Reservoir Delta Dynamics and Backwater Vegetation in the Context of Physical Drivers

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Acronyms and Abbreviations

AOI	Area of Interest
C	Celsius
cfs	cubic feet per second
cm	centimeters
cms	cubic meters per second
Corps	United States Army Corps of Engineers
CRSP	Colorado River Storage Project
DEM	digital elevation model
ft	feet
GIS	Geographic Information System
km^2	square kilometers
LFCC	Low Flow Conveyance Channel
m	meters
mi	square miles
mm	millimeters
MTD	metric tons per day
RM	river mile
TBDEM	topobathymetric digital elevation model
U.S.	United States
WSE	water surface elevation

Symbols

°	degree
%	percent

Contents

Page

Executive Summary

The physical and biological processes that structure river-mouth deltas are well studied and understood. However, despite the world-wide proliferation of large dams and reservoirs (ICOLD 2020) reservoir deltas are less well studied. They form in response to the same physical processes but are uniquely dynamic, temporally and spatially, because of reservoir fluctuations that respond to seasonal variation in inflows and reservoir management, as well as multi-year wet and dry cycles and long-term changes in climate. Drawing attention to the novel ecosystems created by reservoir sedimentation, Johnson (2002) speculated that newly formed habitats and the biological diversity supported by these novel environments might offset the loss of some ecological processes and biological diversity documented along rivers downstream of dams. Moreover, new physical habitat created by reservoir delta and related backwater ecosystems in the vast Missouri River basin represents more than twice the areal coverage of remnant flood plain forests (Volke et al. 2015). Examination of a Missouri River reservoir delta-backwater ecosystem revealed a dynamic assemblage of riparian and wetland plants including young stands of native woody species that are now rare along remnant river reaches below dams (Volke et al. 2019). Based on work from European rivers, Liro (2019) presented a conceptual model of the effects of fluctuating reservoir levels on the abiotic and biotic components of fluvial systems and emphasized that little work has been directed at understanding and quantifying the effects of such disturbances on river bottomlands.

Given the potential importance of newly formed reservoir delta-backwater environments as habitat, their broad spatial occurrence and a dearth of comparative studies, our overall research objective included the assembly of datasets relevant to the formation and dynamics of delta-backwater ecosystems. Specific research questions were structured around the following working hypotheses: 1) the development of reservoir delta-backwater sedimentary surfaces is similar across reservoirs and the geomorphic effects of a reservoir extend upstream of the maximum pool elevation; 2) the areal coverage of riparian and wetland vegetation increases along river bottomlands influenced by reservoir-related sedimentation; 3) these hybrid vegetation assemblages are dominated by early successional species and may provide habitat being lost in river reaches below dams; 4) the structure, composition and dynamics of delta-backwater ecosystems are driven by multiple interacting factors, including regional climate, geomorphic setting, influent water and sediment, and the frequency and magnitude of reservoir pool fluctuations; 5) ongoing and predicted climate warming may shift the spatial, temporal and successional dynamics of delta-backwater ecosystems through its effect on long-term changes in mean reservoir pool elevation.

To address our research objective and working hypotheses, we performed the following: 1) selected four representative reservoirs and delta-backwaters that vary with regard to regional climate, geomorphic setting, age of reservoir, reservoir operations, contributing stream discharge, and the volume of stream sediment delivered; 2) used existing physical data, such as historical and contemporary cross section surveys, lidar, reservoir pool elevations, and regional climate records to characterize the progression of physical changes that have occurred as a result of base level changes to the contributing stream and backwater effects associated with reservoir operations; 3) acquired historical and contemporary aerial imagery and, in a Geographic Information System (GIS) platform, mapped the areal extent of delta-backwater vegetation and surface cover types over time; 4) related vegetation development and dynamics to measured physical variables; and 5) used supervised classification of recent imagery to quantify categorical vegetation cover, such as woody versus herbaceous, stressed versus healthy, to assess general structure and condition. Mapping and classification of vegetation has been completed for two reservoirs and is on-going for the remaining two.

There was uniformity in the development of sedimentary surfaces across all four reservoirs. Longitudinal profiles from channel cross-sections show sediment accumulating in the upper reaches with greatest accumulations between the maximum and minimum pool elevations. Accumulation depths were greater in the bedrock canyon reaches of the Colorado River at Lake Mead and Lake Powell than in the broad alluvial bottomland of the Missouri River at Fort Peck Lake. Detailed channel cross-section elevation measurements on the Missouri River above Fort Peck Lake illustrate that the geomorphic effects of change in base level extends 24 river kilometers upstream of maximum pool elevation. These findings are consistent with results of a related study on the White River, a tributary to a reservoir on the lower Missouri River (Volke et al. 2019).

Over the decades-long period of delta-backwater development examined, there were quantitative increases in the aerial extent of riparian and wetland surface cover types along the Missouri and Colorado rivers. However, the biophysical processes accounting for these differences were vastly different. Development of the delta-backwater across the wide Missouri River bottomland was accompanied by a progressive increase in mesic riparian cover with little comparative change in cover types upstream of the reservoir backwater influence. Supervised classification indicated that the mesic cover type was dominated by early successional willows, cottonwoods, and herbaceous wetland species. Moreover, a multi-year reservoir drawdown of nine meters exposed 132 square kilometers of bottomland, much of it rapidly colonized by mesic riparian vegetation. In the initial filling of Lake Powell, water displaced most of the pre-dam riparian and upland vegetation in the narrow, bedrock canyon of the Colorado River. With continued sediment deposition in the upper reaches of the reservoir, new surfaces were rapidly colonized and dominated by the early successional, non-native tamarisk (*Tamarix chinensis, Tamarix ramosissima,* and hybrids). Following a 32-meter drop in the pool elevation at Lake Powell between 2000 and 2005, the Colorado River incised the accumulated sediment, creating terraces. Vegetation on these widespread, hydrologically disconnected terraces is now subject to seasonal stress and mortality. Erosion, transport, and deposition of sediment from these terraces created new channel bedforms, some of which have been colonized by woody and herbaceous vegetation. Supervised classification of recent imagery shows notable expansion of xeric and mesic riparian surfaces along with bare sediment cover types, compared with pre-dam conditions. The differential physical and biological responses between these two reservoirs result from several interacting factors, including regional climate, valley slope and confinement, as well as the frequency, magnitude, and duration of reservoir fluctuations.

Each of the reservoirs examined displayed some degree of climate sensitivity, as expressed in the long-term record of pool elevations. Lake Powell, Lake Mead, and Elephant Butte, in particular, demonstrate comparatively wide fluctuations in pool elevations and sustained declines related to previous and on-going regional drought conditions. Such responses are partially a function of basin climatology as well as reservoir storage capacity relative to mean annual streamflow. Reservoirs with a high storage to annual streamflow ratio are prone to sustained low reservoir levels during periods of drought. Lake Powell, operated in concert with Lake Mead, and Elephant Butte both have storage capacities more than four times the annual streamflow, compared with Fort Peck, which stores less than three times the annual flow. Climate modeling for headwater sub basins for each of the reservoirs, using reduced and business-as-usual future carbon emission pathways, projected significant increases in temperatures with no corresponding change in precipitation over the next 50 years. This translates to correspondingly significant changes in the timing of runoff with likely reduced magnitudes, along with significant increases in evaporative demand, and decreases in soil moisture storage. These projections suggest that the observed sustained declines and increased variability in reservoir pool elevations will represent a new state for many reservoirs given ongoing and projected climate warming. New, lower pool elevations would contribute to erosion, fluvial transport and redistribution of sediments deposited during higher reservoir elevations, leading to increased vegetation dynamics and unknown vegetation successional trajectories on new and legacy depositional surfaces.

This investigation focused on large-scale vegetation patterns related to the physical formation of delta-backwater landforms and their dynamic response to short- and long-term fluctuations in reservoir pool elevations. Hybrid plant communities have established, expanding available habitat at the reservoirs we examined. Some of this new habitat appears to be of high quality with an abundance of native species, whereas other reservoirs appear to support primarily non-native species. Further, sustained, climate-driven declines in pool elevations at Lake Powell, Lake Mead, and likely Elephant Butte reservoir, are initiating new vegetation establishment processes and subjecting established vegetation to stress and mortality. Our findings point to a clear need for on-the-ground sampling and quantification of the species composition at these sites, with an eye toward a predictive understanding of the local and regional processes that contribute to the assembly of plant communities at a site. Given the expanding presence of invasive, non-native species across ecosystems world-wide, such an understanding could inform water management actions that would favor the establishment and persistence of native species and improve predictions of plant community responses to projected climate warming.

1. Introduction

Deltas and backwater-affected bottomlands are forming at tributary and mainstem confluences in reservoirs. Prograding deltas, and related hydrogeomorphic changes in river bottomlands in the backwater fluctuation zones of reservoirs, signals the development of new and dynamic riparian and wetland habitats. Considerable research effort has been focused on understanding the physical and biological processes that create and maintain riverine and riparian ecosystems, as well as the downstream effects of dams on riparian ecosystems. However, comparatively little work has been directed at the upstream effects of dams, especially in those dynamic zones where a stream enters a reservoir. The extent of these newly emerging habitats, their dynamics relative to physical drivers (sediment inputs, reservoir fluctuations, climate shifts) and their potential to substitute for habitat loss in regulated river reaches below dams, is largely unknown and in need of further study.

Johnson (2002) first noted the importance of vegetation assembling on newly emerging reservoir deltas and backwaters and inquired about the extent to which delta-backwaters might replace some of the geomorphic processes, shallow aquatic habitats and vegetation dynamics that had been lost. Fluctuations in reservoir backwaters shift base level and thus the locations of delta-backwater processes, which include sediment aggradation in upstream reaches (Holste 2013), alteration of channel form and process (Liro 2017), inundation of existing bottomland vegetation, and exposure of depositional surfaces for colonization by new vegetation during reservoir drawdown (Xu and Shi 1997). Liro (2019) presents a conceptual model of the effects of fluctuating reservoir backwaters on the abiotic and biotic components of fluvial systems and emphasizes that little work has been directed at understanding and quantifying the effects of these disturbances. Further, Volke et al. (2015) reported that the aerial extent of delta-backwater features in the Missouri River basin was more than twice the area of floodplain forest remaining in remnant reaches below or between dams. A recently published paper, Volke et al. (2019), found that the delta-backwater of the White River, a tributary to a Missouri River reservoir, contained many of the native woody species found along natural and regulated river reaches within the basin and supported young stands of native riparian vegetation now in decline in remnant reaches protected from flooding.

Specific research questions in this investigation were structured around the following working hypotheses: 1) the development of reservoir delta-backwater sedimentary surfaces is similar across reservoirs and the geomorphic effects of a reservoir extend upstream of the maximum pool elevation; 2) the areal coverage of riparian and wetland vegetation increases along river bottomlands influenced by reservoir-related sedimentation; 3) these hybrid vegetation assemblages are dominated by early successional species and may provide habitat being lost in river reaches below dams; 4) the structure, composition and dynamics of delta-backwater ecosystems are driven by multiple interacting factors, including regional climate, geomorphic setting, influent water and sediment, and the frequency and magnitude of reservoir pool fluctuations; 5) ongoing and predicted climate warming may shift the spatial, temporal and successional dynamics of delta-backwater ecosystems through its effect on long-term changes in mean reservoir pool elevation.

To explore these hypotheses and investigate reservoir delta dynamics and associated riparian and wetland habitat, we performed the following research tasks:

1) selected four representative reservoirs and delta-backwaters that vary with regard to regional climate, geomorphic setting, age of reservoir, reservoir operations, contributing stream discharge, and stream sediment delivery (volume and particle size);
2) used existing physical data, such as historical and contemporary cross section surveys, lidar, reservoir pool elevations, and regional precipitation records to characterize the progression of physical changes that have occurred because of base level changes to the contributing stream and backwater effects associated with reservoir operations;
3) acquired historical and contemporary aerial imagery and, in a Geographic Information System (GIS) platform, mapped the areal extent of delta-backwater vegetation over time;
4) correlated vegetation development and dynamics to measured physical variables;
5) classified vegetation by categories such as woody versus herbaceous, native versus non-native or invasive, and thus developed a general index of habitat quality.

Our research addresses three goals relevant to environmental issues associated with water delivery and management. First, we obtained a quantitative assessment of the areal extent of delta-backwater riparian and wetland habitats for reservoirs across a broad geographic area. Second, we developed a refined understanding of the lifecycle of these habitat features and their spatial dynamics relative to physical factors such as incoming water discharge, sediment load, and reservoir operations. This would be especially useful in anticipating future changes in the distribution and extent of delta-backwater habitats if predicted climate change were to alter operational reservoir pools. Third, we developed an approach that could be used to assess the quantity and quality of reservoir delta-backwater habitat on a regional or national scale.

2. Reservoir Description and Data

2.1 Fort Peck Reservoir

Fort Peck Dam and Reservoir are in northeastern Montana on the mainstem Missouri River (Figure 1). Fort Peck Dam is the largest hydraulically filled earthen dam in the United States (U.S.) and was constructed between 1933 and 1937 with a closure date of June 24th, 1937. The project is comprised of the dam, flood control tunnels, a spillway and power plant, operated together for flood control, navigation, hydropower generation, along with other uses like irrigation and recreation. The dam was the first of six Missouri River mainstem dams operated by the U.S. Army Corps of Engineers (Corps).

Fort Peck Dam is 76.4 meters high and 6.4 kilometers long (excluding the spillway). The Maximum Operating Pool of the reservoir has an elevation of 686 meters. The study area or area of interest (AOI) for this investigation includes 143 kilometers (89 miles) of river, extending from just downstream of the confluence with the Musselshell River at river mile 1856, upstream to river mile 1945. Here we use river miles supplied as a GIS shapefile by the Corps, representing miles upstream of the confluence with the Mississippi River and based on the river's channel alignment in 1960.

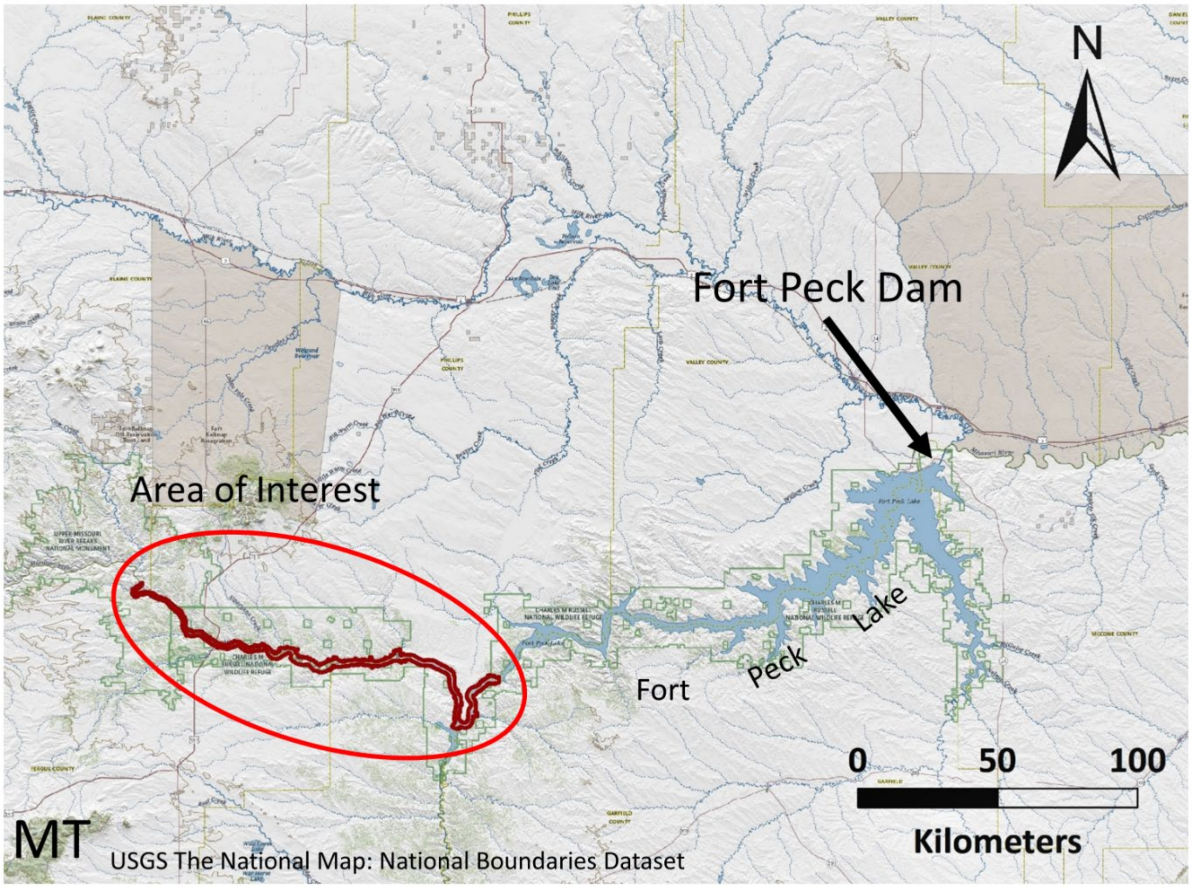


Figure 1. Location map showing Fort Peck dam and lake (reservoir) and this investigation's AOI, which include the current delta and backwater formed by Fort Peck reservoir.

2.1.1 Watershed Characteristics

The watershed area above Fort Peck Dam is 149,000 square kilometers. The reach of the Missouri River within the AOI has a snowmelt hydrograph with annual flow peaks typically occurring in May or June. Two large upstream dams, Canyon Ferry on the Missouri River and Tiber on the Marias River, were completed in 1954 and 1956, respectively, and have altered the natural flow regime. Although the seasonal timing of flows has not been altered, the magnitude of peak flows has been reduced up to 40 percent (%), and the low flow portions of the historic hydrograph have generally increased (Scott et al. 1997, Bovee and Scott 2002). Cottonwood recruitment is not strictly flood dependent; however, most forest area (62%) downstream of the US Geological Survey gage at Virgelle (1960 river mile 2034) was established in association with a small percentage of flood years (29%), which includes the two years following a flood (Bovee and Scott 2002). A flood in this instance is a discharge larger than 1850 cubic meters per second (cms) as measured at the Virgelle gage. Flows of this magnitude position seedlings above the zone of frequent ice-drive disturbance (Auble and Scott 1998). Ice-drive disturbance has been shown to limit the establishment of cottonwood forest patches in ice-prone reaches along northern Great Plains streams (Smith 1980).

In the upper portion of the AOI (river miles 1910 to 1942), the river occupies a relatively narrow, postglacial valley incised from 150 to 560 meters (m) below the surrounding landscape (Alden 1932). Here, side valley exposures of shales and sandstones constrain channel movement, and the river channel is dominantly single threaded, relatively straight, and has alternate bars. Most cottonwood forest patches are small and scattered, matching pre-settlement descriptions of riparian forest by the Lewis and Clark Expedition (Coues 1893). Below river mile 1910, the Missouri River encounters broad exposures of easily erodible Bear Paw shale at river level, and the valley widens. The channel in this reach features a series of constrained meanders with point bars and cut banks and larger, more continuous stands of willow (*Salix* spp.) and cottonwood occupy the channel point bars (Scott and Auble 2002).

The regional climate encompassing the AOI is continental and characterized by hot summers and cold, dry winters. Average annual temperature for the area is 6° Celsius (C) with temperatures ranging from –53° C in February to 44° C in July and August. The average minimum temperatures in January are near –18° C and average summer high temperatures are between 27° and 32° F with up to 120 frost free days annually. Atmospheric humidity is generally low and evaporation rates high, owing to the warm, dry summers. Average precipitation at the Fort Peck weather station is 29 centimeters (cm) with up to 80 % falling between April and September. Snowfall averages 41 cm annually (USACE 2013). Widespread and intense rainstorms along the eastern front of the Rocky Mountains in northern Montana, USA, and southern Alberta, Canada, are characteristic of the climatic history of the upper Missouri River basin. Records indicate a period from 20 May through June when atmospheric conditions are most likely to contribute to heavy rainfall in central Montana (US Weather Bureau 1960). Heavy rainstorms have been directly involved in historical floods on the upper Missouri River in 1894, 1906, 1908, 1916, 1927, 1938, 1948, 1953 and 1964. Although antecedent conditions of snowmelt runoff and rain-soaked soils contributed in varying degrees to these floods, they have been primarily rain-induced (Dightman 1973, Bovee and Scott 2002).

The region surrounding Fort Peck Lake is part of the Great Plains physiographic province and includes three principal landforms: upland plains, badlands, and river bottomlands. The upland plains are flat to undulating prairies underlain by relatively resistant sandstones and dissected by small, sinuous, ephemeral drainages. These surfaces are dominated by prairie grasses and shrubs (shrub steppe), isolated forest of primarily Ponderosa pine and expansive agricultural fields. The badlands are highly dissected sedimentary rock formations consisting of interbedded sandstones, siltstones, and shales and are regionally referred to as the Missouri Breaks. Topographically, the Breaks include steep-sided and poorly vegetated drainages or coulees and steep, narrow valleys separated by thin, sinuous ridges. Native prairie grasses and shrubs occur on exposed ridges and flats. North-facing slopes contain isolate ponderosa pine and juniper, whereas south-facing slopes contain scattered grasses, ponderosa pine or bare exposures of shale (Bovee and Scott 2002). Approximately 50% of the Fort Peck project area is composed of Missouri Breaks topography (USACE 2013). Bottomlands of the Missouri River and larger tributaries range for several yards to nearly two miles wide. The principal tree species on the active floodplains of the broader bottomlands is plains cottonwood (*Populus deltoides* Subsp. *monilifera*). Box elder (*Acer neguno*), green ash (*Fraxinus pennsylvanica*) and peach-leaf willow (*Salix amygdoloides*) occur as less common associates, particularly on islands and in former backchannels that have been filled by alluvial sediments. Understory shrubs on alluvial surfaces include yellow willow (*Salix lutea*), sandbar willow (*Salix exigua*), western snowberry (S*ymphoricapos occidentalis*) and silver sagebrush (*Artemisia cana*) (Scott and Auble 2002).

The creation of Fort Peck Lake imposed a new, shifting base level on the Missouri River and its tributaries. This resulted in the deposition of sediment in river channels and across the bottomlands. Deltas and related backwaters have developed in the headwater reaches of Fort Peck Lake as sediment has accumulated, creating broad, low gradient channels and depositional zones that extend from valley wall to valley wall. Bare deltaic deposits are exposed during low reservoir stages and rapidly become vegetated with woody and herbaceous plant species, creating new wetland and riparian habitat. Such habitat may in turn be inundated and killed with the return of higher reservoir stages. The spatial and temporal dynamics of these depositional features, along with the vegetation that establishes on these new surfaces is the focus of this investigation.

2.1.2 Aerial Imagery

Four image dates were used to interpret and quantify changes in fluvial, geomorphic, and vegetation condition over six decades of development and change in the Fort Peck delta and backwater (Table 1). Imagery from 1953 and 1977 was not orthorectified, which required post-processing with Agisoft Metashape and GIS tools to develop consistent georeferenced images for all years. Because we were not able to obtain and interpret any existing imagery from the 1930s, we were not able to characterize pre-dam or immediate post-dam conditions across the Missouri River bottomland. Nonetheless, our results capture notable change and ongoing dynamics across the Fort Peck delta-backwater across the dates examined. Because river discharge and reservoir pool elevation can influence the pattern and extent of interpreted cover types, we provide Missouri River discharge and reservoir pool elevation information for the days the interpreted imagery was acquired (Table 1).

Table 1. Missouri River discharge and Fort Peck Reservoir water surface elevation (WSE) by image acquisition year and date, for the Missouri River and associated reservoir backwater. The maximum reservoir pool elevation over the five years prior to image acquisition date, was used for interpretation of vegetation distribution within the backwater across years.

Image year	Image acquisition month/day	Missouri River Discharge (cms) on image date	Fort Peck Reservoir Pool elevation (meters) on image date
1953	9/21	122	680.5
1977	8/18, 9/25, 10/11&12	113 - 142	681.1 - 681.5
1996	7/29, 8/23-25	184 - 258	684.5 - 685.1
2015	6/27, 7/19&24,30-31, 8/1-2&23, 9/25	164 - 200	682.5 - 682.0

2.1.3 Reservoir Stage

Water storage in Fort Peck Lake began with the closing of the dam in June of 1937. It took approximately 10 years for the reservoir to approach full pool. Persistent dry conditions from the mid-1950s to the early 1960s dropped the pool below the long-term mean daily surface elevation (Figure 2). The reservoir remained above the mean elevation for the next three decades during a comparatively wet period, followed by alternating lower and higher than mean pool elevations. Reservoir pool elevations are driven chiefly by regional temperature and precipitation patterns, which influence runoff and inflows from the major tributaries.

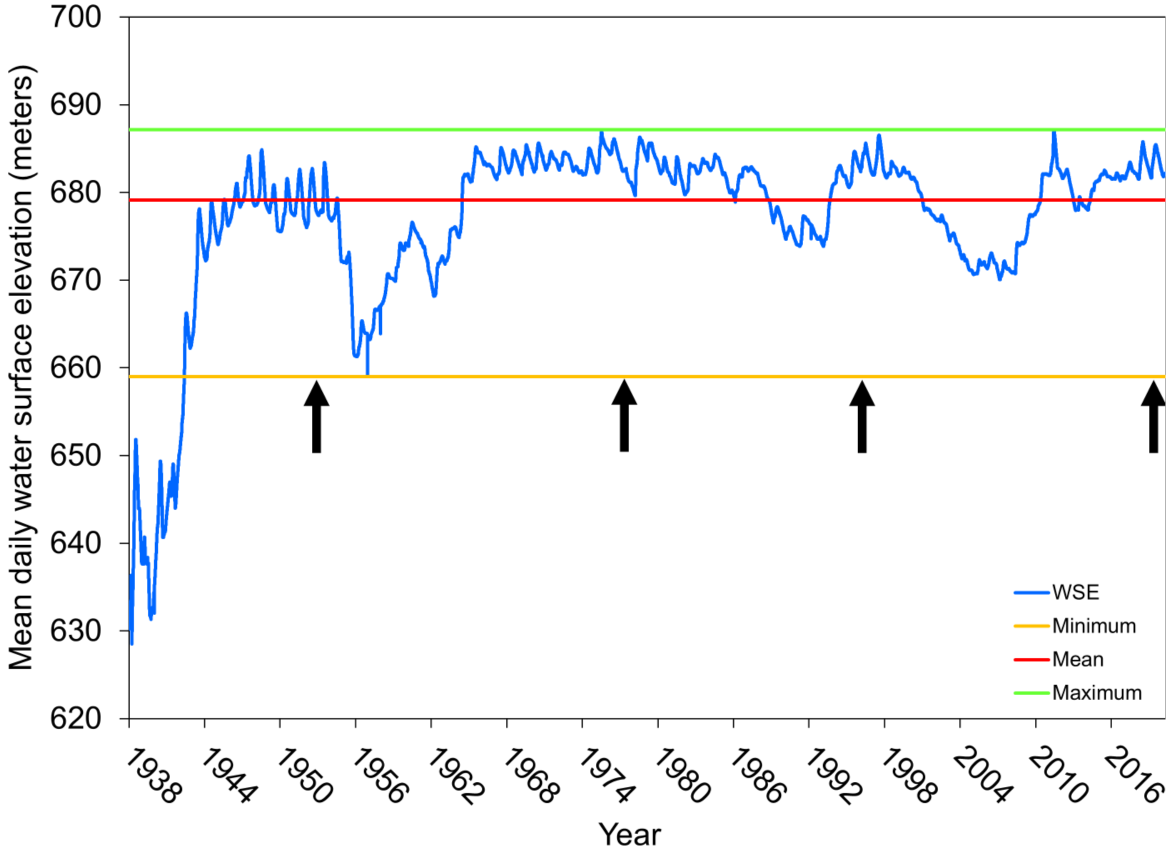


Figure 2. Record of Fort Peck reservoir pool elevations in meters beginning with the completion of Fort Peck dam in 1937 to 2020. Maximum, minimum and long-term mean reservoir pool elevations are given for the period commencing in 1946, when the reservoir approached full pool., Data provided by the US Army Corps of Engineers.

2.1.4 Reservoir Inflows and Climate-driven Change in Water Resources

Stream inflows to Fort Peck reservoir that most directly influence the delta/backwater system include the mainstem Missouri River and the Musselshell River. We obtained daily surface water and suspended sediment data from USGS gage 06115200, Missouri River near Landusky, MT and gage 06130500, Musselshell River at Mosby, MT, using the U.S. Geological Survey National Water Information System Mapper (https://maps.waterdata.usgs.gov/mapper/index.html). Plots of mean daily discharge for the Missouri River near Landusky, MT (Figure 3) and the Musselshell River at Mosby, MT (Figure 4), show similar long-term trends in discharge that are reflected in the record of pool elevation for Fort Peck Reservoir. Below mean pool elevations through the 1950s to early 1960s, late 1980s to early 1990s and through the 2000s (Figure 2) correspond with regional dry periods and lower than the average mean-daily discharge for the period of record on both rivers. Likewise, sustained periods of higher than mean reservoir pool elevations correspond with regional, multi-year wet periods where mean daily discharge is higher than the long-term average (Figure 3).

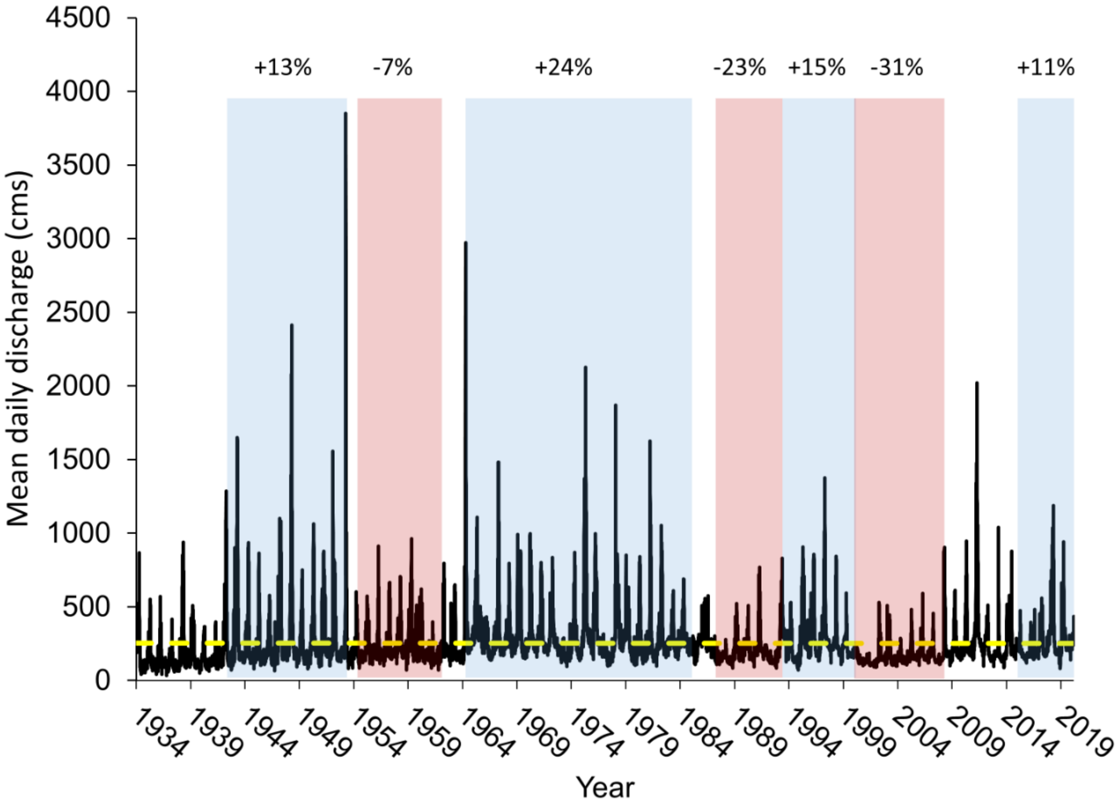


Figure 3. Plot of mean daily discharge in cubic meters per second for the Missouri River near Landusky, MT (gage #06115200). The yellow dashed line is the average mean daily discharge for the period of record (1934-2020) and the shaded bars represent multi-year periods during which mean daily discharge averages higher (blue) or lower (red) than the long-term average mean-daily discharge. Numbers above the bars represent the percentage increase or decrease in mean-daily discharge for the period compared with the long-term average.

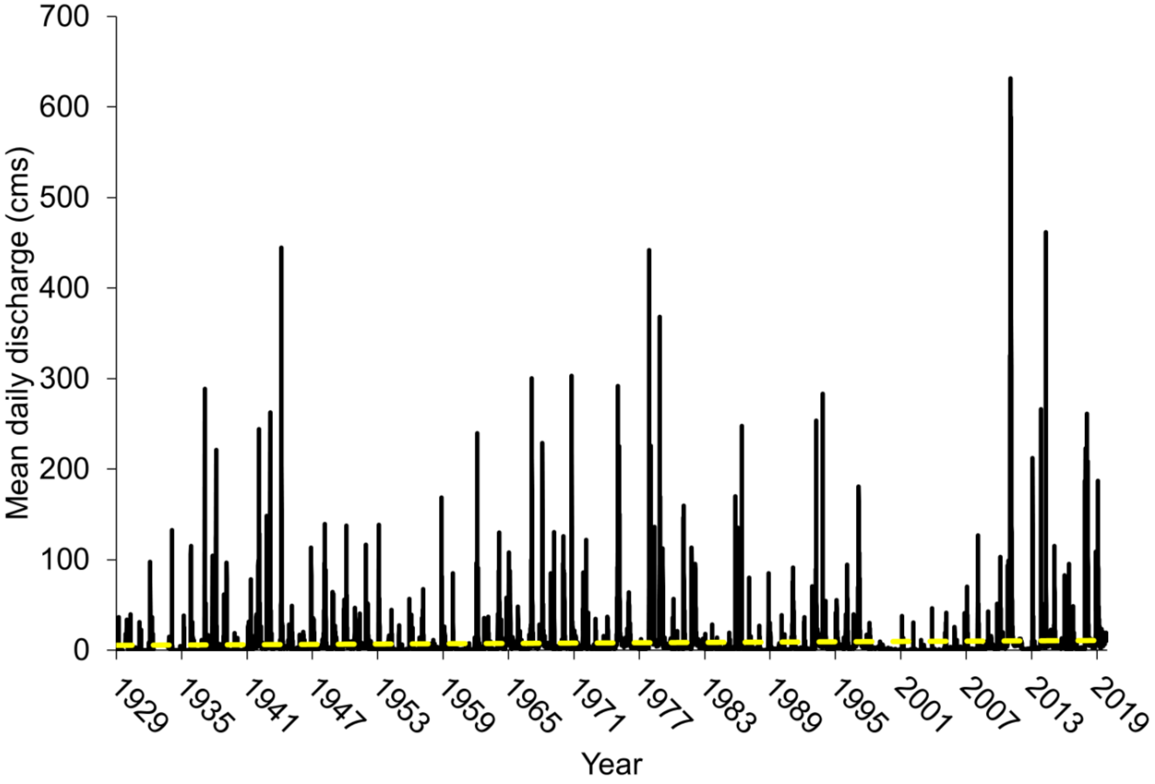


Figure 4. Mean daily discharge in cubic meters per second for the Musselshell River at Mosby, MT. The yellow dashed line is the average mean daily discharge for the period of record (1929-2020). Periods where discharge averages lower or higher than the long-term average mirror those of the mainstem Missouri near Landusky, MT (Figure 3).

In a review of current climate trends and projected future climate change likely to influence water management in the Missouri River basin, the US Army Corps of Engineers conducted a review of relevant climate change literature. A broad consensus from this review was that temperature and precipitation within the Missouri River basin have increased. Annual rainfall amounts have increased during the summer, but rainfall events are more sporadic. Furthermore, large rain events are now more frequent and punctuated by longer intervening dry periods (U.S. Army Corps of Engineers 2018). Warming temperatures result in more winter precipitation falling as rain, reducing mountain snowpacks and causes them to melt earlier, which in turn alters runoff patterns. The National Climate Change Viewer (https://www.usgs.gov/tools/national-climate-change-viewer-nccv) was used here to compare predicted trends in runoff for four subregional Hydrologic Unit Codes (HUC-4 basins) in the upper Missouri River basin, for the period 2025-2049, compared against a historical (1981-2010) reference period (Figure 5). Results illustrate that for all four hydrologic subregions, predicted runoff will begin earlier, increasing during the January to May period and decreasing from May through September, relative to historical trends. Runoff magnitudes are predicted to remain close to or slightly less than historical values.

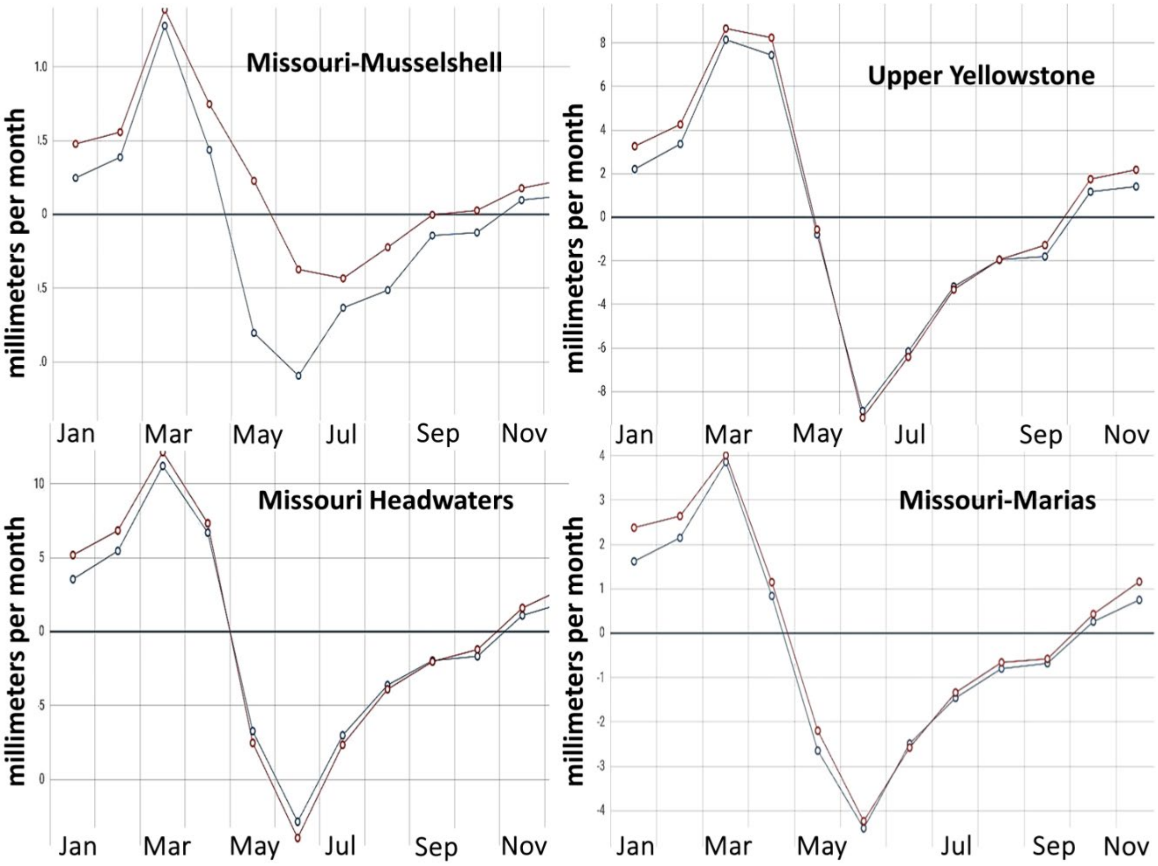


Figure 5. Predicted timing and magnitude of runoff (millimeters per month) for four hydrologic subregions (HUC-4) of the upper Missouri River basin, based on the USGS Climate Change Viewer (https://www.usgs.gov/tools/national-climate-change-viewer-nccv). The graphs compare predicted changes in runoff for the period 2024-2049 compared against a 1981-2010 reference period, using RCP4.5 (red lines) and RCP8.5 (blue lines) pathways for future atmospheric CO2 concentrations. Departures from 0 represent the timing and degree of change from the reference.

These results are consistent for both Representative Concentration Pathways for future atmospheric CO_2 concentrations. Possible future changes in the magnitude and timing of runoff to receiving reservoirs can have a range of important implications for water storage, management, and infrastructure as well as the structure and composition of vegetation assemblages in reservoir backwaters and deltas.

Suspended sediment inputs to Fort Peck reservoir were examined using measurements from USGS gages: 06130500 on the Musselshell River at Mosby, MT and 06115200 on the Missouri River near Landusky, MT. Sediment input from the Musselshell River averaged 726 metric tons per day (MTD) for the period of record (1982-1995) and the Missouri River averaged 16,036 MTD for the period 1971-2006. Sediment delivery on both rivers was highly variable with large pulses of sediment corresponding with peaks in mean daily discharge, as illustrated for the Missouri River (Figure 6). Because of the short period of record and comparatively small amount of sediment delivered from the Musselshell River, only the sediment and water discharges from the Missouri River are presented here. For the period of record on the Missouri, there was a decreasing trend in sediment delivery, which mirrored a similar trend in mean-daily discharge. This decreasing trend in suspended sediment discharge was not obvious in the shorter record for the Musselshell River.

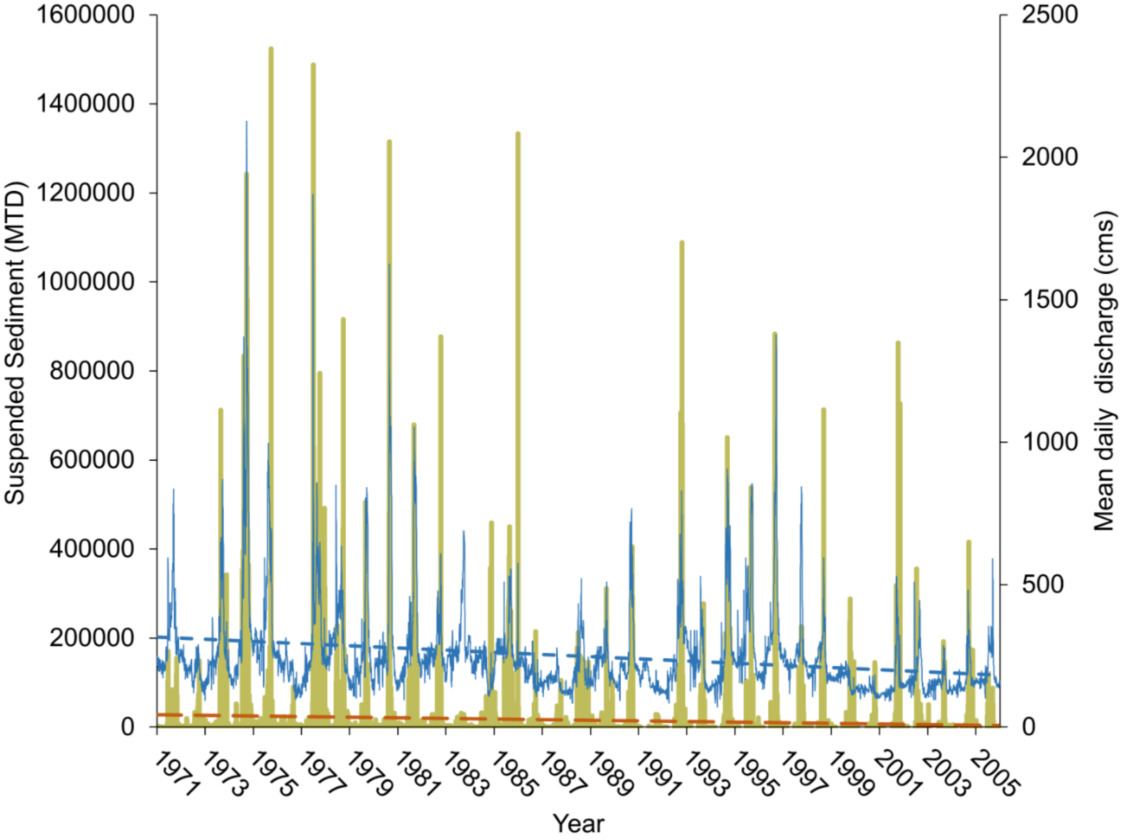


Figure 6. Suspended sediment in metric tons per day (gold line) and mean daily discharge in cubic meters per second (blue line) for the Missouri River near Landusky, MT (gage #06115200). Trend lines for suspended sediment (red dashed line) and discharge (blue dashed line) show declining trends over the period of record.

2.1.5 Topobathymetric Surveys

A total of 126 channel range lines or cross-sections were established between Fort Peck Dam and the upstream limit of the Flood Control reservoir pool, to evaluate the pattern and extent of sediment deposition associated with the reservoir. Seven range lines were established in 1937-1938 and an additional 77 were established in 1946. A total of 42 were added subsequently. Topographic change prior to the use of a Global Positioning System was assessed using optical surveying equipment by measuring elevation along a line between two monumented endpoints at each range line location. Most of the endpoints have been surveyed into the U.S. Coast and Geodetic Survey triangulation system. In 2007 new elevations and Montana state-plane coordinates were established with a Global Positioning System (GPS), using Montana NAD83 as the horizontal datum and elevation data in the NGVD 1929 vertical datum (USACE 2013). For the current report, we converted the NGVD29 values to the NAVD88 datum and then converted from feet to meters for consistency with other data sets.

Repeat surveys of elevation along the range lines (from 1937 to 2007) provides information on where sediment is being deposited and how these deposits change over time. Elevation data from the range lines were derived from work done in association with the report *Sedimentation Conditions at Fort Peck Lake 2013,* M.R.B. Sediment Memorandum 08a (USACE 2013), to evaluate changes in the storage capacity of Fort Peck Lake. We use this data here to evaluate the geomorphic effects of Fort Peck reservoir on the Missouri River. Specifically, the delta and backwater areas that have formed within the Missouri River bottomland since the construction of Fort Peck Dam.

Fort Peck reservoir imposed a change in base level along the Missouri River, resulting in substantial sediment deposition, chiefly between the maximum and minimum reservoir pool elevations. The longitudinal extent and magnitude of sediment deposition and the resulting effect on channel gradient can be seen in a plot of the channel thalweg profile derived from the range lines (Figure 7). From the relatively flat pre-inundation thalweg profile, the channel began filling near the dam as the reservoir filled. This filling progressed upstream through the 1960s. By the 1970s and 1980s, a distinct hinge point had formed above the long term mean pool elevation, perhaps in association with the prolonged above mean pool elevation of the reservoir that persisted from the late 1960s through the 1980s. By 2007, this hinge point had shifted downstream and coincident with the long-term mean pool elevation.

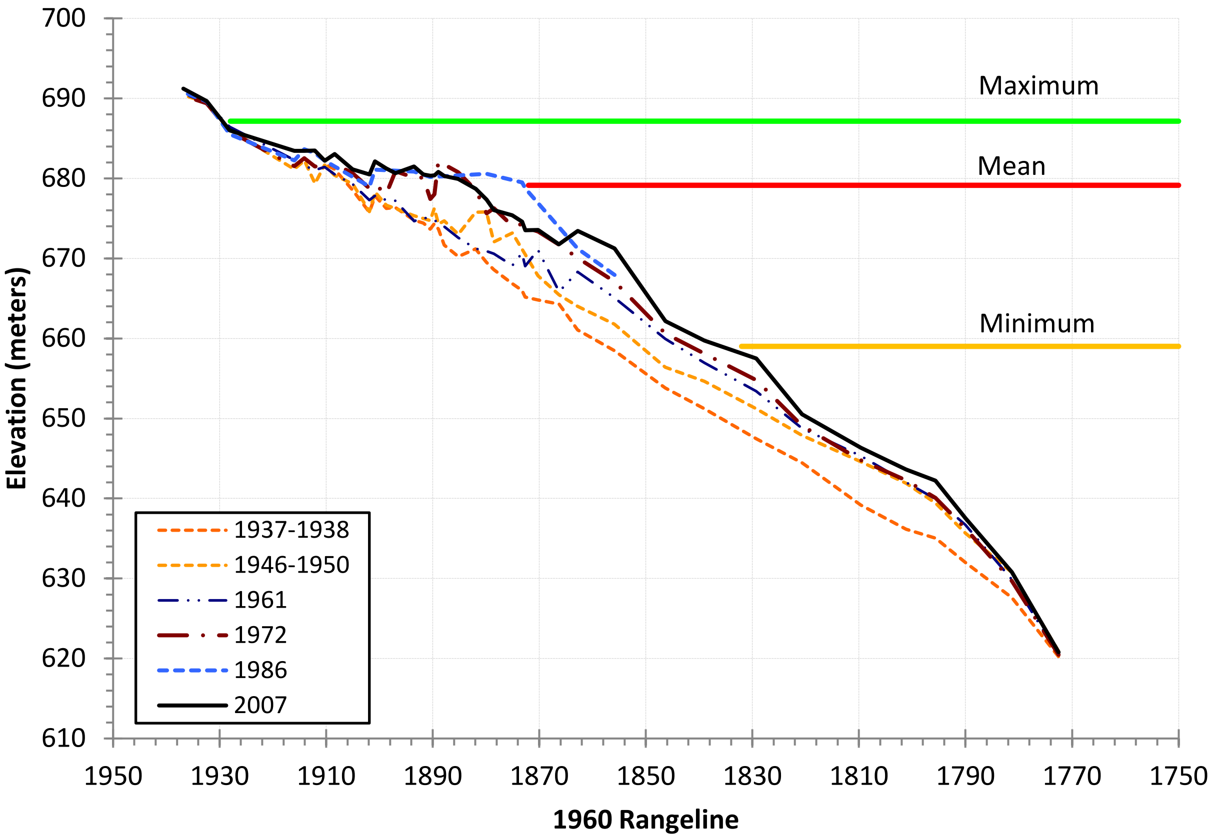


Figure 7. Longitudinal profile of the Missouri River channel thalweg elevation in feet, from Fort Peck dam to the upstream-most channel range line at 1936.8. Range lines are labeled based on the river alignment in 1960. Horizontal lines labeled as Maximum, Mean, and Minimum refer to the historical (1946-2020) pool elevations of the reservoir water surface.

Channel cross-sectional geometry has also been transformed along the Missouri River in response to both changes in streamflow, as well as base level changes related to the reservoir. We illustrate these changes using representative range line profiles from three geomorphically distinct reaches: non-backwater affected, backwater affected, and reservoir affected (see section 3.1 for more complete reach descriptions). The non-backwater reach occurs upstream of the detectable geomorphic influence of the reservoir and the primary channel thalweg and width remain similar to previous range line measurements (Figure 8). However, some flood plain surfaces have aggraded less than five feet and a side channel has slowly filled over the measurement period. This is consistent with a general narrowing of the Missouri River channel attributed to decreased frequency and magnitude of high flows associated with upstream water management as described by Scott et al. (2013).

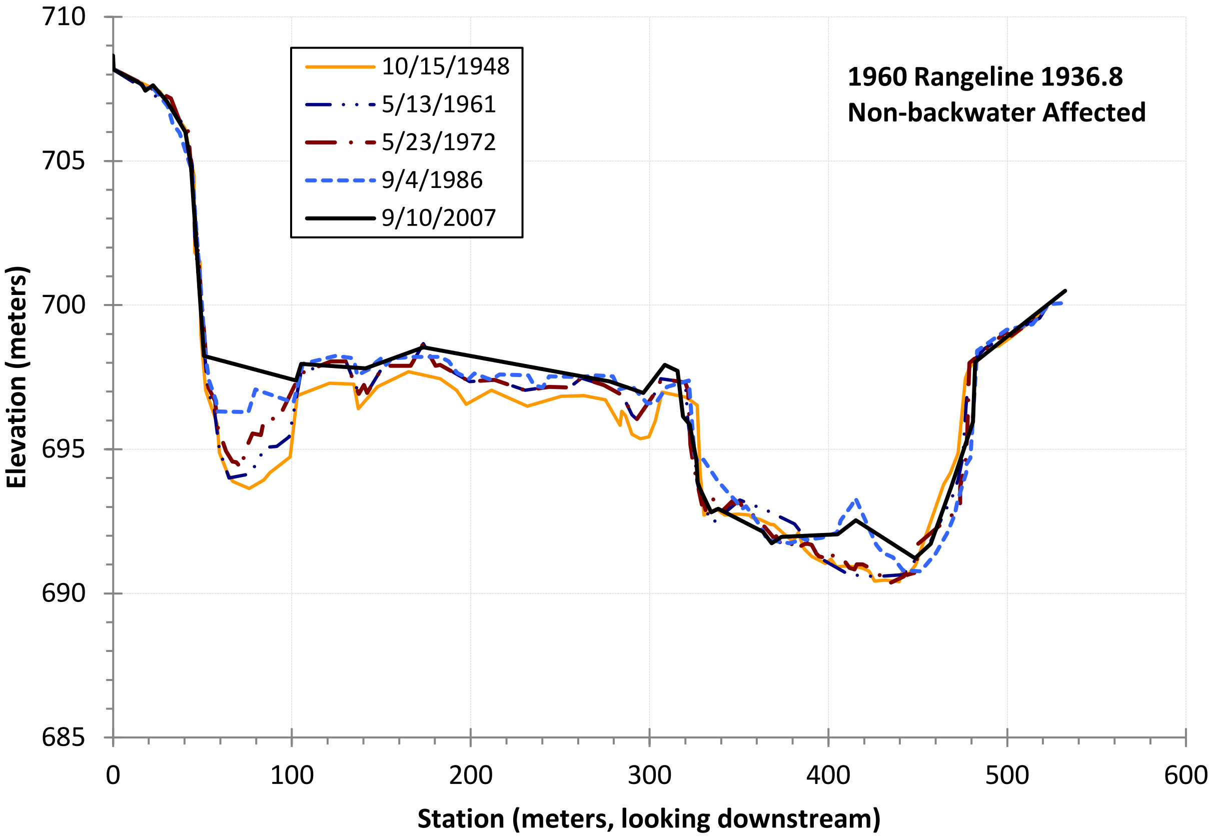


Figure 8. Channel cross-sectional elevations for multiple years in the non-backwater affected reach of the Missouri River at 1960 range line 1936.8.

Against the backdrop of channel narrowing, channels have filled and floodplain surfaces have aggraded up to 1.5 meters across the bottomland in the backwater affected reach (Figure 9), which is influenced by base level changes but not subject to inundation by the maximum reservoir pool. In the reservoir affected reach, base level changes and inundation by the reservoir, between maximum and minimum pool elevations, have filled and narrowed channels, produced levees, and have aggraded flood plain surfaces from valley wall to valley wall; up to 15 meters in some locations (Figure 10).

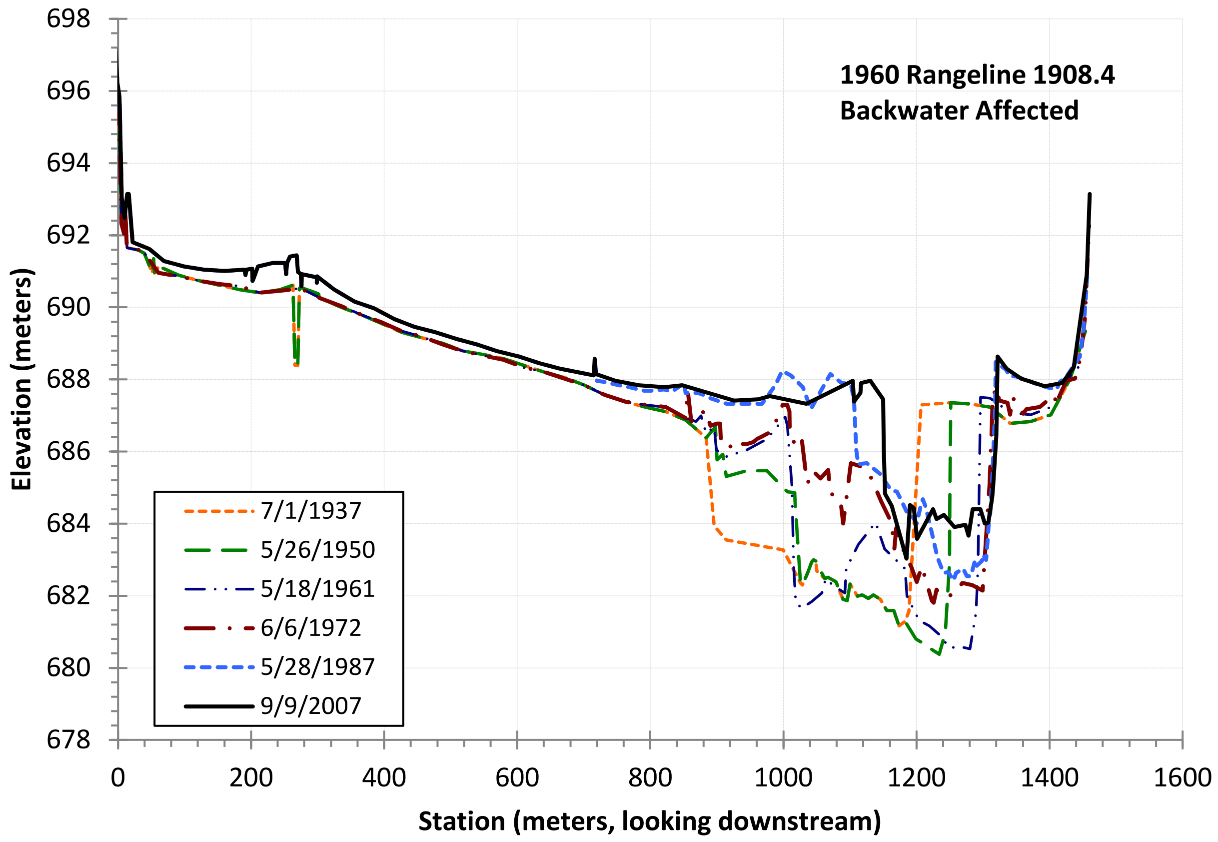


Figure 9. Channel cross-sectional elevations for multiple years in the backwater affected reach of the Missouri River at 1960 range line 1908.4.

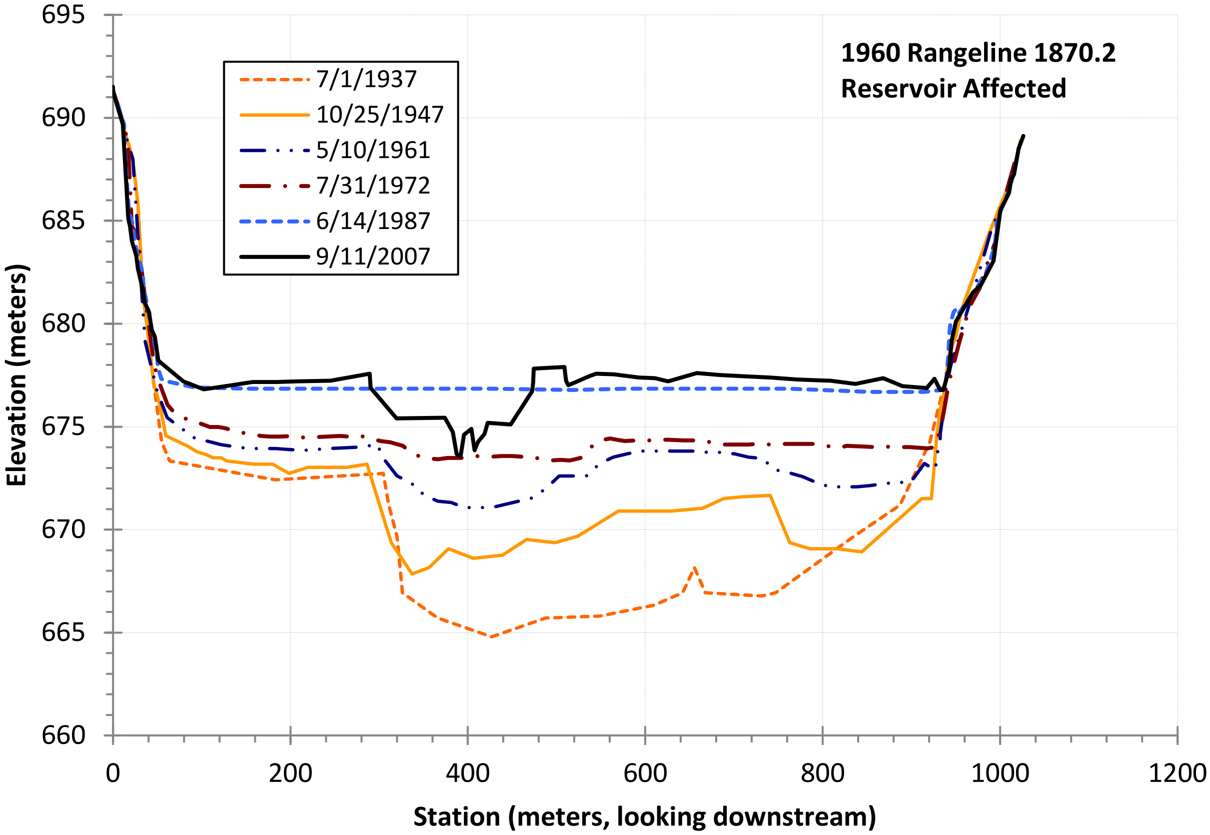
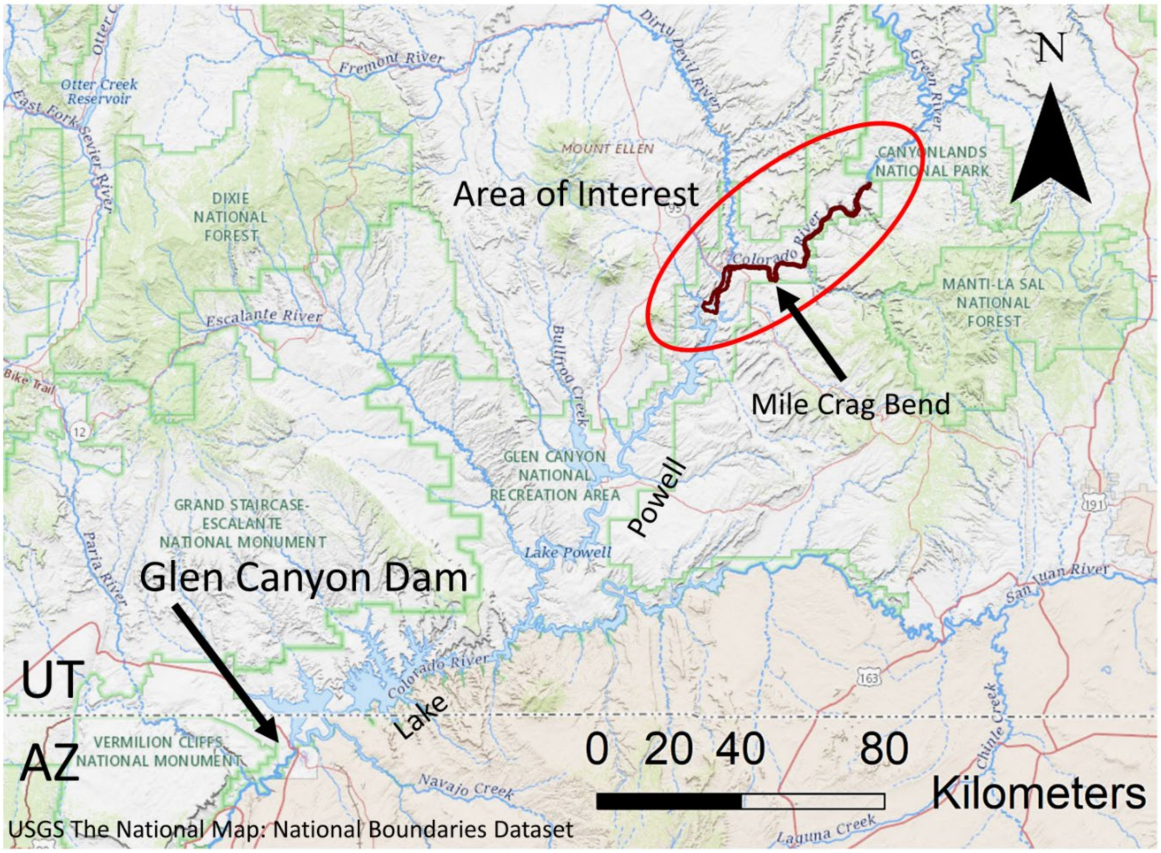


Figure 10. Channel cross-sectional elevations for multiple years in the reservoir affected reach of the Missouri River at 1960 range line 1870.2.

2.2 Lake Powell

Lake Powell is the second largest constructed water storage reservoir in the US and one of the primary water storage facilities of the Colorado River Storage Project (CRSP). Under the 1922 Colorado River Compact, Lake Powell was designed to provide regulatory water storage and use for states of the Upper Colorado River Basin while meeting flow obligations to Lower Colorado River Basin states. This large reservoir is formed by Glen Canyon Dam located on the Colorado River in north central Arizona approximately 15 river miles upstream of Lees Ferry, Arizona (Figure 11).

Construction of Glenn Canyon Dam was authorized by Congress in April 1956 with construction beginning in 1957. Regulation of flows downstream of the dam and filling of the reservoir began with closure of the diversion tunnels on March 13th, 1963. Glen Canyon Dam is a concrete structure with a hydraulic height of 5176 meters and a length of 475 meters. The top of the active conservation storage is at an elevation of 1128 meters with a surcharge capacity up to 1131 meters. The reservoir had and initial calculated storage capacity of 33,303,960,000 cubic meters. The maximum elevation of the reservoir to date, 1130 meters, was reached on July 14th, 1983, prompting the first major use of the spillways. The AOI for Lake Powell in this report includes 105.6 river miles along the mainstem Colorado River, extending from subaerial delta deposits exposed near the mouth of Woodruff Canyon and extending upstream to the Glen Canyon National Recreation boundary with Canyonlands National Park (Figure 11).



USGS The National Map: National Boundaries Dataset

Figure 11. Location map showing Glen Canyon dam, Lake Powell (reservoir) and this investigation's AOI, which includes the current delta and backwater formed by Lake Powell reservoir.

2.2.1 Watershed Characteristics

The watershed area above Glen Canyon Dam is approximately 278,942 square kilometers draining portions of the middle and southern rocky mountain across six states. The upper reaches of the basin drain glaciers and snowfields of peaks exceeding 4,267 meters in elevation. Flows into Lake Powell are influenced by upstream storage reservoirs and diversions on the Green, Colorado, and San Juan rivers. Flow records for the USGS Green River gage at Green River, UT extend back to 1894 providing a valuable long-term record of flow for the upper watershed. This record, along with related changes in channel geometry and riparian vegetation, was summarized by Allred and Schmidt (1999). They report a climate-related decrease in mean annual discharge of ~28% and a 33% decrease in the two-year recurrence flood, beginning in about 1930. These flow changes correspond with decreases in warm season rainfall in the early 1930s (Hereford and Webb 1992) and a midcentury period of increased drought from about 1940 to the late 1970s (http://esp.cr.usgs.gov/projects/sw/historical/precip_sw.html). A second decrease in peak flow of ~15%, in the two-year recurrence flood, followed the completion of Flaming Gorge Dam, in 1963, on the upper Green River. Decreases in channel width and establishment of riparian vegetation corresponded temporally with these changes in streamflow (Allred and Schmidt 1999, Scott and Miller 2017).

The complex terrain of the upper watershed includes high mountain peaks, intermountain basins and parks, high plateaus ranging up to 2,438 meters and deep, narrow canyons. Lake Powell, including the AOI, is situated within the Canyonlands section of the Colorado Plateau Physiographic province, which is characterized by sedimentary rock structures slightly deformed by anticlines, synclines, and monoclines, forming basins and broad plateaus that are extensively dissected by deep canyons. Lake Powell, formed behind Glen Canyon Dam, occupies most of Glen Canyon, a long, narrow canyon incised by the mainstem of the Colorado into members of the Glen Canyon Group, including Wingate Sandstone, the Kayenta Formation (thin-bedded sandstones, shales, and limestones) and Navajo Sandstone. The upper reaches of the reservoir, and within the area of interest (Figure 11), including the current subaerial delta and backwater, is variously bounded by members of the Triassic Chinle and Moenkopi formations and the Permian Cutler formation as well as Quaternary deposits including alluvium, landslide and colluvial deposits, gravel and aeolian sand (Thaden et al. 2008). Whereas most of the streamflow entering Lake Powell is derived from snowmelt in the Rocky Mountains, sediment is derived primarily from lower elevation and more erodible tributary watersheds (Allred and Schmidt 1999). As of 1988, the net sediment contributing area, minus upstream reservoir surface areas and their basins, was estimated to be approximately 215,357.51 square kilometers. The average annual sediment accumulation rate, between March of 1963 and September 1986, was estimated to be 45,572,152 cubic meters (Ferrari 1988).

The climate of the region surrounding the area of interest for Lake Powell is semiarid, with hot, dry summers and cool to cold winters. Temperature and precipitation vary by elevation with mean annual precipitation ranging from 210 to 255 mm and mean annual temperature from 10.7 to 12.2 °C in nearby Canyonlands National Park. On average, precipitation is greatest during the months July to October, with approximately 50% of the annual total falling as rain produced by convective thunderstorms during this four-month period (from Western Regional Climate Center, http://www.wrcc.dri.edu). With vast exposures of bedrock in a semiarid climate, vegetation patterns are primarily controlled by underlying geology and soil development and their combined influence on soil moisture availability.

Exposed sandstone bedrock tablelands, cliff rims, and other sites with little soil development, surrounding Lake Powell and the Colorado River within the area of interest specifically, are typically dominated by short-statured woodlands of two-needle pinon (*Pinus edulis*) and Utah juniper (*Juniperus osteosperma*) with understory shrubs including Utah serviceberry (*Amelanchier utahensis*), littleleaf mountain mahogany (*Cercocarpus intricatus*) cliffrose (*Purshia mexicana* var. *stansburiana*) and Bigelow's sagebrush (*Artemisia bigelovii*). Mesa tops and alluvial benches, where soils are more developed over an underlying hardpan or bedrock, are commonly dominated by blackbrush (*Coleogyne ramosissima*) shrublands along with galleta grass (*Pleuraphis jamesii*), Torrey's ephedra (*Ephedra torreyana*) and shadscale (*Atriplex confertifolia*). On even deeper soils above bedrock, grasslands dominated by needle-and-thread (*Heterostipa comata*), Indian ricegrass (*Achnatherum hymenoides*), blue grama (*Bouteloua gracilis*), galleta grass and the shrubs winterfat (*Krascheninnikovia lanata*) and green ephedra (*Ephedra viridis*), are common.

Riparian shrub communities are found along perennial streams and the Colorado River as it enters the backwaters of Lake Powell. Stands of tamarisk (*Tamarix chinensis, Tamarix ramosissima,* and various hybrids (Gaskin and Schaal 2002)), along with sandbar willow (*Salix exigua*), line the banks in places along the Colorado and Green rivers upstream of our area of interest. Mesic sites above the active channel in more protected locations support scatter individuals of Fremont cottonwood (*Populus fremontii*) and desert olive (*Foresteria pubescens*) along with several mesic herbaceous wetland species such as Baltic rush (*Juncus balticus*), creeping bentgrass (*Agrostis stolonifera*), common reed (*Phragmites australis*) and desert saltgrass *(Distichlis spicata*) (Loope 1977, Tendick et al. 2012).

2.2.2 Aerial Imagery

Four image dates were used to interpret and quantify changes in fluvial, geomorphic, and vegetation condition prior to the construction of Glen Canyon dam as well as the physical development and vegetation change across the Lake Powell delta and backwater related to the filling and fluctuations of the reservoir pool over the past 50 years (Table 2). We obtained the imagery from USGS Earth Explorer. Older images were not orthorectified, which required post-processing with Agisoft Metashape and GIS tools to develop consistent georeferenced images for all years. High river discharges in the 1993 imagery inundated near channel features, decreasing the overall coverage of mapped cover types relative to the mapped coverage of water.

Table 2. Combined discharge of the Colorado, Green and San Juan rivers and Lake Powell Reservoir water surface elevation (WSE) by image acquisition year and date, for the Colorado River and associated reservoir backwater. Note the high river discharge during the 1993 image acquisition dates.

Image year	Image acquisition month/day(s)	Cumulative River Discharge (cms) on image date(s)	Lake Powell Reservoir Pool elevation (meters) on image date(s)
1959	08/07	235	Pre-reservoir
1974	09/20-21, 23-24, 27	155 – 200	1114.1-1114.4
1993	06/13-14	1179 – 1251	1115.6-1115.7
2018	07/25, 29-30; 08/13,24,28; 09/7	134 – 186	1097.0-1100.0

2.2.3 Reservoir Stage

There is a strong correlation between water year precipitation in the upper Colorado River basin and estimated water year natural flow at Lees Ferry (Lukas et al. 2020). Thus, the pattern of storage reflected in reservoir pool elevations is evident in long term precipitation patterns for the basin. Glen Canyon dam began storing water on March 13th, 1963, with the closure of the diversion tunnels. Coming out of an extended mid-20th century period of below average precipitation for the basin, it took 17 years for the reservoir to full to the top of conservation storage at an elevation of 1128 meters. A series of wet years beginning in the late-1970s kept Lake Powell near full pool through most of that decade. This was followed by low precipitation years between 1988 and 1991, which briefly dropped reservoir levels below the long-term mean pool elevation but recovered with increased precipitation through the 1990s. The period beginning in 2000 has been drought-prone and exacerbated by progressive warming across the basin, which began about 1980 (Lukas et al. 2020). Declines in runoff and increasing temperatures within the basin have combined to drop the reservoir to its lowest levels since it began filling (Figure 12, data from https://www.usbr.gov/rsvrWater/HistoricalApp.html).

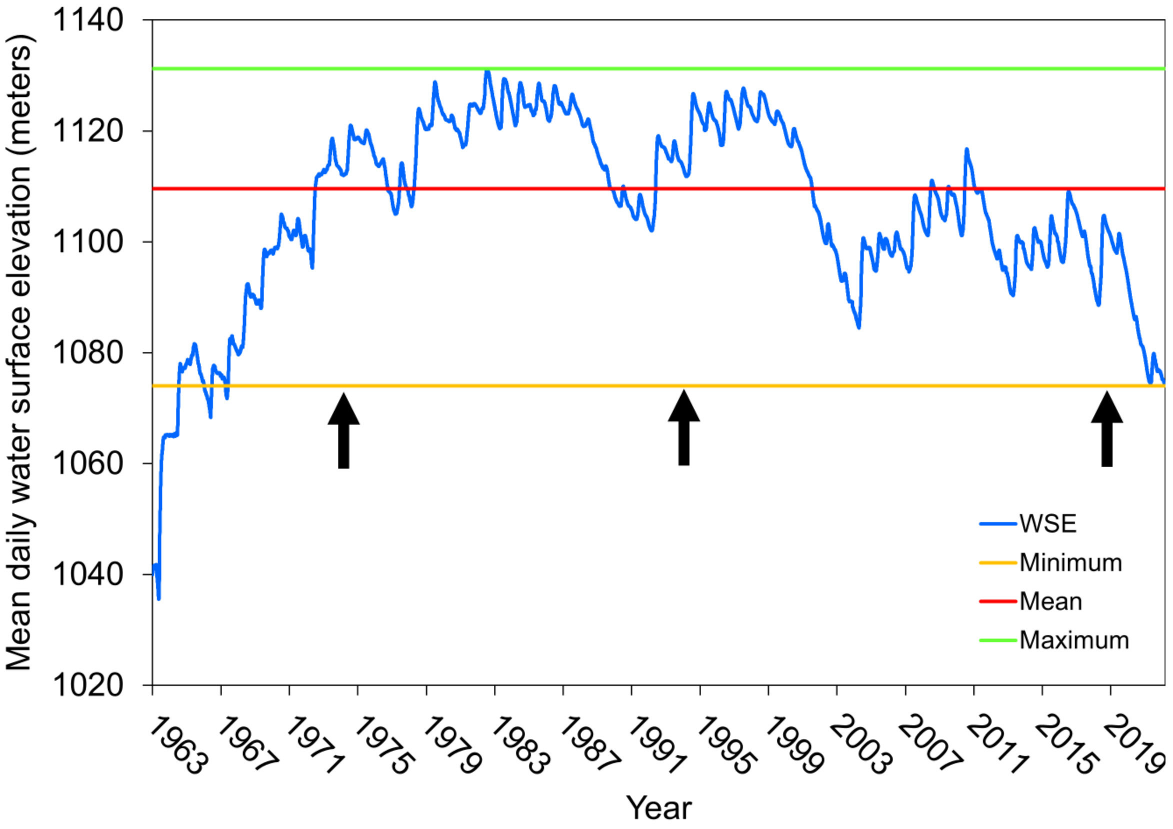


Figure 12. Record of Lake Powell reservoir pool elevations in meters for the period 1963 to 2021. Maximum, minimum and long-term mean reservoir pool elevations are given for the period commencing in 1980, when the reservoir reached full operating pool.

2.2.4 Reservoir Inflows and Climate-driven Change in Water Resources

The principal tributaries that most directly influence the delta/backwater system in Lake Powell include the Colorado, Green, and San Juan rivers, which contribute approximately 90% of the inflow to Lake Powell (Lukas et al. 2020). We obtained daily surface water discharge and suspended sediment data from USGS gages: 09379500 San Juan River near Bluff, UT; 09315000 Green River at Green River, UT; and 09180500 Colorado River near Cisco, UT, using the U.S. Geological Survey National Water Information System Mapper (https://maps.waterdata.usgs.gov/mapper/index.html). Combined mean daily discharge for the three rivers from 1914 to 2023 (Figure 13) illustrates the yearly variability in runoff, driven chiefly by variability in precipitation within the basin. The ratio of Lake Powell storage capacity to the mean annual runoff of the upper Colorado River is 2.4. In combination with Lake Mead, these two reservoirs store more than 4 times the average annual runoff. A declining trend in mean daily discharge over the period of record is evident as are decreases in the magnitude of peak flows as well as increases in low flows in the early 1960s. These observed shifts in discharge are consistent with the construction and operation of upstream, mainstem dams on the Green and San Juan rivers, which characteristically increase low flows and decrease peak flows.

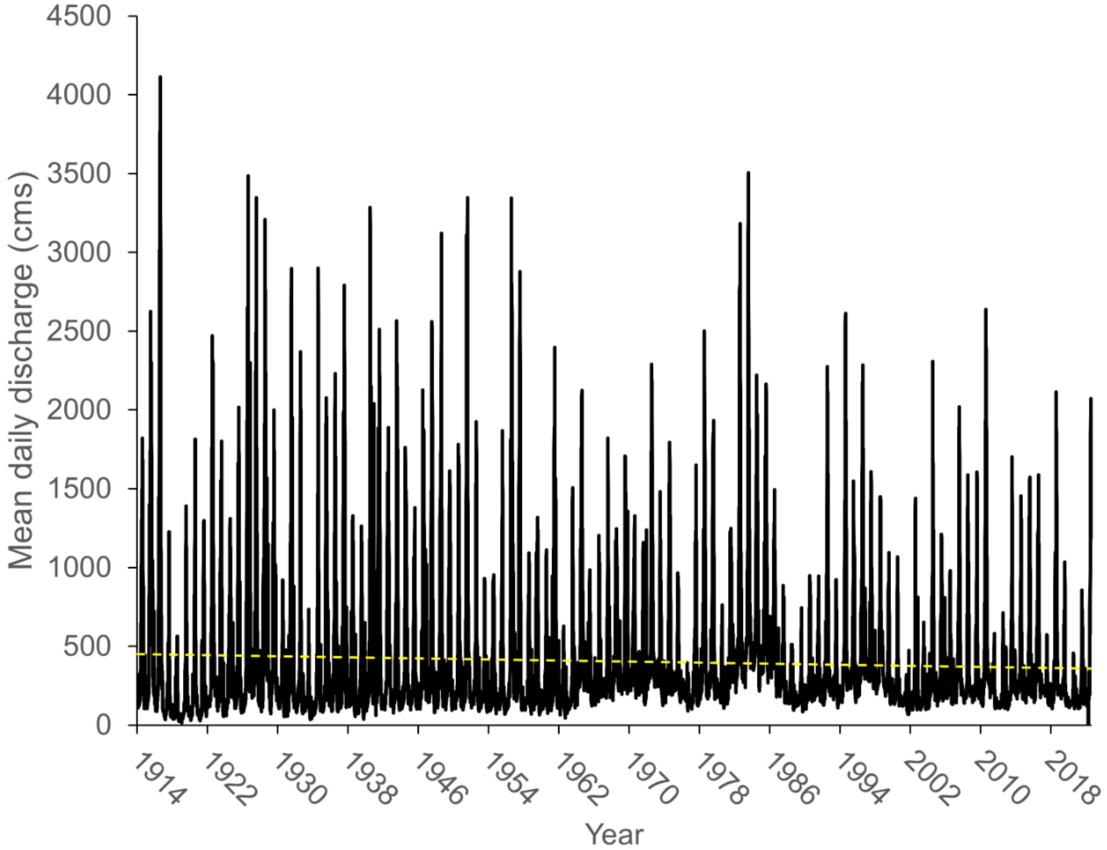


Figure 13. Plot of mean daily discharge in cubic meters per second (cms) representing the combined discharge of the Colorado, Green and San Juan rivers. The yellow dashed line is a fitted linear trend of average mean daily discharge for the period of record (1914-2023) showing a declining trend over the period.

A steady increase in temperature of 1.4 °C in the upper Colorado River basin has been documented over the past 40 years, with no corresponding trend in precipitation noted over the same period (Lukas et al. 2020). Flow in the Colorado River is sensitive to changes in temperature in the basin with an average 6.5% reduction in annual flow per 1 °C rise in annual temperature (Vano et al. 2014). Such sensitivity suggests that secular warming across the basin has and will have important implications for upper basin runoff and Colorado River flows into Lake Powell, and thus, the physical and ecological dynamics of the associated delta and backwater ecosystem. During the years 2000 to 2014, calculated natural upper basin flows at the Lees Ferry gage were the lowest (-19%) for any 15-year period in the historical record. An average of one third of this loss was attributed to temperature increases alone (Udall and Overpeck 2017). They make the case that past droughts within the Colorado River basin were primarily driven by reduced precipitation, whereas the most recent drought is partly the result of, and exacerbated by, a warming climate. They point to recent estimates of flow sensitivity to temperature and climate model-driven temperature projections to suggest declines in Colorado River flows of 20% by mid-twenty first century and 35% by end of century under business-as-usual greenhouse gas emissions.

As with the Missouri River and Fort Peck reservoir, we used The National Climate Change Viewer (https://www.usgs.gov/tools/national-climate-change-viewer-nccv) to compare predicted trends in runoff for two subregional Hydrologic Unit Codes (HUC-4 basins) in the upper Colorado River basin, for the period 2025-2049, compared against an historical (1981-2010) reference period (Figure 14). These results mirrored those from the Missouri River basin, which predicted runoff beginning and peaking earlier in the year than at present with significantly increased runoff in February and March and significantly reduced runoff in June, July, and August. Model output also indicates no significant increases in precipitation over the prediction period (2024 to 2049) with corresponding significant increases in vapor pressure deficits (except for March), significant decreases in snow water equivalent (March through June), significant reductions in soil water storage in the spring, and significant increases in evaporative deficit (Alder and Hostetler 2013).

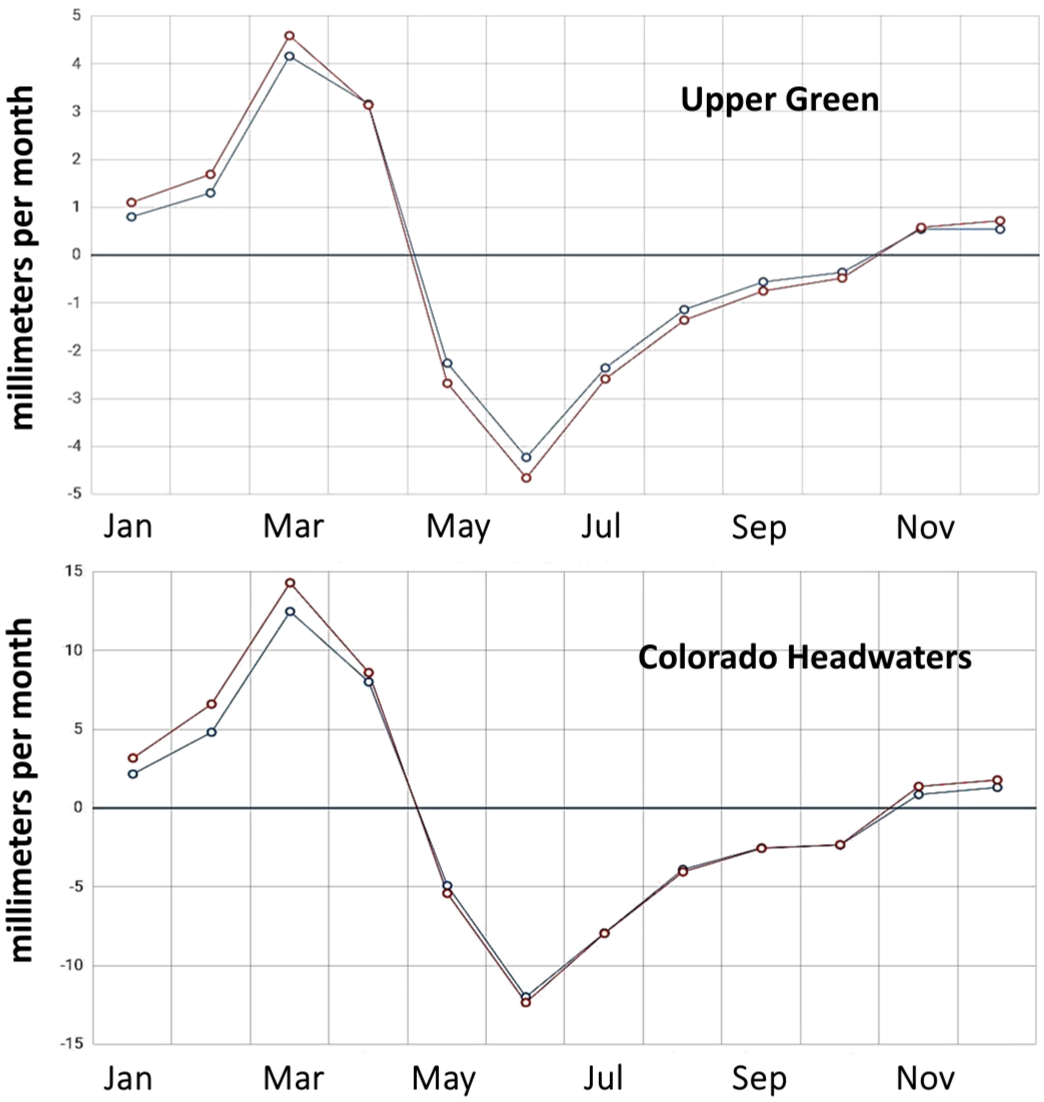


Figure 14. Predicted timing and magnitude of runoff (millimeters per month) for two hydrologic subregions (HUC-4) of the upper Colorado River basin, based on the USGS Climate Change Viewer (https://www.usgs.gov/tools/national-climate-change-viewer-nccv). The graphs compare predicted changes in runoff (mm per month) for the period 2024-2049, compared against a 1981-2010 reference period, using RCP4.5 (red lines) and RCP8.5 (blue lines) pathways for future atmospheric CO2 concentrations. Departures from 0 represent the timing and degree of change from the reference.

Suspended sediment inputs to Lake Powell were examined using combined measurements from the same USGS gages as those for daily discharge (see above) for the years 1941 through 1984. During the period of record, as on the Missouri River, suspended sediment inputs were pulsed with large inputs associated, but not exclusively, with larger mean daily discharges. Over the period of record, there is a declining trend in suspended sediment input with a slight increase in daily discharge, owing partly to large snowmelt runoff peaks in 1983 and 1984 (Figure 15).

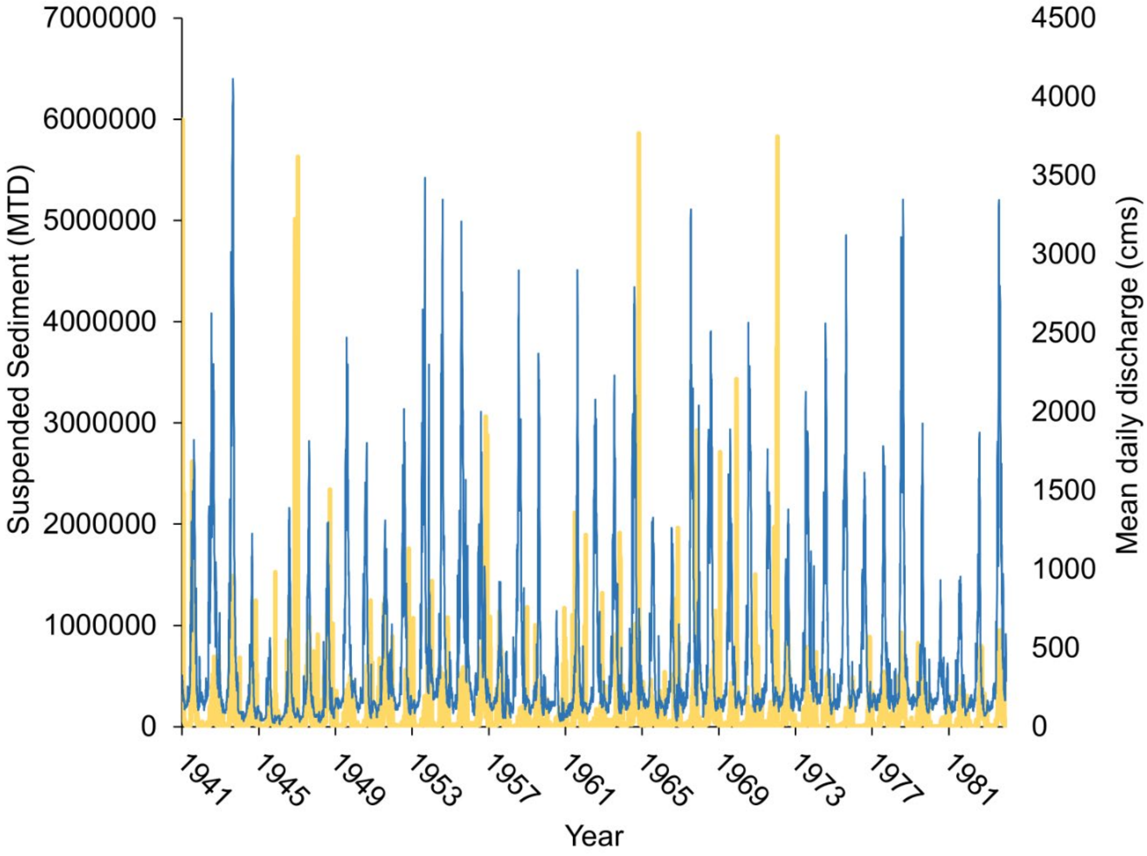


Figure 15. Combined suspended sediment discharge in metric tons per day (gold line) and mean daily discharge in cubic meters per second (blue line) for the San Juan River near Bluff, UT (gage #09379500); Green River at Green River, UT (gage #09315000); Colorado River near Cisco, UT (gage #09180500). Trend lines for suspended sediment (red dashed line) show a slightly declining trend over the period whereas discharge (blue dashed line) shows a slightly increasing trend resulting primarily from large snowmelt peak flows in the mid-1980s.

In the 23 years following the completion of Glen Canyon dam in 1963, 1,070,945,574 cubic meters of sediment accumulated below the conservation pool elevation of 1128 meters, including 64,264,308 cubic meters estimated to have accumulated in the original channels of the Colorado and San Juan rivers. As of 2022, the storage capacity of Lake Powell was estimated to be 31,034,356,800 cubic meters.

2.2.5 Topobathymetric Surveys

In contrast to Fort Peck reservoir, no sediment range lines were established prior to completion of Glen Canyon dam. Instead, 409 range line locations were established in 1986 to evaluate the water storage capacity of the reservoir, map the location of sediment deposits, and quantify loss of reservoir storage capacity resulting from sediment accumulation. With the reservoir near full pool, most of the sediment elevations were determined by bathymetric survey using sonic depth recording equipment. Backwater elevations were surveyed for the extreme upper reaches of the Colorado and San Juan rivers (Ferrari 1988). These elevations were used for determining channel cross-section elevations and the channel longitudinal profile in 1986. We were unable to locate digital data for the

1986 range lines and thus digitized those range lines that were included in a digital copy of the report. The report, however, did not include data for all the range lines, including the four upstream-most range lines.

The original pre-dam range line profiles were based on historical topographic surveys made of the future Colorado River arm of the reservoir in 1958-1959. These maps, at a contour interval of 3-meters, were digitized into vector data and a hydrologically corrected, 2-meter DEM was developed from this data using the Topo to Raster tool in ArcMap (https://www.usgs.gov/data/digital-elevation-model-glen-canyon-prior-flooding-lake-powell-historic-topographic-surveys). This DEM was then used to reconstruct pre-dam elevations at the range lines established in 1986.

Finally, we used a modified topobathymetric digital elevation model (TBDEM) for Lake Powell based on a 2017 1-meter multibeam bathymetric survey, a 2018 topographic lidar derived digital elevation model (DEM) and the DEM of historical topography described above. Because this modified TBDEM did not extend far enough to include our upstream-most range lines, we located existing 2021 elevation data (https://www.sciencebase.gov/catalog/item/61bd792cd34ee9cd54ed2a56, https://www.sciencebase.gov/catalog/item/61bd7933d34ee9cd54ed2a62) for these range lines using the USGS National Map downloader https://apps.nationalmap.gov/downloader/. Together, these data sources were used to visualize the spatial and temporal development of the Lake Powell delta and backwater by plotting elevation profiles across some of the range lines established in 1986. A longitudinal profile of the reservoir was constructed by plotting the lowest elevation at each of the range lines.

The average annual sediment accumulation rate for the first 23 years of the reservoir was estimated to be 45,572,152 cubic meters with most of the sediment being deposited between the minimum and maximum pool elevations (Figure 16). Sediment accumulation between 1986 and 2018 has decreased storage capacity of the reservoir by an additional 1,293,920,520 cubic meters (Root and Jones 2022). The relatively high stage of the reservoir during the 1980s resulted in the deposition of sediment between the maximum and long-term mean reservoir pool elevation as seen in the 1986 longitudinal sediment profile (Figure 16). These deposits now stand as exposed, high terraces as the river has incised these features to below mean pool elevations following the sustained declines in the reservoir pool beginning in 2000 (see Figure 12).

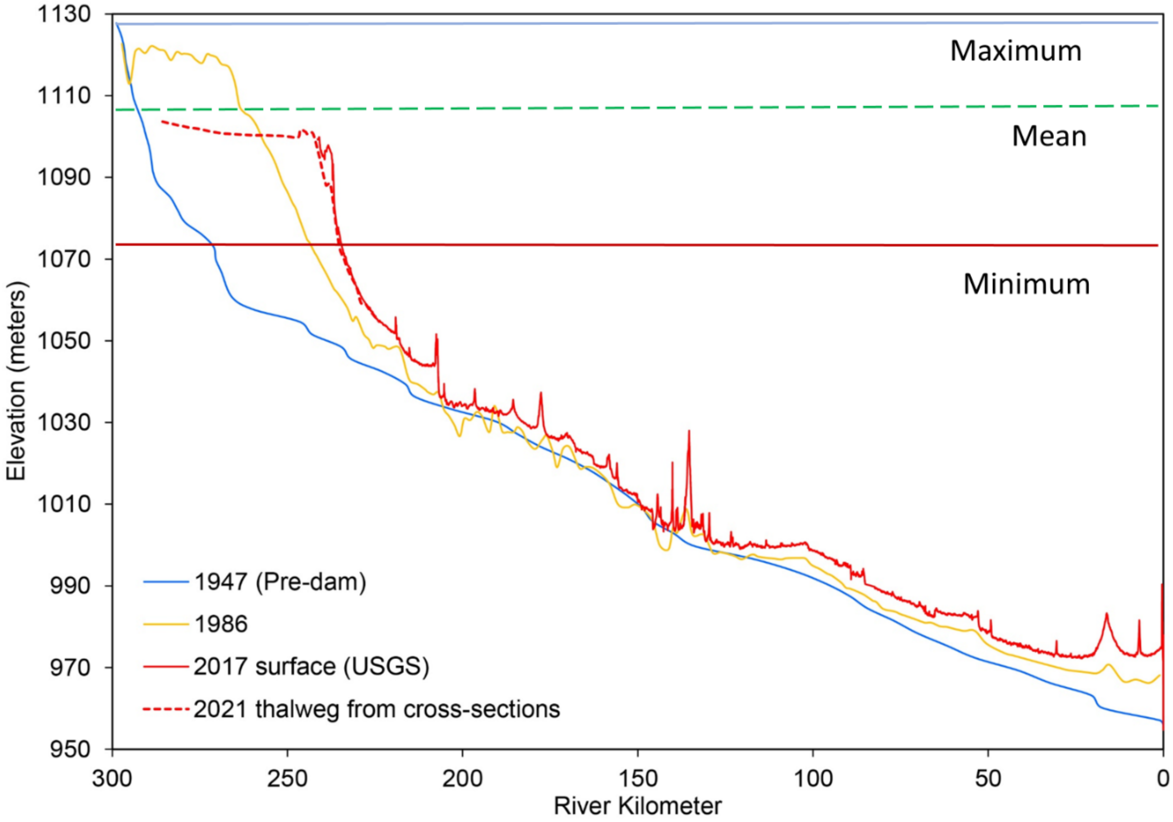


Figure 16. Longitudinal profile of the thalweg elevation (in meters) of the Colorado River above Glen Canyon dam, comparing three time periods: pre-dam (1958-1959, blue line); 1986 (orange line); and 2017 (green line). The closing of Glen Canyon dam and subsequent filling of Lake Powell, resulted in the deposition of sediment, particularly at the periphery of the reservoir and above the long-term minimum pool elevation.

The rapid redistribution of sediment related to this drop in pool elevation includes subaqueous gravity flows that move sediment at rates far greater than was originally transported by the river (Pratson et al. 2008). In the canyon-bound reach of the Colorado, the upstream-most range line (R360), occurs just downstream of where the 3700-foot contour line crosses the river (USGS National Map). Thus, the range lines established in 1986 as part of the first Lake Powell sediment survey extended only to the top of the reservoir affected reach. The longitudinal slope of the pre-dam Colorado River channel is much steeper than that of the Missouri River, so the Lake Powell delta likely does not extend as far upstream as the Fort Peck delta. Because the surveyed range line data are not as spatially and temporally robust as that for Fort Peck, we were not able to characterize geomorphic changes that may have occurred in non-backwater and backwater affected reaches as we did with Fort Peck reservoir. Instead, we provide data from range lines that reflect geomorphic changes across the range of reservoir affects. At range line 360, the pre-dam and 2021 elevations show essentially the same channel elevation with possible narrowing of the channel (Figure 17) although a visual comparison of imagery from 1959 with current World Imagery (Esri), at range line 360, shows no apparent change consistent with left bank surface inflation of >5 meters. This evidence suggests that this range line is upstream of significant reservoir affected geomorphic change to the Colorado River channel.

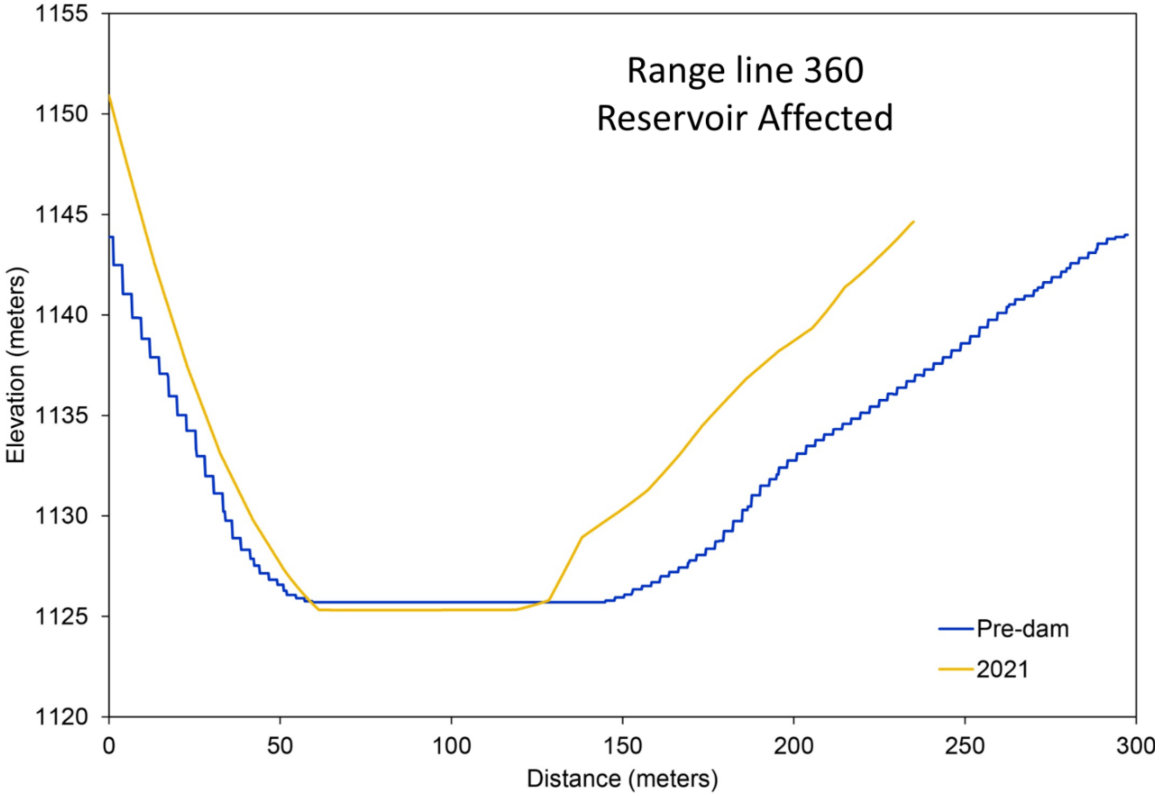


Figure 17. Channel cross-sectional elevations for pre-dam (1953) and 2021 at the upstream-most range line (360), near the full pool elevation.

In contrast, range lines closer to the current subaerial delta show filling of the original Colorado River channel by 1986 with up to 60 meters of sediment. Incision of deposited sediments is evident by 2021 as baselevels shift in response to declines in reservoir pool elevations (Figure 18).

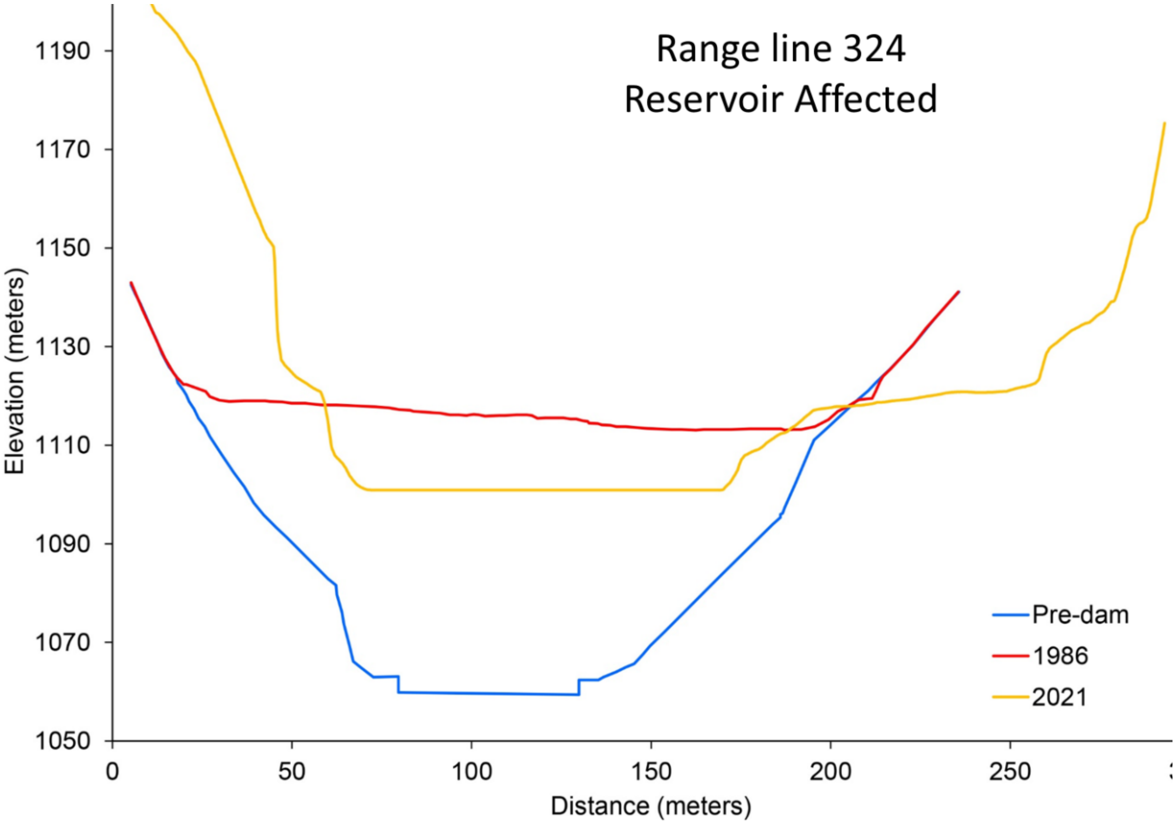


Figure 18. Channel cross-sectional elevations in 1953 (pre-dam), 1986 and 2021, at range line 324 in the reservoir affected reach of the AOI.

2.3 Lake Mead

Lake Mead is the reservoir formed by Hoover Dam, which impounds the Colorado River in Nevada and Arizona (Figure 19). Hoover Dam began storing water on February 1, 1935, and is a concrete gravity arched structure with a hydraulic height of 180 meters and crest length of 379 meters (Ferrari 2008a). There are two identical spillways along the Arizona and Nevada canyon walls with a combined capacity of about 1,784 cms. A recomputed estimate of the original storage capacity of Lake Mead was 39,942,277,994 cubic meters. The most recent 2001 survey estimated a total storage capacity of 36,978,509,255 cubic meters. Completion of Glen Canyon Dam in 1963, about 370 river miles upstream, altered the Hoover Dam flood control operation and significantly lowered sediment loads entering Lake Mead by reducing the drainage area that contributes sediment by about two thirds.

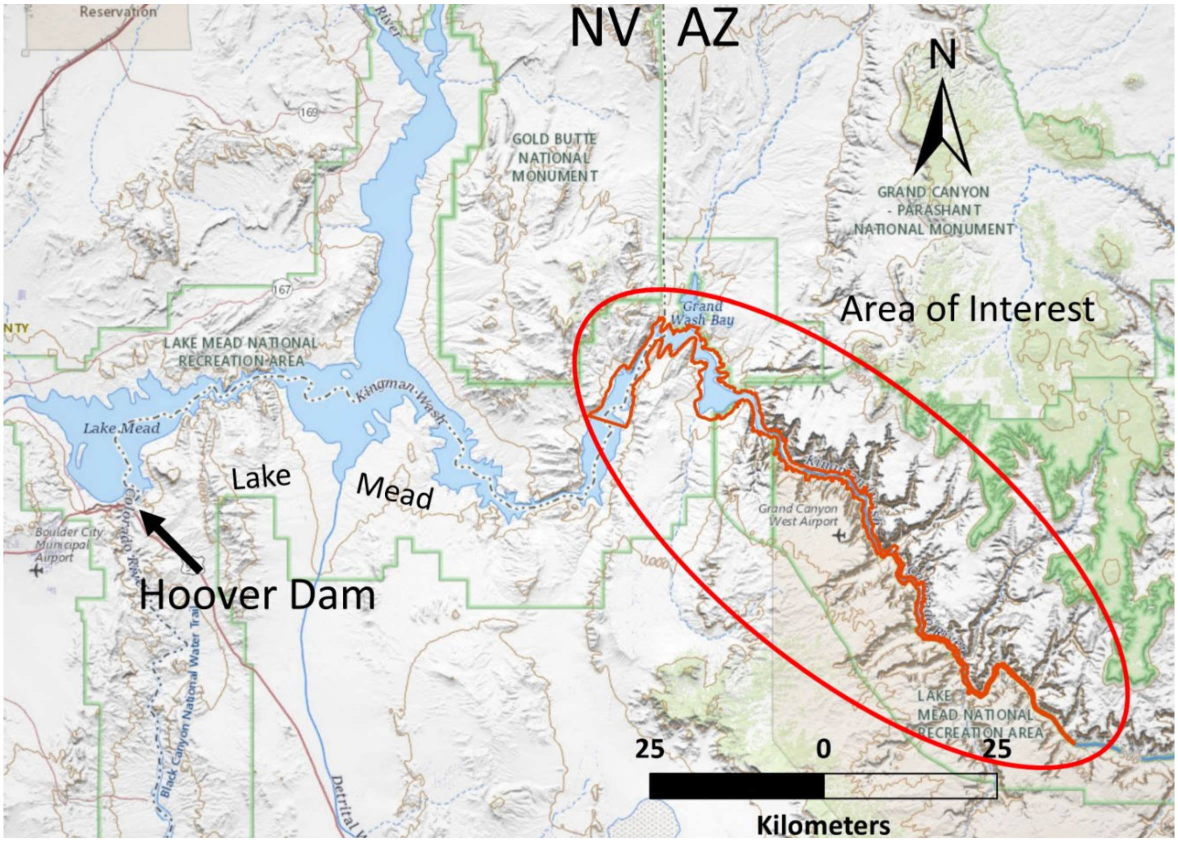


Figure 19. Location map showing Hoover dam, Lake Mead (reservoir) and this investigation's AOI, which includes the current delta and backwater formed by Lake Mead reservoir, Arizona and Nevada.

2.3.1 Watershed Characteristics

The drainage area that contributes sediment above Hoover Dam was 444,183 square kilometers before Glen Canyon Dam closed in March 1963, which reduced the sediment contributing area to 154,881 square kilometers. The 2001 sedimentation survey calculated that the weighted-average drainage area was 273,373 square kilometers between 1935 and 2001 when accounting for the time ratio when Glen Canyon Dam began controlling upstream sediment delivery. Lake Mead has an average width of 2.66 kilometers, ranging from hundreds of meters to 13 kilometers. The total length is 245 kilometers, which combines the Colorado and Overton reaches (Ferrari 2008a). Other watershed characteristics are consistent with those described above for Lake Powell.

2.3.2 Aerial Imagery

Several image dates are available to interpret and quantify changes in fluvial, geomorphic, and vegetation condition across the Lake Mead delta and backwater related to the filling and fluctuations of the reservoir pool (1950, 1958, 1965, 1971, 1976, 1981, 1990, 1995, 2005, 2010, 2017). We obtained the imagery from USGS Earth Explorer. Older images were not orthorectified, which required post-processing with Agisoft Metashape and GIS tools to develop consistent georeferenced images for all years. Analysis of the aerial imagery will be described in a subsequent study.

2.3.3 Reservoir Stage

The Lake Mead reservoir pool filled rapidly after water storage began in 1935, reaching within three decimeters of the spillway crest on August 6, 1941, before the Arizona spillway gates were lowered (Ferrari 2008a). The stage decreased during the mid-1940s and remained near the long-term mean through the early-1950s before further decreasing during the mid-1950s (Figure 20, data provided by Reclamation's Lower Colorado Basin Region, Water Operations Control Center). Reservoir elevations increased and then lowered again from the mid-1950s to the mid-1960s. The stage increased to near full pool in 2000 before decreasing during the ongoing drought.

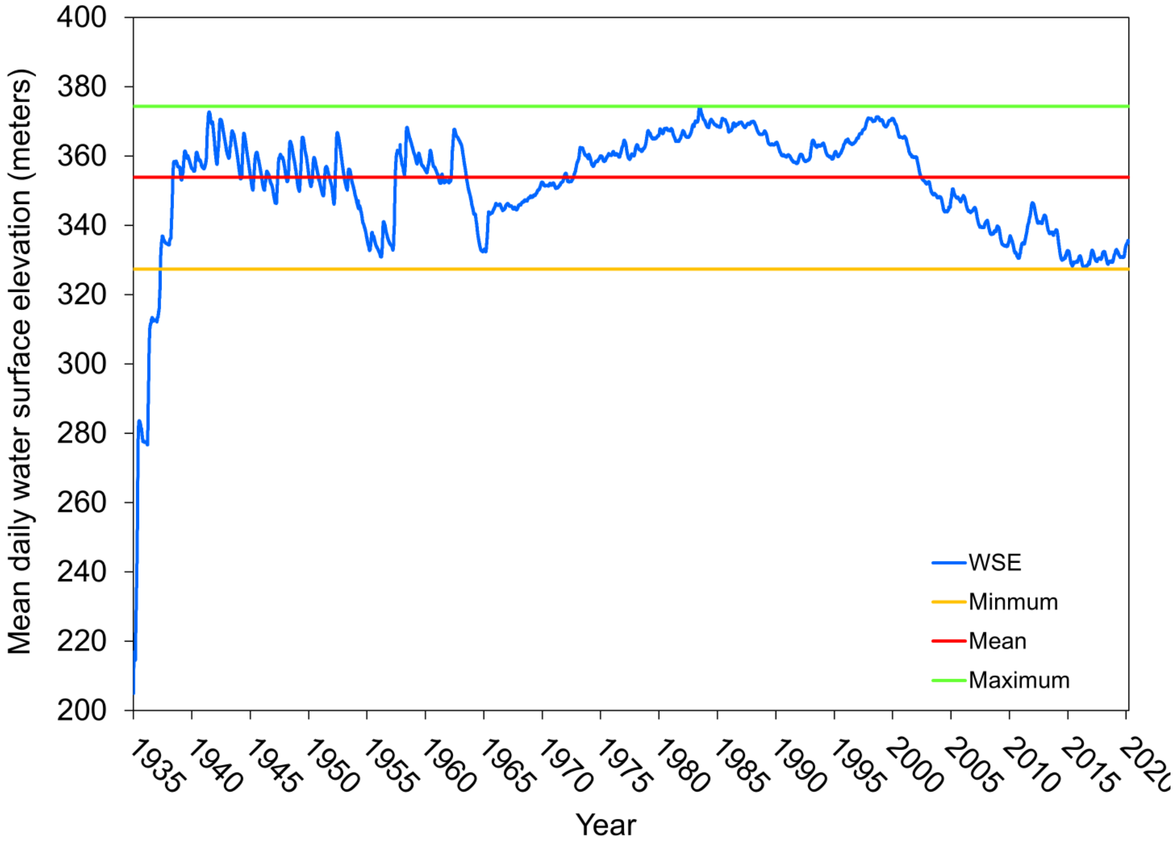


Figure 20. Record of Lake Mead reservoir pool elevations in meters above sea level (meters) for the period 1935 to 2020. Maximum, minimum and long-term mean reservoir pool elevations are given for the period commencing in 1946, when the reservoir reached full operating pool.

2.3.4 Reservoir Inflows and Climate-driven Change in Water Resources

Reservoir inflows to Lake Mead exhibit similar trends as the upstream Lake Powell inflows after 1963. Peak flows and overall variability were much larger prior to the closure of Glen Canyon Dam, reflecting a more natural hydrograph and a wetter hydrologic period during the early 1900s (Figure 21). Taken together, Lake Powell and Lake Mead store more than 4 times the average annual runoff of the Colorado River basin.

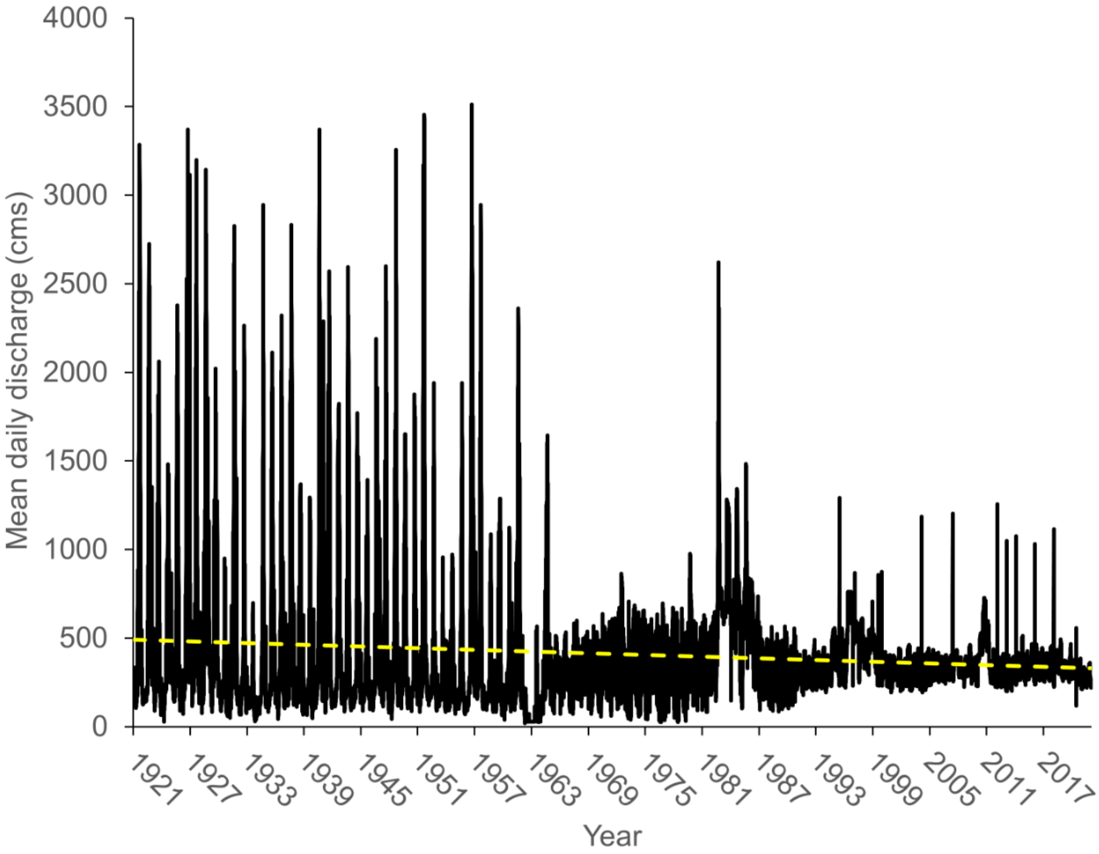


Figure 21. Plot of mean daily discharge in cubic meters per second (cms) for the Colorado River near Grand Canyon, Arizona. The yellow dashed line is the fitted linear trend line of average mean daily discharge for the period of record (1921-2022). Note the effect of upstream closing of Glen Canyon Dam, particularly on the decreased magnitude of high flows after 1963 and the increase in low flows beginning about 1993, reflecting a change in operating rules. Relatively regular small peaks after 1993 are planned High Flow Experiments.

2.3.5 Topobathymetric Surveys

Ferrari (2008a) details the 2001 sedimentation survey, which is the most recent full survey of Lake Mead. That report also summarizes previous survey efforts and presents data from 1935, 1948, and 1963 (Figure 22). Ferrari (2008a) calculated that about 2,960,352,000 cubic meters of sediment accumulated between 1935 and 2001 with an average annual rate of 44,405,280 cubic meters. Results from the 1963 survey indicate that the average annual sedimentation rate was 108,546,000 cubic meters during the first 30 years of reservoir operations. Figure 23 (upstream) through Figure 25 (downstream) present cross sections that illustrate sediment accumulation for different reaches of the reservoir pool.

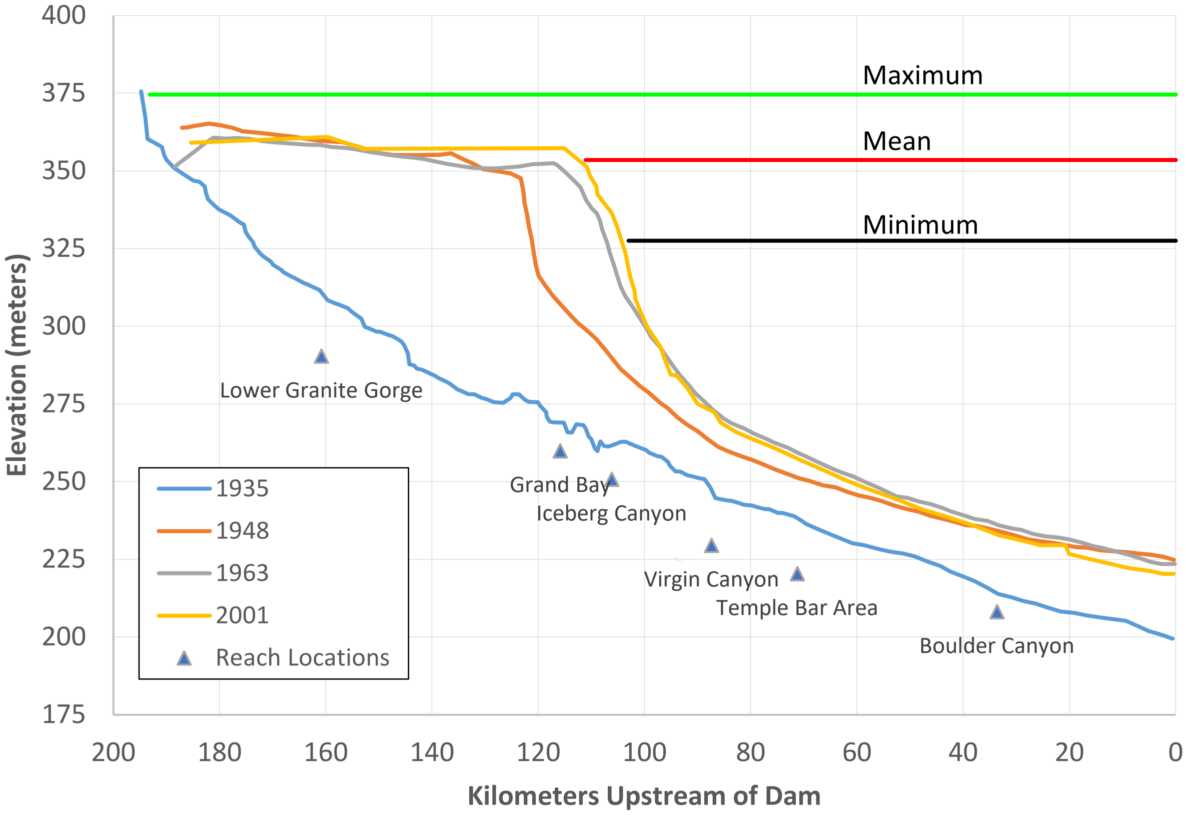


Figure 22. Longitudinal profile of the thalweg elevation (in meters) of the Colorado River above Hoover Dam, comparing four time periods: 1935 (blue line), 1948 (dark orange line), 1963 (gray line) and 2001 (light orange line). The closing of Hoover Dam and subsequent filling of Lake Mead, resulted in the deposition of sediment, particularly at the upper edges of the reservoir and above the long-term minimum pool elevation. Points represent range line locations for channel cross section elevations.

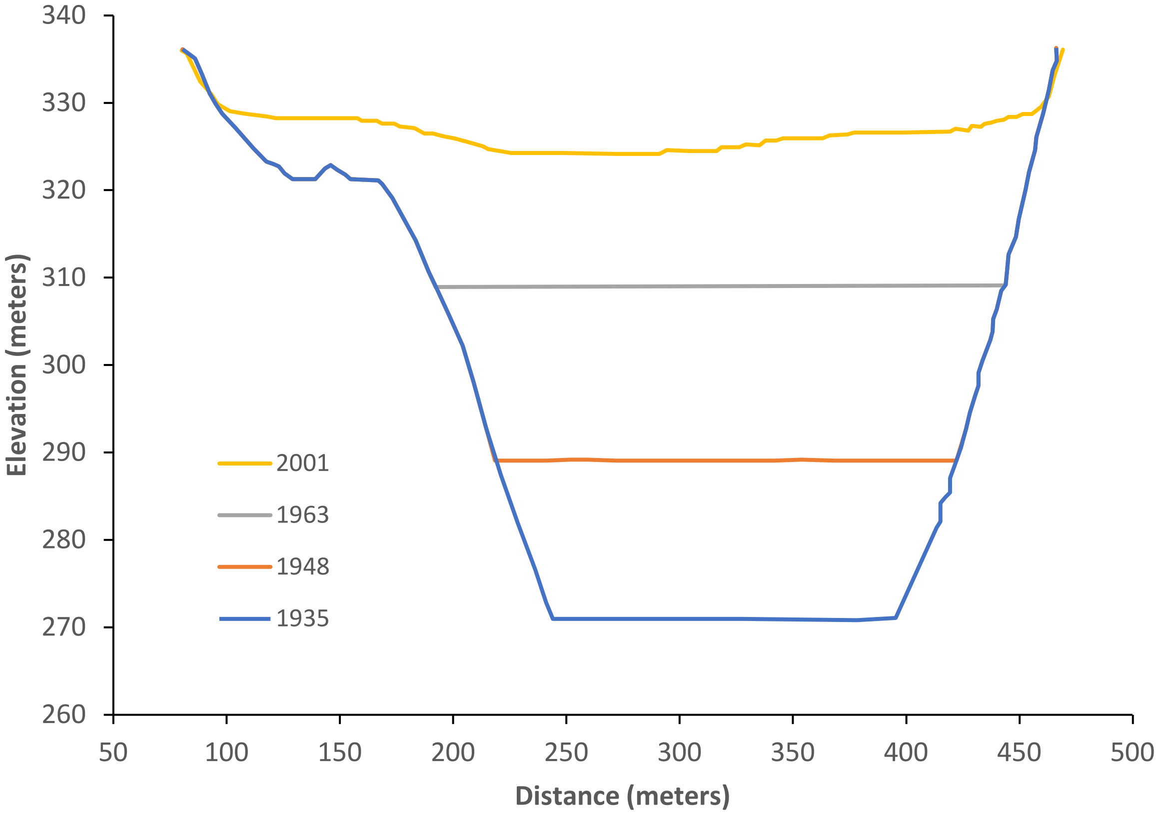


Figure 23. Channel cross-sectional elevations from 1935 through 2001 at the upstream-most range line in Lower Granite Gorge. Note the progressive filling of the channel associated with the filling of Lake Mead behind Hoover Dam.

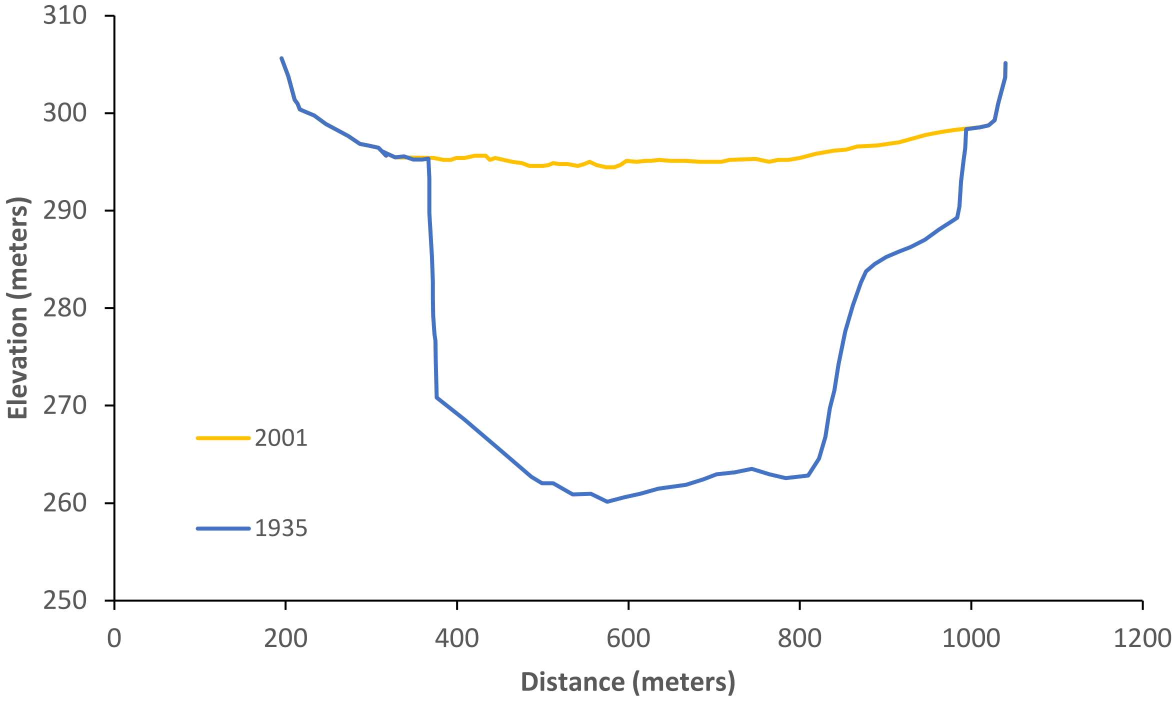


Figure 24. Channel cross-sectional elevations from 1935 and 2001 at the range line in Grand Bay. Sediment deposits here represent maximum accumulations of 38 meters.

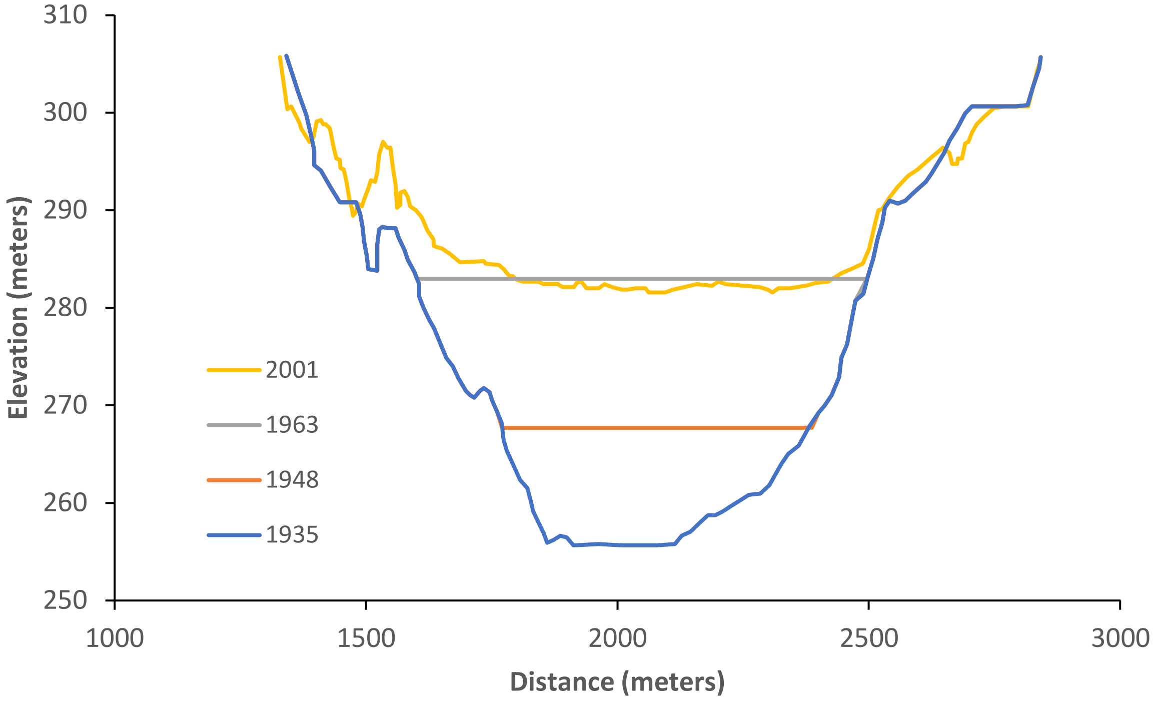


Figure 25. Channel cross-sectional elevations from 1935 through 2001 at the range line in Iceberg Canyon.

2.4 Elephant Butte Reservoir

Elephant Butte Reservoir is formed by Elephant Butte Dam, which impounds the Rio Grande in southern New Mexico (Figure 26). Elephant Butte Dam began storing water in January 1915, and is a concrete gravity structure with a hydraulic height of 60 meters that provides water for irrigation and power generation. Additional benefits include recreation and flood risk reduction (Randle and Benoit 2019).

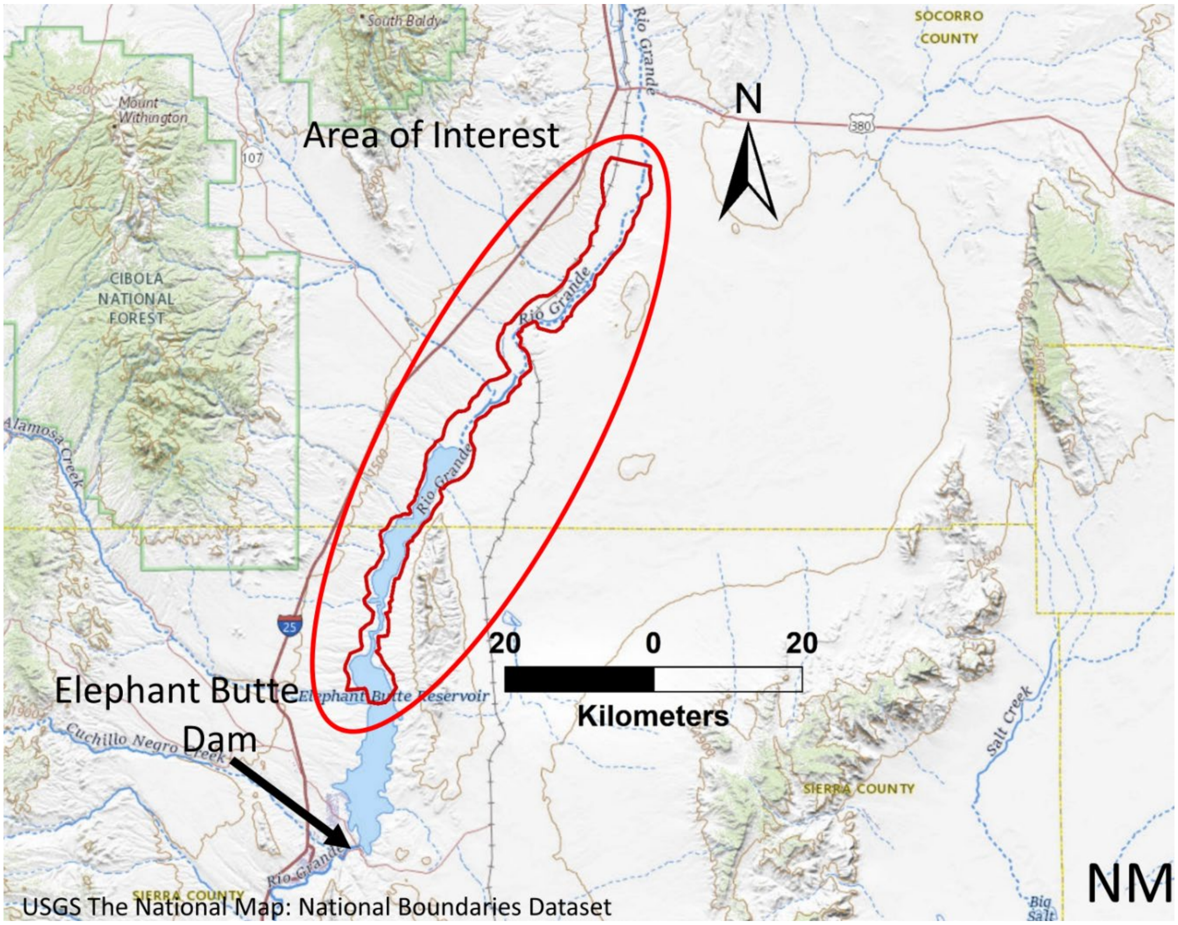


Figure 26. Location map showing Elephant Butte dam, Elephant Butte reservoir and this investigation's AOI, which includes the current delta and backwater formed by Elephant Butte reservoir, New Mexico.

2.4.1 Watershed Characteristics

The net sediment-contributing drainage area to Elephant Butte is 31,002 square kilometers (Ferrari 2008b), which is 45 percent of the contributing watershed area of 26,510 mi^2 (Randle and Benoit 2019). Cochiti Dam and Reservoir, along with other upstream lakes and reservoirs that trap sediment, comprise the other 55 percent of the watershed. The watershed of the sediment contributing drainage area is steep, mostly arid, dissected by numerous arroyos, and has cities, towns, and pueblos along the Rio Grande valley.

The most dominant surficial geologic types in the sediment-contributing drainage area are clastic sedimentary rock (31.4%), undifferentiated unconsolidated (22.1%), unconsolidated and sedimentary

(17.5%), volcanic (15.2%), and undifferentiated sedimentary (7.5%). A variety of other rocks compose the other 6.3 percent (Randle and Benoit 2019). The unconsolidated sediments (40 percent of drainage area) are much more erodible than the rock. These unconsolidated sediments have formed the Rio Grande valley from near Cochiti Dam downstream to near San Acacia, NM. The flood plains and terraces of the valley are composed of alluvium and contribute large quantities of sediment to the Rio Grande (Randle and Benoit 2019).

2.4.2 Aerial Imagery

Reclamation's Albuquerque Area Office and Denver Technical Service Center have maintained a database of aerial imagery spanning the years 1935 to 2022. Images are available approximately every 10 to 20 years during this period to interpret and quantify changes in fluvial, geomorphic, and vegetation condition across the Elephant Butte delta and backwater related to the filling and fluctuations of the reservoir pool. Analysis of the aerial imagery will be described in a subsequent study.

2.4.3 Reservoir Stage

The Elephant Butte reservoir pool filled rapidly after water storage began in 1915, nearly filling in July 1920. The stage remained high until the reservoir spilled in 1941 before decreasing during a period of low flow years in the mid- to late-1940s (Figure 27, data from https://www.usbr.gov/rsvrWater/HistoricalApp.html). The reservoir remained low through 1978 when a series of wet years filled the reservoir in the 1980s. At the onset of the current drought in 2000, the reservoir pool lowered and has remained below the long-term mean elevation. The approximately 37-meter decrease in reservoir stage from 1999 to 2019 corresponds to a longitudinal decrease in wetted reservoir length of about 40 kilometers (25 river miles, RM) (Figure 28). Reservoir pool fluctuations cause changes to the upstream channel bed elevation (Figure 29). Locations near the reservoir pool respond quickly and at a larger magnitude, while locations further upstream have a lagged response with a more stable bed elevation.

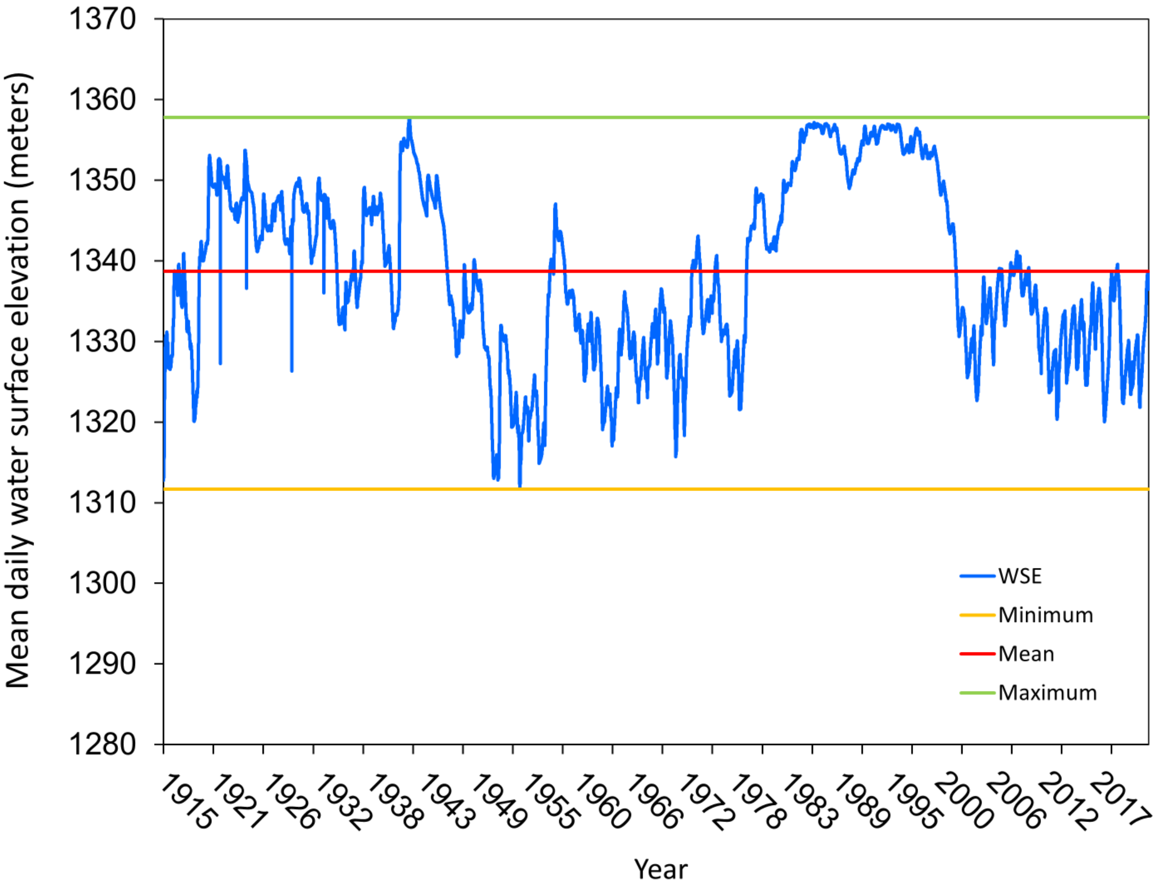


Figure 27. Record of Elephant Butte reservoir pool elevations in meters above sea level (meters) for the period 1915 to 2021. Maximum, minimum and long-term mean reservoir pool elevations are given for the period commencing in ~1920, when the reservoir approached full operating pool.

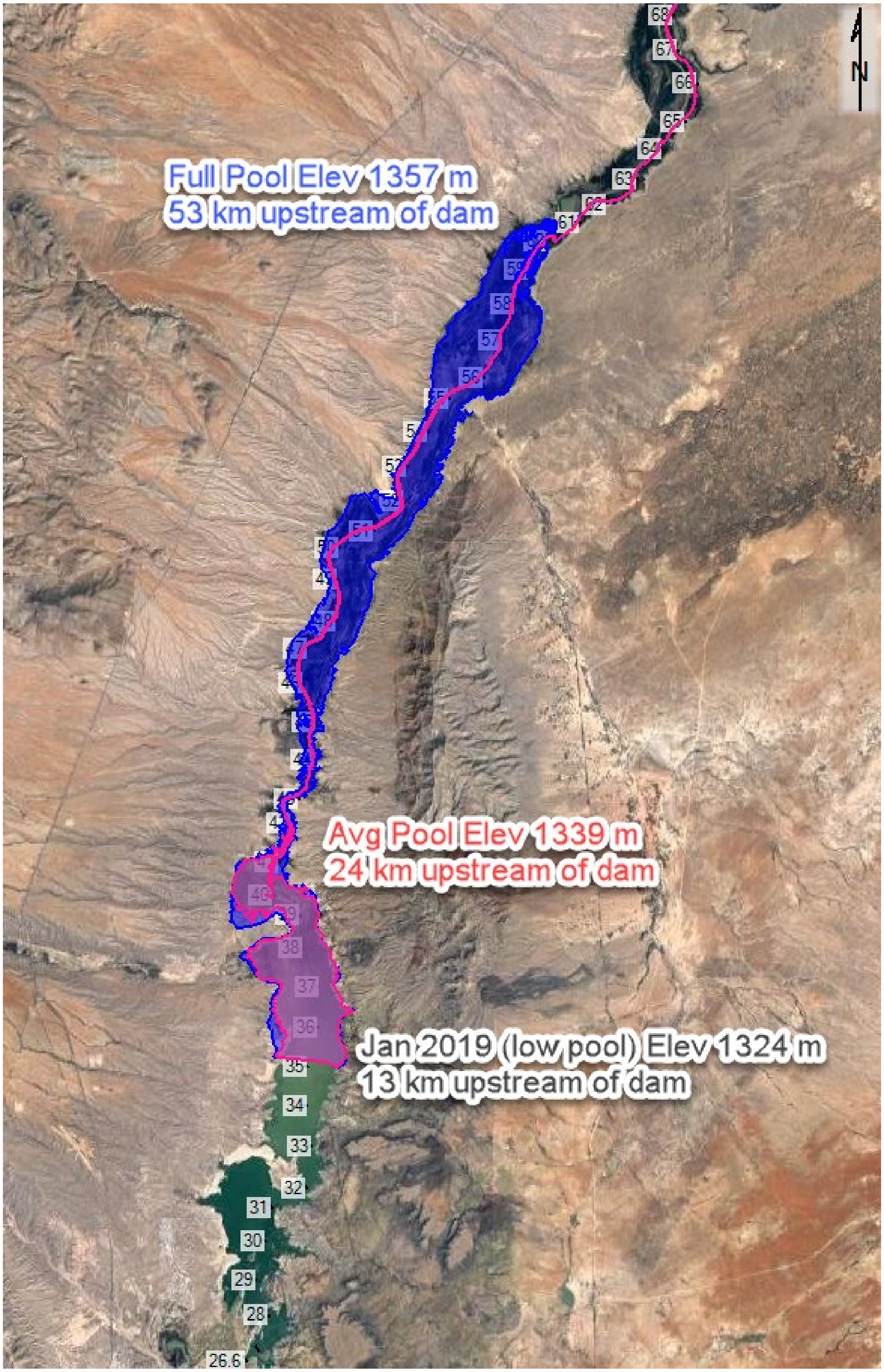


Figure 28. Spatial extent of average (pink) and full pool (blue) reservoir elevations overlain on January 2019 terrain surface (recent low pool elevation). Rio Grande also shown in pink with labeled river miles.

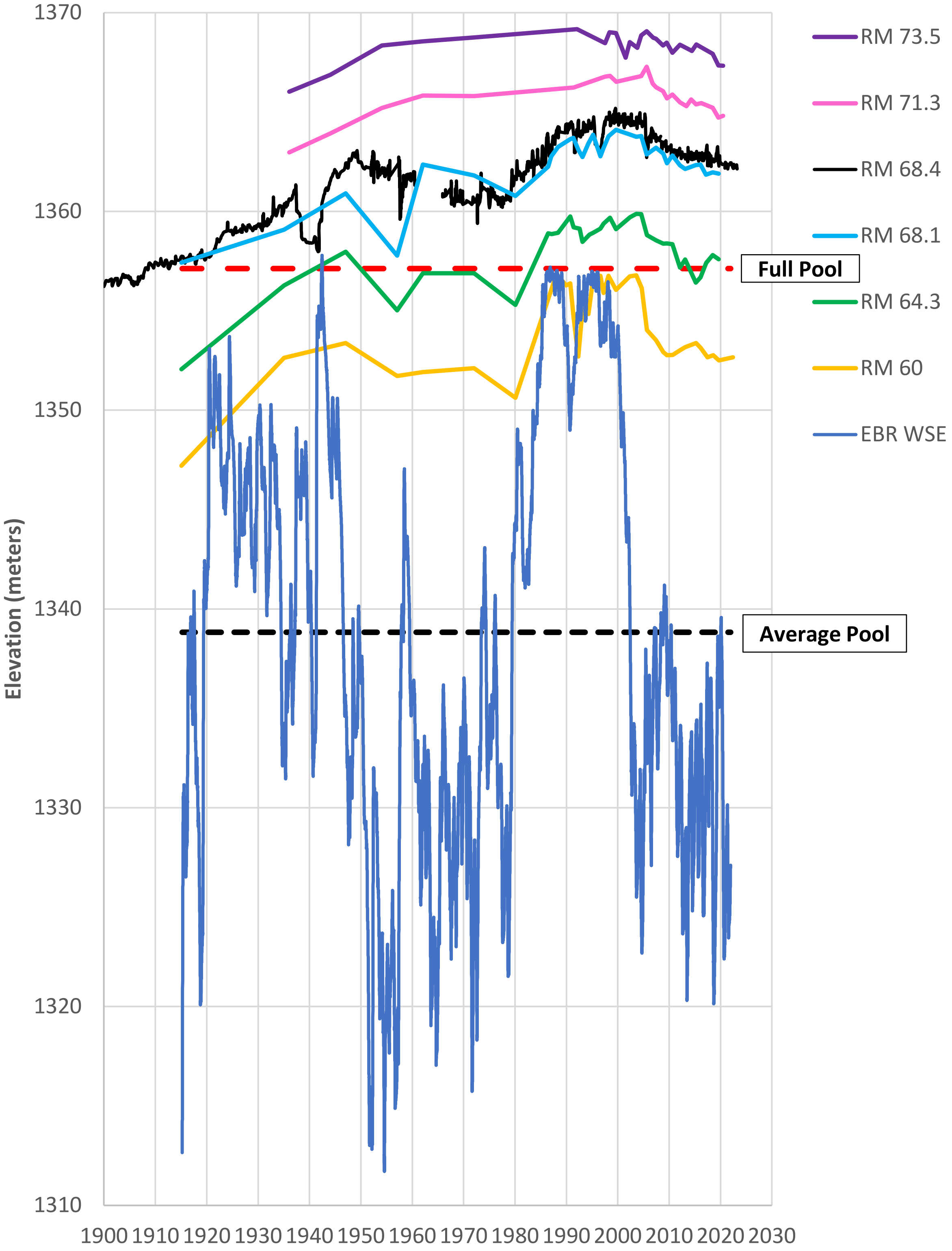


Figure 29. Comparison of Elephant Butte Reservoir water surface elevation (EBR WSE) to channel bed elevation at various river miles (RM). Elevations at RM 68.4 are from the USGS San Marcial river channel gages (08358400 and 08358500).

2.4.4 Reservoir Inflows and Climate-driven Change in Water Resources

Reservoir inflows are primarily from the Rio Grande (93% of the total contributing drainage area) (Randle and Benoit 2019). Stream flows are highly variable, both seasonally and from year to year. Based on San Marcial stream flow records from water years 1964 through 2016, the mean-annual runoff is 624,523,259 cubic meters per year (20 cubic meters per second, cms). The average annual runoff from the contributing arid watershed is 0.91 centimeters per year. This runoff is primarily from snowmelt in the upper portions of the watershed and infrequent monsoon storms in the lower portions of the watershed. The ratio of Elephant Butte Reservoir storage capacity to the mean annual runoff is nearly 4. During the early 1950s, Reclamation constructed the Low Flow Conveyance Channel (LFCC) to divert water from the Rio Grande at San Acacia and deliver it to the reservoir in a separate channel for the Rio Grande Compact. Nearly all flows less than 57 cms were diverted during many years in the 1950s–1970s (Figure 30). The San Acacia diversion has not operated since 1985 and the LFCC collects groundwater and irrigation return flows. Inflows to Elephant Butte can be approximated by adding the USGS San Marcial gages for the Rio Grande and LFCC.

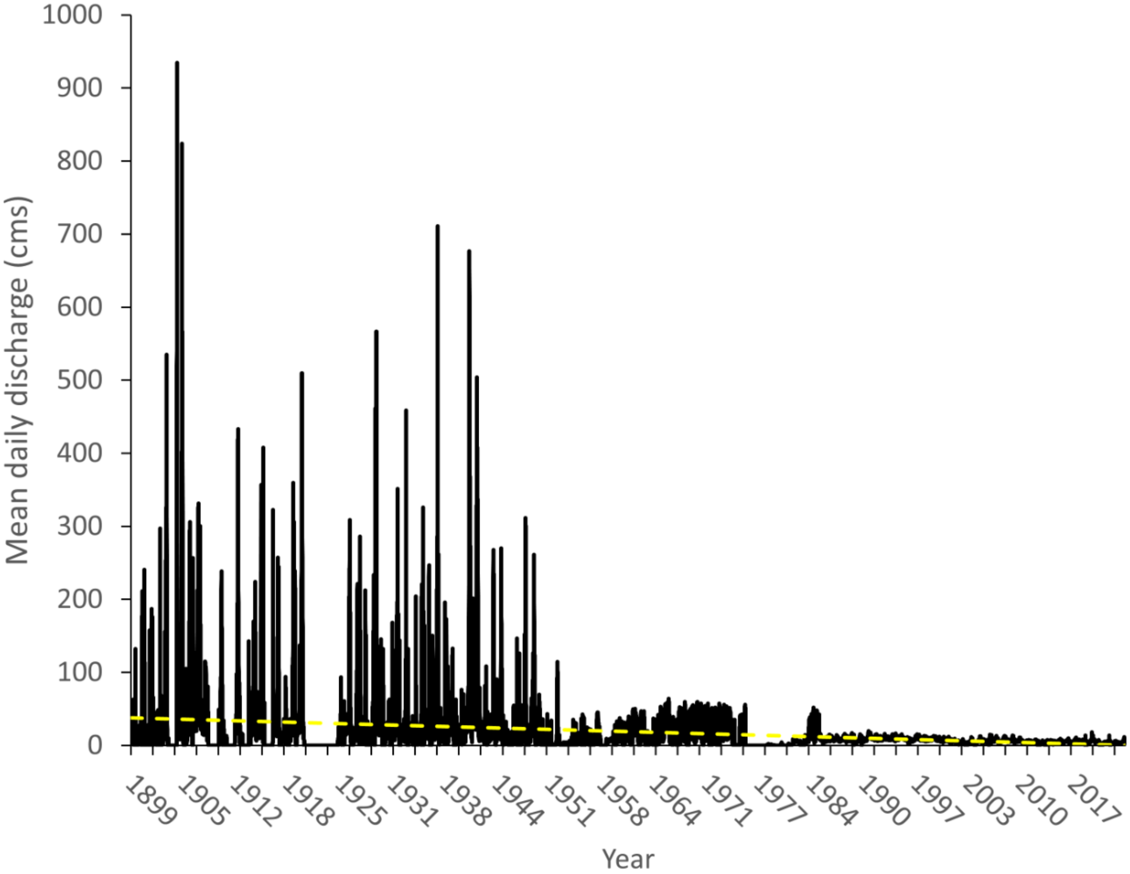


Figure 30. Plot of mean daily discharge in cubic meters per second (cms) for the Rio Grande at San Marcial, NM. The measured discharge from 1899 to 1951 is from USGS gage 08358500. From 1951 to the present, discharge is the combined flow of USGS gages 08358500, 08358400 and 08358300, at San Marcial. The yellow dashed line is the fitted linear trend line of average mean daily discharge for the period of record (1899-2023).

Climate change predictions estimate that the Rio Grande headwaters will have an earlier snowmelt runoff in March with a decrease during May and June when runoff typically peaks (Figure 31). The model also predicts lower summer monsoon runoff on average.

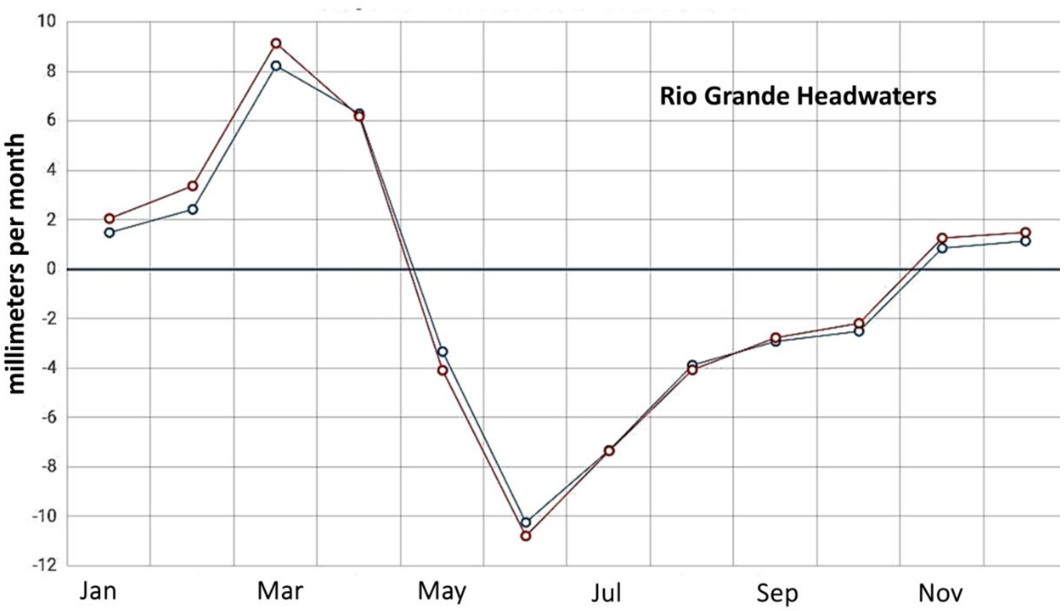


Figure 31. Predicted timing and magnitude of runoff (millimeters per month) for the hydrologic subregion (HUC-4), Rio Grande Headwaters, based on the USGS Climate Change Viewer (https://www.usgs.gov/tools/national-climate-change-viewer-nccv). The graphs compare predicted changes in runoff (mm per month) for the period 2024-2049, compared against a 1981-2010 reference period, using RCP4.5 (red lines) and RCP8.5 (blue lines) pathways for future atmospheric CO2 concentrations. Departures from 0 represent the timing and degree of change from the reference.

2.4.5 Topobathymetric Surveys

Prior to dam closure and initial reservoir filling, a topographic survey was conducted in 1903-1904 and 1907-1908 to measure the original surface areas and corresponding storage capacities (Randle and Benoit 2019). Plane-table survey would have been the most likely method for this period. A 10-foot contour interval map was produced from this original survey.

Range lines were surveyed along the reservoir prior to the initial storage in 1915. These range lines have been surveyed multiple times since 1915 (Table 3). Range line EB-90 is near the dam while range line EB-9 is upstream from the reservoir and under the influence of the reservoir delta (Ferrari 2008b). A complete bathymetric (multibeam) survey of the reservoir was conducted during June 2017. Above water, the topographic surface was surveyed by lidar on January 17, 2019. Comparing longitudinal profiles from the most recent surveys to the original 1915 survey demonstrates that about 15 meters of sediment has deposited in the subreach near the average pool elevation (Figure 32). Most of the total sediment deposition occurred within the first 20 years after water storage began (1915-1935) and the bed elevation continued to increase within the upstream channel through

2002. Between 2002 and 2012, the channel incised as a headcut migrated upstream in response to the lower reservoir pool levels in the early to mid-2000s (Figure 33).

Table 3. Previous Bathymetric Reservoir Surveys of Elephant Butte Reservoir

Survey Year	**Extent of Survey**	**Survey Method**	**Depth Sounder**	**Above water survey**
1915	Full	Contour		Plane table assumed
1925	Partial	Range line		
1935	Full	Range line		
1940	Partial	Range line		
1946	Full	Range line		
1951	Partial	Range line		
1957	Full	Range line	Single beam	No change assumed
1969	Full	Range line	Single beam	No change assumed
1980	Full	Range line	Single beam	No change assumed
1988	Full	Range line	Single beam	No change assumed
1999	Full	Range line	Single beam	1980 photo revised U.S. Geological Survey 7.5 minute quadrangle map
2007	Full	Surface Mapping	Multibeam	USGS Quadrangle contours and 2004 and 2007 lidar surveys
2017 & 2019	Full	Surface Mapping	Multibeam	2019 lidar

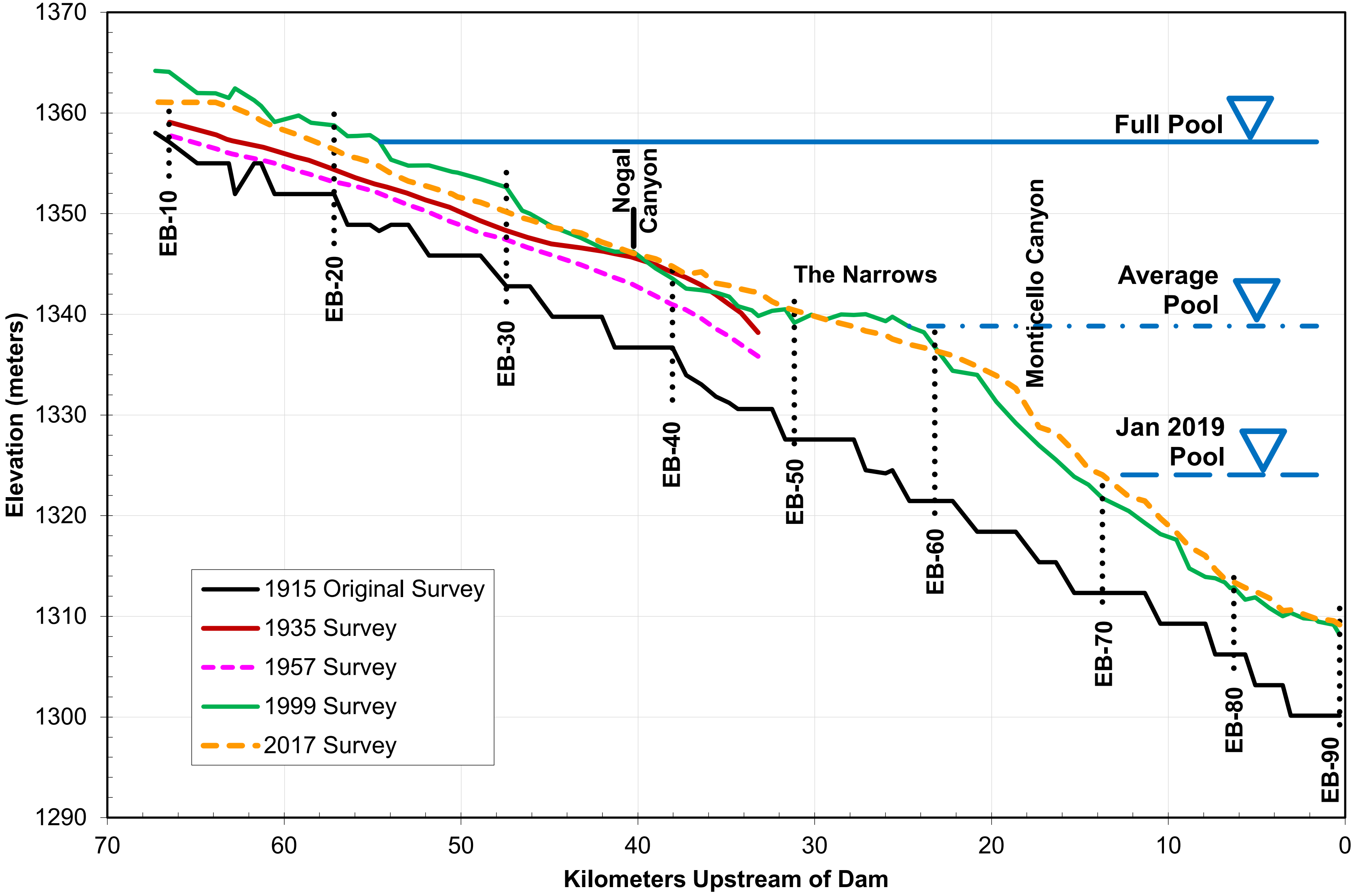


Figure 32. Longitudinal extent of full pool, average pool, and January 2019 pool elevation overlain on reservoir longitudinal profiles (modified from Randle and Benoit 2019).

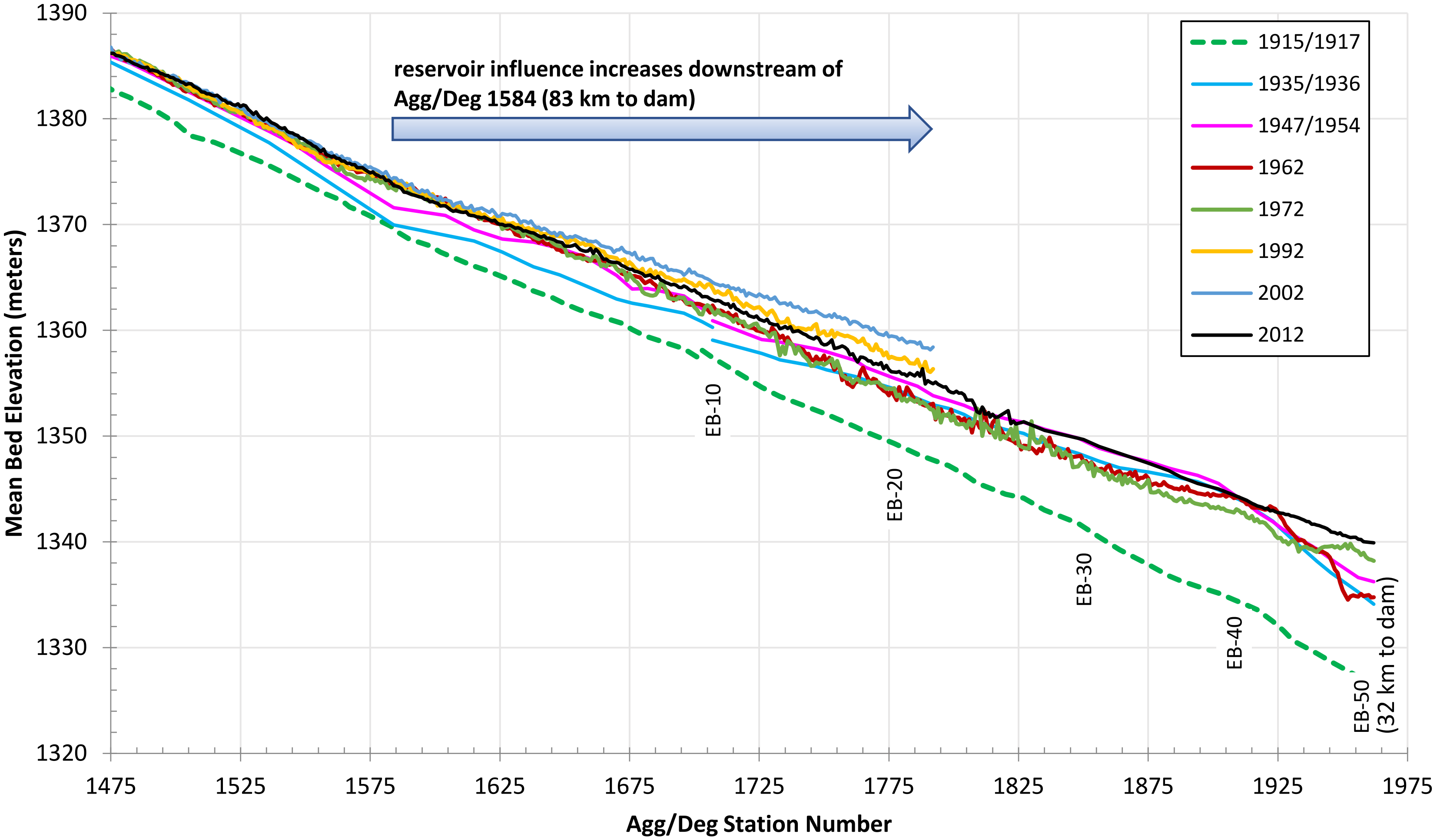


Figure 33. Historical bed elevation profiles above average pool elevation. Compiled from Elephant Butte Reservoir data (1915, 1935, 1947), digitized Soil Conservation Service cross sections (1936, 1954), Reclamation photogrammetry (1962, 1972, 1992, 2002), and Reclamation lidar (2012).

3. Methods

Methods are described in detail for Fort Peck Reservoir and Lake Powell. Subsequent studies will use similar methods to expand the analysis to include Lake Mead and Elephant Butte Reservoir.

3.1 Fort Peck Reservoir

3.1.1 Land Cover Mapping

Study area or bottomland boundary

The study area for the Fort Peck backwater and subaerial delta was first bounded as the "FtPeck_bottomland_bndry_all". This boundary principally followed the extent of Quaternary alluvium and some older, undivided alluvium, as mapped by Porter and Wilde (2001) and Wilde and Bergantino (2004). The bottomland in the upper part of the study area is bounded by, and in places intersects, the Judith River Formation with some limited exposures of Claggett Shale, both of Cretaceous age, downriver to Manning Bottom (river mile 1909). From this point, downstream to the end of the study area, Cretaceous Bearpaw Shale is the dominant surficial material and downstream of Hawley Creek (river mile 1883), Quaternary landslide deposits are included within and flank the bottomland boundary (Wilde and Bergantino 2004).

This boundary serves all the imagery years examined (1953, 1977, 1996, and 2015). The bottomland boundary was interpreted based primarily using ESRI World Imagery, along with historical imagery years, a Map Preview of the cited 1:100,000 scale Geologic Maps in the USGS National Geologic Map Database, and the USGS World Topographic Map, available in ESRI online Basemaps. Topographic contour lines, and high-resolution online World Imagery, in conjunction with the geologic map, were particularly useful in defining this boundary.

Wetted channel

Next, the wetted channel of the Missouri River was interpreted from River mile 1942, just upstream of the upstream-most range line, to River mile 1856, just upstream from were delta-backwater sediments were being exposed during the low reservoir stage of 2007 (669.6 meters). Interpretations were made for each of the four image years ("FtPeck_water_1953", "FtPeck_water_1977", etc.). Side channels with water connected to the main channel were included as channel features. Shade and texture were useful in identifying water in the older, lower resolution black and white imagery. However, the transition from wet sediments to shallow water at the reservoir pool margin were challenging to discriminate in some image years.

Unvegetated sediments

Unvegetated sediments, here defined as having less than 30% vegetation cover, were mapped for each of the image years examined and named as "FtPeck_sediment_1953", etc. Mapped fluvial sediments were clipped to adjacent water features. Unvegetated sediments as such, represent part of the active channel and thus provide a relatively short-term reflection of the fluvial geomorphic dynamics of a particular stream (Hupp and Osterkamp 1996).

Trees

Riparian vegetation provides important migratory corridors in a continental scale as well as important habitat diversity for a wide array of species at regional and local scales, especially in semiarid landscapes (Tabacchi et al. 1998, Scott et al. 2000). The rationale for mapping trees in this investigation was their contribution to the structural diversity of vegetation (vertical stratification), which is broadly related to biological diversity. Trees, as defined here, are greater than ~5 meters in height and were mapped for each of the image years examined and named as "FtPeck_trees_1953", etc. Previous research on the upper Missouri River, including the upper portion of the study reach, have documented that plains cottonwood (*Populus deltoides* Subsp. *monilifera*) is the principal tree along this portion of the river, although peach-leaf willow, green ash and box elder trees are less common associates that reach tree stature (Scott and Auble 2002, Scott et al. 2013). Tree canopies were visually distinctive in all imagery years and tree height was assessed by relative shadow length as well as personal knowledge of specific stands in the upper reaches of the study area. In addition, canopies of Russian olive, an invasive non-native riparian tree species (Friedman et al. 2005), were distinct in the 2015 imagery, and identified in the attribute table under field "Class_12" as "Tree_Ro". Canopies that intersected or were separated by less than 3 meters, were mapped in the same polygon, where total canopy within a polygon was greater than 75%. All isolated tree canopies were mapped separately.

3.1.2 Geoprocessing and Surface Cover Types

Once the above features were mapped, all water and tree polygons were clipped to the bottomland boundary. Next, within Arc Toolbox, Analysis toolbox, Intersection and Union procedures were performed on the following polygon pairs for all interpreted years to eliminate overlapping polygons: water to sediment; water to trees; and trees to sediment.

Following these operations, we defined the following surface cover types: **Upland Terraces** are surfaces that occur within the bottomland boundary, primarily on Quaternary deposits that are no longer inundated by the modern river. These surfaces are dominated by upland coniferous trees along with primarily Great Plains Mixedgrass Prairie along with some Great Plains Shrubland vegetation (https://fieldguide.mt.gov/displayES_LCLU.aspx). **Xeric riparian** surfaces are defined as typically supporting stands of mature cottonwoods, and that have accreted sediments from past floods and are now infrequently inundated by large floods. The understory vegetation in these cottonwood stands is like the shrubland component of the adjacent Upland Terrace, including strong representation by western wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve) and silver sage (*Artemesia cana* Pursh), both facultative upland species (Scott et al. 1997, Auble and Scott 1998). **Mesic riparian** surfaces are defined as being typically inundated during moderate to large floods in the riparian portion of the study area and are inundated as a function of flow in the Missouri River channel as it interacts with fluctuation in the water surface elevation of Fort Peck Reservoir. Mesic riparian surfaces contain a mix of woody vegetation, dominated by species of willow, and a mix of wetland and weedy herbaceous species (Auble and Scott, unpublished data).

The following features classes, upland terrace ("FtPeck_uplandterrace_1953", etc.); xeric riparian ("FtPeck_xericriparian_1953"; etc. and mesic riparian surfaces ("FtPeck_mesicriparian_1953", etc.), were delineated. Upland terrace and xeric riparian surfaces were mapped for each image year evaluated, based on visual appearance, digital topographic information, and on-the-ground knowledge of sites in the upstream, riparian portion of the study area. In the backwater-affected portion of the study area, beginning at about range line 2045.7 (-12084189.497, 6042884.771 Meters) xeric riparian surfaces become more challenging to identify because of increased flooding from the river associated with fluctuations in the reservoir pool. Thus, we used 2011 NAIP imagery, taken following a comparatively large flood on the Missouri River and associated with a relatively high stand of Fort Peck Reservoir.

The flooded areas in the imagery, in conjunction with the USGS National Map (https://apps.nationalmap.gov/viewer/), which indicates inundated areas (National Hydrography Dataset layer), and a full pool elevation of 686 meters, were used to broadly discriminate xeric from mesic riparian surfaces in the Fort Peck backwater. Flooded surfaces in the 2011 imagery agreed closely with inundated areas in the National Map and were considered too frequently inundated to be mapped as xeric riparian unless they supported live trees. Thus, only surfaces supporting trees were mapped xeric riparian downstream of the 686 meter contour (River Mile 1893), which is considered full pool elevation (https://www.nwd-mr.usace.army.mil/rcc/projdata/summaryengdat.pdf). Mesic riparian surfaces comprised the remaining unclassified areas within the bottomland boundary and were delineated by performing a geometric union of the following feature classes within each imager year: bottomland boundary; upland terrace, xeric riparian; water and sediment using the Union geoprocessing tool in ArcMap with mesic riparian defined as the output feature class. We deleted the unioned features, leaving the remaining polygons as the mesic riparian feature type.

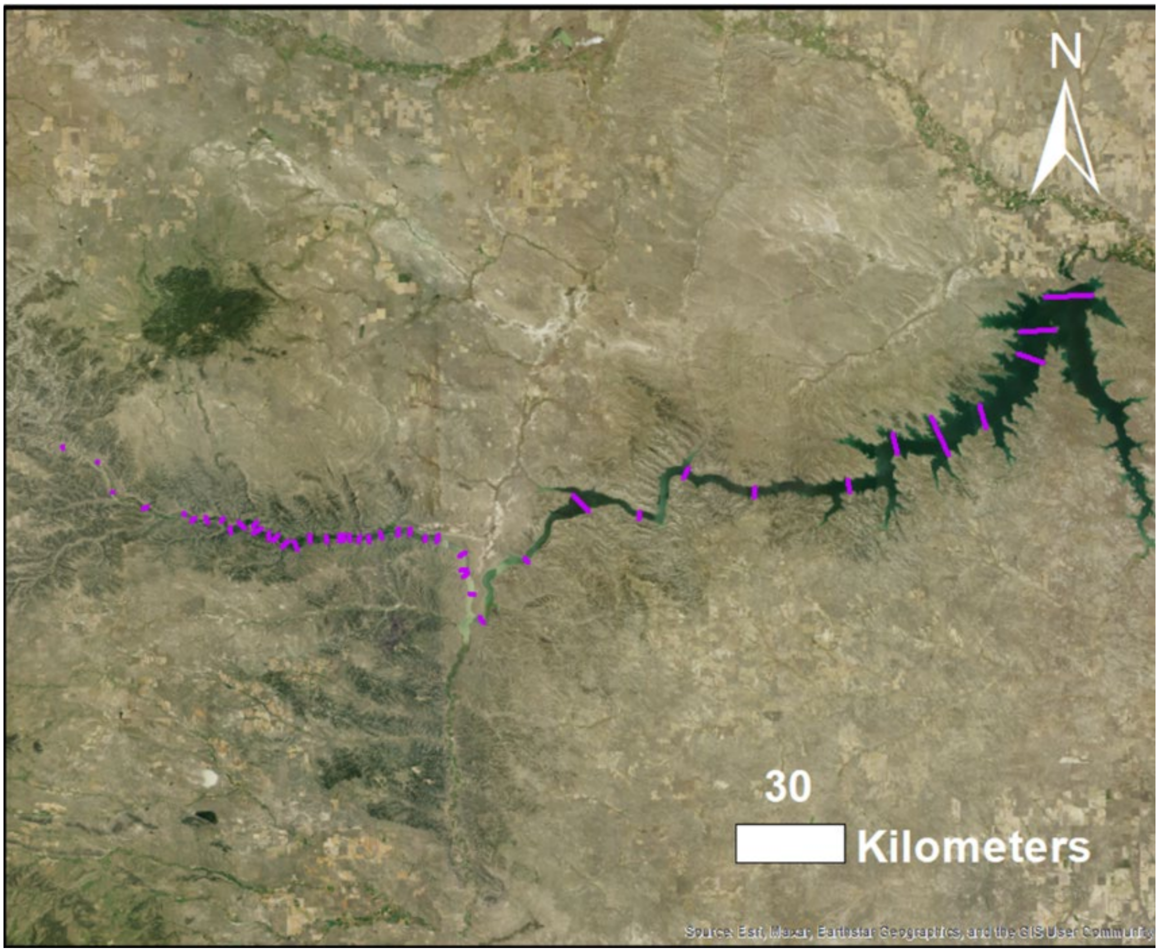
3.1.3 Supervised Classification of Fort Peck Bottomland Cover Types

We used 2017 NAIP Imagery, collected 7/6/2017 at a pool elevation of 683 m. This imagery is 0.6 m resolution and is comprised of four spectral bands (red, green, blue, near infrared). Individual 3.75' x 3.75' quarter quadrangles of NAIP imagery were loaded into ArcGIS Pro and mosaicked into a single image spanning the bottomland boundary area. We conducted supervised pixel-based classification by delineating approximately 20 training polygons for each of nine land cover types (*bare soil/sediment, cottonwood, Great Plains shrubland, herbaceous wetland, open water, Russian olive, mixedgrass prairie, sandbar willow, asphalt*). Note that the *bare soil/sediment* class also included gravel and dirt roads in the bottomland. Great Plains shrubland and mixedgrass prairie cover types were identified using on-the-ground knowledge of the area of interest (M.L. Scott, and G.T. Auble, unpublished data) and the classification of the ecological systems of Montana (https://fieldguide.mt.gov/displayES_LCLU.aspx). Using the spectral reflectance values of each of the four bands within these training polygons, we performed supervised classification using a support vector machine learning approach in ArcGIS Pro, which resulted in each pixel of the mosaicked NAIP image being classified as one of the nine land cover types above. We subsequently assessed cover-specific and overall classification accuracy by selecting 20 random pixels of each land cover class and determining whether they were correctly classified using the supervised approach.

Overall classification accuracy (i.e., rate of correct prediction across all nine land cover types) was 85%.

3.1.4 Topographic Channel Cross-sections or Channel Range Lines

A total of 45 topographic channel range lines were established by the Corps of Engineers to measure the geomorphic effects of Fort Peck dam and reservoir. These range lines begin just upstream of Fort Peck dam and extend upstream 165 river miles (Figure 34). These range lines were surveyed on near-decadal time steps between 1938 and 2007. The data from these range lines provides a detailed record of the pattern and extent of changes in Missouri River channel profiles resulting from the filling and operation of Fort Peck dam and reservoir.

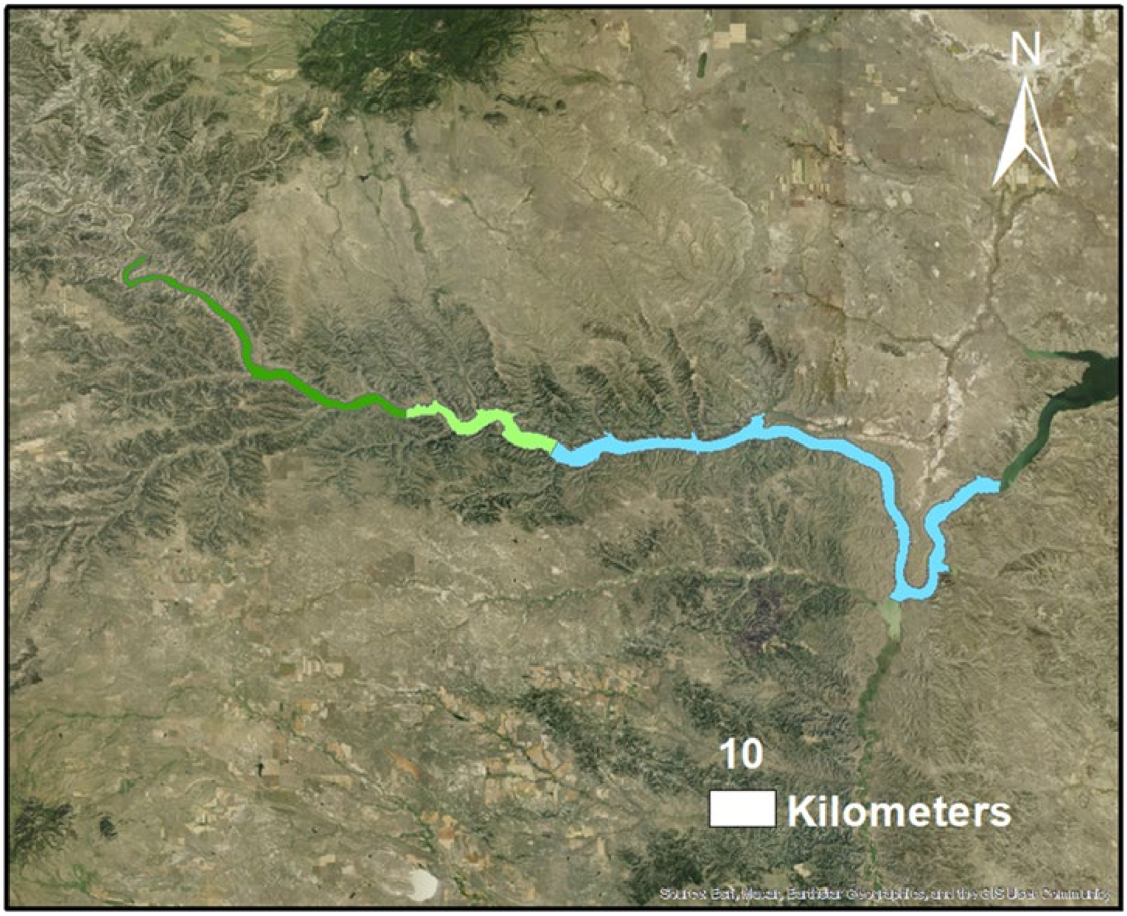


Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 34. The distribution of range lines from just upstream of Fort Peck dam at river mile 1772.5 to the upstream-most range line at river mile 1963.8.

3.1.5 Geospatial Analyses and Reaches of Influence

Following the mapping of surface types for each image year, Thiessen polygons, centered on the topographically surveyed range lines and clipped by the bottomland boundary, were constructed for the study area of interest. Thiessen polygons are used to define an area of influence around sample points, such that any point within the polygon is closer to a sample point than any other sample point (https://pro.arcgis.com/en/pro-app/latest/tool-reference/analysis/create-thiessen-polygons.htm). Next, the area of interest in this investigation was divided into three distinct reaches, which are influenced to different degrees by the reservoir. We define these reaches of influence as follows: 1**) Non-backwater affected reach**, above the influence of base level changes associated with the reservoir; 2) **Backwater affected reach**, influenced by base level changes imposed by the reservoir but never directly inundated by the reservoir and 3) **Reservoir affected reach**, influenced by base level changes as well as possible inundation by the reservoir depending on pool elevation. Finally, Thiessen polygons within each of the three reaches of influence were joined using the dissolve tool in ArcGIS to produce the three reaches (Figure 35). These segments were then intersected with each of the surface types described above to generate segment-specific aerial estimates of each of the surface cover types.



Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 35. The Fort Peck reservoir area of interest depicting three reaches of differing reservoir influence: non-backwater affected (dark green); backwater affected (light green) and reservoir affected (blue).

3.2 Lake Powell

3.2.1 Land Cover Mapping

Study area or bottomland boundary

The study area for the Lake Powell backwater and subaerial delta was bounded as the "LkPowell_bottomlandbdry". The upstream-most end of the delineated bottomland begins at the Glen Canyon National Recreation Area boundary (~ river mile 362) where the Colorado River and its tributaries are entrenched in a surface capped by Permian Cedar Mesa sandstone with river level exposures of Pennsylvanian marine limestones of the upper member of the Hermosa Group (Honaker Trail Formation), transitioning to lower Cutler beds, just past the apex of Mile Crag Bend at approximately river mile 313.7 (see Figure 11). Here the limestones drop below river level, and the canyon is set in Cedar Mesa sandstone. A high angle fault, down dropped in the downstream direction, crosses the river at approximately mile 288 and exposes the Permian Organ Rock Shale of the Cutler Formation at river level (Thaden et al. 2008). The downstream end of the bottomland boundary ends at river mile 256.4. The bottomland boundary, as defined here, followed the 3,760-foot contour line using the online ESRI World Topographic Map (https://www.arcgis.com/home/item.html?id=30e5fe3149c34df1ba922e6f5bbf808f). This elevation contour also corresponds with the endpoints of most of the topographic cross sections.

Wetted channel

The wetted channel of the Colorado was mapped for each image year within the bottomland boundary. Of the 1950s imagery (1951 and 1959), 1959 provided the most complete coverage and was the highest resolution. Thus, it was primarily used to interpret the extent of pre-dam wetted channel. The 1951 imagery was used, however, to help define edge of water, particularly in deeply shadowed areas in the older imagery throughout deep, narrow canyon reaches of the study area. Again, color shade and texture were helpful in delineating the extent of the wetted channel.

Unvegetated sediments

Unvegetated sediments, with less than 30% vegetation cover were also mapped for all image years. In the 1950s imagery, unvegetated surfaces appeared as a rather uniform, bright white or light grey. Other large fluvial deposits with higher apparent vegetation cover, were darker grey in color but discerning level of vegetation cover was difficult given the resolution of this imagery. Thus, the 30% cover cutoff is approximate. However, examination of alluvial surfaces in recent, higher resolution imagery in Cataract Canyon, just upstream of the study area, shows a distribution and extent of unvegetated alluvial features like those mapped in the pre-dam imagery.

Trees

Trees were defined in the Lake Powell area of interest as being greater than ~3 meters in height, as judged by color, texture and shadow lengths in the 1959 black and white imagery. The 1951 imagery was used to assist in identifying trees in shaded portions of the canyon as well as assessing shadow length. Again, examination of the pattern and extent of tree-sized woody vegetation in recent, high-resolution imagery of Cataract Canyon are generally consistent with what was mapped in the pre-dam imagery. In addition, published studies from and riparian vegetation monitoring of the Green and Colorado rivers immediately upstream of the study area indicate the principal species attaining tree height are Freemont cottonwood (*Populus fremontii*), netleaf hackberry (*Celtis laevigata* Willd. *var. reticulata* (Torr.) L.D. Benson) and tamarisk (*Tamarix chinensis* Lour.) and hybrids (D. Perkins, NPS, unpublished data). Canopies that intersected or were separated by less than 3 meters, were mapped in the same polygon, where total canopy within a polygon was greater than 75%. All isolated tree canopies were mapped separately.

3.2.2 Supervised Classification of Lake Powell AOI

In the most recent imagery examined for Lake Powell, 2018, there were complicated and intermingled patterns of mesic herbaceous and woody vegetation along with stressed and non-stress vegetation. Thus, we attempted to tease out this complexity by doing a supervised classification of 2018 imagery. We downloaded 2018 NAIP ortho infrared imagery from the USDA Geospatial Data Gateway (https://datagateway.nrcs.usda.gov/GDGHome_DirectDownLoad.aspx) for San Juan County, UT, which covered our AOI. The 2018 bottomland boundary, which defined our AOI, was used to mask or clip the raster image to limit the extent of the supervised classification to our AOI. Imagery classification tools in ArcGIS Pro were used to create training samples for the following classes: trees, herbaceous, sediment (unvegetated), water, stressed vegetation and shadows. We then performed a Maximum Likelihood classification on the masked imagery using our defined training samples. Finally, we used the Raster to Polygon geoprocessing tool to convert our classified raster dataset to a polygon feature. Areas for each class were then read from the attribute table.

4. Results

Results are described for Fort Peck Reservoir and Lake Powell. Subsequent studies will expand the analysis to include Lake Mead and Elephant Butte Reservoir.

4.1 Fort Peck Reservoir

4.1.1 Formation of Fort Peck Delta and Backwater and Reaches of Influence

Sediment has accumulated within the Missouri River bottomland behind Fort Peck dam because of direct and indirect effects of Fort Peck reservoir. Repeat topographic surveys of channel cross-sections or range lines indicate this accumulated sediment extends upstream of the dam for approximately 232 river kilometers with maximum depths reaching 13.4 meters, roughly corresponding with long-term mean reservoir elevation (Figure 2). Below full pool elevation of the reservoir, the delta-backwater system has developed from a combination of sub-aquatic or lacustrine deposition during high reservoir stages (direct effects) and overbank flooding of river channels and alluvial deposition during low reservoir stages (indirect effects), resulting from decreased channel slope as the river experienced a changing base level imposed by fluctuating reservoir pool elevations. Range line surveys further indicate that increased sedimentation has also occurred above full pool, again the result of decreased channel slope associated with changing base levels. This deposition, resulting from the upstream progression of channel slope adjustments, extended an additional 24 river kilometers upstream and represents a transition zone between upstream, purely fluvial, versus a combination of fluvial and lacustrine depositional processes.

The three reaches of influence, as described in Methods, are illustrated in Figure 35. Within the reservoir affected reach, multi-year periods of below average reservoir pool elevations, like those in the 1950s, early 1990s and 2000s (Figure 2), expose spatially extensive areas of water-transported or alluvial sediment, which becomes colonized relatively quickly by mesic riparian vegetation followed by xeric vegetation, including cottonwood. Using the water shapefile, we estimate that 13,169 hectares (132 square kilometers) of bottomland were exposed with a 9-meter drop in the reservoir pool elevation between 1998 and 2007 (Figure 36).

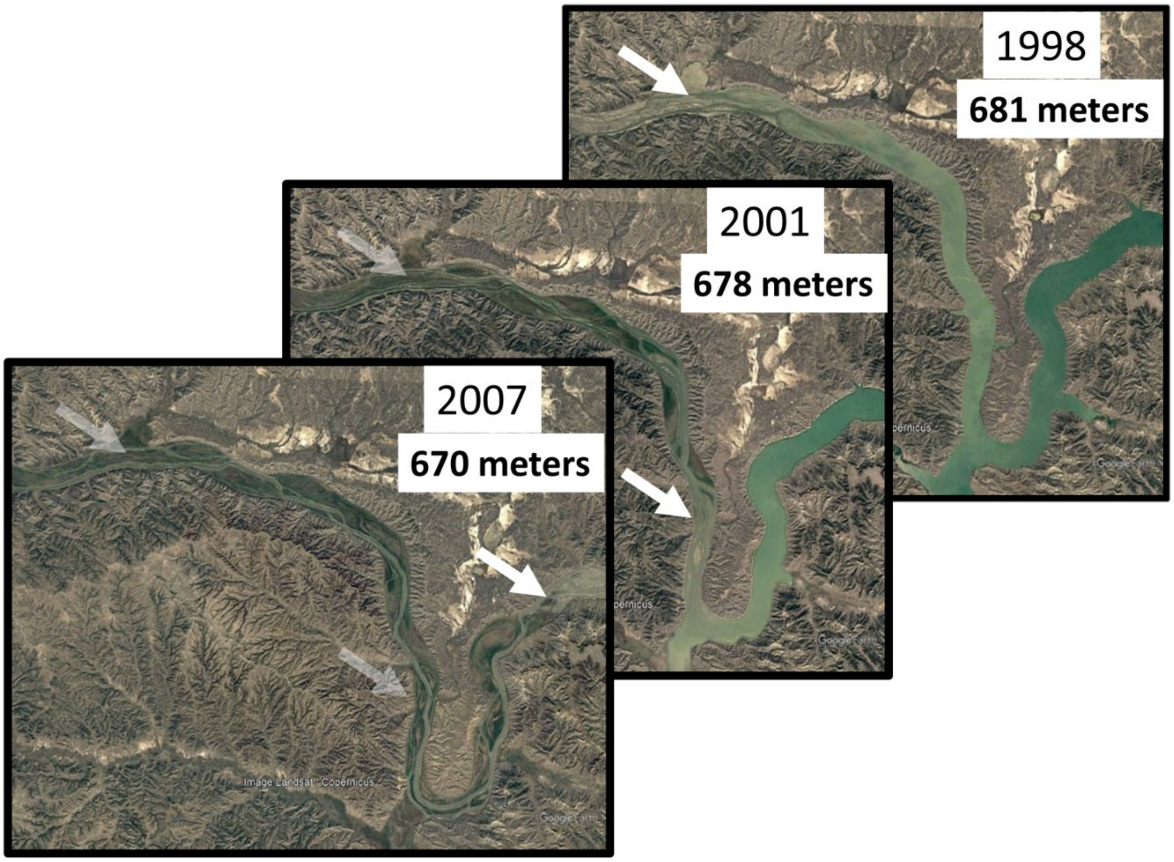


Figure 36. Progressive declines in Fort Peck reservoir levels (solid arrows) from 1998 to 2007, with corresponding pool elevations in meters, illustrate the sub-aerial exposure of delta/backwater deposits and the colonization of those surfaces by vegetation. Small drops in pool levels create spatially extensive areas of new riparian and wetland habitat.

4.1.2 Vegetation Response to the Fort Peck Delta-Backwater

The three reaches of influence (see Figure 35) each show distinctive changes in the extent of mapped vegetation cover types across time, reflecting different fluvial geomorphic and disturbance processes within each reach.

Non-backwater Affected Reach

Upland terrace and xeric riparian vegetation dominate the bottomland in this reach and show little change in coverage across the years examined (Figure 37). In contrast, mesic riparian vegetation cover, although a small percentage of overall bottomland cover in this reach, showed a consistent increase in cover from 1953 to 2015. Bare sediment showed a corresponding decrease across time and the trends in both these cover types are consistent with reduced flow variability and channel narrowing, which has been documented for this portion of the Missouri River (Scott et al. 2013). The cover of open water (~25% of total cover) varied slightly and inconsistently across years, and is attributable, in part, to differences in stream discharge on the dates the imagery was taken (Table 2.1.2.1).

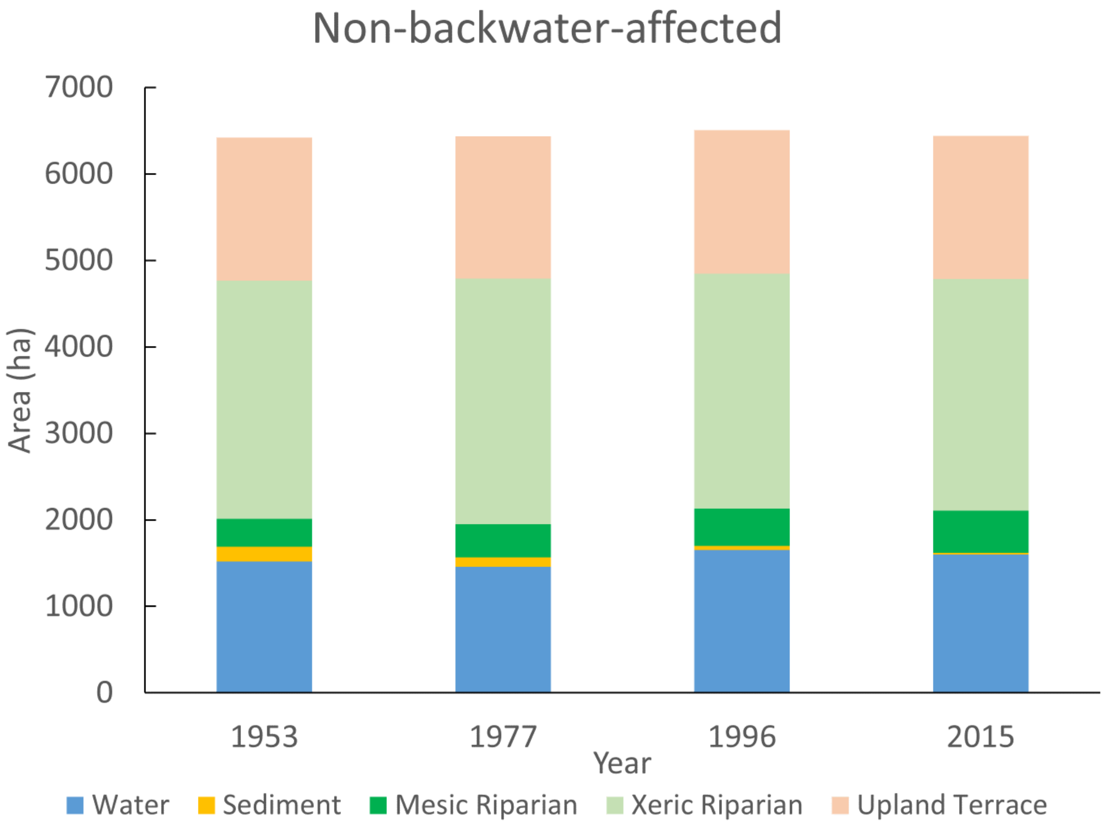


Figure 37. Aerial coverage (in hectares) of mapped land cover types, across four time periods, for the non-backwater affected reach of the Fort Peck reservoir AOI.

Backwater Affected Reach

The most notable change in this reach is the secular decrease in xeric riparian cover of about 32% and a corresponding increase in mesic riparian cover of about 57% (Figure 38). The cover of bare sediment declined to very low levels in the last two time periods and the cover of open water remained consistently low (~15% of total cover) across all time periods.

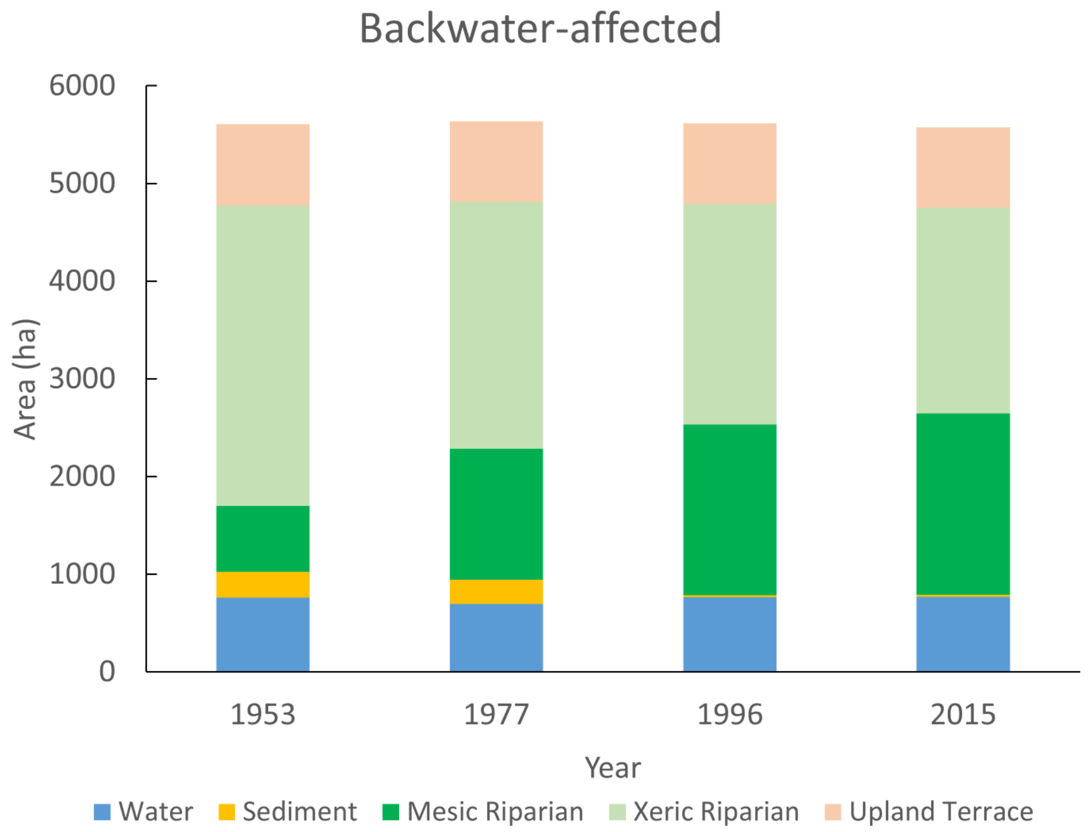


Figure 38. Aerial coverage (in hectares) of mapped land cover types, across four time periods, for the backwater affected reach of the Fort Peck reservoir AOI.

Reservoir Affected Reach

Open water dominated overall cover (~70% of total cover) as the downstream portions of this reach were inundated by relatively high reservoir stages that spanned the entire bottomland in each of the imagery years examined. Also notable are the comparatively large, systematic increases in mesic riparian vegetation over the same period (Figure 39).

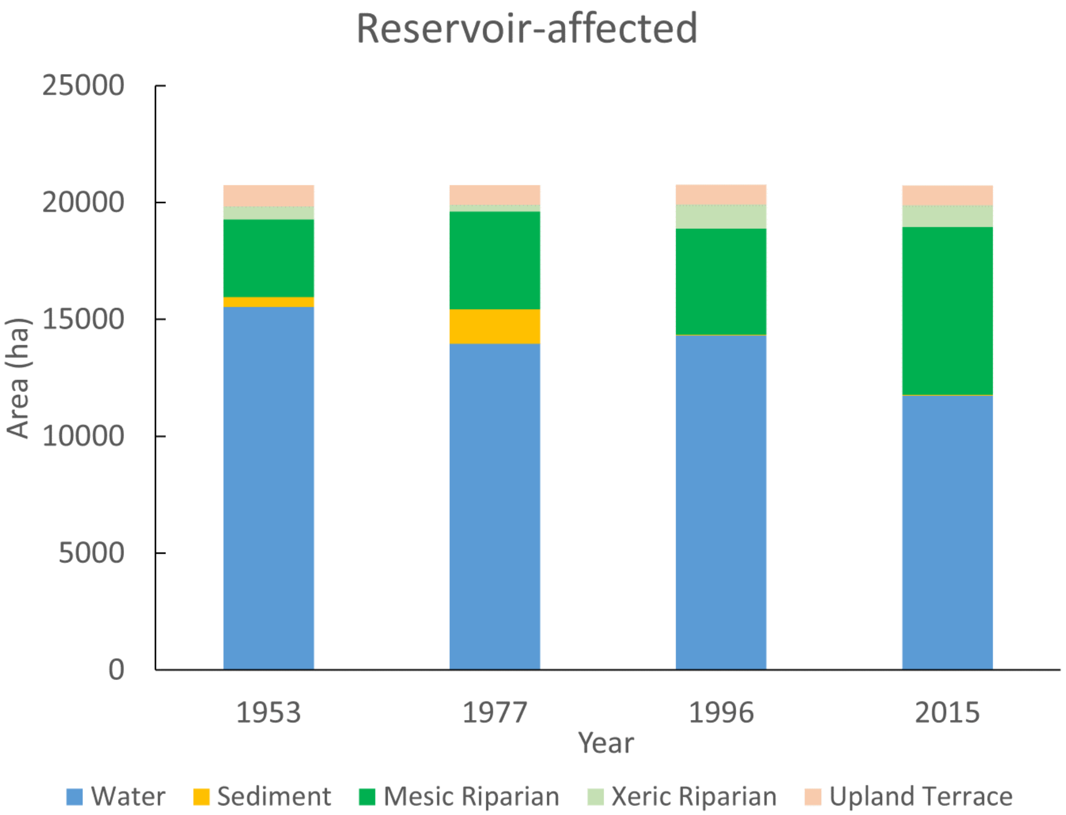


Figure 39. Aerial coverage (in hectares) of mapped land cover types, across four time periods, for the reservoir affected reach of the Fort Peck reservoir AOI.

4.1.3 Tree Dynamics Across the Missouri River Bottomland

Because of their structural importance in the landscape, we specifically examined the dynamics of trees, primarily plains cottonwood, across the Missouri River bottomland and especially in relation to the development of the Fort Peck delta and related backwater. Across the bottomland, xeric riparian trees represented one the most spatially extensive cover types in the pre-dam and reservoir landscape, comprising largely older, established forest stands (Scott et al. 1997).

Non-backwater Affected Reach

Within the non-backwater affected portion of the bottomland xeric riparian trees increased from the 1950s through the 1970s and then declined over the following decades (Figure 40). Upland terrace trees, a minor component, followed a similar trend, reflecting mid-twentieth century establishment and a progressive loss of older trees on these higher, drier surfaces over time (Scott et al. 1997). At the same time, mesic riparian trees showed a steady increase over the decades (Figure 40). corresponding with a long-term channel narrowing processes along this portion of the bottomland not influenced by the reservoir and backwater (Scott et al. 2013).

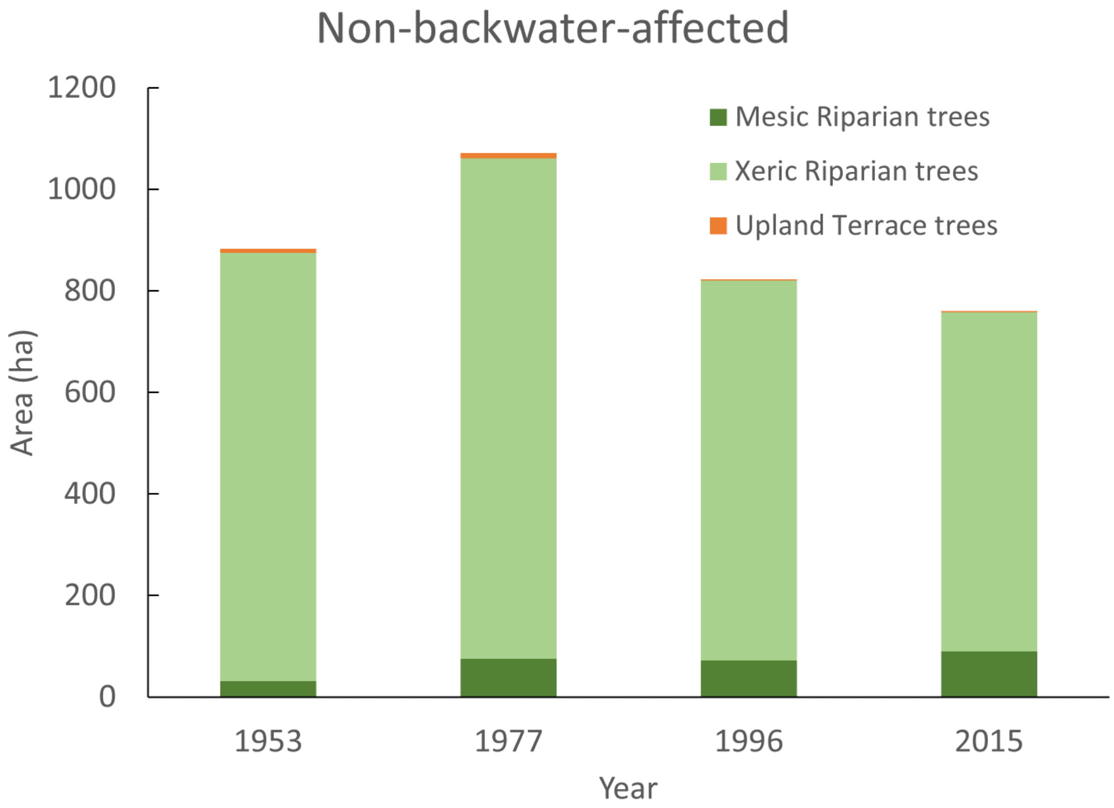


Figure 40. Aerial coverage (in hectares) of mapped tree cover, within three land cover types and across four time periods, for the non-backwater affected reach of the Fort Peck reservoir AOI.

Backwater Affected Reach

Trees in the Backwater affected portion of the bottomland had similar cover values for upland, xeric and mesic cover types in the 1950s following a decade of mean daily water surface elevations near the long-term mean for the period of record (Figure 41). Following a period of above average reservoir water surface elevations beginning in the mid-1960s, by 1977, xeric and mesic tree cover had declined, as flooding and sediment accretion killed trees in downstream portions of this reach (Figure 41). By 1996, trees had re-established on newly expanded xeric and mesic surfaces following below average reservoir pool elevations between 1988 and a brief return to higher-than-average reservoir elevations by 1993. Both xeric and mesic tree cover declined slightly by 2015 following an extended low reservoir stand (2001-2010) and subsequently a higher-than-average pool since 2014 (Figure 2).

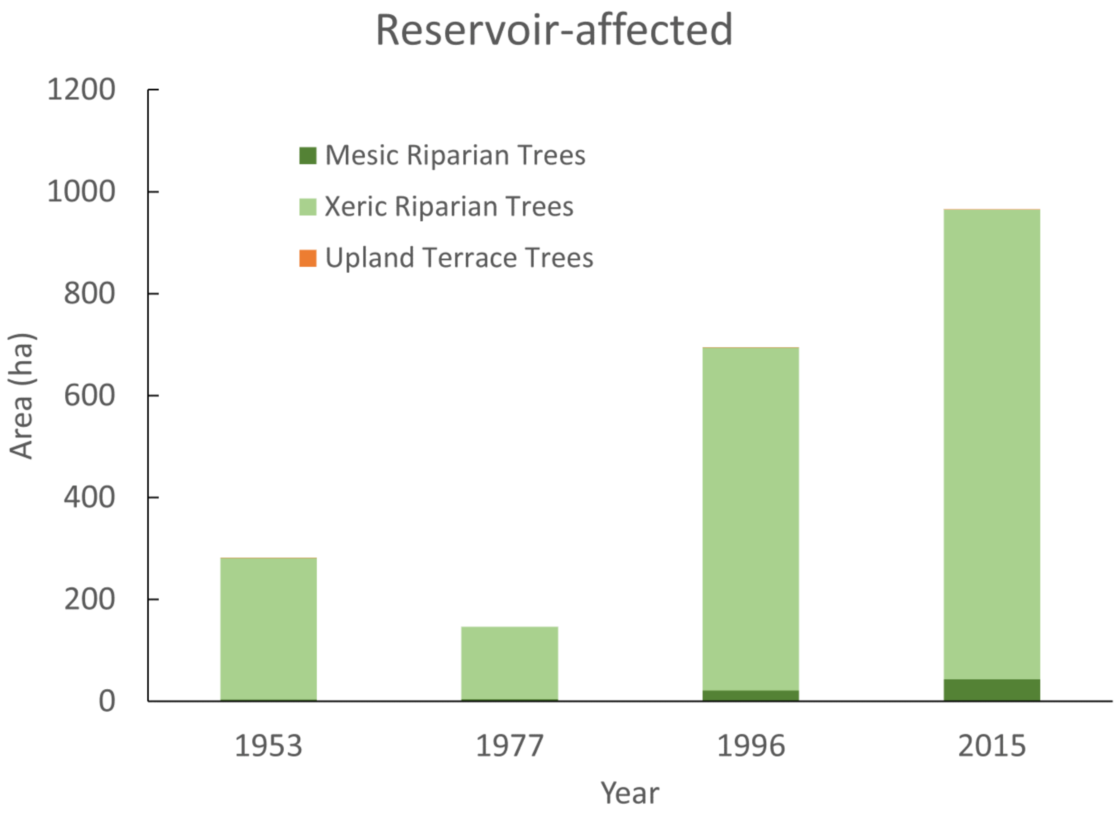


Figure 42. Aerial coverage (in hectares) of mapped tree cover, within three land cover types and across four time periods, for the reservoir affected reach of the Fort Peck reservoir AOI.

4.1.4 Supervised Classification of 2017 Missouri River Bottomland Vegetation

Examination of several key land cover classes using a supervised classification of the 2017 NAIP imagery, for each of the reaches of influence, shows a distinctive trend in the shift of vegetation types driven by the long-term development of the Fort Peck delta-backwater. This shift represents a continuum of change in bottomland vegetation from primarily dry site assemblages like Great Plains Shrubland and xeric riparian tree patches in the non-backwater affected reach to broader representation of more mesic stands of sandbar willow and open stands of cottonwood across the bottomland in the backwater affected reach. Finally, in the reservoir affected reach, scattered young cottonwood exist within a matrix of sandbar willow and herbaceous wetland vegetation. These vegetation types spread across the bottomland and are edged by narrow bands of Great Plains Shrubland and Mixed grass Prairie on upland terraces (Figure 43). Overall, in 2017, water made up 32% of the AOI, cottonwood, willow, and wetland herbaceous plants 24%, and unvegetated sediment 9%. Most of the remaining 35% of classified cover consists of Mixedgrass Prairie and Great Plains Shrubland on upland terrace surfaces.

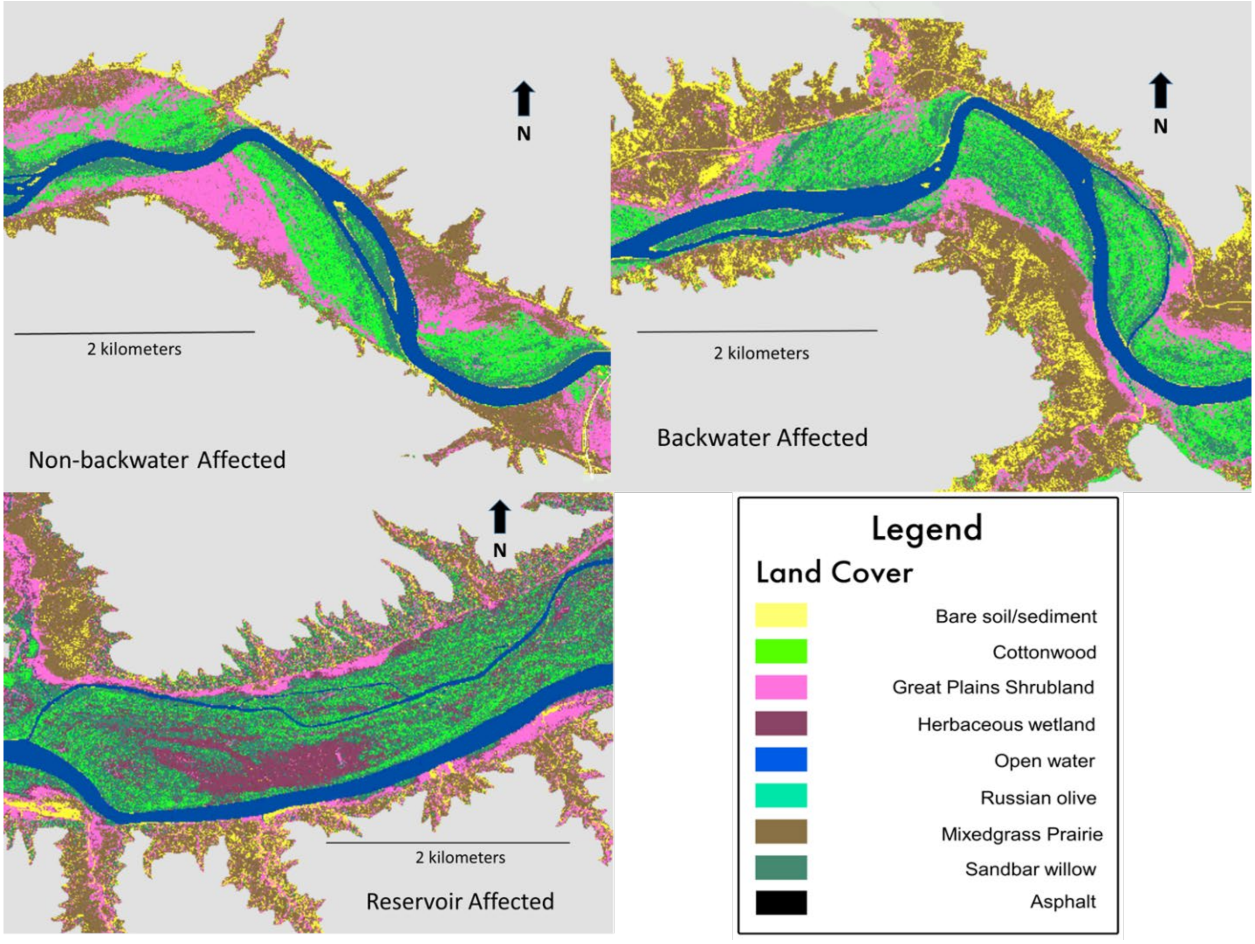


Figure 43. Results of supervised classification of 2017 NAIP imagery. Three panels depicting non-backwater affected, backwater affected, and reservoir affected reaches of influence, illustrate the transformation from primarily dry-site vegetation (non-backwater affected) to primarily wet-site vegetation across the Missouri River bottomland. These changes are brought about by fluvial geomorphic changes imposed by Fort Peck Reservoir.

4.2 Lake Powell

4.2.1 Formation and Dynamics of the Lake Powell Delta and Backwater

Sediment has accumulated in the bedrock canyons of the mainstem Colorado and tributary drainages inundated by Lake Powell. Topobathymetric surveys indicate that sediment inflow to Lake Powell reduced reservoir storage capacity by 2,260,968,840 cubic meters between 1963 to 2018 (Ferrari 1988). This accumulated sediment extends upstream of the dam for approximately 300 river kilometers with most sediments accumulating between the maximum and minimum pool elevations and with maximum depths of around 50 meters. As observed in Fort Peck and the White River reservoirs (Volke et al. 2019), maximum sediment accumulations approximately correspond the with long-term mean reservoir elevation.

Sediment accumulated as sub-aquatic deltaic deposits at the periphery of the reservoir during high stands of the reservoir during the 1980s and mid-to late 1990s. Fluctuations in reservoir levels exposed and inundated these developing surfaces as recorded by depositional sequences that reflect alternating lacustrine and fluvial conditions. This sediment now forms terraces that are being incised by the river (Figure 44) and transported downstream to newly forming deltas defined by lower, shifting baselevels as the reservoir pool dropped to new lows during a sustained period of reduced runoff beginning in 2000 (see section: 2.2.4 Reservoir Inflows and Climate-driven Change in Water Resources). Newly formed deltaic deposits provide substrates for the establishment of vegetation once they become sub-aerial. Large volumes of sediment supplied to Lake Powell, combined with dynamically fluctuating reservoir levels, have driven large changes in the pattern, extent, and composition of vegetation across the Lake Powell delta and backwater.

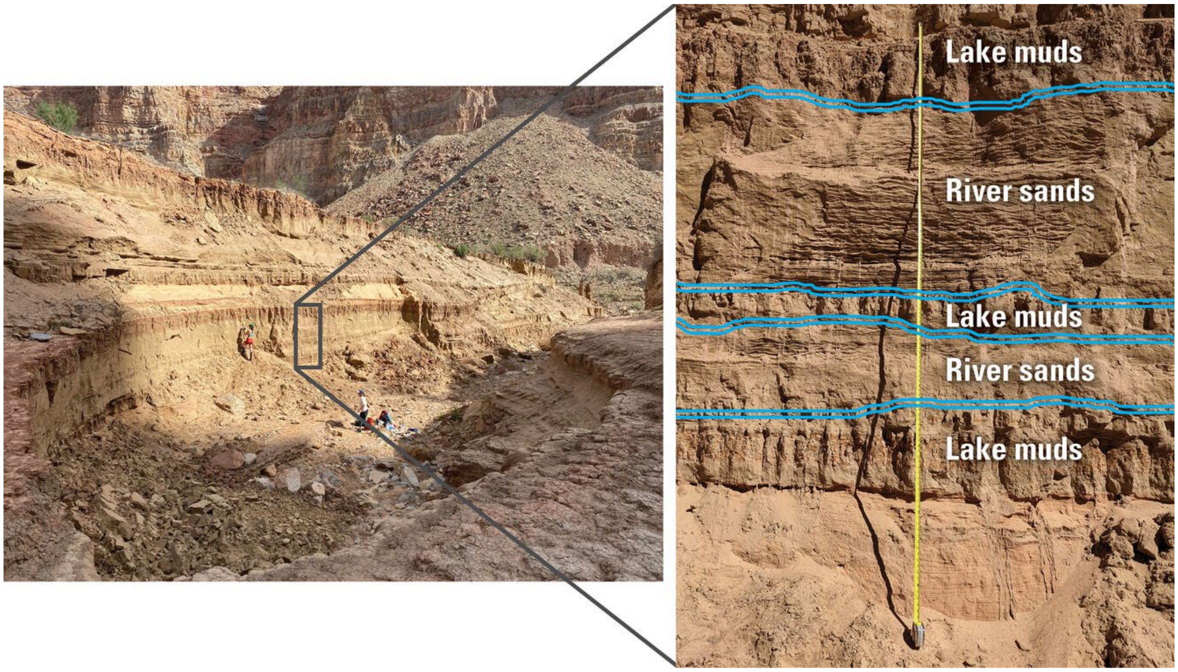


Figure 44. Alternating lacustrine and fluvial sediments near Waterhole Canyon in the Lake Powell AOI record the complex depositional history of sediment terraces now exposed by persistent declines in the pool elevation of Lake Powell. Photo credit: https://www.usgs.gov/news/science-snippet/history-lake-powell-written-sediment.

4.2.2 Riparian Vegetation Response to the Lake Powell Delta-Backwater

The Colorado River within our area of interest (Figure 11) reflects a range of physical and biological conditions typical of bedrock-bound rivers across the Colorado Plateau. In the upper two thirds of the AOI (from below Big Drop rapid to the apex of Mile Crag Bend) the river is set in a canyon of interbedded sandstones and thin-bedded limestones. Throughout much of this reach the channel is constrained by broad, continuous talus deposits and debris fans. From Mile Crag Bend to the mouth of the Dirty Devil River massive Cedar Mesa sandstone appears at river level and talus deposits become more discontinuous. Below the Dirty Devil confluence, to the end of our AOI, Organ Rock and Moenkopi formations appear at river level and the valley widens. Imagery from August 1959, at a discharge of 235 cms, shows a channel in the upper reaches flanked by coarse-texture rock debris and channel constrictions formed by debris fans. Fine-grained material, primarily sands, form eddy deposits at debris fans, as described elsewhere for rivers in bedrock canyons on the Colorado Plateau (Schmidt 1990, Grams et al. 1999). The pre-dam river in the wider, lower portions of the

AOI featured lateral and mid-channel sand bars and sandy point bars. Woody riparian vegetation in the pre-dam imagery is primarily associated with these fine-grained deposits at elevated positions or in flow-protected locations like that described in the Grand Canyon (Scott et al. 2018) and mapped upstream in Cataract Canyon. This vegetation includes stands of Tamarisk, sandbar willow, Fremont cottonwood and desert olive. Mesic, primarily herbaceous, vegetation is also associated with perennially wet fine-grained deposits and woody vegetation with high water tables (Tendick et al. 2012).

Mapping of the pre-dam AOI shows that upland terrace represented 64% of overall cover (Figure 45), which primarily includes talus slopes and bedrock exposures of sandstone and shale that typically support sparse shrublands along with widely scattered juniper and grasses (Tendick et al. 2020). At a relatively low discharge (235 cms), water occupied 22% of the AOI. Unvegetated sediment, mapped here as unvegetated fine-textured sand deposits, was limited at 0.6%, particularly in the steep, upstream third of the AOI. Mesic riparian surfaces, that typically support herbaceous vegetation, were uncommon, at ~2% of total cover. Finally, xeric riparian surfaces, supporting discontinuous stands of woody vegetation (see species above), was about 12% of total cover. The filling of Lake Powell, subsequent sediment deposition and the development of a delta-backwater ecosystem have altered these pre-dam conditions.

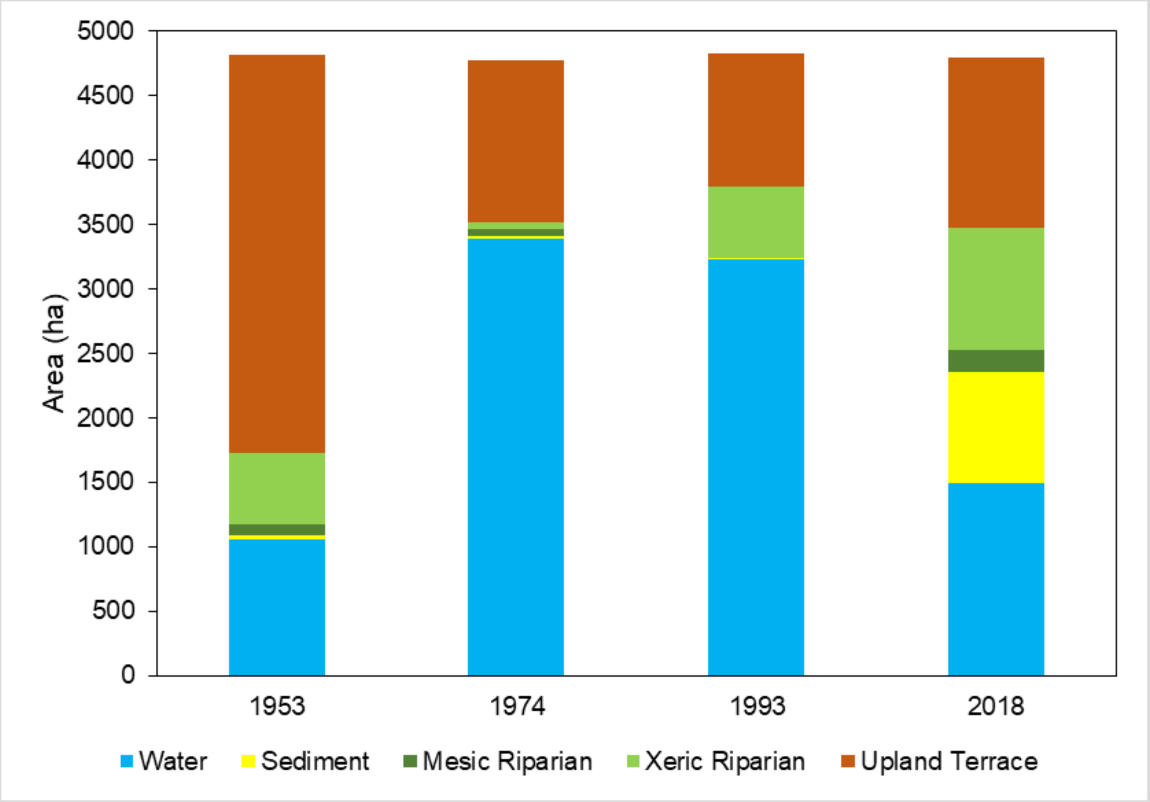


Figure 45. Changes in digitized cover types, in hectares (ha), for pre-dam (1953) and three post-dam time periods, within the Lake Powell AOI.

In the 1974 imagery, a still-filling Lake Powell reached a pool elevation of 1113 meters and the rising waters had reached the mouth of Beef Basin Wash near the upstream end of the AOI. Here, and upstream for approximately five river kilometers, reduced stream gradients associated with the advancing reservoir pool produced large, fine-grained sediment deposits (Figure 46A). Downstream, the reservoir had inundated most of the pre-dam channel and riparian features, as well as portions of former upland terrace. Water represented 71% of the AOI with upland terrace making up and additional 26%. Together, sediment, mesic and xeric riparian cover made up the remaining 3% (Figure 45) and were confined largely to the short upstream portion of the AOI not yet inundated.

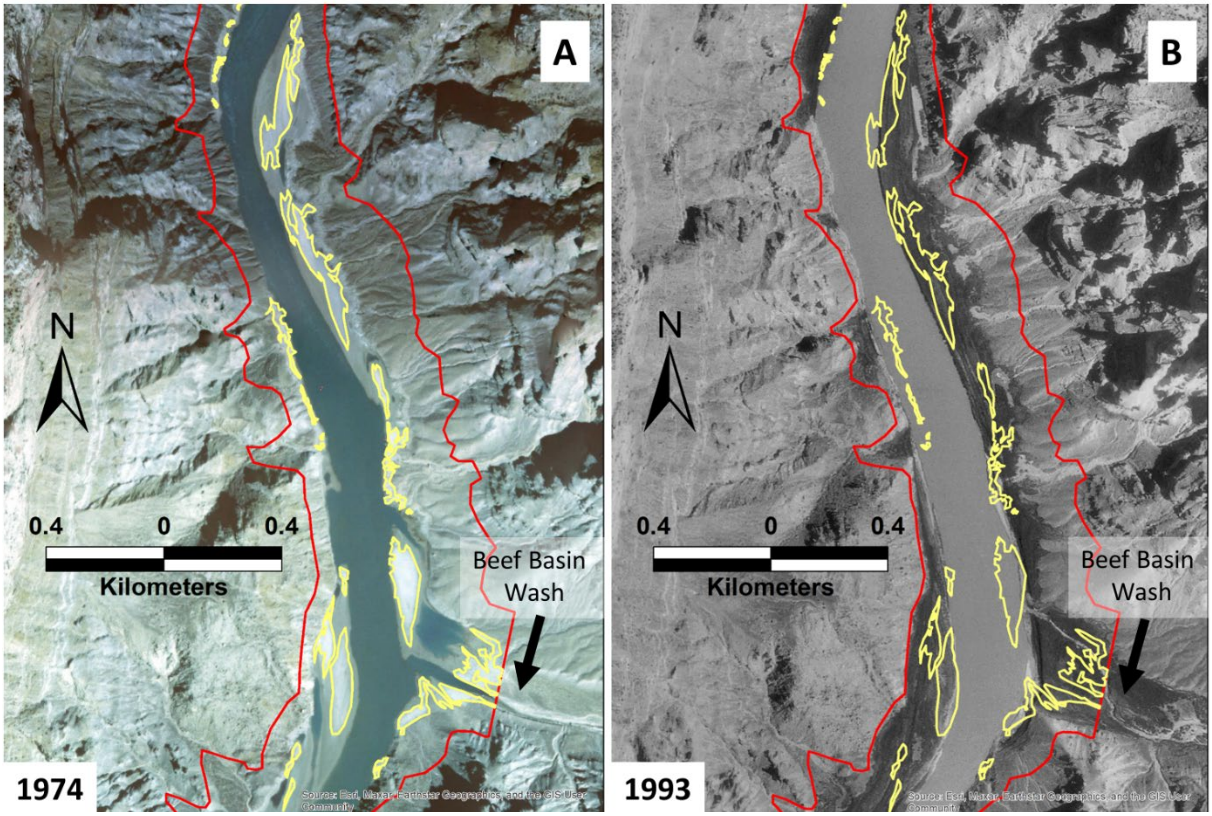


Figure 46. A) Unvegetated, fine-grained sediment deposits (yellow polygons) formed at and upstream of the advancing Lake Powell reservoir pool near Beef Basin Wash in 1974. B) The same deposits were inundated or eroded by high discharges in 1993 or had been incorporated into more expansive depositional surfaces that formed when the reservoir was at or near full pool during the 1980s.

Lake Powell reached full pool in 1980 and remained high throughout most of the 1980s. It briefly dropped below mean pool elevation beginning in 1989. By 1993, pool elevation had recovered to an elevation of 1114 m at the time the imagery was flown that year. A comparison of the reach at Beef Basin Wash in 1993, at a discharge >1,133 cms, illustrates that some of the depositional surfaces in 1974 had been eroded or inundated by the high discharges in 1993 or incorporated into more extensive sediment deposits formed during the high stage of the reservoir. It also attests to how quickly these surfaces are vegetated once they become sub-aerial following reservoir pool declines. (Figure 46B). With reservoir levels a meter higher than in 1974, and much greater discharge, the cover of upland terrace within the AOI in 1993 declined to 21% of total. But water also declined to 67%. The reason being the deposition that occurred during the high stage of the reservoir, and which became vegetated surfaces by 1993. Because these alluvial and lacustrine surfaces are dominated by stands of the woody, small tree, tamarisk, these surfaces were mapped as a xeric riparian cover type. Despite inundation of much of the AOI by the reservoir, xeric riparian cover in

1993 was like that mapped under pre-dam conditions and accounted for 11% of total cover in the AOI (Figure 45).

Sustained lower inflows from the Colorado River to Lake Powell beginning in 2000 dropped the reservoir to below mean pool elevations for most of the past two decades. The declining reservoir pool progressively exposed new sediment deposits, portions of which were subject to erosion (Figure 44), transport, and deposition by the Colorado River. Extensive stands of vegetation on remaining sediment terraces, were subject to increasing moisture stress as the reservoir continued to drop. The complex patterning of vegetation (e.g., herbaceous and woody, stressed and healthy) across these new and emerging surfaces, prompted us to perform a supervised classification of our most recent 2018 imagery.

4.2.3 Supervised Classification of the Lake Powell AOI in 2018

Despite some misclassification errors, the supervised classification performed well, particularly where discriminating stressed from healthy plants as well as trees from herbaceous vegetation (Figure 47). The supervised classification of the 2018 imagery clearly illustrates the legacy physical and biological effects from both the filling as well as the persistent, climate-related drawdown of Lake Powell.

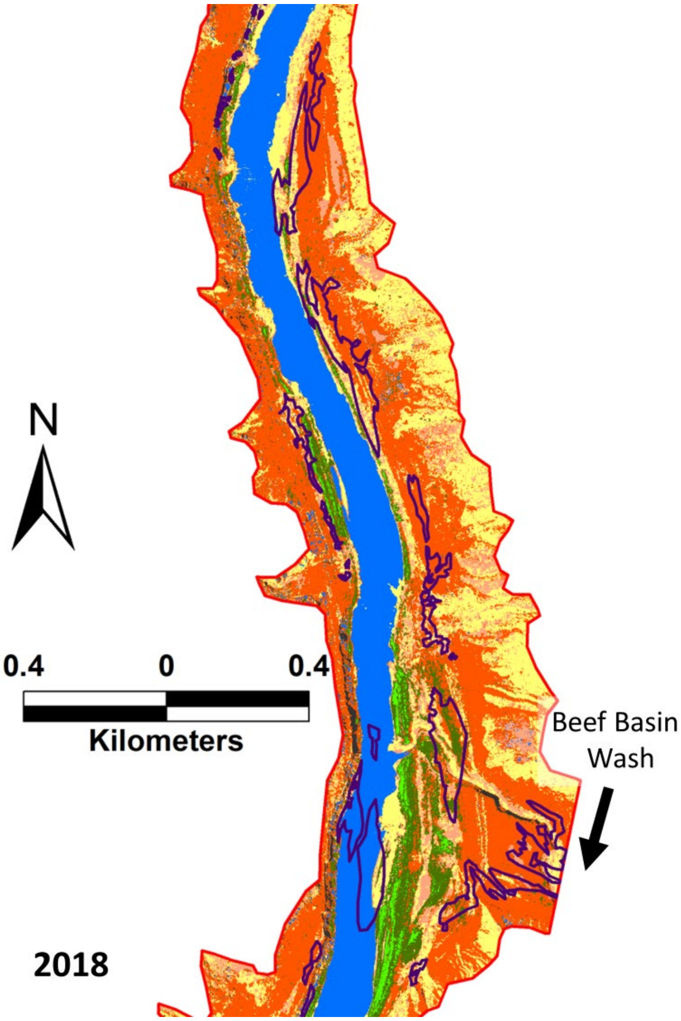


Figure 47. Supervised classification of 2018 imagery showing a reach within the AOI at Beef Basin Wash. Polygons (purple lines) represent mapped deposits of unvegetated sediment in 1974 (see Figure 46 for comparison). These deposits have been either eroded by the river channel (blue) or have been incorporated into more extensive surfaces covered by riparian vegetation, including woody trees (dark green) mesic herbaceous vegetation (light green), or stressed riparian vegetation (red). Fine-grained sediments (yellow), include both sand bars and upland colluvial material.

These changes are evident in the shifts in the area of mapped cover types compared with pre-dam conditions (Figure 45). By 2018, the reservoir pool had fallen over 30 m to an elevation of 1097 m and just upstream of the lower end of the AOI. Thus, the area of water within the AOI was 31% of the total area and only 9% greater than the pre-dam percentage. The drop in reservoir elevation resulted in the sub-aerial exposure of unvegetated deltaic deposits. This, combined with erosion, transport, and alluvial deposition of upstream sediment, created large areas of unvegetated sediment in lower portions of the AOI (Figure 48A). Fine-grained, unvegetated sediment, a minor element within the pre-dam AOI, represented 18% of the total area in 2018. Reservoir-induced sedimentation combined with rapid vegetation establishment on sub-aerial surfaces (Figure 48B), led to post-dam expansion of xeric riparian cover (20%) and mesic riparian cover (4%) and displacement of upland terrace cover in the 2018 AOI (Figure 45).

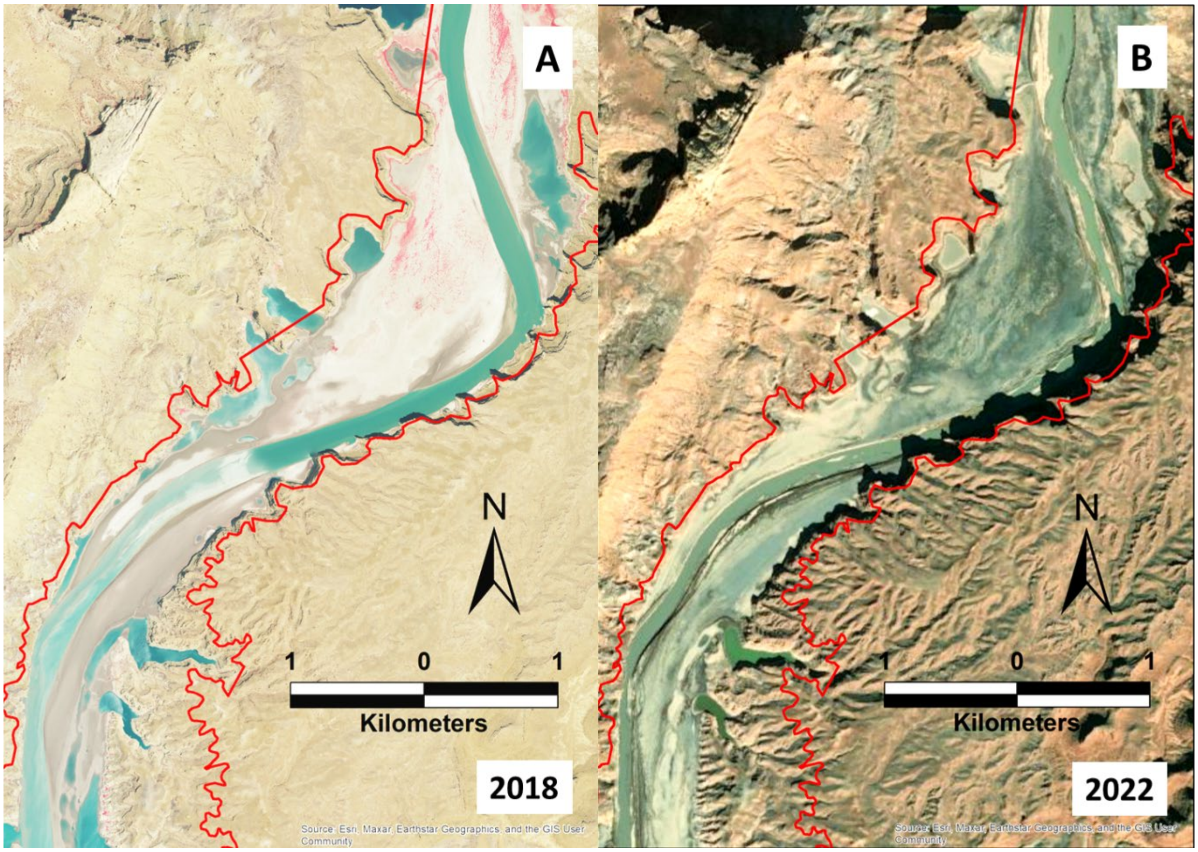


Figure 48. Lower reach of the Lake Powell AOI illustrating rapid revegetation of recently deposited alluvial and lacustrine sediments. A) Imagery from 2018 at a river discharge of 156 cms and a reservoir elevation of 1097 m. B) Imagery from 01/22/2022 (World Imagery, ESRI) at a river discharge of 137 cms and a reservoir elevation of 1077 m.

Large, sustained drops in reservoir elevations create vegetated sediment terraces that are disconnected from surface and groundwater. In a semi-arid climate, this can create widespread moisture stress and mortality for riparian plants that established on these surfaces when there was direct access to surface or groundwater. This pattern of vegetation stress and mortality can be seen in the 2018 imagery (Figure 49) and its extent, as quantified by the supervised classification, represented 13% of the AOI. The vegetation stress/mortality process had important longer-term implications for the pattern, extent, and composition of vegetation on these features.

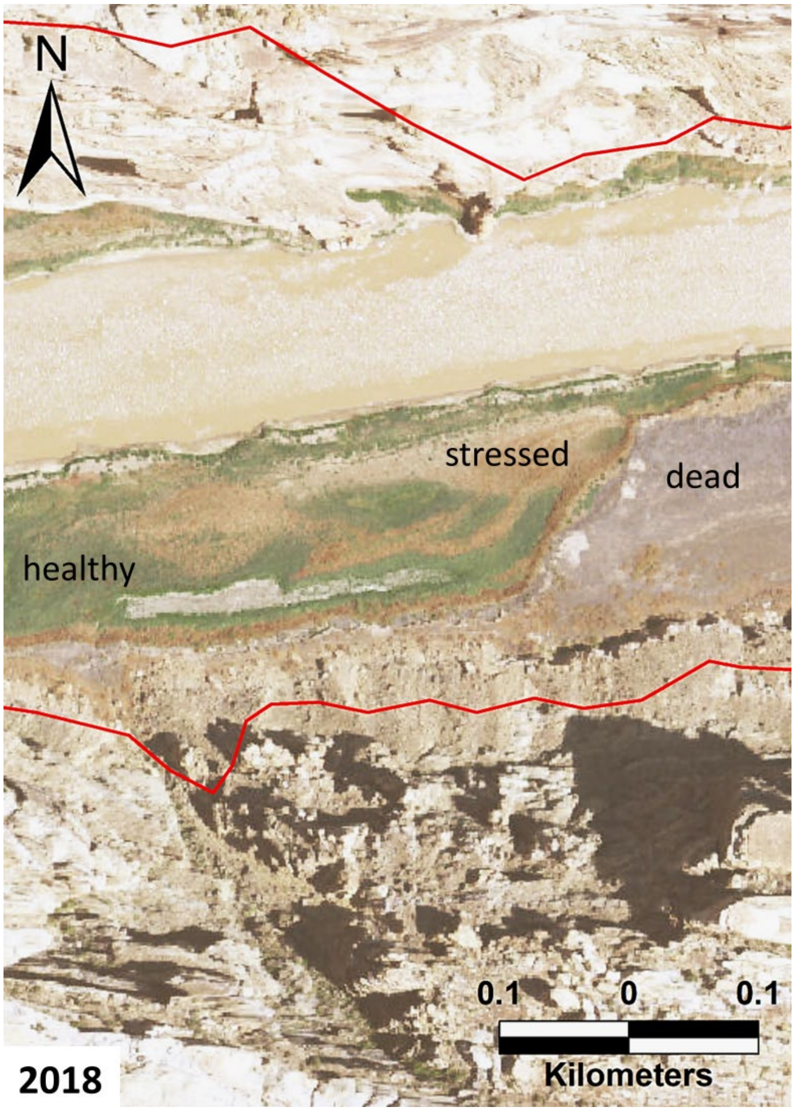


Figure 49. A mosaic of healthy, stressed, and dead riparian vegetation from the Lake Powell AOI in August 2018. In a semi-arid climate, vegetation on alluvial/lacustrine sediment deposits, disconnected from surface and groundwater during falling reservoir levels, is subject to moisture stress and mortality.

5. Discussion

5.1 Delta and backwater formation and processes

The hydrogeomorphic changes and broad vegetation responses to reservoir delta and backwater formation appear relatively uniform across the reservoirs we examined. Pre-dam bottomland channels and associated fluvial geomorphic features, along with wetland, riparian, and upland vegetation are inundated by the filling reservoir. Shifting baselevels, associated with fluctuating pool elevations, produce a complex of sub-aquatic deltaic and sub-aerial fluvial sediment deposits. As illustrated by longitudinal channel thalweg elevations, most of the sediment accumulates between maximum and minimum pool elevations with thickest accumulations near mean pool elevation. Maximum sediment accumulations were variable across reservoirs with depths of over 53 m in Lake Mead but only 15 m in Fort Peck reservoir.

Using spatially and temporally robust channel elevation data from range lines for the Missouri River, we were able to identify three reaches of influence, based on changes in channel slope and cross-sectional profiles. Of note was the backwater affected reach, defined as being above full pool, and thus not subject to effects of direct inundation, but influenced nonetheless by changes in base level imposed by the reservoir. This reach extended 24 river kilometers upstream of full pool and between 1948 and 2007, channel slope flattened from 0.23 to 0.06 meters/kilometer. This was accomplished primarily by changes in channel cross-sectional geometry involving channel filling, which ranged from 0.03 to 4.3 meters across the reach. Channel narrowing accompanied filling at most locations along with prominent levee formation. These geomorphic changes are consistent with backwater affects reported along the White River, a tributary of the Missouri in South Dakota, and are associated with increased overbank flooding and land use changes within adjacent river bottomlands (Liro 2019, Volke et al. 2019). The extent to which these backwater affects extend upstream of the direct reservoir footprint does not appear to be widely appreciated. These backwater affects would be expected to shift spatially, particularly with sustained or permanent declines in reservoir elevations associated with climate warming.

5.2 Climate Warming and Climate-change Projections

Pool elevations for the reservoirs in this study respond, somewhat uniquely, to a variety of factors, including climate and physiographic setting of the contributing basin, reservoir size, upstream water use, and operational mandates. All the reservoirs reflect some degree of climate sensitivity. Fort Peck reservoir has remained the most consistently near full pool over the period of record, with three primary multi-year departures below mean pool elevation coinciding with periods of below average mean annual precipitation. Temperature and precipitation have increased in the basin over the period although seasonal distribution and intensity have changed. In contrast, Lake Powell and Lake Mead reflect a two-decade long decline in pool elevation coincident with a 1.1 °C increase in temperature and multiple dry years with consequently reduced runoff within the upper Colorado River basin (Udall and Overpeck 2017). Elephant Butte reservoir, in part because of its smaller storage capacity and system demands, appears particularly vulnerable to shifts in climate. Pool elevations feature multi-decadal periods of relatively high and low mean elevations that broadly reflect known regional wet and dry periods. From studies in the Colorado River Basin examining relationships among temperature, precipitation, and flow, emerge the concepts of temperature sensitivity (percent change in annual flow per degree rise in temperature) and precipitation elasticity (fractional change in annual flow divided by fractional change in annual precipitation) (Vano et al 2012). These variables may be broadly useful and applicable for use in predicting future flows in response to interactive changes in temperature and precipitation.

Predicted trends in temperature, precipitation, and runoff, for the period 2025-2049 in headwater hydrologic unit (HUC-4) sub-basins for the Missouri, Colorado and Rio Grande rivers project similar outcomes using both reduced and business-as-usual future carbon emission pathways. Specifically, significant increases in temperature with no significant changes in precipitation across these basins, contribute to significant predicted increases in runoff earlier in the season and significantly reduced runoff later in the season, with likely reduced runoff overall. With the upper basin of the Colorado River accounting for 85% of all the flow in the basin, and operational linkage between Lake Powell and Lake Mead, these predictions hold for both reservoirs. These predicted future climate conditions strongly suggest that the sustained low reservoir pool elevations seen for Lake Mead, Lake Powell, and Elephant Butte reservoirs will be a condition common across the reservoirs examined here as well as other reservoirs in regions with similar projected climate futures. New, lower mean reservoir pool elevations, would also cause erosion, fluvial transport, and redistribution of sediments deposited during higher reservoir stages, leading to vegetation dynamics and unknown successional trajectories on new and legacy depositional surfaces.

5.3 Vegetation Responses to Delta-Backwater Dynamics

We hypothesized that extensive, new areas of riparian and wetland plant communities would result from the formation and development of delta-backwaters associated with reservoirs. In addition, these new vegetation assemblages would, at least initially, be dominated by early successional plant species establishing on newly formed or exposed depositional surfaces. The cover of riparian and wetland vegetation on the delta-backwaters we mapped clearly exceeded mapped coverages for pre-dam and early-stage delta-backwater conditions. In the canyon-bound, delta-backwater of Lake Powell, Mesic Riparian cover increased 90% and Xeric Riparian cover 71% over the 55-year post-dam period we examined. Development of the Fort Peck delta-backwater over the past 60 years led to a 113% increase in Mesic Riparian cover but a 9.5% decrease for Xeric Riparian cover, owing in part to ongoing sediment accretion and low topographic diversity across the broad Missouri River bottomland, and recent high reservoir levels. The present delta-backwater ecosystems associated with the reservoirs we examined represent hybrid ecosystems (sensu. Volke et al. 2019) consisting of vegetation associated with pre-dam fluvial processes and post-dam vegetation assembled under the novel hydrological and sedimentological conditions within the reservoir affected reach.

Hypothesized dominance of early successional species on new or exposed depositional surfaces within reservoir delta-backwaters is based on a long-established ecological literature describing primary plant succession (Huston and Smith 1987), fluvial disturbance and establishment of early successional riparian species along rivers (Scott et al. 1996) and a review of vegetation response to dam removal (Shafroth et al. 2002). Our mapping of woody vegetation from aerial imagery, and field observations (M. Scott, personal observation), indicate that newly formed or exposed delta-backwater depositional surfaces were rapidly colonized by primarily native, early successional willows and cottonwood in the case of the Fort Peck reservoir. These results align with findings from sampling and mapping of woody vegetation on the White River delta-backwater (Volke et al. 2019). Comparable delta-backwater surfaces at Lake Powell, by contrast, were dominantly colonized by tamarisk, an early successional, invasive, non-native woody species. Tamarisk was noted in the

Grand Canyon in the early 1940s (Clover and Jotter 1944) and has spread widely along river systems throughout the western US, including the Colorado River system. It is the third most commonly occurring riparian species across 17 western states (Friedman et al. 2005). The degree to which native versus non-native species are reflected in the herbaceous communities across these reservoirs is not reported as far as we know but weedy, non-native herbs were dominant on alluvial surfaces near the Hite Marina on Lake Powell (M. Scott, personal observation). Ground-based sampling of vegetation across these delta-backwater systems was beyond the scope of this investigation but would be an important follow up in assessing habitat quality, long-term successional trends and identifying factors related to observed differences in species composition.

With a globally expanding human footprint, the number of non-native species is increasing across all regions of the world, with potential consequential effects on native species communities and the ecological services they provide (Richardson et al. 2007, Seebens et al. 2016). Frequent fluvial disturbance, an abundance of bare, moist, nutrient-rich sediments and connectivity to a regional drainage network, make riparian and riverine ecosystems especially vulnerable to invasion by non-native species and they typically support a higher percentage of non-native species than other ecosystems (Planty-Tabacchi et al. 1996). Delta-backwater ecosystems may be similarly vulnerable, and concerns have been raised about the role these ecosystems might play in facilitating non-native species invasions across entire drainage networks (Chen et al. 2016). Early successional plants associated with site conditions found in delta-backwaters (bare, moist, nutrient-rich substrates with little or no seed bank) are typically ruderal species displaying rapid growth, abundant seed production and highly effective dispersal mechanisms (Lenhart 2000). Non-native species may represent a substantial proportion of delta-backwater plant assemblages. A multi-year sampling of natural re-vegetation following a reservoir drawdown in Colorado, showed a relatively constant percentage of non-native species over time, ranging from 44 to 60% of all species; a much higher percentage than recorded in the adjacent upland (Auble et al. 2007). Quantifying the abundance of invasive, non-native species in delta-backwater vegetation assemblages, along with understanding the physical environmental factors that promote or suppress their establishment and spread, should be a focus of future research efforts in these ecosystems. A metacommunity ecological approach (Heino 2013), combining an understanding of local factors (e.g., environment conditions, competition) and regional factors (dispersal, stream network connectivity, propagule pressure) would contribute to an improved understanding of patterns and abundance of invasive, non-native species in delta-backwater environments.

Possible large-scale physical factors and processes, associated with some of the observed differences in vegetation between Fort Peck reservoir and Lake Powell, involve the valley setting in which the delta-backwaters form as well as the frequency and amplitude of reservoir fluctuations. The broad, relatively low gradient, alluvial valley of the Missouri River contrasts with the narrow, steeper, bedrock canyon of the Colorado River. Long-term development of the delta-backwater in the reservoir affected reach of the Missouri River featured a broad depositional surface that spanned the bottomland from valley wall to valley wall. The flattening of the stream gradient, narrowing of the channel and levee development likely contributes to increased overbank flooding and more prolonged inundation of the relatively featureless flood plain during lower reservoir levels. During higher reservoir levels, vegetation would be influenced by shallow groundwater or a gradual inundation depth gradient. This, together with extended periods of relative stability in reservoir pool elevations, and comparatively small amplitude pool fluctuations, is consistent with the following outcome: A 9 m drop in the pool elevation of Fort Peck reservoir, between 1998 and 2007, exposed 132 square kilometers of Missouri River bottomland, much of which was rapidly colonized by mesic native woody riparian and herbaceous wetland vegetation. These newly assembled vegetation communities provided extensive, high-quality habit that was quickly utilized by wildlife (Volke et al. 2015).

This contrasts sharply with Lake Powell where much thicker delta-backwater deposits formed in the narrow, bedrock confined portion of the study reach. Following a 32 m drop in the pool elevation at Lake Powell between 2000 and 2005, the Colorado River incised the accumulated sediment, creating terraces. Vegetation on these widespread, hydrologically disconnected terraces were subject to seasonal stress and mortality. The current and long-term composition of vegetation on these surfaces is unknown but could be expected to transition from primarily xeric riparian to upland species. Similar physical and biological responses have occurred in the delta-backwater at Lake Mead. The vegetation transitions on remnant terrace features are important to understand as they may serve as leading indicators of a possible delta-backwater response mode to climate warming, where steep, sustained drops in pool elevations drive incision of delta-backwater surfaces and rapid transitions in vegetation structure and composition.

6. Conclusions

6.1 Summary of Key Findings

1) The physical development of delta-backwaters in response to base level changes imposed by a reservoir appears to be rather uniform across the reservoirs examined in this investigation. The bulk of sediment accumulated between maximum and minimum pool elevations with maximum thicknesses near long-term mean elevation.

2) Geomorphic effects of reservoir backwaters, on the channel geometry of tributary streams, may extend upstream of full pool for considerable distances. The milder the longitudinal river slope, the greater the upstream distance of the geomorphic effect. In the case of Fort Peck reservoir, this influence extended 24 river kilometers upstream of full pool.

3) Accumulating sediment provides surfaces upon which vegetation establishes, creating hybrid vegetation assemblages that have similarities to pre-reservoir fluvial conditions as well as novel hydro-geomorphic conditions established by the reservoir. The pattern, extent and biophysical dynamics of these hybrid ecosystems are influenced in part by the valley slope and confinement in which they form, in combination with short- and long-term water-surface fluctuations of each reservoir.

4) The broad, low-gradient alluvial valley of the Missouri River, and relatively stable, low amplitude reservoir fluctuations, appear to produce very different ecological outcomes than the bedrock-constrained canyons of the Colorado River, where climate-driven variations in reservoir pool elevations are more extreme. For example, a 9 m drop in the elevation of Fort Peck reservoir, over 10 years, exposed 132 square kilometers of bottomland dominated by mesic vegetation with apparently high representation of native species. In contrast, a 32 m drop in Lake Powell over six years, incised delta-backwater surfaces, creating sedimentary terraces upon which vegetation, including non-native tamarisk, was subject to moisture-induced stress and mortality.

5) Although beyond the scope of this investigation, on-the-ground sampling of vegetation across delta-backwater surfaces at the reservoirs examined, is strongly recommended. Such information would clarify the extent to which non-native plant species are represented in these ecosystems. A metacommunity ecological perspective, recognizing the role of local and regional factors in structuring vegetation assemblages, could improve understanding and predictions of how delta-backwater vegetation communities respond to physical and environmental variability. This is especially important considering predicted future climate warming.

6) Each of the reservoirs examined displayed some degree of climate sensitivity, especially Lake Powell, Lake Mead, and Elephant Butte, which to some extent is also a function of reservoir size and operational mandates. Climate modeling for headwater sub basins for each of the reservoirs, using reduced and business-as-usual future carbon emission pathways, projected significant increases temperatures with no corresponding change in precipitation. This translates to corresponding significant changes in the timing of runoff with likely reduced magnitudes, along with significant increases in evaporative demand, and decreases in soil moisture storage. These projections suggest that the observed sustained declines and increased variability in reservoir pool elevations will represent a new state for many reservoirs given ongoing and projected climate warming. New, lower pool elevations would contribute to erosion, fluvial transport and redistribution of sediments deposited during higher reservoir elevations, leading to increased vegetation dynamics and unknown vegetation successional trajectories on new and legacy depositional surfaces.

6.2 Future Research Needs, Plans, and Products

This investigation focused on large-scale vegetation patterns related to the physical formation of delta-backwater landforms and their dynamic response to short- and long-term fluctuations in reservoir pool elevations. Hybrid plant communities have established, expanding available habitat at the reservoirs we examined. Some of this new habitat appears to be of high quality with an abundance of native species, whereas other reservoirs appear to support primarily non-native species. Further, sustained, climate-driven declines in pool elevations at Lake Powell, Lake Mead, and likely Elephant Butte reservoir, are initiating new vegetation establishment processes and subjecting established vegetation to stress and mortality. Our findings point to a clear need for on-the-ground sampling and quantification of the species composition at these sites, with an eye toward a predictive understanding of the local and regional processes that contribute to the assembly of plant communities at a site. Given the expanding presence of invasive, non-native species across ecosystems world-wide, such an understanding could inform water management actions that would favor the establishment and persistence of native species and improve predictions of plant community responses to projected climate warming.

An important outcome of this project is the assembly of disparate data sources that are necessary for an integrated, cross-disciplinary understanding of delta-backwater ecosystems. With these datasets, we plan to produce two peer-reviewed scientific publications. The first would focus on a synthesis of the data from three of our reservoirs, (Lake Mead, Lake Powell, and Fort Peck Lake), which represent the first, second and fifth largest reservoirs in the U.S., respectively, emphasizing similarities in the physical processes and formation of delta-backwater features associated with the reservoirs. We will also emphasize the unique vegetation communities that have developed on delta-backwater landforms and discuss the factors that have likely contributed to the distinctive plant assemblages that have formed at each reservoir. Finally, we will contrast the physical and biological outcomes of the large and sustained, climate-related drawdowns and fluctuations of Lake Powell and Lake Mead with the less extreme drawdown of Fort Peck Lake. A working title for this manuscript would be: *Development and Dynamics of Delta-backwater Ecosystems in Large Reservoirs*, with *Ecological Applications* being the target journal. The second manuscript will focus on Elephant Butte Reservoir where reservoir size, operational demands and longer-term climate shifts produce short- and long-term reservoir fluctuations, and related physical and biological responses of the delta-backwater, that could serve as a prologue for other reservoirs given projected future increases in temperatures, vapor pressure deficits, and decreases in soil moisture storage and runoff. A working title for the second manuscript would be: *Reservoir Delta-backwaters: Ecological Responses to Climate Change*, with *Climate Change* being the target journal.

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