Received: 26 January 2022 | Revised: 18 May 2022 | Accepted: 25 May 2022

DOI: 10.1002/rra.4014

RESEARCH ARTICLE

WILEY

Effects of flow regulation and drought on geomorphology and floodplain habitat along the Colorado River in Canyonlands National Park, Utah

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Funding information

National Park Service; U.S. Geological Survey

Abstract

Streamflow regulation compounded by regional drought has resulted in up to 22% reduction in channel width, changes in channel planform, expansion of riparian vegetation, and alterations to floodplain habitat on the Colorado River in Meander Canyon, Utah. Although some changes in channel width occurred between the 1940s and 1980s, coinciding with major phases of upstream water development, larger decreases in channel width occurred between 1993 and 2006 during periods of exceptionally low annual floods. These findings illustrate that low runoff associated with regional drought and climate change may cause changes in river channel form that accelerate and compound the effects of upstream water development. Declining peak flows have also resulted in disconnection between the wetted channel and floodplains, where inundated back-levee depressions provide habitat used by two species of threatened and endangered native fish. Despite this disconnection, some back-levee depressions on the floodplain continue to be inundated by ~1.5-year recurrence floods via connections created by tributary mouths, floodplain outflow channels, and levee breaches excavated by resident beaver. These changes are shown by analysis of aerial images, high-resolution bathymetric and topographic measurements, and 2-dimensional streamflow modeling.

KEYWORDS

climate change, dams, drought, floodplain habitat, geomorphology, river regulation

1 | INTRODUCTION

Rivers in the US and throughout the world have been affected by water development and streamflow regulation (Graf, 1999; Nilsson et al., 2005). In some cases, the effects on river channels have been rapid and well-documented (Pemberton, 1976; Williams and Wolman, 1984), while in other cases changes have been gradual or manifest only after several years (Walker et al., 2020). Because time lags in channel adjustment (Grams et al., 2020) coupled with incremental increases in streamflow reduction caused by water development (Van Steeter and Pitlick, 1998) complicate efforts to evaluate the effects of streamflow regulation, there are river segments where the cumulative impact of upstream water developments has not been recognized. As many river systems enter an era where reductions in runoff and flood magnitude may also result from climate change, the effects of streamflow regulation may be compounded, affecting both the timing and trajectory of channel adjustment. Better understanding of how changes in streamflow regime affect river channels and associated habitat is needed by resource managers as they attempt to anticipate the effects of water development and climate change and seek to develop potential mitigation strategies.

In this study, we describe changes in channel morphology for a 57-km segment of the Colorado River within Canyonlands National Park, Utah, that is heavily impacted by upstream water development and is within a river basin that is experiencing recent declines in runoff associated with changing climate (Udall and Overpeck, 2017). We analyze historical and recent aerial photographs to detail the timing and spatial distribution of reductions in channel width, changes in channel planform, expansion of riparian vegetation, and alterations to floodplain habitat. We also use a two-dimensional streamflow model based on measurements of bathymetry and topography obtained by multibeam sonar and aerial lidar to illustrate impacts to the hydrological connectivity of floodplain habitat used by native fish.

2 | BACKGROUND

2.1 | Description of study area

The Meander Canyon segment of the Colorado River begins 35 km downstream from Moab, Utah, and marks the transition from a mostly gravel-bedded to mostly sand-bedded channel. Our study reach begins 10-km downstream from the beginning of Meander Canyon and extends 57 km to the confluence with the Green River in the center of Canyonlands National Park (Figure 1). Meander Canyon is a classic example of incised meanders (Harden, 1990) in which the river channel and the floodplain are both incised in bedrock and follow the meandering pattern of the canyon rim (Figure 2). Ephemeral tributaries to the Colorado River within Meander Canyon are common but join the river at low-gradient and only rarely cause coarse-grained debris fans or zones of lateral flow recirculation, which are common downstream in Cataract Canyon and many other canyon segments of the Green and Colorado Rivers (e.g., Schmidt and Rubin, 1995; Grams and Schmidt, 1999). We divide the study area into two segments based on valley width. Average valley width is 284 m in upper Meander Canyon and decreases to 160 m in lower Meander Canyon where the limestone-dominated Honaker Trail Formation is first exposed at river level, replacing the less resistant sandstones of the Cutler Group (Belknap and Evans, 2013). Both segments of the study area are low gradient with average slope of 0.00018 in upper Meander Canyon and 0.00027 in lower Meander Canyon.

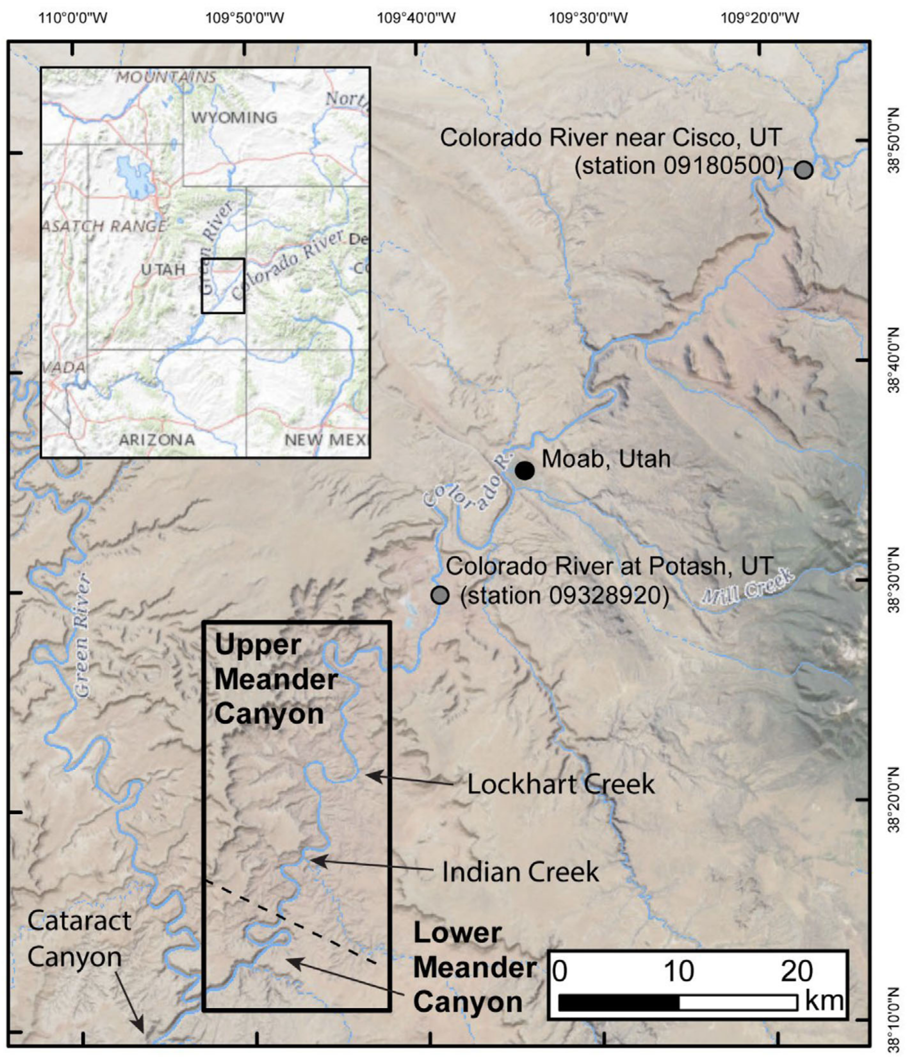

FIGURE 1 Map showing Meander Canyon study area, subdivisions of upper and lower Meander Canyon, and the locations of Lockhart Creek and Indian Creek tributaries and detailed study sites. U.S. Geological Survey gaging stations with station number are also shown [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 2 Aerial oblique views of ~15-km segments of Upper Meander Canyon (left) and Lower Meander Canyon (right). In both images, view is from south and streamflow is from top to bottom. Images from October 20, 2016, Google Earth. [Color figure can be viewed at wileyonlinelibrary.com]

In both segments of Meander Canyon, the bed is mostly sand except where talus blocks have fallen into the channel and where gravel is present at the mouths of some tributaries. Active sand bars that are exposed following annual snowmelt floods are abundant in the form of point bars on meander bends and mid-channel bars (Figure 3). Because the large-scale bedrock meanders are fixed in place, the bars form in approximately the same location during each flood and do not migrate. The floodplain is discontinuous and is variously present on one or both banks. Where the floodplain does occur, it varies in width from a few meters to more than 200 m and consists of two to three distinct topographic levels (Figure 4). The floodplain surfaces typically have a levee near the channel that creates a back-levee depression between the levee and the talus slope or the next higher floodplain surface. The back-levee depressions may be broad and flat or slope gently away from the channel, and sometimes contain a small overflow channel. Although the floodplain was not excavated for this study, exposures in eroding banks indicate deposition by vertical accretion, consistent with observations of similar floodplains on nearby segments of the Green River (Walker et al., 2020). The most common species of woody riparian vegetation on the floodplain are tamarisk (*Tamarix spp*), coyote willow (*Salix exigua*), and Gooding's willow (*Salix gooddingii*).

Narrowing of the river channel in Meander Canyon was observed by Rasmussen and Shafroth (2016), but neither the magnitude nor timing of channel adjustment have been quantified. Van Steeter and Pitlick (1998) described the effects of streamflow regulation on a gravel-bedded segment of the Colorado River near Grand Junction, Colorado. They reported that flow regulation had not significantly affected annual runoff volumes for that segment, but that peak flows were 20% lower in the 1964–1995 period than between 1934 and 1963. This reduction in peak flow magnitude coincided with a significant reduction in channel complexity and a 15% decrease in average channel width in both single-and multi-thread river segments (Van Steeter and Pitlick, 1998).

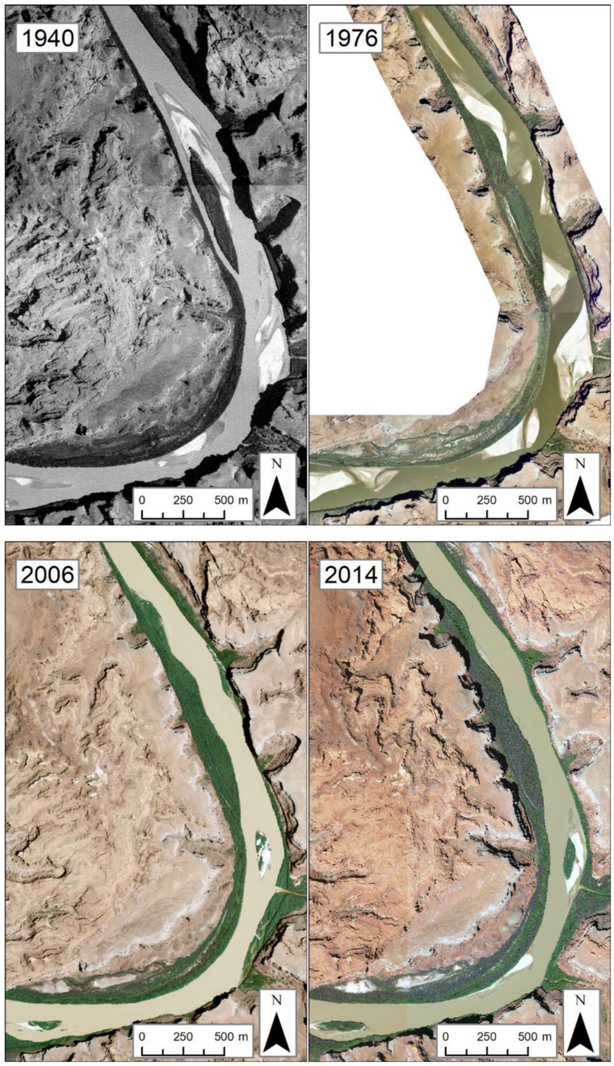

FIGURE 3 Aerial images of the Colorado River in the vicinity of Lockhart Creek (Figure 4) showing channel narrowing and expansion of riparian vegetation. Streamflow is from top to bottom [Color figure can be viewed at wileyonlinelibrary.com]

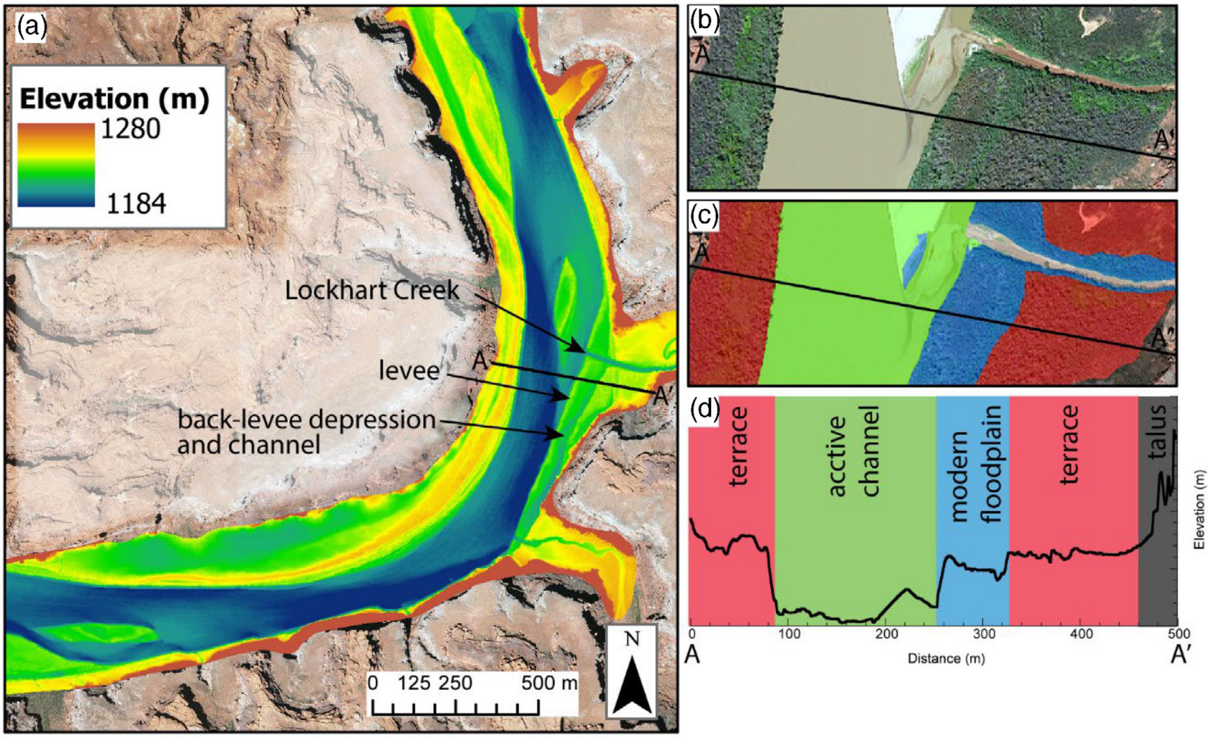

FIGURE 4 (a) Digital elevation model of Lockhart Creek study site created by combining airborne lidar data and bathymetric data acquired by multibeam sonar. Streamflow is from top to bottom and background image is 2014 air photo. (b) Detail of 2014 air photo at cross-section A-A'. (c) Detail showing geomorphic mapping of channel and floodplain from 2014 air photos. (d) Topographic profile of cross-section A-A' with labels for geomorphic mapping from 2014 air photos. Elevations in North American Datum of 1988 (NAVD 88) [Color figure can be viewed at wileyonlinelibrary.com]

In geomorphic character, Meander Canyon has more in common with the low-gradient, meandering segments of the Green River within Canyonlands National Park than the upstream gravel-bedded segments of the Colorado River. In these segments of the Green River, the channel has narrowed by more than 10% with up to 2 m of vertical accretion on newly constructed floodplains that are inset against the pre-regulation floodplain (Walker et al., 2020). The magnitude of channel narrowing was consistent with the degree of reduction in average peak flow magnitude associated with flow regulation by upstream Flaming Gorge Dam (Grams et al., 2020). However, channel narrowing did not occur immediately after the onset of flow regulation in 1963 but occurred during a period of exceptionally low annual floods between 1988 and 2009 (Grams et al., 2020, Walker et al., 2020). These recent episodes of channel narrowing occurred when the 5-year mean peak flow was less than 60% of the long-term (1959–2016) mean peak flow (Grams et al., 2020).

2.2 | Streamflow and sediment supply

Streamflow has been measured since 1914 (with continuous records since 1922) on the Colorado River near Cisco, Utah, 98 km upstream from Meander Canyon (Figure 1). A streamflow gage was established at Potash, Utah, 19.5 km upstream from the study reach in 2014. Development of the Colorado River upstream from the study area for irrigation and diversion to the east slope of the continental divide has included the construction of more than 25 major dams or diversions, with total upstream storage capacity of more than 2.9 billion m^3 (Figure 5). All of the upstream storage dams and reservoirs are on tributaries to the Colorado River and the closest dam to the study reach is McPhee Dam, more than 200 km upstream on the Dolores River (Table S1). Dean et al. (2020) conducted a change-point analysis of the streamflow record for the Cisco gage and reported that 1953–1954 was a significant change point corresponding to a 45% reduction in the magnitude of the 2-year recurrence peak flow from 1354 to 739 m^3/s. Upstream regulation also caused the annual minimum flows to increase from an average of 42 m^3/s for the 1914–1967 period to 67 m^3/s for 1968–2018 (Dean et al., 2020). Despite this level of water development and impacts on peak flows, the long-term mean annual flow was less impacted by development (Figure S1). In 1930, mean annual flow decreased by 25% from 279 to 208 m^3/s (Dean et al., 2020), which was associated with the end of the well-known wet period of the early twentieth century (Stockton and Jacoby, 1976; Woodhouse et al., 2006). An additional 12% decrease in mean annual flow to 184 m^3/s, likely associated with water development, occurred in 1953 (Dean et al., 2020). Although Dean et al. (2020) did not detect a change-point between 1999 and 2000 based with a Pettitt test (Pettitt, 1979), the mean annual flow from 2000 to

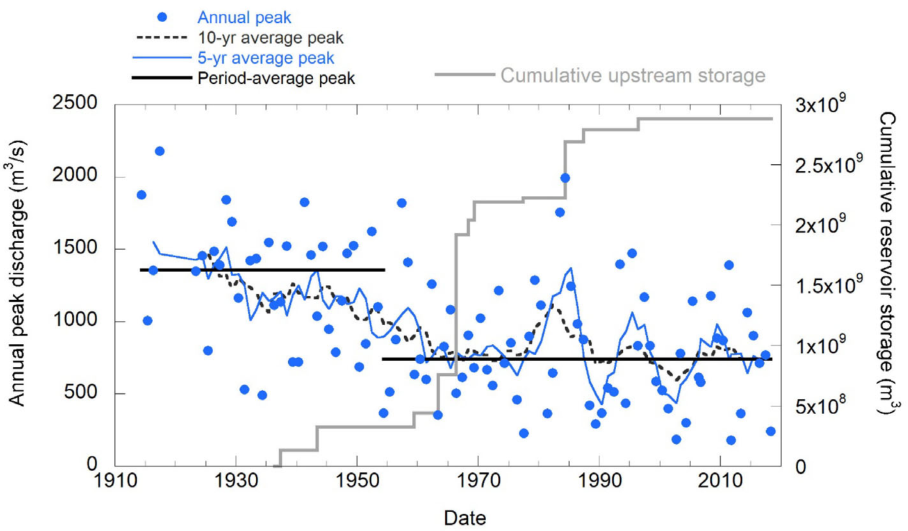

FIGURE 5 Annual peak flows and 10-year and 5-year moving average peak flows for the Colorado River at Cisco, Utah. The period-average peak flows are the 2-year recurrence peak flows for 1914–1953 and 1954–2017 as reported in the change-point analysis by Dean et al. (2020). Cumulative upstream storage is the cumulative full-pool storage capacity for the 11 largest reservoirs upstream from the Cisco, Utah gage [Color figure can be viewed at wileyonlinelibrary.com]

2020 of 153 m^3/s was significantly lower than the mean annual flow from 1953 to 1999 of 196 m^3/s (Figure S1). This decrease in mean annual flow is consistent with recent studies that have shown decreases in precipitation and runoff (Udall and Overpeck, 2017; Tillman et al., 2020) and increases in temperature (Tillman et al., 2020) since the early 2000's, attributable to climate change (Udall and Overpeck, 2017).

Dean et al. (2020) also conducted an analysis of changes in suspended-sediment loads measured at the Cisco gage and concluded that there were significant reductions in both suspended sand loads and suspended silt and clay loads associated with water development on upstream tributaries. Closure of McPhee Dam alone on the Dolores River in 1986 resulted in a factor of ~2 decline in sand loads (Dean et al., 2020).

2.3 | Native fish in meander canyon

The construction of dams and reservoirs that block fish migration, regulate streamflow, and change water temperature and habitat, combined with the introduction of non-native predators and competitors, have contributed to declines and, in some cases, extirpation of native fish in the Colorado River basin (Minckley and Deacon, 1968; 1991). Two native fish species currently listed as threatened or endangered by the U.S. Fish and Wildlife Service are found in Meander Canyon or potentially use habitat that is available in Meander Canyon: the Colorado pikeminnow (*Ptychocheilus lucius*) and the razorback sucker (*Xyrauchen texanus*). Back-levee depressions which occur on the floodplains in Meander Canyon (Figure 4) can provide low velocity, heavily vegetated habitat that is important for juvenile Colorado pikeminnow and razorback suckers (LaGory et al., 2003, Mueller, 2006). However, to provide usable habitat, the depressions must be inundated and connected to the main channel for one or two months in the late spring and summer following the annual flood to allow juvenile fish to grow and develop before returning to the main channel (Mueller, 2006; Osmundson et al., 1997). We identified these potential habitats and used streamflow modeling to determine the discharges required for inundation by mechanisms such as levee overtopping and breaching.

3 | METHODS

3.1 | Measurements of channel change

Changes in channel morphology were evaluated by mapping the active channel and floodplains from seven sets of orthorectified aerial photographs acquired between 1940 and 2018 (Table 1). The earliest three sets of images were obtained as scanned images and were orthorectified for this study in ERDAS IMAGINE Photogrammetry 2015 using photogrammetric block calibration. The root mean square (RMS) error of the rectified images ranged between 0.2 and 1.5 m, depending on scale of the photo series (Grams et al., 2022). The remaining four sets of images were obtained as georeferenced digital images.

We manually digitized lines along the banks to delineate channel and floodplain features. The active channel included all bare-sediment alluvial surfaces and the wetted channel. Specific features within the active channel such as secondary channels, isolated pools, sandbars, and islands were delineated. The floodplain deposits included both a modern floodplain and an alluvial terrace, which was typically 1 to 2 m above the modern floodplain. Based on the topographic information and stage-discharge relations, the lowest-elevation areas of the modern floodplain begin to be inundated by flows as low as 425 m^3/s (post-1954 1.2-year recurrence flood) and the floodplain is almost completely inundated by the largest post-1954 floods (~1840 m^3/s). Consistent with periodic inundation, the modern floodplain is dominated by riparian vegetation, including stands of mature plants and seedlings. The alluvial terrace is often occupied by upland vegetation and is not inundated or only rarely inundated in the current hydrologic

TABLE 1 Summary information for aerial images used to map channel width

Year	Date	Pixel resolution (m)	Mean daily discharge at Cisco, Utah (m^3/s)	Extent[a]	Source[b]	Image Type[c]	Uncertainty (percent of polygon area)[d]
1940	30-Aug	0.8	80.7	MC	UGS	BW scanned image	4.0
1951	1-Sep	0.5	155.7	MC	UGS	BW scanned image	1.9
1976	31-Aug	0.16	54.4	L/IC	NPS	Color scanned image	4.7
1993	19-Jun	1	773.9	L/IC	Earth explorer	BW DOQ	4.8
2006	14-Jul	1	178.1	MC	Earth explorer	Color NAIP	3.6
2014	3-Sep	1	126.3	MC	Earth explorer	Color NAIP	2.4
2018	7-Sep	1	69.9	MC	Earth explorer	Color NAIP	2.4

[a]Portion of study reach covered. MC = all of Meander Canyon study reach; L/IC = Lockhart Creek and Indian Creek detailed study reaches only.
[b]Source of images. UGC = Utah Geological Survey; NPS = National Park Service, Canyonlands National Park; Earth Explorer = https://earthexplorer.usgs.gov/.
[c]Image Type. BW = black and white. Scanned images were orthorectified for this study. The DOQ (digital orthoquads) and NAIP (National Agriculture Imagery Program) images were obtained as georeferenced digital products.
[d]Uncertainty is the sum of weighted mean error based on repeat digitizing of polygons and estimated orthorectification error (Supplement Table S2 and Head, 2020).

regime. Non-Colorado River deposits, such as tributary channels and alluvial fans were also mapped. The map units were digitized on-screen in ArcGIS and the most current version was checked in the field. The entire length of the 68-km study reach was mapped for five of the image sets (Table 1). For the 1976 and 1993 image sets, orthorectified digital images were only available for two reaches within the study area. These were a 1.5-km reach near Lockhart Creek and a 1-km reach near Indian Creek (Figure 1). The mean elevation above baseflow water surface for the active channel, modern floodplain, and terrace map units was estimated by intersecting the map based on 2014 images with airborne lidar data collected in 2015 (State of Utah and Partners, 2019) and is included with map unit descriptions in Table S2. Uncertainty is reported as a percent of feature area (Table 1) and was estimated by repeat digitizing a subset of features (Table S3). Active channel width for each image set was computed in 1-km segments by dividing the sum of all active deposits and the water surface by the segment length (1000 m).

3.2 | Measurements of floodplain topography and channel bathymetry

We selected a 3.4 km reach near Lockhart Creek to examine the relationships among channel and floodplain geomorphology, streamflow, and floodplain habitat. This reach includes a diverse range of geomorphic features, including islands, side channels, and tributaries and is representative of the channel in Upper Meander Canyon. Topography of the exposed banks and floodplains was measured by airborne lidar collected in October and November 2015 (State of Utah and Partners, 2019) supplemented with ground-truth measurements in 2016 by real-time kinematic (RTK) Global Navigation Satellite System (GNSS). Bathymetry in the channel was measured with multibeam sonar in June 2016. The three datasets were merged to produce a 1-m resolution DEM for analysis. Further details on data collection and processing are described in the supplement. All data are referenced in NAD 1983 UTM zone 12 N with elevations in the NAVD88 vertical datum.

3.3 | Hydrodynamic modeling

The FaSTMECH solver in the International River Interface Cooperative (iRIC) streamflow modeling package (Nelson et al., 2016) was used to estimate the discharge required to inundate the back-levee portions of the floodplains on each side of the river in the Lockhart Creek study reach. Water surface elevation for the downstream end of the modeled reach was determined from a stage-discharge relation constructed from the field surveys (Head, 2020). Roughness and drag coefficients were determined by calibrating the model to match observed water surface elevations for discharges of 457 and 900 m^3/s. The root-mean square error on model-predicted water surface elevation and discharge for the calibration were 0.02 m and 1.0 m^3/s respectively. We present model results for three different discharges that illustrate degrees of floodplain and back-levee inundation for average (< 2-year recurrence) and rare (> 30-year recurrence) floods. Roughness coefficients from the low-discharge calibration were used for the model runs conducted at 425 and 566 m^3/s; and the coefficients from the high-discharge calibration were used for the 1840 m^3/s model run (Table S5).

4 | RESULTS

4.1 | Changes in channel and floodplain morphology, 1940–2018

Morphological changes occurred in every interval between aerial photos, including changes in the number and size of sandbars within the active channel, accretion of new floodplain, and bank erosion (Figure 3). The dominant change since 1940 was the construction of new floodplain and this caused net channel narrowing in most intervals between 1940 and 2018 throughout upper Meander Canyon (Figure 6). The higher temporal resolution for the Lockhart Creek and Indian Creek reaches reveals that the greatest decreases in channel width occurred between 1993 and 2006 (Figure 6). During this interval, average width decreased by 15% in the Lockhart Creek reach and by 16% in the Indian Creek reach. The measurements from these photographs also indicate that there was an earlier period of narrowing between 1940 and 1976 and some channel widening between 1976 and 1993, which most likely occurred during a period of large peak flows in the 1980s (Figure 5).

The 1940 and 1976 aerial photographs show large bare sandbars and narrow floodplain strips throughout Meander Canyon (Figure 3). Between 1976 and 2006, floodplains accreted along the channel margins, and this accretion was often concentrated on the inside of river bends and downstream from tributary mouths. Some floodplain accretion occurred on mid-channel bars resulting in attachment of those bars to the bank and in the formation of new islands (Figure 3). Together, these changes resulted in a decrease in the complexity of the active channel and an increase in the extent of floodplain surfaces (Figure S2). Bare sand mid-channel islands that create multi-thread channel segments are now less frequent. Although the area of active sandbars that may be measured from the areal images depends on the discharge at the time the images were captured, the most recent images were taken at a lower discharge than the 1940 and 1951 images and show fewer sandbar islands (Figure S2). The process of channel narrowing likely contributed to the simplification of the active channel by concentrating flow in a narrower channel thereby increasing flow velocities reducing the likelihood of bar formation. Meanwhile, the floodplain now comprises multiple surfaces with complex topography (Figure 4). The changes described above are representative of segments of relatively wide channel width in upper Meander Canyon. Less change in channel width occurred in the relatively narrow lower Meander Canyon (Figures 6 and 7). Throughout Meander Canyon, the amount of decrease in width was negatively correlated with the initial channel width in 1940 (Figure S3), thus decreasing the overall variability in width and homogenizing the channel (Figure 7), similar to the observations of Walker et al. (2020) for nearby segments of the Green River.

4.2 | Floodplain inundation

4.2.1 | Hydrodynamic modeling of the Lockhart Creek reach

The bottomland on river right (when looking downstream) in the Lockhart Creek reach, which is mainly composed of the terrace map unit (Figure 4), is not dissected by tributary channels and has no hydrologic connectivity to the main channel except during the largest floods. By iterative modeling of streamflow, we found that a discharge of 1840 m^3/s is required to overtop the levee at the downstream end of the river-right floodplain and inundate the back-levee basin (Figure 8). This discharge has a post-1954 recurrence interval of 38 years and has been exceeded only twice since 1920 (in 1928 and 1984). Because inundation is infrequent, this floodplain does not provide viable bottomland fish habitat.

The bottomland on river left includes an area of modern floodplain (Figure 4) that is dissected by a tributary has a breach through the levee that was excavated by beavers. Because the beaver excavation is hidden in dense riparian vegetation, it was not visible on the air photos and was only discovered when the high-resolution lidar data (Figure 4) were used for the streamflow modeling. This feature allows inundation of a portion of the back-levee basin at discharges as low as 425 m^3/s (Figure 8), which has a post-1954 recurrence of 1.2 years.

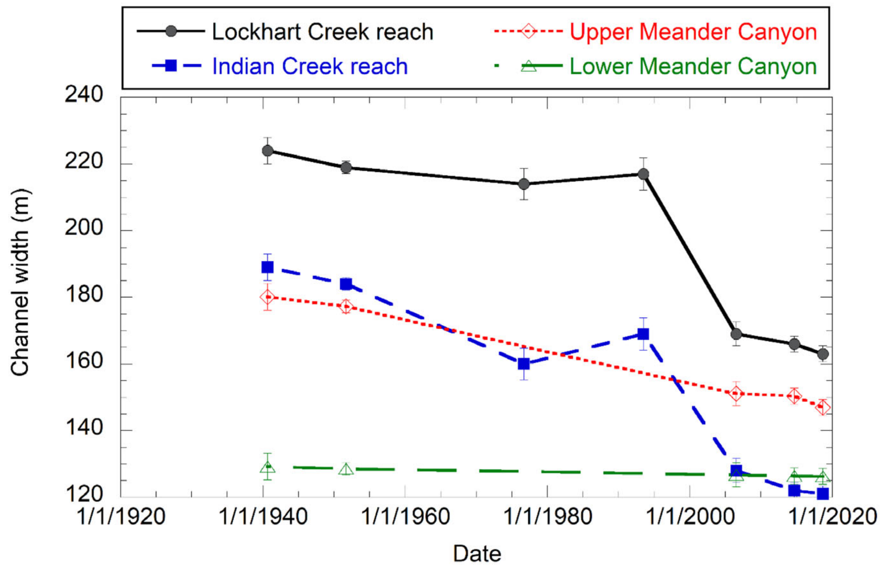

FIGURE 6 Average channel width for indicated portion of study area as measured from aerial photos. Error bars show mapping uncertainty (Table 1) [Color figure can be viewed at wileyonlinelibrary.com]

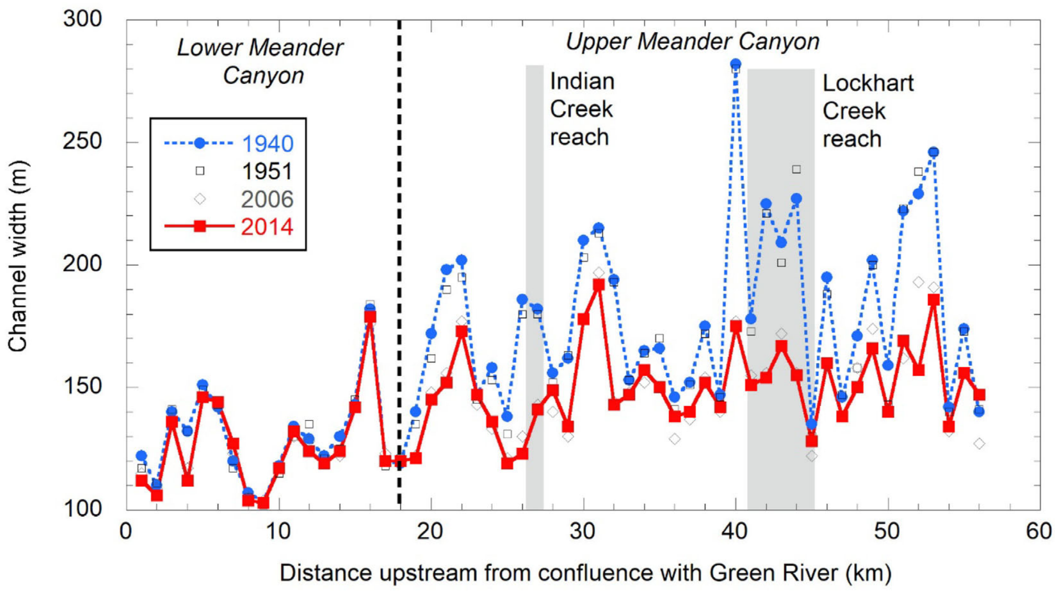

FIGURE 7 Average channel width in each 1-km segment of Meander Canyon for 1940, 1951, 2006, and 2014 [Color figure can be viewed at wileyonlinelibrary.com]

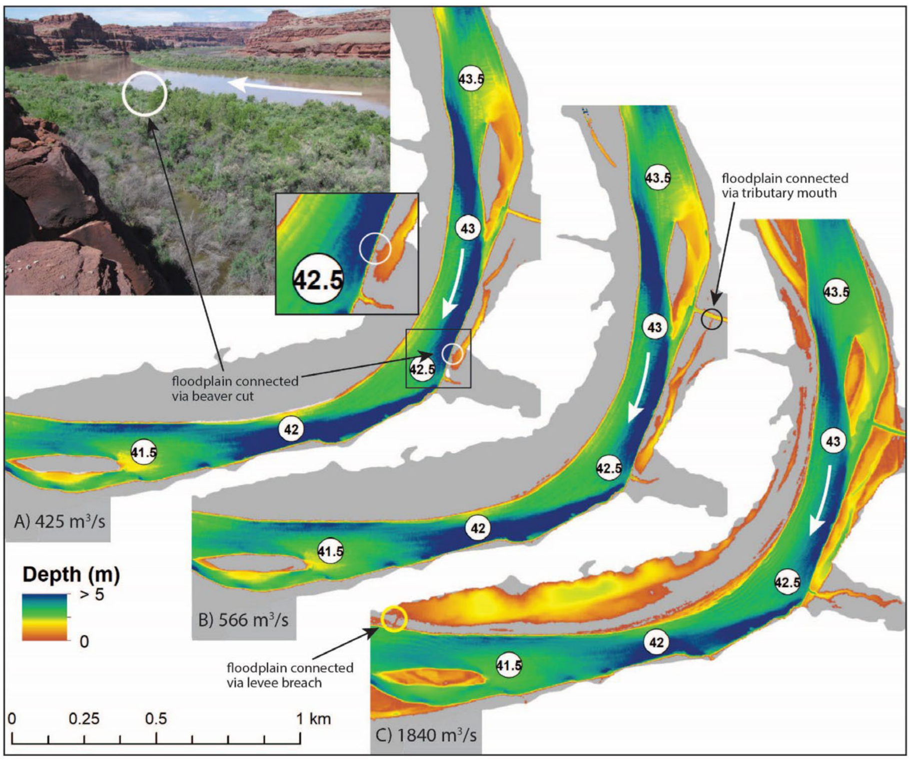

FIGURE 8 Depth of inundation for the Lockhart Creek streamflow modeling reach at 425, 566, and 1840 m^3/s. The inset map detail and photograph shows the heavily vegetated back-levee depression on the floodplain that is connected by both a beaver cut in the levee and by a tributary channel mouth. The circled numbers are distance upstream from the Green River confluence, in kilometers [Color figure can be viewed at wileyonlinelibrary.com]

This provides approximately 8400 m^2 of fish habitat at frequently occurring flows. Although this discharge also inundates the tributary mouth, it does not provide connection to the floodplain via the flooded tributary. A slightly higher discharge of 566 m^3/s (post-1954 recurrence interval of 1.5 years) is required to connect the flooded tributary mouth to the back-levee basin (Figure 8), increasing the area of flooded bottomland to 17,118 m^2.

4.2.2 | Lidar analysis of meander canyon floodplains

Although bathymetric data for streamflow modeling were only collected at the Lockhart Creek study reach, the high-resolution lidar data were available for all of the Meander Canyon study area (State of Utah and Partners, 2019). Using the lidar-derived DEM and the map created from the 2014 images, we inspected the study area for

TABLE 2 Summary of back-levee depressions identified from lidar-derived DEM within the Meander Canyon study reach

Connection to main channel at 566 m^3/s	Count	Total area (m^2)	Average area (m^2)
Levee-breach and tributary channel	1	10,455	10,455
Levee-breach only	5	20,360	4072
Tributary channel only	1	1674	1674
Floodplain outflow channel	4	39,396	9849
All connected back-levee depressions	11	71,885	6535
Non-connected back-levee depressions	32	124,410	3888

locations where either a tributary dissected the modern floodplain map unit, or where the levee separating the modern floodplain map unit from the channel contained a low point no greater than 2.2 m above the water surface measured during the lidar overflight. We used 2.2 m as a threshold for connection, because this is the approximate elevation of the location that allows inundation at 566 m^3/s, the 1.5-year recurrence flow. Applying these criteria, we find that conditions similar to those that occur in the Lockhart Creek reach are infrequent and we found no other locations where a back-levee depression was likely to be inundated by both a levee breach and by a tributary channel. Of 42 additional back-levee depressions where the elevation drops below the 566 m^3/s stage, the lidar data indicate that only 11 have possible connections to the channel. One of these depressions is connected by a tributary that dissects the floodplain and nine of the depressions are connected either by a levee breach or by water accessing the depression from an outflow channel (Figure S4). Including the back-levee depression within the Lockhart Creek modeling reach, we estimate that about 72,000 m^2 of back-levee depressions on floodplains could be inundated at 566 m^3/s (Table 2).

5 | DISCUSSION

Maps based on aerial photographs show that the width of the active channel of the Colorado River in Meander Canyon decreased by 17% between 1940 and 2018 (Figure 6). Decreases in width were greatest in Upper Meander Canyon where the average decrease in width was 22%. Analysis of more frequent photographs in the Lockhart Creek and Indian Creek reaches indicate that most of this narrowing occurred in the 13-year period between 1993 and 2006. This period followed the completion of the largest upstream water storage projects and immediately followed a 5-year period of extremely low peak flow magnitude (1988–1992) and included a second 6-year period of low peak flow magnitude (1999–2004; Figure 5). These periods of below-average peak flow magnitude are similar to the cycles of low annual peak flows identified on the Yampa River (Manners et al., 2014) and the Green River (Topping et al., 2018; Walker et al., 2020; Grams et al., 2020). Between 1988 and 1992, the annual peak flow was less than the average peak flow every year and the 5-year average peak flow was 425 m^3/s, which was the lowest 5-year average peak flow on record and less than 60% of the magnitude of the long-term average peak flow of 739 m^3/s. Another sequence of low annual floods occurred from 2000 to 2004 when peak flows were less than or equal to the average peak flow every year and the 5-year average peak flow was 437 m^3/s, the second lowest 5-year peak flow on record. This low-flow period coincides with the onset of the ongoing post-Millennium drought affecting the entire Colorado River basin (Udall and Overpeck, 2017; Xiao et al., 2018) that is associated with a 22% decrease in mean annual flow of the Colorado River near Cisco, Utah (Figure S1). These same periods of low runoff and extremely low peak flow magnitude have been associated with channel narrowing on the nearby segment of the Green River in Canyonlands (Walker et al., 2020; Grams et al., 2020). Thus, even though Meander Canyon has a different history of streamflow regulation than the Green River, recent episodes of channel narrowing were likely triggered by the same periods of extremely low runoff and low peak flows that occurred in the late twentieth and early twenty-first century. This recent phase of channel narrowing follows a smaller phase of narrowing that occurred between 1940 and 1976. The mechanisms for channel narrowing are likely similar to the processes observed on other regulated rivers where periods of low flows allow establishment of vegetation, which then promotes sediment accretion during average or higher peak flows that are not sufficient to scour the vegetation (Manners et al., 2014; Walker et al., 2020).

In Meander Canyon, the narrowing process has resulted in the formation of vertically accreted levees, which in most cases disconnect the floodplain from the modern river. Although levees were likely present in the period before flow regulation, they would have been overtopped more frequently by higher peak flows. Where these levees are dissected, either by ephemeral tributaries or other mechanisms, there is continued connection between the modern river and the floodplain back-levee basins. Previous studies of potential floodplain fish habitat on the Green River within Canyonlands National Park concluded that the floodplain adjacent to the main channel was hydrologically disconnected from the river and that the only viable nursery habitat for native fish were side channels and backwater areas within the active channel and a few flooded tributary mouths (FLO Engineering, 1996). Those conclusions are consistent with our modeling results for most of the floodplain and terrace surface, which show that discharges with recurrence intervals of ~38 years would be required to breach the levees that line most of the channel. However, the high-resolution DEM based on airborne lidar measurements allowed us to find low-elevation back-levee depressions and connection points that could allow connection and inundation at average peak flows (~1.5-year recurrence). Although these back-levee depressions that have potential connections at low peak flows are rare and total only about 70,000 m^2 for all of Meander Canyon, they may nevertheless provide important habitat for native fish (Table 2).

The value of these back-levee depressions as potential fish habitat depends on both the frequency and duration of inundation. Although the features we identified in Meander Canyon are inundated by the ~1.5-year recurrence flow, that discharge has only been equaled or exceeded an average of 12 days per year since 2000 (Figure S5). Although this average duration of inundation is low, it is also highly variable and includes years when 566 m^3/s is never exceeded and years when it is exceeded for three weeks and even up to 12 weeks, which occurred in 2011 (Figure S6).

These findings, while specific for the Meander Canyon segment of the Colorado River, have important implications for all river systems facing potential changes in runoff associated with water development and/or climate change. Even if long-term changes in runoff and peak flow magnitude are moderate, cycles of low peak flow magnitude may initiate channel narrowing and habitat alteration. In river systems where managers have the ability and flexibility to adjust dam and reservoir operations, it may be possible to prevent or forestall additional channel narrowing by adjusting dam releases to interrupt cycles of low peak flow magnitude. This is more feasible in systems like the Green River where streamflow is regulated by a single large dam (Grams et al., 2022) than on the Colorado River in Meander Canyon, which is affected by many smaller upstream dams. Alternatively, the effects of channel narrowing on floodplain habitat may be partially mitigated by mechanical excavation to breach levees and improve connection between back-levee depressions and the river channel, which has been done on the Green River in Utah (LaGory et al., 2019). The feasibility of constructing mechanical levee breaches on the Colorado River would require further study.

6 | CONCLUSION

The width of the active channel of the Colorado River in Meander Canyon decreased by 17% between 1940 and 2018 and most of this change occurred between 1993 and 2006. This study is consistent with the findings of Walker et al. (2020) and Grams et al. (2020) for segments of the nearby Green River and illustrates a new stage in river channel adjustment to upstream water development. Early studies of the downstream effects of dams found erosion where there was sediment deficit and clear-water floods (Grams et al., 2007; Pemberton, 1976; Williams and Wolman, 1984) and channel narrowing where floods were eliminated (Andrews 1986; Everitt 1993) or reduced (Grams and Schmidt, 2002). We now have strong evidence that in recent decades channel narrowing has occurred contemporaneously on each major trunk stream of the Colorado River system, initiated by cycles of low peak floods and low runoff that are likely related to climate change and compounded by upstream flow regulation. As a result, floodplain habitats used by native fish have become increasingly limited in spatial extent, and floods large enough to inundate these areas for significant periods of time may only occur during the wettest years which may occur less frequently than in the past under projected climate change scenarios for the Colorado River basin (Udall and Overpeck, 2017).

ACKNOWLEDGEMENTS

This work was funded by the National Park Service and the U.S. Geological Survey. We acknowledge the interest and support provided by Mark Miller, Terry Fisk, and Mark Wondzell. Assistance with field data collection and processing was provided by Paul Kinzel, Daniel Buscombe, Keith Kohl, and Colin Evans. Tom Gushue and Rob Weber assisted with orthorectification of aerial images. The data used in this study are available in the U.S. Geological Survey ScienceBase catalog of Grams et al. (2022). Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

DATA AVAILABILITY STATEMENT

All data associated with this study will be made available in the public data repository of Grams et al. (2022).

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REFERENCES

Andrews, E. D. (1986). Downstream effects of flaming gorge reservoir on the Green River, Colorado and Utah. *Geological Society of America Bulletin*, *97*(August), 1012–1023. https://doi.org/10.1130/0016-7606(1986)97<1012

Belknap, B., & Evans, L. B. (2013). *Canyonlands River guide*. Evergreen, Colorado: Westwater Books.

Dean, D. J., Topping, D. J., Grams, P. E., Walker, A. E., & Schmidt, J. C. (2020). Does channel narrowing by floodplain growth necessarily indicate sediment surplus? Lessons from sediment-transport analyses in the green and Colorado Rivers, Canyonlands, Utah. *Journal of Geophysical Research: Earth Surface*, *125*, e2019JF005414. https://doi.org/10.1029/2019JF005414

Everitt, B. (1993). Channel responses to declining flow on the Rio Grande between Ft. Quitman and presidio, Texas. *Geomorphology*, *6*, 225–242.

FLO Engineering. (1996). *Green River flooded bottomlands investigation Ouray wildlife refuge and Canyonlands National Park*. Utah, Denver, Colorado: U.S Fish and Wildlife Service Upper Colorado River Endangered Fish Recovery Program.

Graf, W. L. (1999). Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research*, *35*(4), 1305–1311.

Grams, P. E., Schmidt, J. C., & Topping, D. J. (2007). The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen canyon downstream from Glen canyon dam, 1956-2000. *Geological Society of America Bulletin*, *119*(5/6), 556–575. https://doi.org/10.1130/B25969.1

Grams, P. E., Head, E., & Kinzel, P. (2022). *Aerial images, digital elevation models, channel width maps, and river metrics along the Colorado River in Canyonlands National Park*, Utah (1940–2018). U.S. Geological Survey Data Release. https://doi.org/10.5066/P95DYGMU

Grams, P. E., Dean, D. J., Walker, A. E., Kasprak, A., & Schmidt, J. C. (2020). The roles of flood magnitude and duration in controlling channel width and complexity on the Green River in Canyonlands, Utah, USA. *Geomorphology*, *371*, 107438. https://doi.org/10.1016/j.geomorph.2020.107438

Grams, P. E., & Schmidt, J. C. (1999). Geomorphology of the Green River in the eastern Uinta Mountains, dinosaur National Monument, Colorado and Utah. In A. J. Miller & A. Gupta (Eds.), *Varieties of fluvial form* (pp. 81–111). Chichester: John Wiley & Sons Ltd.

Grams, P. E., & Schmidt, J. C. (2002). Streamflow regulation and multi-level flood plain formation: Channel narrowing on the aggrading Green River in the eastern Uinta Mountains, Colorado and Utah. *Geomorphology*, *44*, 337–360.

Harden, D. R. (1990). Controlling factors in the distribution and development of incised meanders in the Central Colorado plateau. *Geological Society of America Bulletin*, *102*, 233–242.

Head, E. (2020). Channel narrowing and floodplain inundation in meander *canyon, Colorado River, Canyonlands National Park Utah*. Northern Arizona University, unpublished thesis. https://www.proquest.com/dissertations-theses/channel-narrowing-floodplain-inundation-meander/docview/2409107562/se-2

LaGory, K. E., Hayse, J. W., & Tomasko, D. (2003). *Recommended priorities for geomorphology research in endangered fish habitats of the upper Colorado River basin*. Argonne, Illinois. Retrieved from https://coloradoriverrecovery.org/uc/wp-content/uploads/sites/2/2021/11/TechnicalReport-ISF-Lagory-2003-Geomorphology.pdf

LaGory, K., Bestgen, K., Patno, H., Wilhite, J., Speas, D., and Trammell, M. (2019). Evaluation and suggested revisions of flow and temperature recommendations for endangered fish in the Green River downstream of flaming gorge dam, Final Report, U.S. Fish and Wildlife Service, Upper Colorado River Endangered Fish Recovery Program, October, 2019.

Manners, R. B., Schmidt, J. C., & Scott, M. L. (2014). Mechanisms of vegetation-induced channel narrowing of an unregulated canyon river: Results from a natural field-scale experiment. *Geomorphology*, *211*, 100–115. https://doi.org/10.1016/j.geomorph.2013.12.033

Minckley, W. L., & Deacon, J. E. (1968). Southwestern fishes and the enigma of "endangered species." *Science*, *159*(3822), 1424–1432. Retrieved from http://www.jstor.org/stable/1724004

Minckley, W. L., & Deacon, J. E. (Eds.). (1991). *Battle against extinction: Native fish Management in the American West*. University of Arizona Press: Tucson, AZ. Retrieved from http://hdl.handle.net/10150/625250

Mueller, G. A. (2006). *Ecology of bonytail and razorback sucker and the role of off-channel habitats in their recovery*. Reston, VA: Scientific Investigations Report. https://doi.org/10.3133/sir20065065

Nelson, J. M., Shimizu, Y., Abe, T., Asahi, K., Gamou, M., Inoue, T., … Watanabe, Y. (2016). The international river interface cooperative: Public domain flow and morphodynamics software for education and applications. *Advances in Water Resources*, *93*, 62–74. https://doi.org/10.1016/j.advwatres.2015.09.017

Nilsson, C., Nilsson, C., Reidy, C. A., & Dynesius, M. (2005). Fragmentation and flow regulation of the world 's. *Large River Systems*, *308*(5720), 405–408. https://doi.org/10.1126/science.1107887

Osmundson, D. B., Ryel, R. J., & Mourning, T. E. (1997). Growth and survival of Colorado squawfish in the upper Colorado River. *Transactions of the American Fisheries Society*, *126*(4), 687–698. https://doi.org/10.1577/1548-8659(1997)126<0687:GASOCS>2.3.CO;2

Pemberton, E. L. (1976). Channel changes in the Colorado River below Glen canyon dam. In 3rd Federal Interagency Sedimentation Conference (pp. 5–73). Sedimentation Committee of the Water Resources Council.

Pettitt, A. N. (1979). A non-parametric approach to the change-point problem. *Journal of the Royal Statistical Society. Series C (Applied Statistics)*, *28*(2), 126–135. https://doi.org/10.2307/2346729

Rasmussen, C. G., & Shafroth, P. B. (2016). Conservation Planning for the Colorado River in Utah. Retrieved from https://www.coloradomesa.edu/water-center/documents/rasmussen_shaftroth_2016_watercenter_cmu.pdf

Schmidt, J. C., & Rubin, D. M. (1995). Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans. In J. E. Costa, A. J. Miller, K. W. Potter, & P. R. Wilcock (Eds.), *Natural and anthropogenic influences in fluvial geomorphology* (Vol. Geophysica, pp. 177–195). Washington, DC: American Geophysical Union. https://doi.org/10.1029/GM089p0177

State of Utah and Partners. (2019). Regional Utah high-resolution lidar data 2015–2017. Collected by Quantum Spatial, Inc., Digital Mapping, Inc., and Aero-Graphics, Inc. and Distributed by OpenTopography. https://doi.org/10.5069/G9RV0KSQ

Stockton, C. W., & Jacoby, G. C. (1976). Long-term surface-water supply and streamflow trends in the upper Colorado River basin. Lake Powell Research Project Bulletin, National Science Foundation Research Applied to National Needs, *18*, 73.

Tillman, F.D., Gangopadhyay, S. & Pruitt, T. (2020). Recent and projected precipitation and temperature changes in the Grand Canyon area with implications for groundwater resources. *Scientific Reports*, *10*, 19740. https://doi.org/10.1038/s41598-020-76743-6

Topping, D. J., Mueller, E. R., Schmidt, J. C., Griffiths, R. E., Dean, D. J., & Grams, P. E. (2018). Long-term evolution of sand transport through a river network: Relative influences of a dam versus natural changes in grain size from sand waves. *Journal of Geophysical Research: Earth Surface*, 1879–1909. https://doi.org/10.1029/2017JF004534, *123*(8): 1879, 1909

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*, *53*, 2404–2418. https://doi.org/10.1002/2016WR019638.Received

Van Steeter, M. M., & Pitlick, J. (1998). Geomorphology and endangered fish habitats of the upper Colorado River: 1. Historic changes in streamflow, sediment load, and channel morphology. *Water Resources Research*, *34*(2), 287–302. https://doi.org/10.1029/97WR02766

Walker, A. E., Moore, J. N., Grams, P. E., Dean, D. J., & Schmidt, J. C. (2020). Channel narrowing by inset floodplain formation of the lower Green River in the Canyonlands region Utah. *Geological Society of America Bulletin*, *132*, 2333–2352. https://doi.org/10.1130/B35233.1

Williams, G. P., & Wolman, M. G. (1984). Downstream effects of dams on alluvial Rivers. U. S. Geological Survey Professional Paper 1286, 83 p. Retrieved from https://pubs.er.usgs.gov/publication/pp1286

Woodhouse, C. A., Gray, S. T., & Meko, D. M. (2006). Updated streamflow reconstructions for the upper Colorado River basin. *Water Resources Research*, *42*(W05415), 2006. doi:10.1029/2005WR004455

Xiao, M., Udall, B., & Lettenmaier, D. P. (2018). On the causes of declining Colorado River Streamflows. *Water Resources Research*, *54*(9), 6739–6756. https://doi.org/10.1029/2018WR023153

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Grams, P. E., Head, E., & Mueller, E. R. (2022). Effects of flow regulation and drought on geomorphology and floodplain habitat along the Colorado River in Canyonlands National Park, Utah. *River Research and Applications*, 1–11. https://doi.org/10.1002/rra.4014