



Geomorphic and Ecological Responses to Human Modification of the Fremont River, Capitol Reef National Park, Utah



Upstream view of the Fremont River adjacent to Utah State Route 24, including part of a multi-tiered waterfall that ends the river's artificially cut flow path through Navajo Sandstone.

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Geomorphic and ecological responses to human modification of the Fremont River, Capitol Reef National Park, Utah

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Abstract

This study documents impacts to the Fremont River that were initiated by the construction of Utah State Route 24 in 1962 within what is now Capitol Reef National Park (CARE). The highway and related river modifications led to an artificial abandonment of a 4000 ft long river meander, creation of a channel bed knickpoint (i.e., waterfall), and at least 9 ft of vertical incision into the underlying Navajo Sandstone. Channel incision also appears to have translated upstream, as we found a significant trend of a deeper channel immediately upstream of the knickpoint that transitioned to being wider and shallower upstream. The rate of upstream propagation of these geomorphic changes may be as high as 20 ft/yr, with ongoing and future incision threatening the stream-riparian system further. The knickpoint and its upstream propagation through a knickzone have also affected the Fremont River riparian vegetation community within the less frequently flooded incised reach by shifting it toward more dry-adapted species. In contrast, the channel in the less incised reference reach inundates its floodplain more frequently, has a higher mean vegetation abundance, and supports more wet-adapted species. Upstream propagation of a more deeply incised channel will likely continue through the Navajo Sandstone segment and into the more vulnerable alluvial segment upstream. Reactivation of the abandoned river meander to restore the Fremont River and its riparian corridor will require channel realignment to match elevations between the current and abandoned channels. Additionally, further upstream in a sub-reach where the highway has been repeatedly impacted by overbank flows, direct observations by park staff are supported by our hydraulic modeling indicating that the highway is inundated by flows of between 1000 and 1900 cubic feet per second, which are expected to occur every 2–5 years. Mitigation to improve flood resiliency and to alleviate river-highway conflicts may also be appropriate. Overall, this study's findings can help inform current river management decisions, state highway corridor planning, and future river restoration efforts in CARE.

Executive Summary

This study documents impacts to the Fremont River and its riparian ecosystem due to construction of Utah State Route 24 in 1962 through what is now Capitol Reef National Park (CARE). The study's objective is to support current river management decisions, transportation corridor planning, and future river restoration efforts. The highway construction and associated channel modifications include artificially abandoning a 4000 ft (1200 m) long river meander, creating a knickpoint/waterfall through the Navajo Sandstone, and at least 9–10 ft (3 m) of vertical incision into the bedrock, a rate of about 2 in/yr (5 cm/yr). Channel incision also appears to have translated upstream as there is a statistically significant, positive correlation between width-to-depth ratio and distance upstream from the diversion point, leaving the channel relatively deep and incised upstream of the knickpoint but becoming wider and shallower further upstream. Based on cross-section comparisons between reaches, the rate of upstream propagation of these geomorphic changes may be as high as 20 ft/yr (6 m/yr), and the more incised condition will likely continue to migrate upstream. Knickpoint creation and local oversteepening has contributed to simplification of the channel planform from multi-thread to single-thread, as seen in historical aerial imagery.

Knickpoint development and its upstream propagation have affected riparian vegetation by shifting communities towards more dry-adapted (upland) species in the incised reaches where overbank flooding is less frequent, requiring higher flows to inundate the floodplain. The less incised channel, located 1.5 miles (2.4 km) upstream of the knickpoint outside of its zone of impact, inundates its floodplain more frequently, requires lower flows to inundate the floodplain and has an overall higher mean vegetation abundance (percent cover) and a higher number of occurrences of wet-adapted (facultative wetland and obligate) species.

Reactivation of the abandoned meander to restore the river and riparian corridor will require channel realignment to match elevations between the abandoned meander and current channel. At the inlet to the abandoned meander, the entrance point in the active channel is just 0.08 ft (2 cm) higher than the entrance point in the cutoff meander. The exit point of the abandoned meander is about 11 ft (3.4 m) higher than the current channel, so a stable drop structure or extensive fill removal in the meander needs to be part of a restoration design.

Hydraulic modeling of the reach between mile marker 82.0 and 82.3, a location where the highway has been repeatedly impacted by overbank flows, indicates that the lower elevation side of the road surface is inundated by flows of between 1000 and 1900 ft³s⁻¹ (30–53 m³s⁻¹). Based on flood frequency analysis of peak annual flow values from USGS StreamStats, this discharge is in the range of about a 20–50 percent annual chance of flooding, or one we would expect to see every 2–5 years. This indirect hydrologic estimate is consistent with direct observation of flooding events through this reach and suggests that this reach of the Fremont River is very prone to overbank flows and associated road damage. Thus, some form of mitigation to provide flood resiliency and lessen conflicts between the Fremont River and highway may be appropriate.

Consistent with known fluvial processes, the knickpoint incision and the upstream propagation of a more deeply incised channel will likely continue into the foreseeable future, both in the Navajo

Sandstone segment (knickpoint and knickzone) and potentially in the more vulnerable alluvial segment upstream. Without intervention, this headward erosion may ultimately impact the riparian ecosystem, the transportation corridor, water diversion structures, and other infrastructure associated with the Fremont River.

Introduction

The Fremont River provides valuable ecological and scenic attributes within the arid landscape of CARE. However, Utah State Route 24 (UT-24) runs adjacent to the river through much of the park, restricting the river's fluvial processes while providing access to over 1 million CARE visitors annually (National Park Service 2022). This report summarizes the development of a knickpoint (i.e., an over-steepened river section that manifests as a waterfall) and an abandoned meander on the Fremont River in CARE, both of which were created during construction of UT-24 in 1962. We present data and analyses on the Fremont River's fluvial ecogeomorphic responses to human disturbance and then suggest management strategies. To determine geomorphic responses, we used geospatial data to measure channel planform and the knickpoint migration rate through time, and we conducted topographic surveys to measure channel width and depth. We used vegetation surveys to characterize riparian vegetation throughout the study area. To determine flood inundation patterns, we used a one-dimensional (1D) steady flow model and compared results between a reference reach and the impacted reach. In order to inform potential future river and floodplain restoration, we provide estimates of fill removal required to reconnect the abandoned channel to the active channel, and we also report results from a 1D model in an upstream river reach that frequently floods UT-24. Additional information can be found from our related investigations that were focused on the influence of knickpoint development on riparian vegetation, with results published in a University of Colorado Boulder master's thesis (Johaneman 2022) and a peer-reviewed journal (Johaneman et al., 2023).

Knickpoint Migration and Changes to Channel Planform

Channel modifications and road construction resulted in the development of a knickpoint (Figure 1) and an abandoned meander on the Fremont River in 1962. Knickpoints often migrate upstream during their development (Gardner 1983). We investigated the knickpoint's migration rate and effects on channel planform throughout the past 70 years using historic and current aerial imagery and topographic surveys of channel slope and channel cross-section using a total station. We collected images from 1958, 1974, and 2018 using Earth Explorer and the Utah Geologic Survey website. Aerial images ranged in scale and resolution. Images from 1974 and 2018 were georeferenced by the download provider. The 1958 image was georeferenced in ArcMap version 10.8.1 (root mean square error for georeferencing was 4.785 m). Using this series of aerial images, we attempted to identify the location of the knickpoint, how it has changed through time, and its effects on channel planform. We also measured the depth of the slot channel (e.g., the bedrock channel incised into a bedrock bench) in the knickzone (an over-steepened bedrock channel that extends up to 200 m upstream of the knickpoint) to estimate a minimum amount of incision since knickpoint formation (Figure 2). Because we do not know the elevation of the channel bed in the knickzone when the river was re-routed, a very conservative estimate of incision since 1962 is the difference between the top of the bedrock bench and the bottom of the slot channel.

Due to the poor resolution of historic imagery and the size of the knickpoint relative to the scale, we could not accurately identify the knickpoint's location and thus could not determine the migration rate of the knickpoint itself. Although the knickpoint was difficult to identify, the images did show how the channel changed from 1958 to 2018. In 1958, the meander had not yet been cutoff and the channel in its current alignment with a knickpoint did not exist. The Fremont River had several secondary channels and flowed through the now-abandoned meander (Figure 3). In 1974, after the meander was cut off and the knickpoint was formed, the Fremont had fewer secondary channels (Figure 3). Imagery from 2018 shows a single channel (Figure 3). Thus, it is likely that the knickpoint creation and local oversteepening has simplified the channel planform. Although we cannot determine the rate of knickpoint migration from historic imagery, we have determined that the knickpoint has incised downward through the bedrock since its formation in 1962 and has developed a slot channel over the past 60 years. A slot channel is a narrow bedrock channel that forms when a stream or river flows over a bedrock surface and incises downward; downward incision in slot channels is typically greater than bank erosion (Johnson, Whipple, and Sklar 2010), thus slot channels are typically narrow and deep. The formation and development of slot channels through Navajo sandstone, which is the same lithology as the knickpoint and knickzone in this study, has been observed in the nearby Henry Mountains (located 40 km SE of CARE; Johnson, Whipple, and Sklar 2010), and found that the slot channels found in the Henry Mountains undergo rapid fluvial erosion. Depth measurements of the slot channel within the knickzone (Figure 3) indicate that it has incised downward at least 3 m since its formation in 1962. Measurements of the difference in elevation between the bedrock bench and the bottom of the slot channel (Figure 2) ranged from 1.42 m to 3.5 m.



Figure 1. Upstream view of the knickpoint and plunge pool on the Fremont River, showing where it exits the Navajo Sandstone within the artificially cut off reach.



Figure 2. Image of the incised bedrock slot channel in the knickzone, looking upstream. The knickpoint is located just downstream of this slot channel and study reach 2 (R2) is located just upstream.

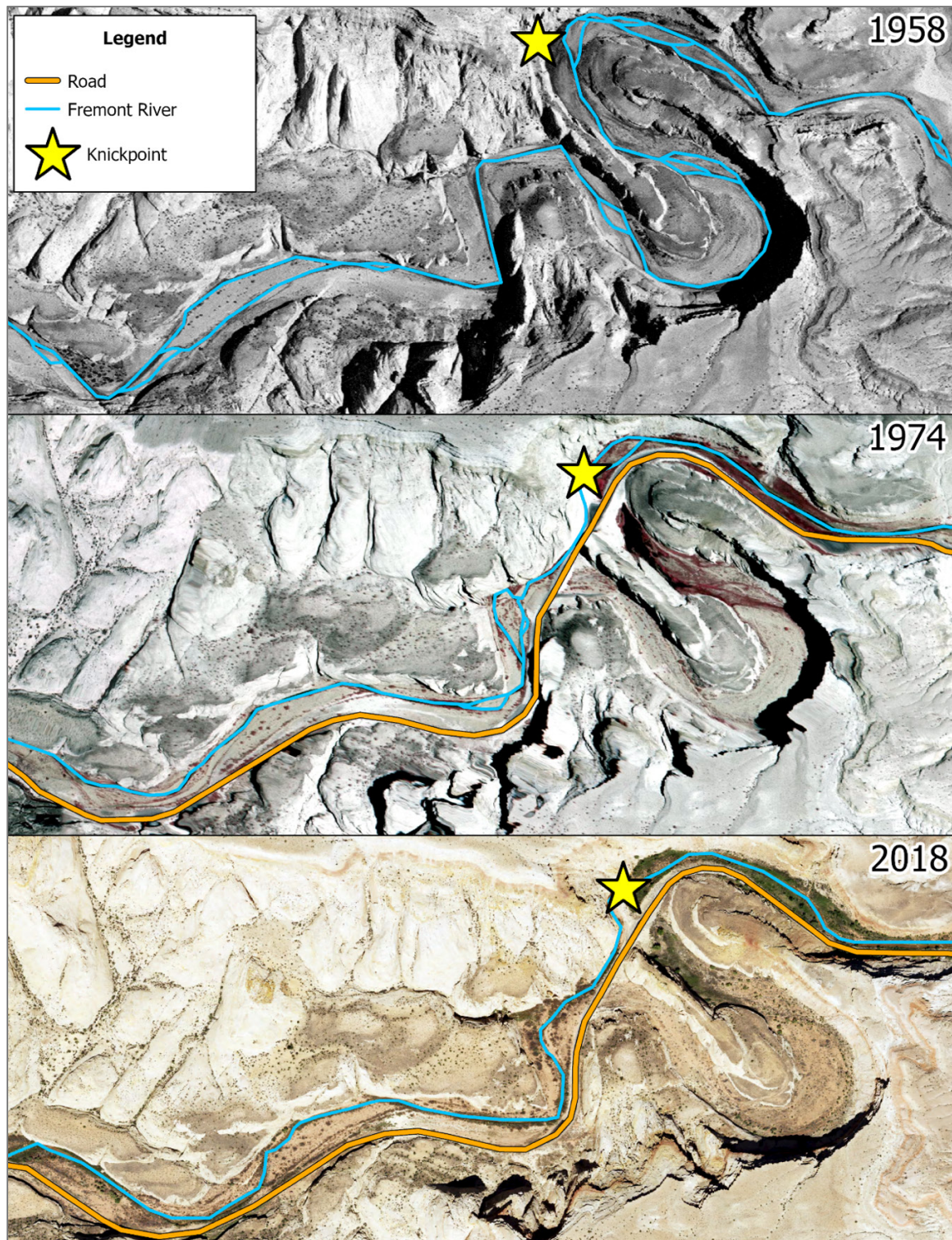


Figure 3. Aerial images of the Fremont River in 1958, 1974, and 2018. Flow goes from left to right in each image. The river generally follows the canyon in the 1958 image and follows the road and canyon in the 1974 and 2018 images. In 1958, flow goes through the meander on the right side of the image, as the channel was cut off and the knickpoint was created in 1962. The abandoned meander and knickpoint are on the right side of the 1974 and 2018 images.

A comparison of channel morphology between two reaches on the Fremont, one 5 km upstream of the knickpoint (Reach 1, also referred to as R1; Figure 4) and the other a couple hundred meters upstream of the knickpoint (Reach 2, also referred to as R2; Figure 4) provide some indication of the extent of the impact of the knickpoint on channel morphology. Figure 5 shows how the width-to-depth ratio of the channel changes with distance downstream in R1 and R2. In R2, there is a significant negative correlation between width-to-depth ratio and distance downstream (Figure 5). In other words, the channel is getting deeper and narrower as you travel downstream towards the knickzone and knickpoint. R1 does not show this relationship, likely due to its relatively far distance upstream and disconnection from the knickpoint. The decreasing width-to-depth ratio that is present in R2, but not in R1, and the incision within the knickzone suggest that knickpoint development is causing upstream incision that is propagating into R2. At ~800 m distance downstream in R2, the width-to-depth ratio (2.87) falls below the minimum width-to-depth ratio in R1 (2.94; Figure 5); this may be an indication of how far upstream the knickpoint-driven incision has reached. Given that the downstream end of R2 is 248 m upstream of the knickpoint and the knickpoint may be causing incision 200 m into R2 (moving upstream), we can calculate a first-order approximation of the potential rate at which incision has been moving upstream since the knickpoint first formed in 1962. The estimated rate is 7 to 8 m/yr (i.e., about 450 m in 60 years), but this estimate should be taken with caution as it relies only on assessment of trends in plots and likely has significant error.

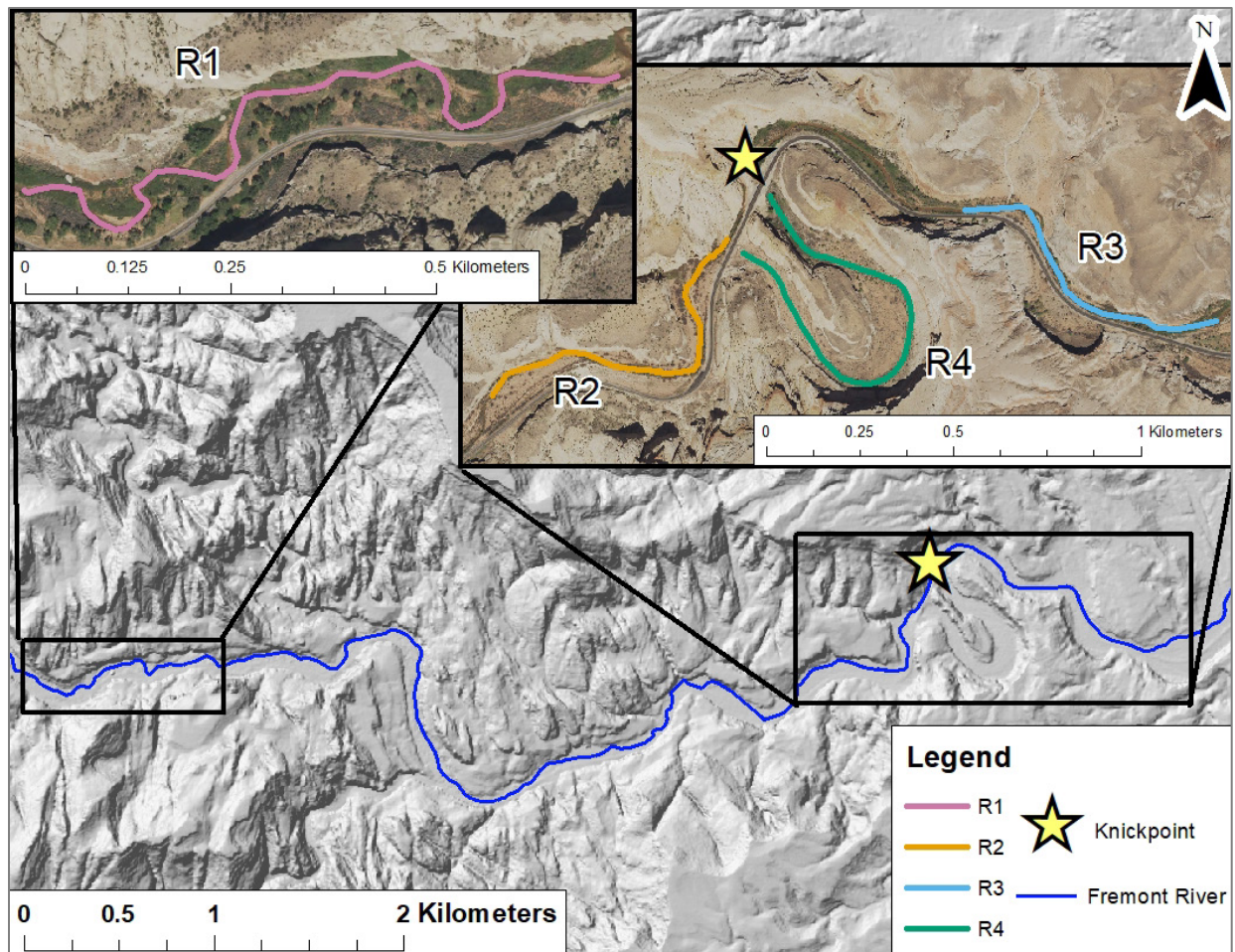


Figure 4. Map showing the four study reaches on the Fremont River. The knickpoint is denoted with a star, and the abandoned meander created during road construction is R4.

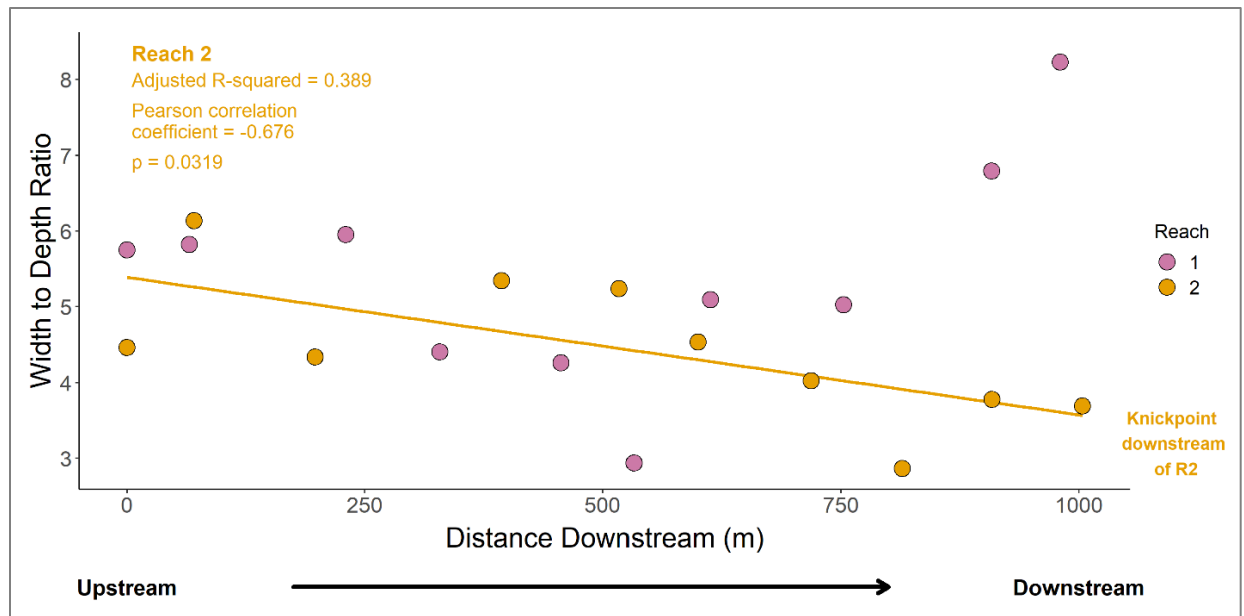


Figure 5. Changes in width-to-depth ratio with distance downstream in R1 and R2. The upstream end of each reach is represented by 0 m on the x-axis and the downstream end is represented by 1000 m. The knickpoint is located just downstream of R2. R3 is not shown due to the low number of transects surveyed ($n=3$) and R4 is not shown because it is not a part of the current active channel. A line of best fit is not drawn for R1 as the relationship between width-to-depth ratio and distance downstream is not significant in R1.

Hydrogeomorphic and Ecological Responses to Knickpoint Development

Riparian vegetation is strongly influenced by hydrogeomorphic processes. Many studies have demonstrated the effects of flow and sediment dynamics on riparian vegetation, but few studies have determined the influence of knickpoint development on these processes. We investigated the influence of knickpoint development on flood inundation patterns, channel and floodplain morphology, and riparian vegetation on the Fremont River in CARE. To investigate the relationship between channel form changes, flooding patterns, and riparian vegetation, we conducted fieldwork in four 1 km-long reaches with varying proximities to the knickpoint, completing topographic and vegetation surveys (number of plots = 374) along 33 transects. We also developed 1D hydraulic models using HEC-RAS to model flood inundation over a range of flows. We used logistic regressions and linear mixed models to evaluate controls on riparian vegetation. Predictor variables included the discharge required to inundate plots, elevation of the plots above the channel, and other hydrogeomorphic variables. Additionally, we employed statistical tests (e.g., PerMANOVA, PermDISP, and others) to evaluate fluvial ecogeomorphic interactions. During the data analysis, we grouped vegetation species according to Wetland Indicator Status (WIS; Table 1) to assess trends in wet-adapted and dry-adapted vegetation between reaches. The WIS classification system is a standardized classification that is widely used in management contexts for determining jurisdictional wetland status in the United States.

Table 1. Wetland indicator status (WIS) used in this study with example species, based on the National Wetland Plant List (Arid West). Colors denote species' status as a nonhydrophyte or hydrophyte to describe the WIS. WIS go from UPL, shown in deep orange, which are nonhydrophytes, to OBL, shown in deep blue, which are hydrophytes.

WIS ^A	Code	Example Species	Common Name
Upland	UPL	<i>Bromus tectorum</i>	Cheatgrass
Facultative Upland	FACU	<i>Sporobolus cryptandrus</i>	Sand dropseed
Facultative	FAC	<i>Chrysothamnus linifolius</i>	Spearleaf rabbitbrush
Facultative Wetland	FACW	<i>Juncus balticus</i>	Baltic rush
Obligate	OBL	<i>Carex nebrascensis</i>	Nebraska sedge

^A WIS cell shading: Upland = deep orange; Facultative Upland = orange; Facultative = pale blue; Facultative Wetland = medium blue; Obligate = deep blue.

The data are fully described in Johaneman (2022) and support our expectation that knickpoint development has affected riparian vegetation through its influence on geomorphic and hydrologic processes. In both reaches, overbank flows for vegetation plots located on the floodplain ranged from 17 to 155 m³s⁻¹ (Table 2), but average overbank flows was higher in R2 (98 m³s⁻¹) than in R1 (54 m³s⁻¹; Table 3). Note that floodplain vegetation plots are named V1–V3 on river right and V10–V12 on river left (Figure 6), but on some transects the floodplain were too narrow for all twelve plots. R1 had a relatively shallow channel (Figure 7b), flooded more frequently (Figure 8b), and required

lower flows to inundate the floodplain (Figure 8a). R2 had a relatively deep channel (Figure 7b), flooded less frequently (Figure 8b), and required higher flows to inundate the floodplain (Figure 8a). Overall mean vegetation abundance (percent cover) was higher in R1 (55.7%) than in R2 (30.1%; Figure 9a). Additionally, R1 had a higher number of occurrences of wet-adapted (facultative wetland and obligate) species than R2 (198 and 79, respectively; Figure 10). The data show that R3 may be similarly impacted as R2, in that overall mean vegetation abundance is lower in R3 than R1 (Figure 9a), but more data is needed to confirm this, as R3 only had 36 vegetation surveys. Statistical models indicate that hydrogeomorphic characteristics, including elevation above the channel and the number of days inundated (based on a flow duration curve developed from a nearby gaging station), influence riparian vegetation presence and abundance within plots. Contrasts in fluvial ecogeomorphic characteristics between reaches indicate that knickpoint development has likely resulted in channel incision in R2, reducing inundation duration and shifting vegetation towards more dry-adapted species. In addition, the artificial channel cutoff has shifted vegetation toward dry-adapted species in the abandoned meander (Reach 4). This work will inform natural resource management practices aimed at maintaining habitat for riparian vegetation. More information on the effects of knickpoint development on fluvial ecogeomorphic interactions on the Fremont River can be found in Johaneman's thesis completed at the University of Colorado Boulder (2022) and a forthcoming journal article.

Table 2. Flows required to inundate the floodplain for R1 and R2 (see Figure 4 for reach locations). Transects are numbered from upstream to downstream for each reach. Vegetation plot locations relative to the channel are shown in Figure 6.

Transect	Reach	Floodplain Vegetation Plot	Elevation Above Channel Thalweg (m)	Inundating Discharge (m^3s^{-1})
1	1	V1	2.15	56.96
1	1	V2	2.15	57.10
1	1	V3	2.05	50.59
1	1	V10	2.04	49.96
1	1	V11	1.90	41.63
2	1	V1	1.70	42.63
3	1	V3	2.37	99.74
5	1	V3	2.25	85.50
6	1	V1	2.18	38.14
6	1	V2	2.16	37.31
6	1	V12	2.38	49.20
7	1	V2	1.64	40.97
7	1	V3	1.71	45.49
7	1	V10	1.75	47.96
7	1	V11	1.82	52.85
7	1	V12	1.74	47.63
8	1	V7	2.20	82.87

Table 2 (continued). Flows required to inundate the floodplain for R1 and R2 (see Figure 4 for reach locations). Transects are numbered from upstream to downstream for each reach. Vegetation plot locations relative to the channel are shown in Figure 6.

Transect	Reach	Floodplain Vegetation Plot	Elevation Above Channel Thalweg (m)	Inundating Discharge (m³s⁻¹)
8	1	V8	1.12	17.62
8	1	V9	2.36	97.14
9	1	V2	2.30	69.93
9	1	V3	2.36	75.43
10	1	V1	1.79	56.26
10	1	V2	2.31	107.37
10	1	V12	1.33	26.17
10	1	V11	1.20	20.30
10	1	V10	1.18	19.66
11	2	V1	2.16	67.21
11	2	V2	2.40	89.90
11	2	V3	2.52	103.36
11	2	V12	2.67	121.90
11	2	V11	2.68	123.72
11	2	V10	2.27	77.05
12	2	V1	2.04	66.63
12	2	V2	2.38	101.05
12	2	V3	2.41	104.62
13	2	V1	2.75	107.68
13	2	V2	2.93	126.95
13	2	V3	3.05	139.98
13	2	V11	2.95	128.41
13	2	V10	2.42	76.91
14	2	V1	2.67	109.07
14	2	V2	2.35	78.97
14	2	V3	2.23	69.42
14	2	V12	2.53	95.63
14	2	V11	2.98	143.48
14	2	V10	2.70	112.05
15	2	V1	2.46	107.45
15	2	V2	2.21	85.91
15	2	V3	2.66	126.70
15	2	V12	2.94	155.35
15	2	V10	2.27	91.01
16	2	V10	2.82	70.51

Table 2 (continued). Flows required to inundate the floodplain for R1 and R2 (see Figure 4 for reach locations). Transects are numbered from upstream to downstream for each reach. Vegetation plot locations relative to the channel are shown in Figure 6.

Transect	Reach	Floodplain Vegetation Plot	Elevation Above Channel Thalweg (m)	Inundating Discharge (m^3s^{-1})
17	2	V11	2.79	51.16
18	2	V2	3.17	85.13
18	2	V3	2.95	72.11
20	2	V10	2.87	60.40

Table 3. Comparison of flows required to inundate floodplain vegetation plots in R1 and R2, based on vegetation plots in Table 2 above.

Reach	Overbank Flows (m^3s^{-1})			
	Minimum	Maximum	Median	Mean
1	17.62	107.37	49.58	54.48
2	51.16	155.35	98.34	98.32

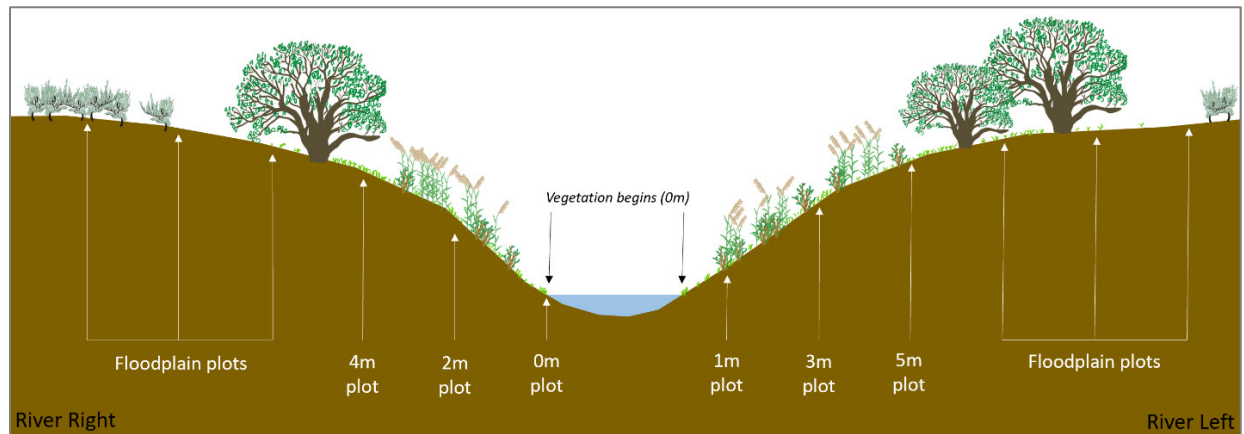


Figure 6. Cross-sectional view of a model vegetation transect showing location of vegetation plots. The distance from channel for the middle six plots was staggered to better include all overbank areas. Vegetation plots on river right were labeled as V1–V6, where V1 was the farthest floodplain plot from the channel. Plots on river left were labeled as V7–V12, where V7 was the plot closest to the channel. For some transects, the floodplain was too narrow to include all 12 vegetation plots.

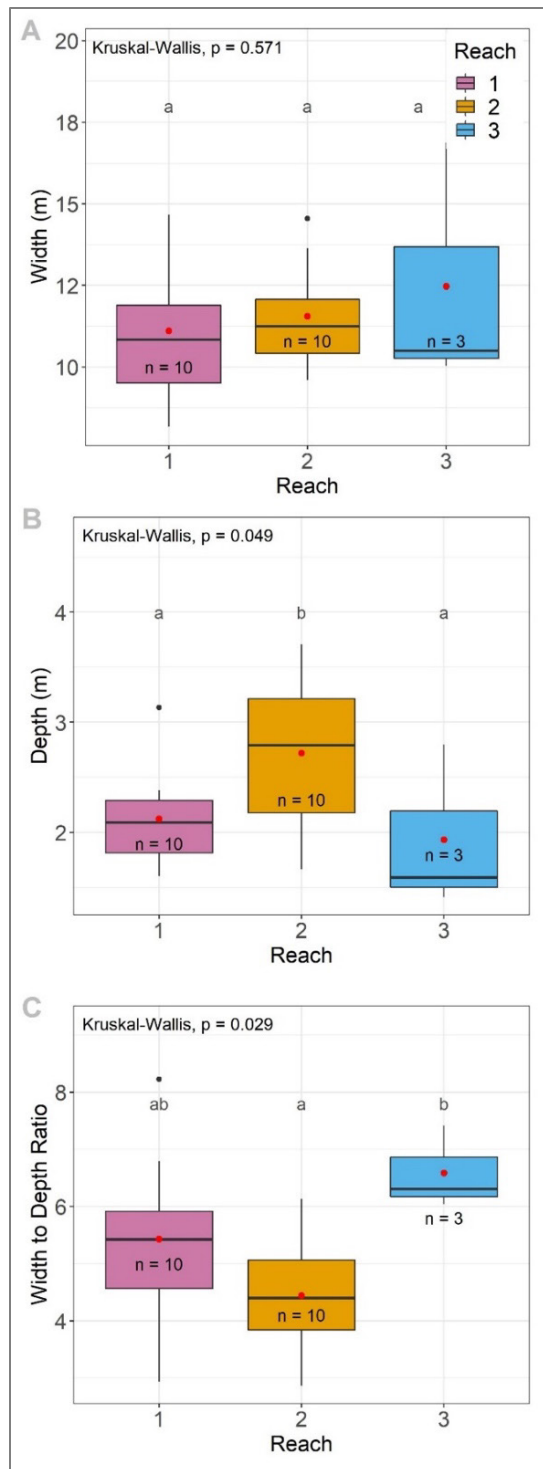


Figure 7. Boxplots of channel width (A), depth (B), and W/D (C) in R1–R3. The black bar in each boxplot represents the median and the red dot represents the mean. Kruskal-Wallis test results between the three reaches are shown in the upper left corner of each graph. Letters above boxplots indicate significantly different groups at $\alpha = 0.1$. R4 was excluded because it is not currently a part of the active channel. These plots demonstrate that R2, which is just upstream of the knickpoint, is incised relative to R1 and R3, which are 5 km upstream and just downstream, respectively.

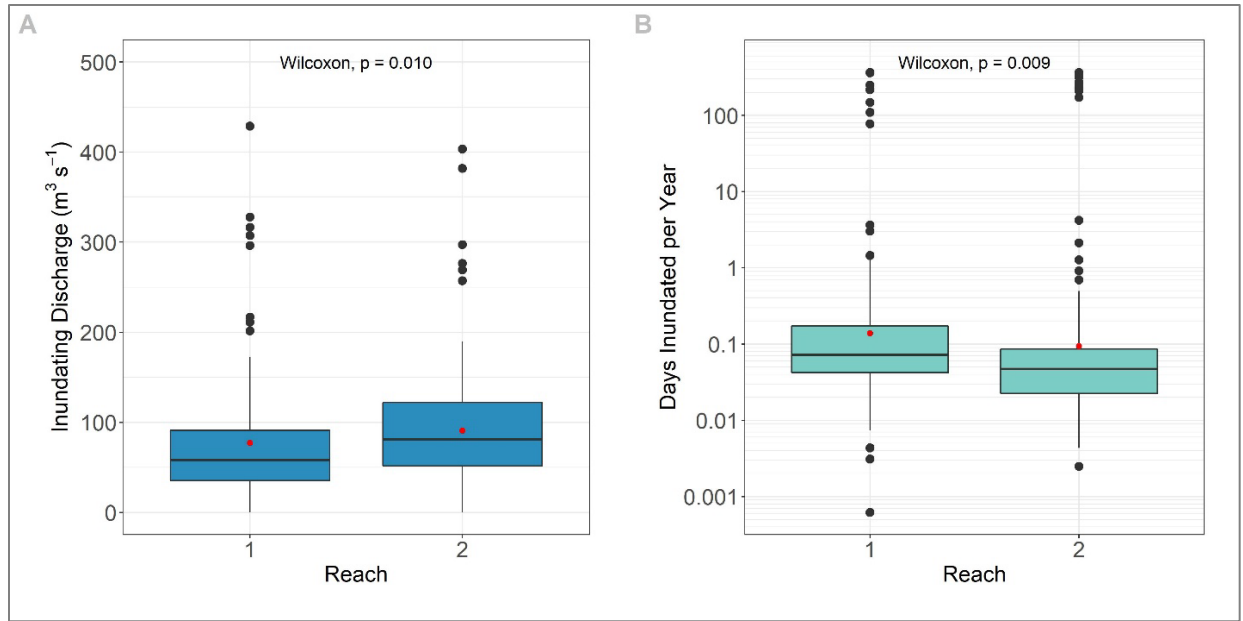


Figure 8. Boxplots showing the differences in flood inundation characteristics for all vegetation plots between R1 and R2. The left panel (a) shows Q_{inun} , which is the discharge required to inundate the plot and the right panel (b) shows days inundated for each plot (note the log y-axis) determined through analysis of the flow duration curve for the Caineville gage (USGS 09330230). The black bar in each boxplot represents the median and the red dot represents the average. Results from Wilcoxon tests are given at the top of each plot. These plots indicate that vegetation plots in R2 require a higher discharge for inundation and are inundated fewer days per year.

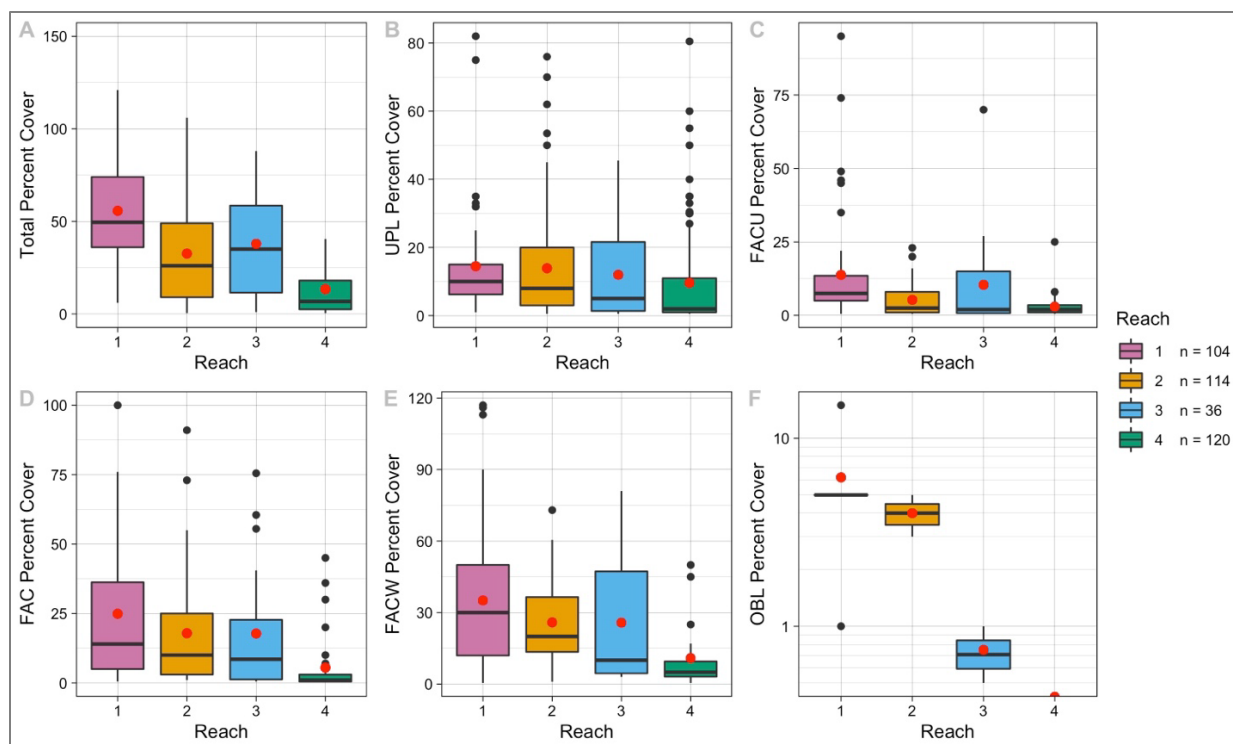


Figure 9. Percent cover of vegetation plots in each reach. Total percent cover (a) and cover of each WIS is shown (b–f). Note log y-axis for graph f. The horizontal black bar in each boxplot represents the median and outliers are represented by black points above and below each boxplot. Means are represented by red points. R2, which is most impacted by the knickpoint, and R4, which is the abandoned meander, have lower overall percent cover.

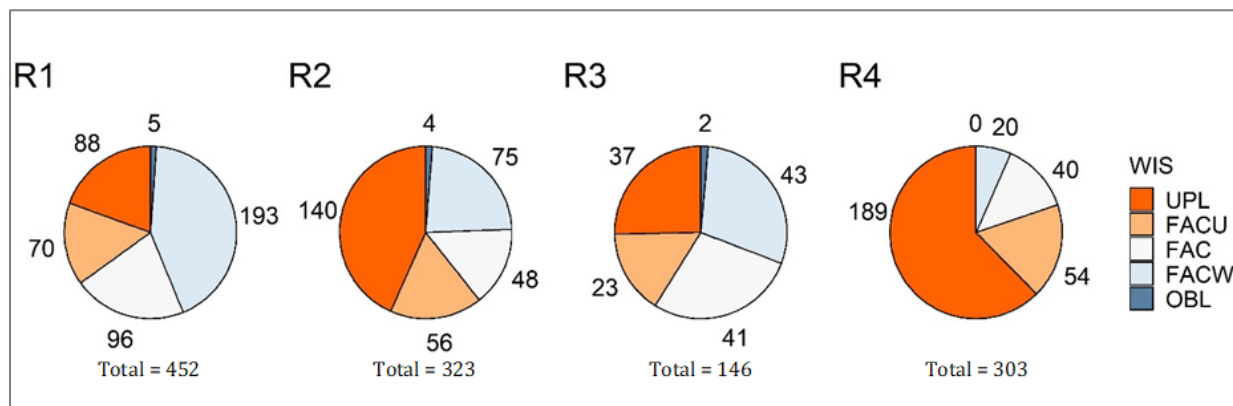


Figure 10. Number of occurrences for each WIS across all plots in each reach. A species is therefore represented by the number of times it was found across plots, irrespective of its abundance within them (i.e., the number of times a species of a particular WIS was noted as present in a plot, summed over the reach). R2 and R4 had higher number of occurrences of upland species, indicating a shift to more dry-adapted species relative to R1 and R3.

Elevation Differences Between the Active and Abandoned Channels

The National Park Service (NPS) has considered potentially restoring flow through the abandoned meander. If this plan were enacted, the elevation differences between the current and abandoned channels would need to be considered in the construction plans. We completed topographic surveys of the abandoned meander to determine elevational differences between the current channel and the abandoned meander at the upstream and downstream of the cutoff using total station surveys. The data show that the current channel and abandoned meander elevations are relatively aligned at the upstream end (meander entrance) but are not aligned at the downstream end (meander exit), and the topography would likely need to be manipulated before flow could be redirected through the abandoned meander. At the meander entrance, the drop in elevation between the active channel elevation and the minimum elevation in the abandoned meander is -0.024 m (Figure 11). At the meander exit, the drop between the abandoned meander elevation and the current channel is 2.52 m (Figure 11).

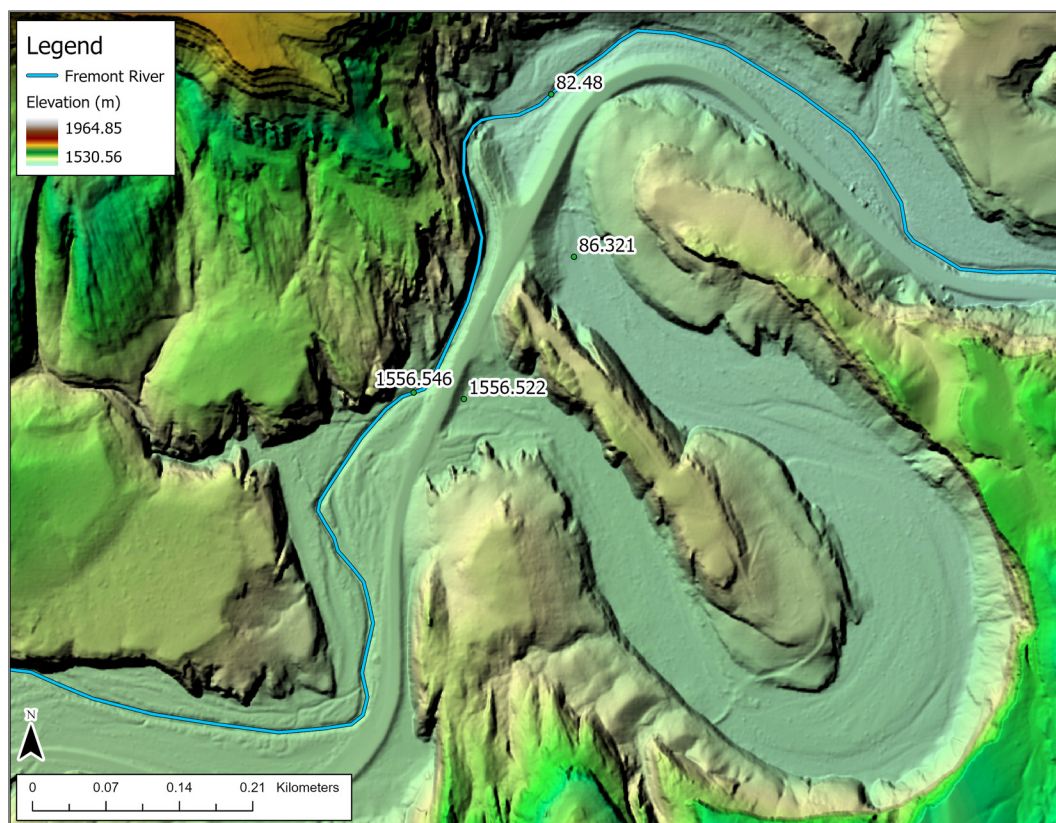


Figure 11. Map of cutoff meander entrance and exit survey points. Four selected points are labeled with their elevations (in meters) to show differences in current channel elevations and the cutoff meander elevations. The two points to the south, at the cutoff entrance, are labeled with their actual elevations (UTM Zone 12). The two points to the north, at the cutoff exit, could not be given real elevations due to a lack of GPS data and thus show elevations relative to the height of the total station (100 m).

The elevation drop of 2.71 m at the meander exit will have to be addressed, or a headcut will likely propagate. The elevation difference would need to be made up by dropping the elevation of the channel in the reconnected meander or it will require some sort of reinforced/stabilized drop structure to reconnect the current channel and meander. The sharp drop in elevation that exists between the abandoned meander exit and the active channel downstream of the knickpoint results in a slope of 1.8% between those two points (Table 4). In R2, upstream of the knickpoint in the active channel from T16 to T19, the river slope is 0.5%. The slope of the active channel downstream of the knickpoint (up to 800 m downstream) is 0.7 %. The slope of the abandoned meander is 0.7%.

Table 4. Slope of the channel for river segments near and within the cutoff meander. Slope calculations between transect 16 in R2 to the channel downstream of the knickpoint at the elevation 1540.1925 m (just off map in Figure 12, downstream of the point labeled '1540.1736'). Numbered sections, transects, and elevation points referenced in this table can be found in Figure 12.

River section	Starting elevation (m)	Ending elevation (m)	Distance between points (m)	Percent slope
Transects 16 to 19 in R2	1561.4341	1559.8514	314.14139	0.5
R4 (cutoff meander)	1557.20	1548.28	1292.4335	0.7
Downstream of knickpoint (end of section 13 to channel elevation 1540.1925 m)	1545.5662	1540.1925	769.60693	0.7
Transects 16 to 19 in R2 through R4 to channel downstream of knickpoint (elevation 1540.1925 m)	1561.4341	1540.1925	2624.7449	0.8
Last R2 survey point to second point in R4 (cutoff entrance) ^A	1556.5460	1556.5508	140.42000	-0.003
Last R4 survey point to first point downstream of knickpoint	1548.2804	1545.5662	153.36000	1.8

^A The second point in R4 was used because it seemed the first point about 1 m higher than the subsequent point and may have been placed on a tree or abnormally high surface in the cutoff.

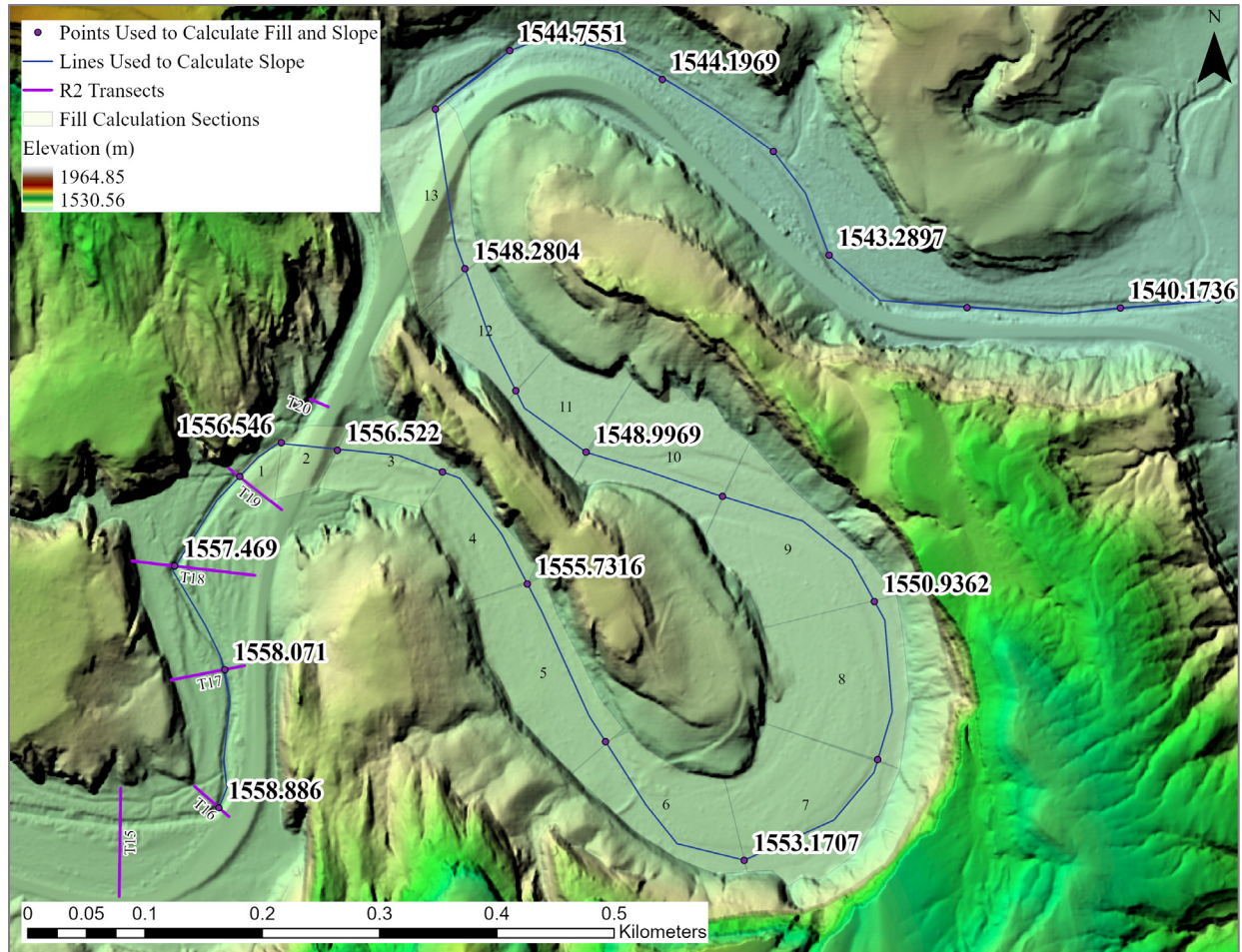


Figure 12. Map of stream segments (Table 5) used in analysis of fill needed for addition/removal if the abandoned meander is restored to a desired slope of 0.6%. Elevations (meters) of select points used to calculate slope and fill change are shown. Numbers in abandoned meander from entrance to exit indicate different sections used for estimating how the landscape would need to be altered to reconnect with abandoned meander while maintaining a similar slope to upstream and downstream in the active channel. Transects labeled 'T15' to 'T20' are in R2. Sections 3 to 12 and beginning of 13 are in R4.

Using recently available LiDAR (1 m resolution), we completed an estimate of the amount of material that would need to be removed to reconnect the abandoned meander with the active channel. We estimated the fill that would need to be removed if the road and road embankment were removed, but also to grade the abandoned meander so that the slope through the meander would be closer to the slopes in R2 (upstream) and the slope of the active channel downstream of the knickpoint. In a preliminary assessment, we estimated that approximately 125,185 m³ of fill needs to be removed from the road embankment and abandoned meander to achieve an average valley slope of 0.8 % (Figure 12, Table 5). However, less could be excavated if an artificial grade control structure were introduced to the channel, but this would not be preferred since it would introduce a static and potentially vulnerable piece of infrastructure to the channel. Given differing elevations and slopes throughout the meander, the amount of fill that needs to be added or removed to achieve an average slope of 0.5–0.7 % varies by sections defined in Figure 12 from the entrance to the abandoned

meander to the exit of the meander (Table 5). Even without grading the abandoned meander itself, approximately 45,361 m³ of fill would need to be removed due to the road and road embankment, of which 10,091 m³ would be removed from Section 2 (meander entrance) and 35,271 m³ would be removed from Section 13 (meander exit; Table 5). After removal of road surfaces, an additional 75,432 m³ in the abandoned meander may need to be removed to achieve a slope similar to the active channel upstream and downstream of the knickpoint (Table 5). Note that this is an estimate and additional surveys would need to be completed to determine the exact amount of fill that needs to be added or removed.

Table 5. Volumes of fill to be removed for reconnecting the Fremont River with its abandoned meander. Sections correspond to sections labeled on Figure 11 above. Meander removal volumes are the fill removal volumes not including the road and road embankment. Road removal volumes are the fill removals needed to eliminate built-up road surfaces and embankments. The total volume of fill to be removed is given in the bottom right cell, highlighted in yellow.

Section	Meander Removal Volume (m ³)	Road and Embankment Removal Volume (m ³)	Total Removal Volume (m ³)
13	20,262	35,271	55,532
12	973	–	973
11	–35 ^A	–	–35 ^A
10	5,382	–	5,382
9	8,250	–	8,250
8	10,031	–	10,031
7	12,818	–	12,818
6	12,671	–	12,671
5	4,254	–	4,254
4	2,921	–	2,921
3	–1,873 ^A	–	–1,873 ^A
2	–323 ^A	10,091	10,413
1	100	–	100
Total	75,432	45,361	125,185

^A Fill additions, also shown highlighted in gray.

Flood Inundation Patterns on UT-24

UT-24 is located on the Fremont River floodplain east of the Visitor's Center in CARE. The road's position relative to the floodplain results in flooding on the road during floods, especially between mile marker 82.0 and 82.3. Knowing the flow magnitude required to inundate the road surface in that location and how frequently that flow occurs would likely be useful for park planning and management of CARE infrastructure. We investigated flood inundation patterns between mile marker 82 and 82.3 using HEC-RAS. R1 includes the section of UT-24 that is flooded most frequently, therefore the 1D steady flow hydraulic model developed to investigate fluvial ecogeomorphic interactions in Section 2.0 above was used to determine flood inundation patterns along this section of road. When completing topographic surveys and developing the HEC-RAS model, we included three additional transects (named H1, H2, and H3) between T2 and T3 in R1 (Figure 13). For all other transects in this study, we ended surveys at the edge of the highway, but for H1–H3, we extended surveys to the canyon wall, thus including the road. We used 15-minute flow data from the Caineville, UT stream gage (USGS 09330230; 1988–2011) and methods reported in Johaneman's thesis (2022) to choose a range of flows to model, and we modeled the flow magnitude (Q_{inun} , the flow required to inundate a specific elevation) in HEC-RAS. We used the 15-minute data from the Caineville gage to construct a flow duration curve; using this curve, we estimated the duration (days inundated) of flows required to inundate specific elevations (e.g., the road surface or vegetation plots on the floodplain). We used 15-minute data from the Caineville gage, rather than daily mean flow, in our analysis due to the flashy nature of the Fremont River; daily mean flow data does not sufficiently capture the high magnitude and low duration floods that often inundate the floodplain along the Fremont River. However, note that the 15-minute data may not have undergone stage shifts for rating curve corrections, thus adding uncertainty to discharges. The Caineville gage was used instead of the Bicknell gage (USGS 09330000), located upstream of CARE, because Caineville flow data are more representative of the study area and include several tributaries (e.g., Sulfur Creek, Grand Wash) that contribute to flash floods in the study area. The Bicknell gage does not include these tributaries and flows are more strongly influenced by diversions and other water transfers compared to the Caineville gage. However, there are still surface water diversions, tributary inflows, and alluvial aquifer interactions affecting the Fremont River between the study reach and the streamgage. To determine the annual exceedance probability of flows, we used StreamStats (USGS) to complete a flood frequency analysis for the reach. This StreamStats location was 15 km upstream of the Caineville discharge gage used elsewhere, introducing a small incongruity across analyses.

Flood inundation patterns were evaluated for the river right side of each transect, where the road is located. Survey points were grouped by location: "Channel" points were located below the top of the bank and in the channel, "Floodplain" points were located between the channel and the road, "Road" points were the points taken on each side of the road, and "Far Floodplain" points were located on the other side of the road opposite of the river.

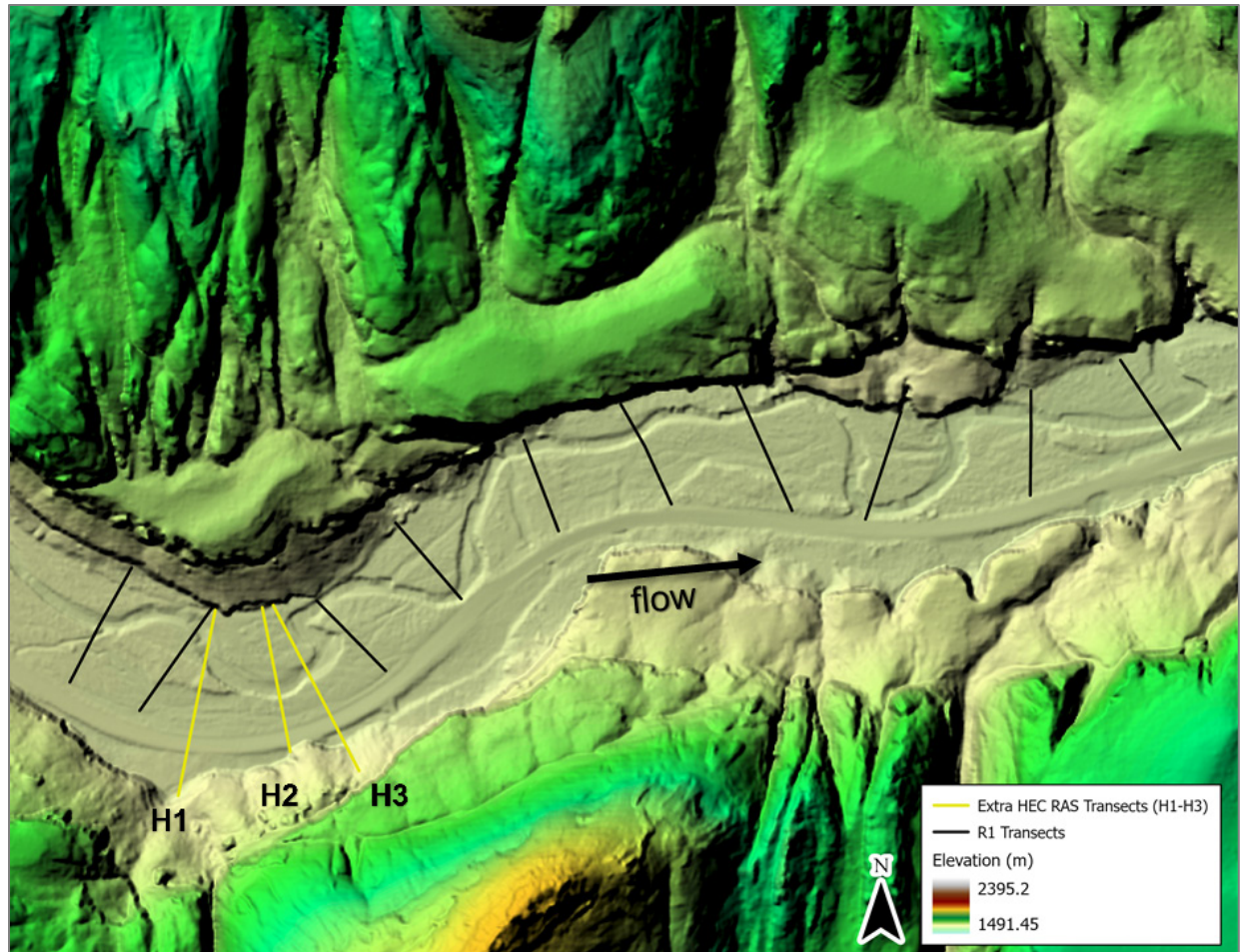


Figure 13. Map of extra HEC-RAS model transects in the sub-reach where UT-24 is commonly flooded. Transects are located in R1, between T2 (upstream of H1) and T3 (downstream of H3). River flow goes from left to right in the image.

The data show that the flood magnitude and duration experienced at a given location is influenced by floodplain surface elevation. Across all three transects, higher elevation vegetation plots on the floodplain had higher Q_{inun} values (Figure 14) and lower number of days inundated values (Table 6). At points above 2 m, for example, Q_{inun} ranged from $36.4 \text{ m}^3\text{s}^{-1}$ to $110.5 \text{ m}^3\text{s}^{-1}$ and days inundated ranged from 0.114 days per year to 0.022 days per year (Table 6). Conversely, at points below 2 m, Q_{inun} ranged from $0.003 \text{ m}^3\text{s}^{-1}$ to $52.5 \text{ m}^3\text{s}^{-1}$ and days inundated ranged from 0.076 days per year to 365 days per year (Table 6). Additionally, the floodplain and the road have similar modeled flow magnitude and duration (Figure 15, Figure 16, Figure 17, and Figure 18), likely due to their similar elevations (2.47 m and 2.25 m above the thalweg, respectively). This demonstrates that the road is located in the floodplain and is subject to inundation when the floodplain is inundated.

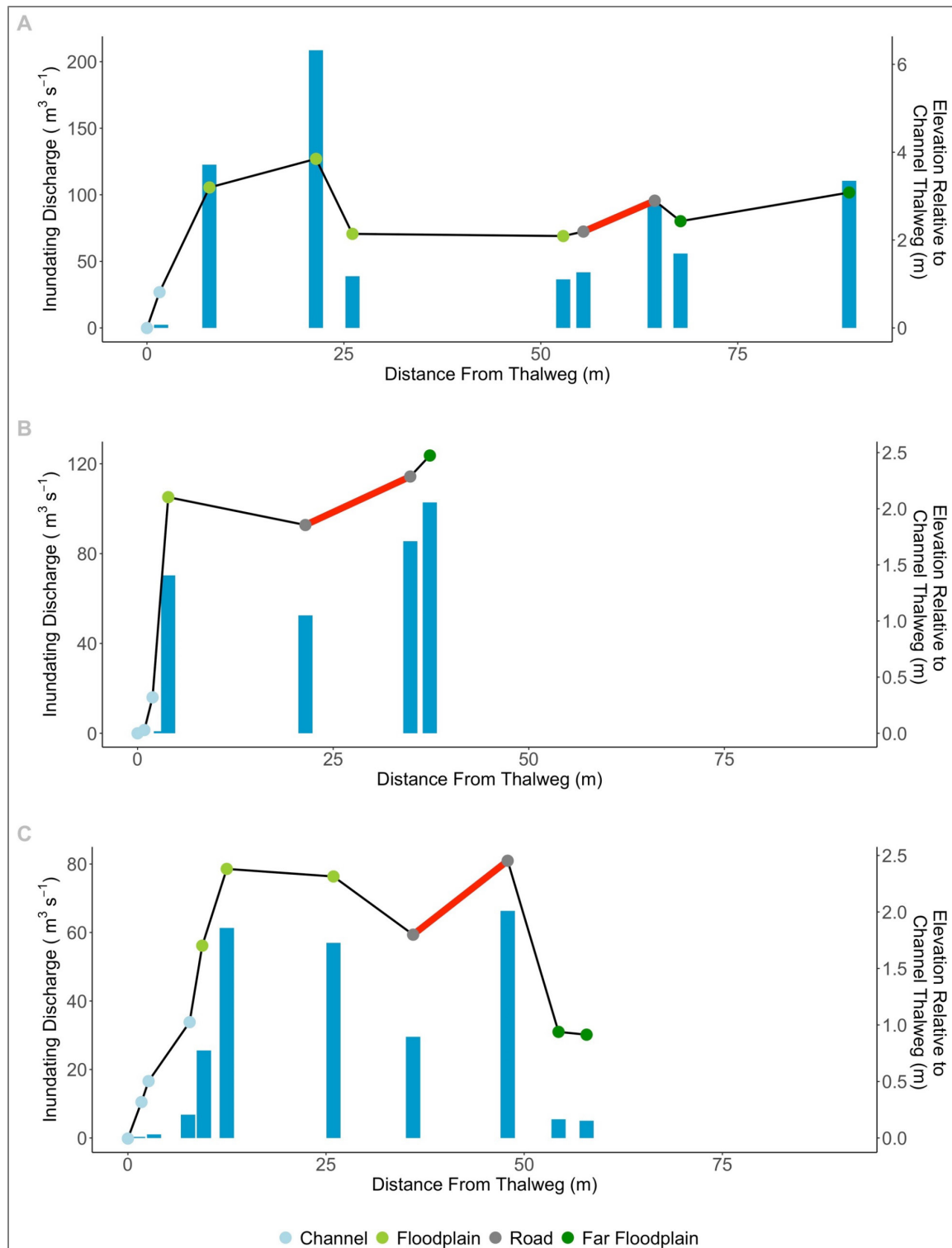


Figure 14. Plots showing Q_{inun} (blue bars), elevation above the channel thalweg (points), and distance from thalweg for H1 (A), H2 (B), and H3 (C). Points included in the graphs are points on the river right side of the thalweg along the transect, which is the river side with the road. The road surface is represented by the thicker red line.

Table 6. Hydrogeomorphic characteristics of the extra transects near where UT-24 is commonly flooded. Days inundated per year, elevation above the channel thalweg, and distance from the thalweg for H1, H2, and H3. Points included in the table are points on the river right side of the thalweg along the transect.

Transect	Point Type ^A	Distance From Thalweg (m)	Elevation Above Channel Thalweg (m)	Q _{inun} (cms)	Days Inundated per Year
H1	Far Flpn	124.811	3.082	110.468	0.022
H1	Far Flpn	103.398	2.429	55.868	0.072
H1	Road	100.120	2.896	92.434	0.033
H1	Road	91.064	2.193	41.693	0.100
H1	Flpn	88.509	2.091	36.378	0.114
H1	Flpn	61.744	2.141	38.925	0.106
H1	Flpn	57.121	3.848	208.573	0.000
H1	Flpn	43.590	3.197	122.684	0.017
H1	Channel	37.252	0.813	2.433	118.968
H1	Thalweg	35.659	0.000	–	365.000
H2	Far Flpn	95.731	2.474	102.813	0.027
H2	Road	93.223	2.287	85.581	0.040
H2	Road	79.822	1.855	52.499	0.076
H2	Flpn	62.292	2.103	70.364	0.055
H2	Channel	60.288	0.320	0.868	300.947
H2	Channel	59.240	0.029	0.003	365.000
H2	Thalweg	58.373	0.000	–	365.000
H3	Far Flpn	106.601	0.914	5.067	4.403
H3	Far Flpn	103.063	0.939	5.436	3.734
H3	Road	96.646	2.453	66.305	0.061
H3	Road	84.719	1.799	29.565	0.146
H3	Flpn	74.668	2.314	56.958	0.072
H3	Flpn	61.208	2.381	61.354	0.068
H3	Flpn	58.118	1.702	25.591	0.194
H3	Channel	56.524	1.025	6.830	2.371
H3	Channel	51.345	0.503	1.070	268.898
H3	Channel	50.451	0.318	0.324	364.759
H3	Thalweg	48.734	0.000	–	365.000

^A Point Type cell shading: Far Flpn = green; Road = gray; Flpn = light green; Channel and Thalweg = blue.

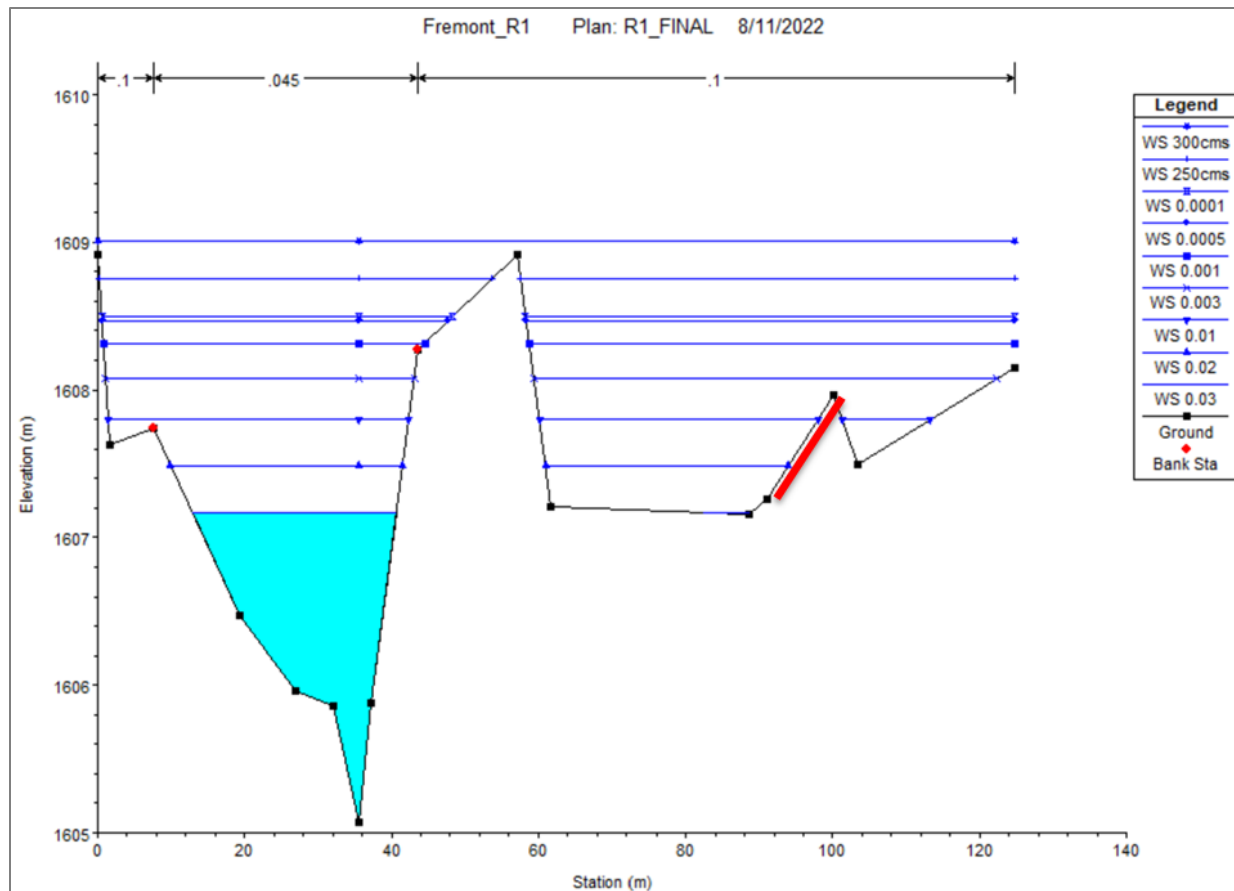


Figure 15. H1 HEC-RAS cross section showing modeled inundation extent at different flows. River left is 0 m on the x-axis and river right is 140 m. Road surface is represented by a red line. Flows labeled as WS 0.03, WS 0.02, WS 0.01, WS 0.003, WS 0.001, WS 0.0005, and WS 0.0001 have discharges of $37.4 \text{ m}^3\text{s}^{-1}$, $54.4 \text{ m}^3\text{s}^{-1}$, $89.2 \text{ m}^3\text{s}^{-1}$, $132.5 \text{ m}^3\text{s}^{-1}$, $171.9 \text{ m}^3\text{s}^{-1}$, $197.4 \text{ m}^3\text{s}^{-1}$, and $203.0 \text{ m}^3\text{s}^{-1}$, respectively.

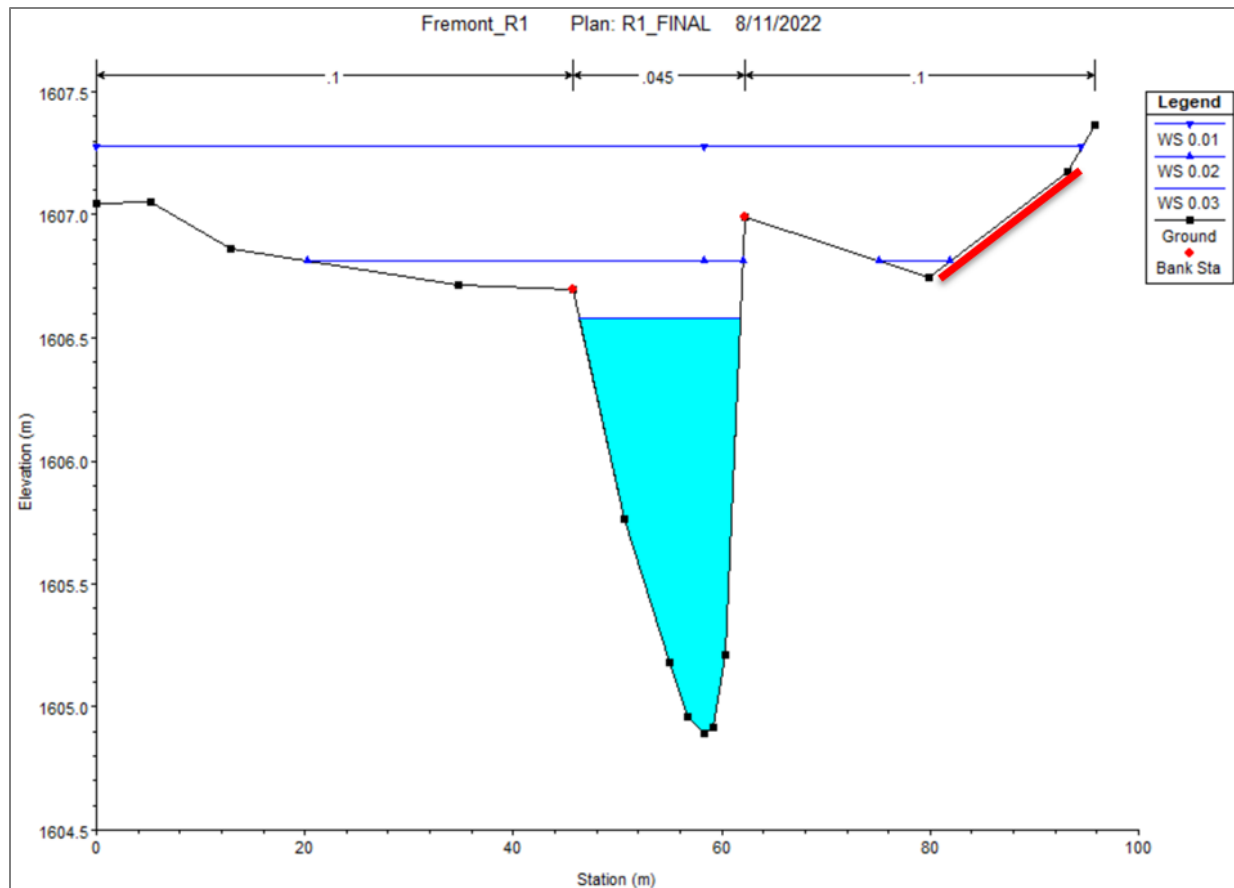


Figure 16. H2 HEC-RAS cross section showing modeled inundation extent at different flows. River left is 0 m on the x-axis and river right is 100 m. Road surface is represented by a red line. Flows labeled as WS 0.03, WS 0.02, and WS 0.01 have discharges of $37.4 \text{ m}^3\text{s}^{-1}$, $54.4 \text{ m}^3\text{s}^{-1}$, and $89.2 \text{ m}^3\text{s}^{-1}$, respectively.

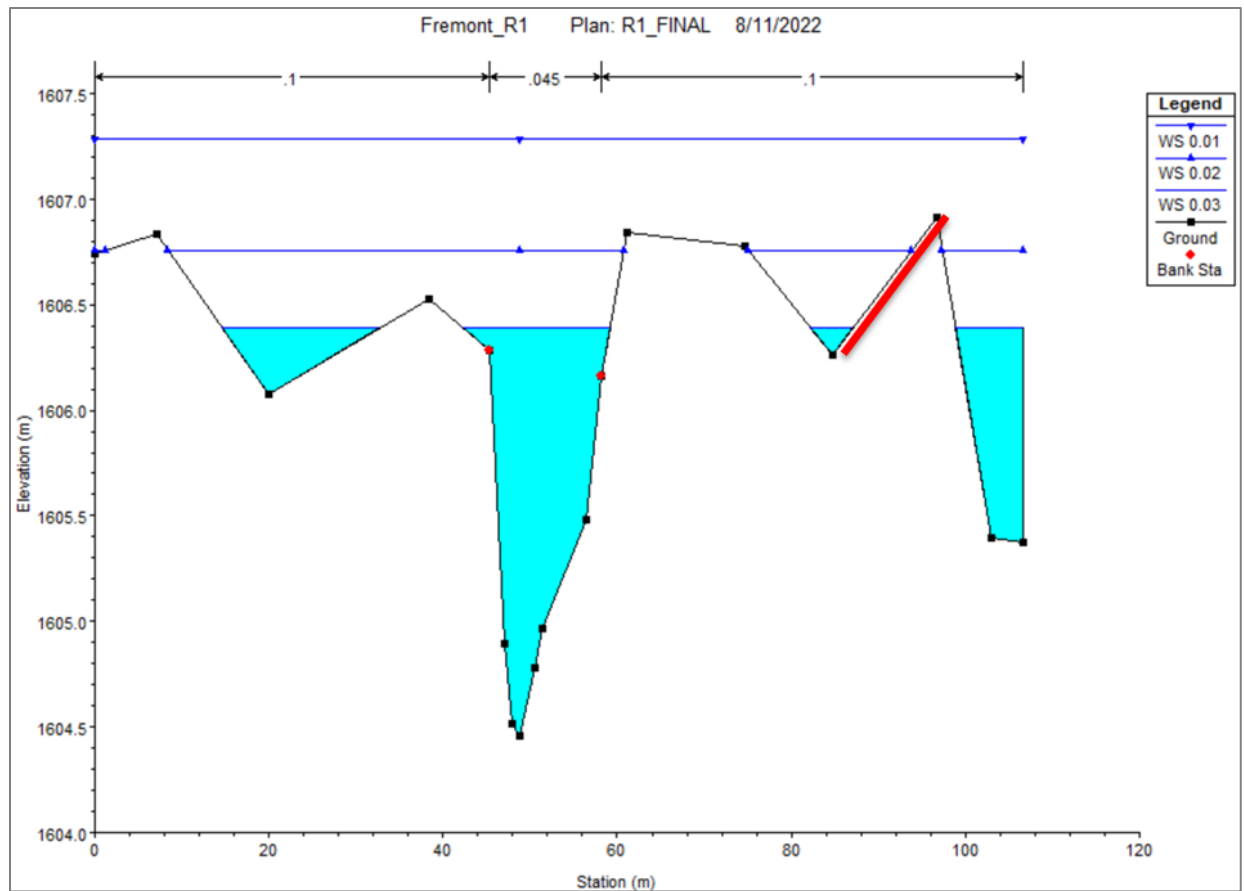


Figure 17. H3 HEC-RAS cross section showing modeled inundation extent at different flows. River left is 0 m on the x-axis and river right is 120 m. Road surface is represented by a red line. Flows labeled as WS 0.03, WS 0.02, and WS 0.01 have discharges of $37.4 \text{ m}^3\text{s}^{-1}$, $54.4 \text{ m}^3\text{s}^{-1}$, and $89.2 \text{ m}^3\text{s}^{-1}$, respectively.

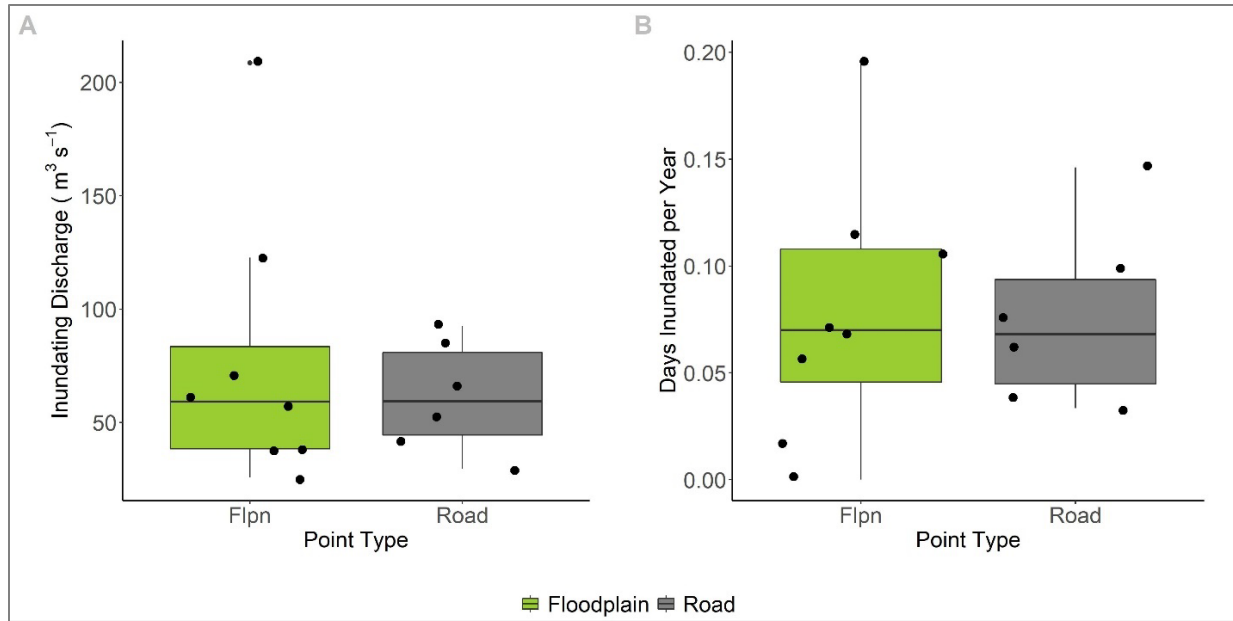


Figure 18. Boxplots of Q_{inun} (A) and days inundated per year (B) for all “floodplain” and “road” survey points in H1–H3.

Although the road is subject to inundation, modeled flows and analyses indicate that inundation duration is relatively short each year along UT-24 between mile marker 82 and 82.3. Days inundated per year for this section of the road ranged from 0.03 days to 0.15 days and Q_{inun} ranged from $29.6 \text{ m}^3\text{s}^{-1}$ (river side of road on H3) to $92.4 \text{ m}^3\text{s}^{-1}$ (canyon wall side of road on H1; Table 6). We used the 24-year record from the Caineville gage to develop a flow duration curve (Figure 19) and found that the $29.6 \text{ m}^3\text{s}^{-1}$ flow is equaled or exceeded only 0.04% of the year. We also performed a flood frequency analysis on the Fremont River that shows the likelihood of the $29.6 \text{ m}^3\text{s}^{-1}$ and $92.4 \text{ m}^3\text{s}^{-1}$ flows occurring, based on a StreamStats analysis (Table 7). Overall, these data and an analysis of the Caineville gage indicate that this section of road would require a flow of at least $29.6 \text{ m}^3\text{s}^{-1}$ to inundate, will be inundated less than one full day every year, but also is likely to be inundated once every 2 years (AEP = 50%) (Table 6 and 7). Inundation along the road likely occurs at times due to flows reaching overbank at the cross-sections of interest as well as via flow that enters the floodplain upstream and follows low elevation areas within the floodplain (see Figure 13). Although of short duration each year based on flow duration estimates, the flow required to inundate the road may occur relatively frequently based on flood frequency analyses from StreamStats, and some additional mitigation to provide flood resiliency may be warranted.

Table 7. The probability of the Fremont River inundating the road, represented by three metrics: percent time flow is equaled or exceeded, annual exceedance probability, and recurrence interval. The $29.6 \text{ m}^3\text{s}^{-1}$ flow is the minimum flow required to inundate the side of the road closest to the river. The $92.4 \text{ m}^3\text{s}^{-1}$ flow is the minimum flow required to inundate the side of the road farthest from the river and thus fully inundate the road. These statistics are based on a flood frequency analysis performed using the USGS StreamStats program.

Flow (m^3s^{-1})	Percent time flow is equaled or exceeded (%)	Annual exceedance probability (%)	Recurrence interval (years)
29.6	0.04	50	2
92.4	0.009	28–30	3.3–3.6

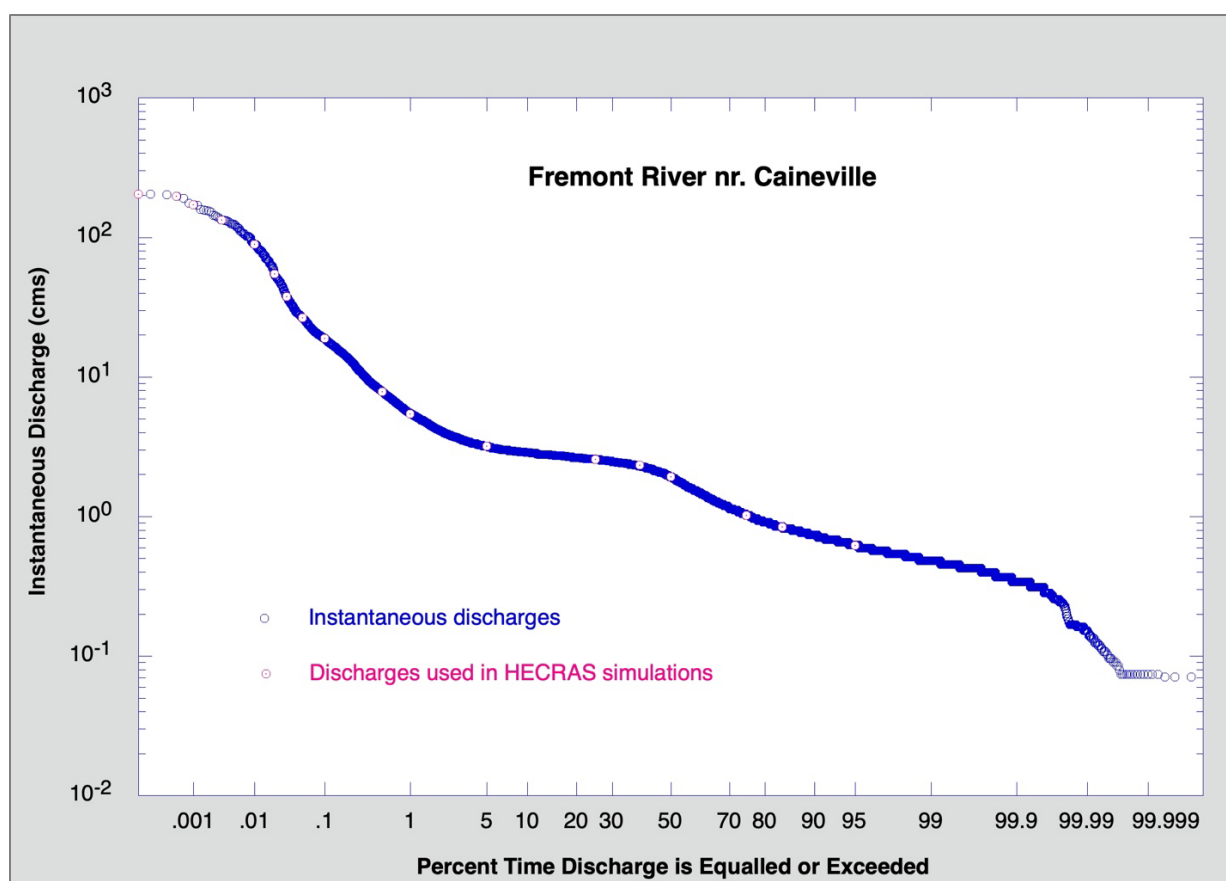


Figure 19. Flow duration curve for the Caineville, UT gage. Flows used in HEC-RAS models are the open circles with pink outlines.

As described above, modeled data suggest that the lowest elevation road surface, which occurs on H3, requires an incoming flow of at least $29.6 \text{ m}^3\text{s}^{-1}$ to inundate. However, this flow level does not include contributions from surface runoff from canyon walls and washes and culverts to the transects. This type of localized runoff is not represented in the HEC-RAS model but would result in more frequent inundation of the road at this location. Field observations just after a flood on the Fremont in

Summer 2021 indicated that there is localized runoff from the valley walls at this location. In addition, in our calculations of days inundated, we used the Caineville gage, which is located ~15 km downstream of the study area; the flows recorded by this gage are likely at least slightly higher than the flows in the study area due to the Pleasant Creek tributary entering the Fremont between the reach of interest and the Caineville gage. This likely resulted in an underestimate of the number of days inundated for the reach of interest. A stream gage positioned on the Fremont River downstream of orchard diversions in CARE would more accurately characterize flows in the study area. Both more robust modeling (e.g., a 2D flow model) and more flow data collected closer to the study area would be useful for better characterizing flood inundation patterns in this location.

Conclusion

The Fremont River has been, and continues to be, affected by anthropogenic activities, such as land use, flow diversions, and channel modifications. In CARE, a knickpoint formed on the Fremont River as a result of the construction of UT-24 and subsequent human-dictated channel cutoff. We investigated the effects of knickpoint development on fluvial ecogeomorphic processes using topographic and vegetation surveys, hydraulic models, and statistical models. We also assessed elevational differences between the current channel and the abandoned meander, estimated the fill that would need to be removed to reconnect the abandoned meander, determined inundation frequency of a section of UT-24 that is of concern to the park, and provided estimates of the discharge required to inundate the floodplain in two of our study reaches.

We found that fluvial ecogeomorphic processes are likely affected by knickpoint development. R2, a reach just 200 m upstream of the knickpoint, had a deeper channel than R1, a reach several kilometers upstream of the knickpoint. We estimated that at least 3 m of incision has occurred in the knickzone as a result of the erosion caused by human modification that shortened and straightened the channel. Thus, a more incised channel and disconnection from the floodplain in R2 is likely the result of human actions. The knickpoint-driven incision has caused the floodplain in R2 to have a lower inundation duration than R1, thus causing the floodplain to be composed of more xeric vegetation species when compared to R1. Topographic surveys revealed that the abandoned meander is at a different elevation than the current active channel. The current channel upstream of the knickpoint is slightly higher in elevation than the abandoned meander entrance, whereas the abandoned meander exit is several meters higher than the current channel downstream of the knickpoint. In summary, this study shows that the river corridor has been affected by knickpoint development and, although this potentially could be remediated by rerouting flow through the abandoned meander, it would require alteration of both the active channel and the abandoned meander.

Hydraulic models suggest that another area of concern on UT-24 in CARE is flooded less than one day per year (based on estimated flow duration) but is also likely inundated approximately every 2 years (AEP = 50%), although these results should be taken with caution and would be significantly improved with additional gaging in the area of concern. Restoring historical flow paths and interconnections between the channel and floodplain would enhance the ecological value and functions of the Fremont River's riparian ecosystem within CARE.

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