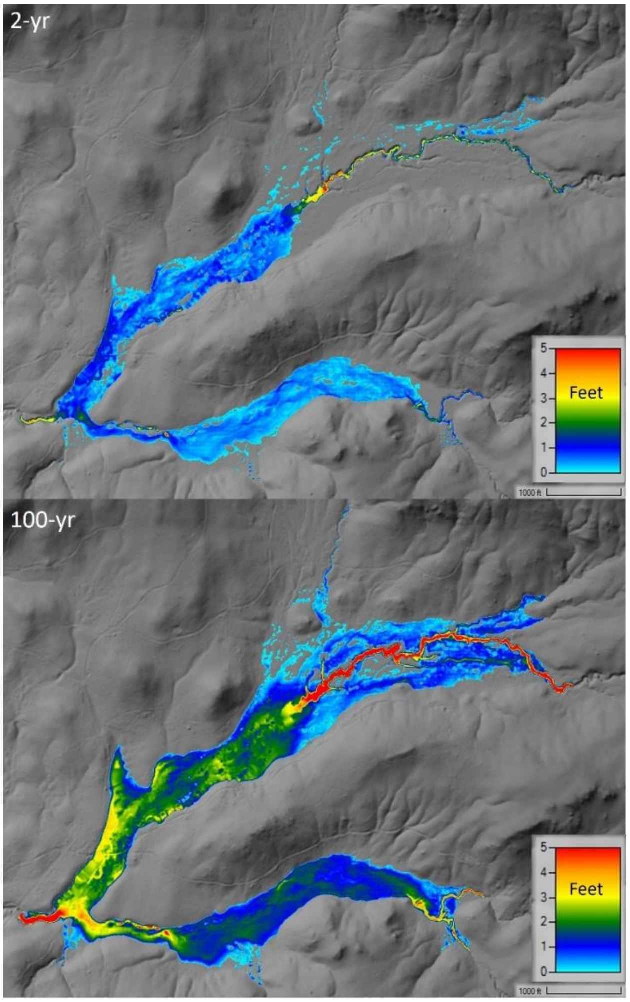

*Figure 19. The modelled flooding extent and water depth for the 2- and 100-yr flow at Ackerson Meadow Phase 1 only of the full gully fill. The lidar topography is shades of grey and the modeled flow depth in feet is represented by colors. Note that from the Phase Transition downstream Ackerson Meadow is flooded across the entire valley floor for the 2-year flow, while flow remains confined to the gully in the unrestored Upper Main section.*

In addition to flow depth, HEC-RAS modeled shear stress, which is an important metric for determining the erosive capacity of flow. For the 100-year flow, shear stress is less than ~2 pounds per square foot (lbs/ft$^2$) across most of the fully-filled meadow. Where flow width is constricted at the Main Ackerson inlet and at the outlet shear stress exceeds 3 lbs/ft$^2$ (Figure 20). At the narrow downstream reaches of Main and South Ackerson, shear stress is between 2-3 lbs/ft$^2$ in patches. The model shows no significant spike in shear stress at the Phase 1 upstream level fill, indicating that this design should be stable for transitioning flow from the unfilled gully to the fully-filled meadow below.

These flow models highlight the locations in the fully-filled meadow where erosion is most likely to occur during a flood event: the Outlet and adjacent Lower Main and Lower South, Main Inlet, and the narrow neck of Middle Main Ackerson. The main safeguard against re-erosion of the placed fill is densely established wetland vegetation. Therefore, the design focuses placement of salvaged sod at the downstream end near the outlet, and installation of erosion blanket and nursery plantings at Upper and Middle Main.

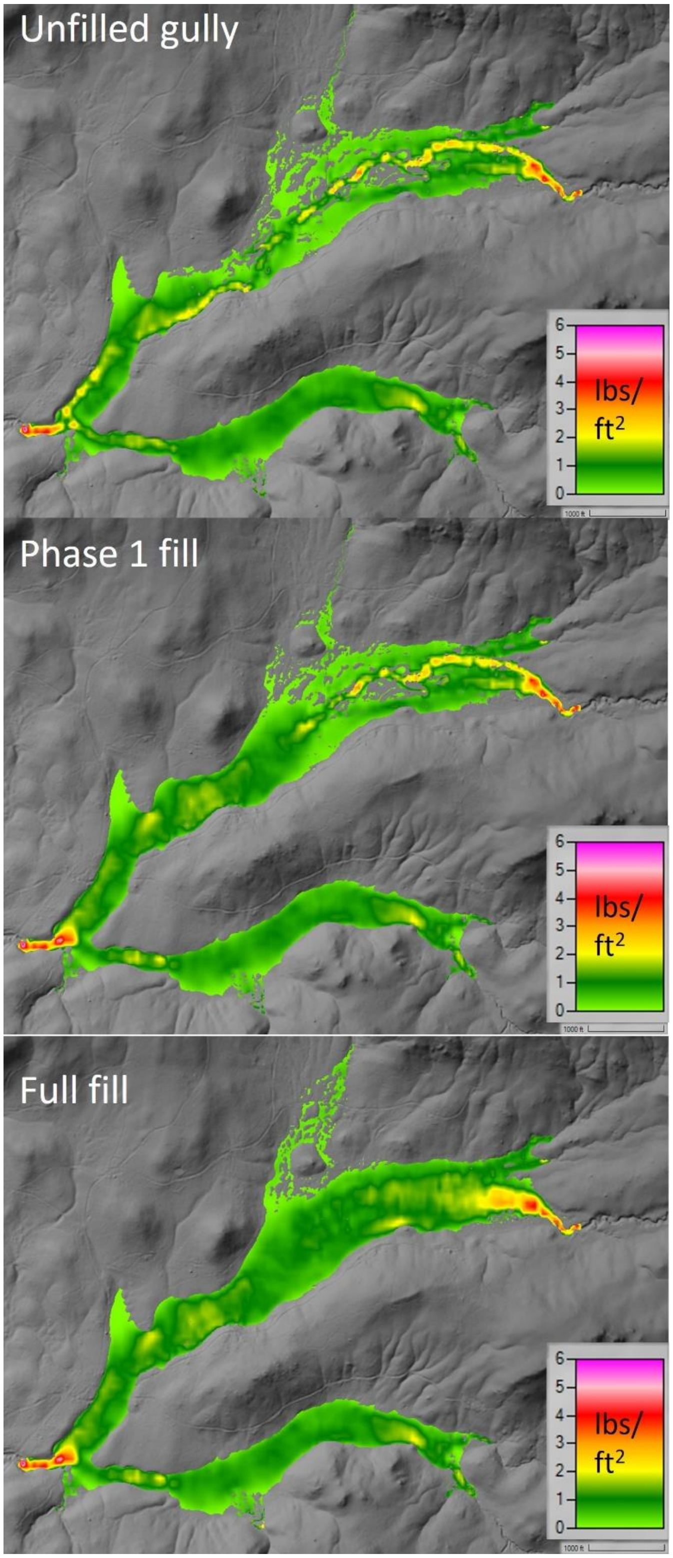

*Figure 20. The modelled shear stress for the 100-yr flow in Ackerson Meadow in its current unfilled gully state, following phase 1 of fill, and after full gully fill. The lidar topography is shades of grey and the shear stress is represented by colors, scale in the lower right. The units of shear stress are lbs/ft$^2$. Note that when fully filled, the Main Inlet and the Outlet experience shear stress of 3 lbs/ft$^2$ or higher, and everywhere else in the meadow is ~2 lbs/ft$^2$ or less. The highest modelled shear stress of ~6 lbs/ft$^2$ occurs at the furthest downstream end.*

The restoration project's downstream extent of gully fill ends with an engineered rock-arch-rapids grade control structure. The grade control structure is needed to convey water from the restored meadow surface elevation at 4600 feet downstream to the unfilled gully bed elevation at 4592 feet elevation. This 8-foot drop occurs over a 141-foot distance, along a 5.7% slope. The grade control structure is positioned at a natural constriction in the valley where, even with a fully-filled gully, flood flows will be concentrated and more erosive. Evergreen Road crosses the erosion gully 630 linear feet downstream of the valley constriction. There is clear evidence that the intact meadow used to extend at least as far as Evergreen Road (Figure 15). However, filling the erosion gully at the road crossing would require redesigning and rebuilding a significant section of Evergreen Road, which was deemed outside the scope of this project. Ending the project 630 feet upstream of the Evergreen Road at the natural valley constriction provides a good location for a rock-arch-rapids installation and will not affect the hydraulics of the current road crossing. The Evergreen Road crossing of Ackerson Creek was redesigned between 2013 and 2019 (see Figure 8) by raising the roadbed to provide a larger water conveyance capacity. By filling the erosion gully and restoring sheet flow hydrology to Ackerson Meadow, peak flows are expected to be attenuated, reducing the risk to downstream infrastructure such as Evergreen Road (Hammersmark, Rains and Mount, 2008; Clilverd *et al.*, 2016).

The rock-arch-rapids is designed to withstand a 100-year flow event. The full gully fill restoration of Ackerson Meadow is designed to reestablish the geomorphic, hydrologic, and biologic forms and processes that maintained a dispersed-flow wet meadow for thousands of years. The relatively short-lived and unnatural grade control structure is the limiting factor in the longevity of the restored ecosystem at Ackerson Meadow. Therefore, it is recommended that the downstream end of the current project, at the rock-arch-rapids, be considered a temporary stopping point. The long-term goal is to complete the gully-fill restoration through to Ackerson Meadow's former natural end point downstream of Evergreen Road. The rock-arch-rapids grade control structure should provide decades of stability to allow time for the planning and implementation of this final restoration and road reconstruction effort.

## References

CA DWR (1965) *Southern Tuolumne County Investigation*. Bulletin 96. California Department of Water Resources. Available at: https://babel.hathitrust.org/cgi/pt?id=uc1.31210018574721.

CDFG (1963) *A summarized report of the Pittman-Robertson program in California, May 1940 to July 1962*. Sacramento, CA: California Department of Fish and Game.

Chase, J.S. (1911) *Yosemite trails: Camp and pack-train in the Yosemite region of the Sierra Nevada*. Boston, MA: Houghton, Mifflin.

Chimner, R.A., Cooper, D.J., Wurster, F.C. and Rochefort, L. (2017) 'An overview of peatland restoration in North America: where are we after 25 years?', *Restoration Ecology*, 25(2), pp. 283–292. Available at: https://doi.org/10.1111/rec.12434.

Clilverd, H.M., Thompson, J.R., Heppell, C.M., Sayer, C.D. and Axmacher, J.C. (2016) 'Coupled Hydrological/Hydraulic Modelling of River Restoration Impacts and Floodplain Hydrodynamics', *River Research and Applications*, 32(9), pp. 1927–1948. Available at: https://doi.org/10.1002/rra.3036.

Cooper, D.J., Kaczynski, K.M., Sueltenfuss, J., Gaucherand, S. and Hazen, C. (2017) ‘Mountain wetland restoration: The role of hydrologic regime and plant introductions after 15 years in the Colorado Rocky Mountains, U.S.A.’, *Ecological Engineering*, 101, pp. 46–59. Available at: https://doi.org/10.1016/j.ecoleng.2017.01.017.

Dodge, F.C.W. and Calk, L.C. (1987) *Geologic map of the Lake Eleanor quadrangle, central Sierra Nevada, California: U.S. Geological Survey, Geologic Quadrangle Map GQ-1639, scale 1:62,500.* Denver, CO: US Geological Survey.

E. F. E. (1939) ‘Golden Rock Ditch location within Yosemite National Park’. Available at: https://pubs.etic.nps.gov/eTIC/YOSE/YOSE_104_60189.pdf.

Finney, S.K. (2012) ‘Higher ground’, *Range Magazine*, pp. 14–17.

Fong, C. and Avdievitch, N. (2019) *Geomorphic and hydrologic assessment of the Ackerson Meadow complex*. Report to Yosemite National Park, El Portal, CA.

Gage, E.A. and Cooper, D.J. (2005) ‘Patterns of Willow Seed Dispersal, Seed Entrapment, and Seedling Establishment in a Heavily Browsed Montane Riparian Ecosystem’, *Canadian Journal of Botany-Revue Canadienne De Botanique*, 83(6), pp. 678–687.

Greene, L.W. (1987) *Yosemite, the park and its resources: a history of the discovery, management, and physical development of Yosemite National Park, California*. Denver, CO: U.S. Dept. of the Interior, National Park Service.

Hammersmark, C.T., Rains, M.C. and Mount, J.F. (2008) ‘Quantifying the hydrological effects of stream restoration in a montane meadow, northern California, USA’, *River Research and Applications*, 24(6), pp. 735–753. Available at: isi:000257964400001.

Hensley, A.L. (1946) ‘A progress report on beaver management in California’, *California Fish and Game*, 30, pp. 87–99.

Hoffmann, C.F. (1868) ‘Notes on Hetch-Hetchy Valley’, *Proceedings of the California Academy of Sciences*, 3(5), pp. 368–370.

Keefe, T.M., Kahl, B.M. and Montague, S.T. (1999) ‘The Ackerson post-fire archeological project, Yosemite National Park, California’, I(5).

Kirkby, M.J. and Bracken, L.J. (2009) ‘Gully processes and gully dynamics’, *Earth Surface Processes and Landforms*, 34, pp. 1841–1851. Available at: https://doi.org/10.1002/esp.1866.

Kitzenberger, J. (2014) ‘125-year tradition’, *Western Horseman*, (June), pp. 58–69.

Loheide, S.P., Deitchman, R.S., Cooper, D.J., Wolf, E.C., Hammersmark, C.T. and Lundquist, J.D. (2008) ‘A framework for understanding the hydroecology of impacted wet meadows in the Sierra Nevada and Cascade Ranges, California, USA’, *Hydrogeology Journal*, 17(1), pp. 229–246. Available at: https://doi.org/10.1007/s10040-008-0380-4.

McIntyre, R.N. (1948) ‘A new park resident’, *Yosemite Nature Notes*, 27(4), pp. 3–8.

Minear, J.T. and Kondolf, G.M. (2009) ‘Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California’, *Water Resources Research*, 45(12). Available at: https://doi.org/10.1029/2007WR006703.

Paden, I.D. and Schlichtmann, M.E. (1955) *The Big Oak Flat Road; an account of freighting from Stockton to Yosemite Valley*. Yosemite National Park, CA: Yosemite Natural History Association.

Prosser, I.P., Dietrich, W.E. and Stevenson, J. (1995) ‘Flow resistance and sediment transport by concentrated overland flow in a grassland valley’, *Geomorphology*, 13(1–4), pp. 71–86. Available at: https://doi.org/10.1016/0169-555X(95)00020-6.

Prosser, I.P. and Slade, C.J. (1994) ‘Gully formation and the role of valley-floor vegetation, southeastern Australia’, *Geology*, 22(12), pp. 1127–1130. Available at: https://doi.org/10.1130/0091-7613(1994)022<1127:GFATRO>2.3.CO;2.

Quantum Spatial (2020) *Yosemite National Park, California 3DEP Lidar Technical Data Report*. Report to USGS. Available at: https://prd-tnm.s3.amazonaws.com/StagedProducts/Elevation/metadata/CA_YosemiteNP_2019_D19/CA_YosemiteNP_2019/reports/Yosemite_California_NIR_Lidar_Technical_Data_Report.pdf.

Ree, W. (1949) ‘Hydraulic characteristics of vegetation for vegetated waterways’, *Agricultural Engineering*, 30(4), pp. 184–187.

State of California (1946) *Thirty-ninth biennial report of the Division of Fish and Game for the years 1944-1946*. Sacramento, CA: California Department of Natural Resources.

Stavros, E.N., Tane, Z., Kane, V.R., Veraverbeke, S., McGaughey, R.J., Lutz, J.A., Ramirez, C. and Schimel, D. (2016) ‘Unprecedented remote sensing data over King and Rim megafires in the Sierra Nevada Mountains of California’, *Ecology*, 97(11), p. 3244. Available at: https://doi.org/10.1002/ecy.1577.

Steen, H.K. (1975) ‘Grazing and the Environment: A History of Forest Service Stock-Reduction Policy’, *Agricultural History*, 49(1), pp. 238–242. Available at: https://www.jstor.org/stable/3742132 (Accessed: 7 February 2022).

Stock, S. (2017) *Ackerson Meadow: What Lives There?* Report to Yosemite National Park.

Surfleet, C., Sanford, T., Vanoosbree, G. and Jasbinsek, J. (2019) ‘Hydrologic Response of Meadow Restoration the First Year Following Removal of Encroached Conifers’, *Water*, 11(3), p. 428. Available at: https://doi.org/10.3390/w11030428.

Townsend, K.F., Nelson, M.S., Rittenour, T.M. and Pederson, J.L. (2019) ‘Anatomy and evolution of a dynamic arroyo system, Kanab Creek, southern Utah, USA’, *Bulletin of the Geological Society of America*, 131(11–12), pp. 2094–2109. Available at: https://doi.org/10.1130/B35195.1.

Tucker, G.E., Arnold, L., Bras, R.L., Flores, H., Istanbulluoglu, E. and Sólyom, P. (2006) ‘Headwater channel dynamics in semiarid rangelands, Colorado high plains, USA’, *GSA Bulletin*, 118(7–8), pp. 959–974. Available at: https://doi.org/10.1130/B25928.1.

Union Democrat and Supervisors of Tuolumne County (1909) *Tuolumne County California: Being a frank, fair and accurate exposition, pictorially and otherwise, of the resources and possibilities of this magnificent section of California*. Sonora, CA: JA Van Harlingen & Co. Available at: https://babel.hathitrust.org/cgi/pt?id=uc1.c2849666.

United States (1937) *Acquisition of certain lands for, and addition thereof to, the Yosemite National Park in the state of California, and for other purposes*. Washington D.C.: United States House of Representatives, 75th Congress, 1st session.

Wills, W. (2020) *Archeological Survey and National Register of Historic Places Evaluations for the Ackerson Meadow Ecological Restoration Project, Yosemite National Park, California*. Report to Yosemite National Park.

Wolf, E., Cooper, D.J. and Wagner, J. (2018) *Restoration Alternatives for Phase 3 Halstead Meadow, Sequoia National Park*. Report to Sequoia and Kings Canyon National Parks.

Wolf, E., Demetry, A., Cooper, D. and Wagner, J. (2015) *Existing condition assessment and preliminary stabilization/restoration alternatives for Cahoon Meadow, Sequoia & Kings Canyon National Parks*. Three Rivers, CA: Sequoia and Kings Canyon National Parks.

Wolf, E.C. and Cooper, D.J. (2016) *Assessment of Soil and Moisture Conservation Crew meadow restoration*. Report to Sequoia and Kings Canyon National Parks. Three Rivers, CA.

Wood, S.H. (1975) *Holocene stratigraphy and chronology of mountain meadows, Sierra Nevada, California*. PhD dissertation, California Institute of Technology.

Woods, S.W. and Cooper, D.J. (2005) 'Hydrologic factors affecting initial willow seedling establishment along a subalpine stream, Colorado, USA', *Arctic, Antarctic and Alpine Research*, 37(4), pp. 636–643. Available at: https://doi.org/10.1657/1523-0430(2005)037[0636:HFAIWS]2.0.CO;2.

# Appendix

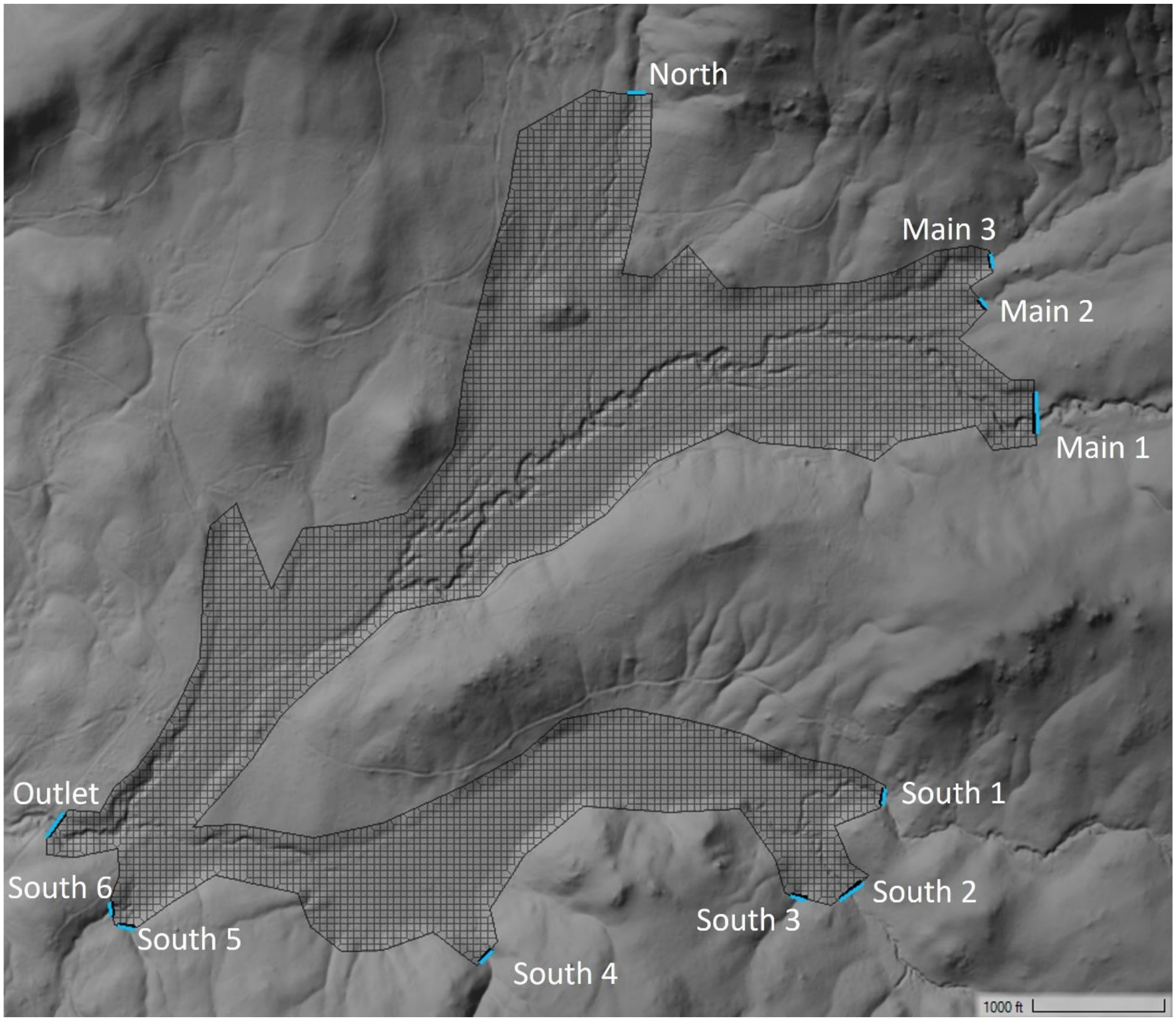

*Figure 21. HEC-RAS model domain consisting of 50-ft squares overlaid on the 2013 lidar topography showing the erosion gully network in Ackerson and South Ackerson meadows. Model boundary conditions are shown as blue lines and are labeled. All boundary conditions represent water input to the system, except "Outlet". The rates of water added at each boundary condition are shown in Table 4.*

*Table 4. Summary table showing the flows (in CFS) for a range of flood-recurrence intervals for each of the HEC-RAS model boundary conditions. All locations are flow inlets except for "Outlet", which discharges the combined total of the inlets. See Figure 21 for a map of the model domain and boundary condition locations*

| | Discharge in cubic feet per second (CFS) at each boundary condition location | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Return interval (yr) | Main 1 | Main 2 | Main 3 | North | South 1 | South 2 | South 3 | South 4 | South 5 | South 6 | Total at Outlet |
| 2 | 365 | 37 | 37 | 10 | 106 | 106 | 10 | 10 | 10 | 10 | 700 |
| 5 | 674 | 67 | 67 | 20 | 199 | 199 | 20 | 20 | 20 | 20 | 1306 |
| 10 | 1020 | 102 | 102 | 35 | 303 | 303 | 35 | 35 | 35 | 35 | 2004 |
| 25 | 1620 | 162 | 162 | 45 | 481 | 481 | 45 | 45 | 45 | 45 | 3131 |
| 50 | 2290 | 229 | 229 | 60 | 680 | 680 | 60 | 60 | 60 | 60 | 4408 |
| 100 | 3130 | 313 | 313 | 80 | 930 | 930 | 80 | 80 | 80 | 80 | 6016 |

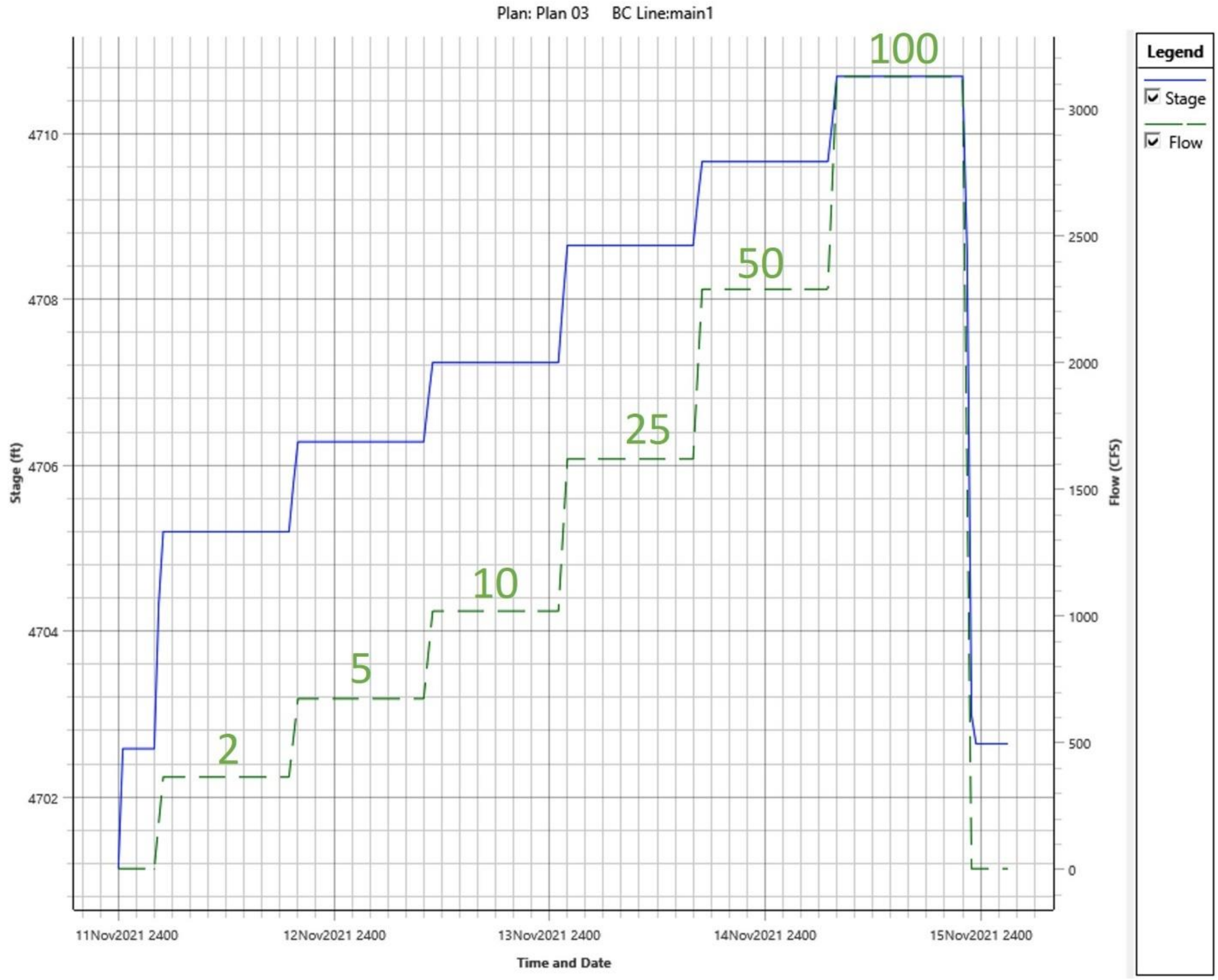

*Figure 22. The "Main 1" boundary condition inlet flood hydrograph for the HEC-RAS model. The green dashed line shows the input flow values for 2- through 100-year recurrence interval floods (right y-axis), and the blue line shows the HEC-RAS computed water level stage at the boundary condition line (left y-axis). Synchronous flood hydrographs were input to the model for each of the inlet boundary conditions, with flow values shown in Table 4.*