Waterfalls in Reservoirs: Tracking the Development of Nickpoints in the Sediments of Declining Reservoirs

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Abstract

Recent drought has resulted in dramatic lowering of the two largest water-storage reservoirs in the western United States: Lake Powell and Lake Mead. These decreases in reservoir elevations have resulted in the re-emergence of over 100 km of the Colorado and San Juan rivers at the upstream end of Lake Powell and over 80 km of the Colorado River at the upstream end of Lake Mead. Upon reservoir lowering, the rivers cut into the lake and delta deposits sometimes establishing a course different than the path of the historical channel. In two locations, the rivers have encountered resistant bedrock resulting in the formation of rapids or waterfalls. In a third location, on the Colorado River arm of Lake Powell near the mouth of the Dirty Devil River, a knickpoint is just beginning to form and a new rapid or waterfall may result if water levels continue to drop. We present repeat measurements with multibeam sonar of the riverbed at this location to document scour at the site of nickpoint formation. Between initial measurements made in October 2020 and the most recent measurements made in May 2022, the riverbed scoured by up to 11 m as the level of Lake Powell dropped by more than 18 m. These knickpoints in former reservoirs have several implications for river and reservoir management, including effects on river dynamics and upstream river ecosystems, impacts to river and reservoir navigation, and the formation of ecological barriers.

Introduction

The water storage levels of Lake Powell and Lake Mead, the two largest reservoirs in the western United States, have dropped dramatically over the past two decades (Figure 1). In combination, the water storage of these two reservoirs has declined by more than 41 km^3. This has equated to the re-emergence of ~100 km each along the Colorado and San Juan rivers at the upstream end of Lake Powell and over 80 km of the Colorado River at the upstream end of Lake Mead. Upon reservoir lowering, the rivers cut into the lake and delta deposits sometimes establishing a course different than the path of the historical channel. In two cases, the rivers have encountered resistant bedrock resulting in the formation of knickpoints and rapids or waterfalls (Figure 2). These have occurred to form Piute Falls on the San Juan River within former Lake Powell sediments (Cathcart et al. 2018) and at Pearce Ferry Rapid on the Colorado River within the former Lake Mead sediments. There is now a potential third case, on the Colorado River within former Lake Powell sediments where a knickpoint is just beginning to form and a new rapid or waterfall appears imminent if water levels continue to drop.

These reservoir-waterfalls have important implications for river and reservoir management. As knickpoints, they control the upstream energy gradient and affect the rate and pattern of evacuation of exposed reservoir delta sediments, thus affecting river dynamics and river

ecosystems far upstream. They also have immediate impacts in the vicinity of the knickpoint on navigation, which affects decisions regarding expensive infrastructure such as boat ramps. They also create ecological barriers that impact the migration of native and nonnative fish. We present descriptions of these phenomena, using repeat measurements with multibeam sonar of the riverbed to document scour at the site of knickpoint formation.

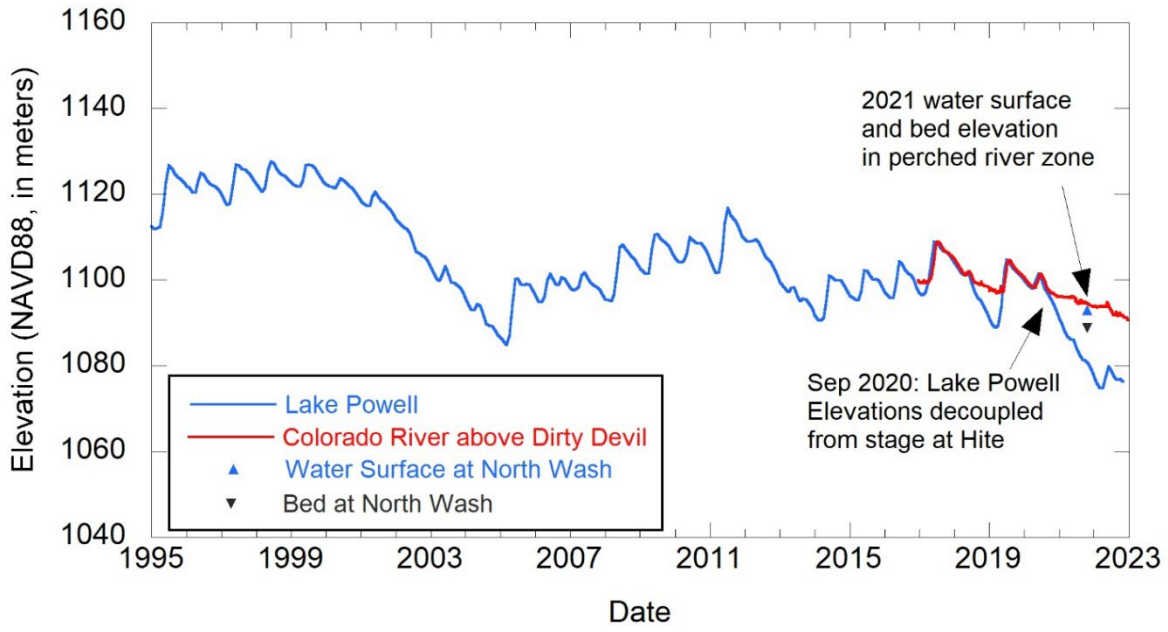


Figure 1. Water surface elevations for Lake Powell at Glen Canyon Dam and the Colorado River above Dirty Devil River near Hite, Utah (USGS gage 09328990). Water elevation at Glen Canyon Dam is measured relative to NGVD29, in feet and water elevation at Hite is measured relative to NAVD88, in feet. The NGVD29 elevations were converted to NAVD88 by adding the difference between the two datums at Hite, Utah (3.14 feet) to the NGVD29 elevations.

Figure 2. Piute Farms waterfall on the San Juan River previously inundated by Lake Powell (left) on January 19, 2022 and Pearce Ferry Rapid on the Colorado River previously inundated by Lake Mead (right) on February 9, 2021.

We report on observations of water surface and bed-elevation change of the Colorado River near the confluence with the Dirty Devil River for a two-year period during which the level of Lake

Powell dropped more than 18 meters. The measurements document dramatic riverbed scour and reveal the possible emergence of a new rapid or a waterfall. In addition to monitoring riverbed change, these observations will be used to develop and calibrate models for sediment evacuation in the delta zones of rapidly changing reservoirs.

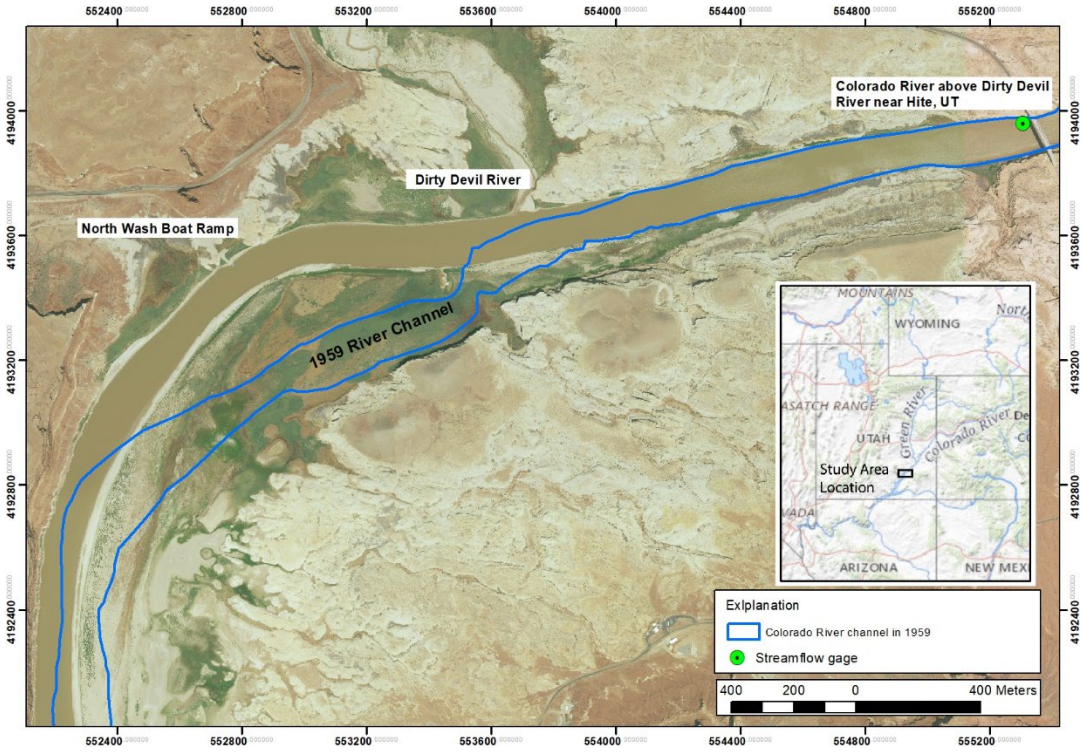


Figure 3. Map of the confluence of the Dirty Devil River and Colorado River near Hite, Utah. Inset shows map location in the Colorado River Basin. The blue outline shows the course of the Colorado River before Lake Powell was filled based on the 1959 topographic map. Streamflow is from upper right to lower left.

Methods

Channel bathymetry was measured in October 2020, October 2021, and May 2022. The 2020 map extends from the confluence of the Dirty Devil downstream to the North Wash Boat Ramp. The 2021 map begins just upstream from the North Wash Boat Ramp and extends downstream to the approximate location where the current river channel rejoins the pre-Lake Powell river channel (Figure 3). The 2022 map spans most of the reach from the Dirty Devil confluence to the downstream extent mapped in 2021. All bathymetric data were collected with a Norbit iWBMSh multibeam echosounder with integrated Applanix POS-MV Oceanmaster inertial navigation system mounted on a motorized pontoon raft (Figure 4). Real-time kinematic (RTK) positioning was achieved with a Trimble R10 GNSS receiver broadcasting corrections from a stable reference point. The raw navigation data (position and attitude information) were post-processed in POSPac MMS 8.6 single base. The resulting smoothed best-estimate of trajectory (SBET) file for each survey was applied to the bathymetric data. The data were then edited in Qimera 2.3.3 to remove bad soundings after applying field-derived patch-test corrections. Because the soundings comprise hundreds of points per square meter, the data were filtered to export on a regular 0.25 square meter grid, the median elevation value among all soundings in that grid cell to produce digital elevation models (DEMs). All elevations were adjusted from

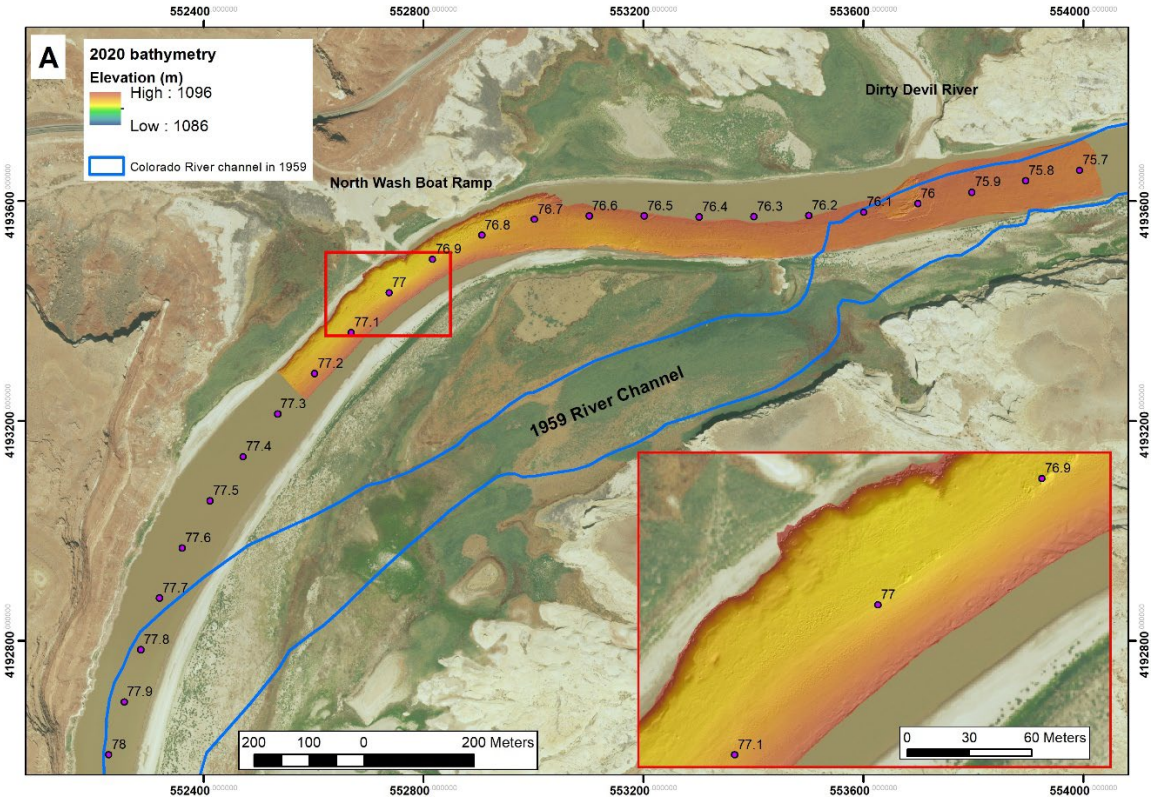
ellipsoid heights to NAVD88 orthometric heights (Geoid 18) by adding a constant value of 21.08 meters. Successive DEMs were subtracted to compute differences in riverbed elevation. The processed DEMs and water surface profiles are available in the data release of Grams et al. (2022).

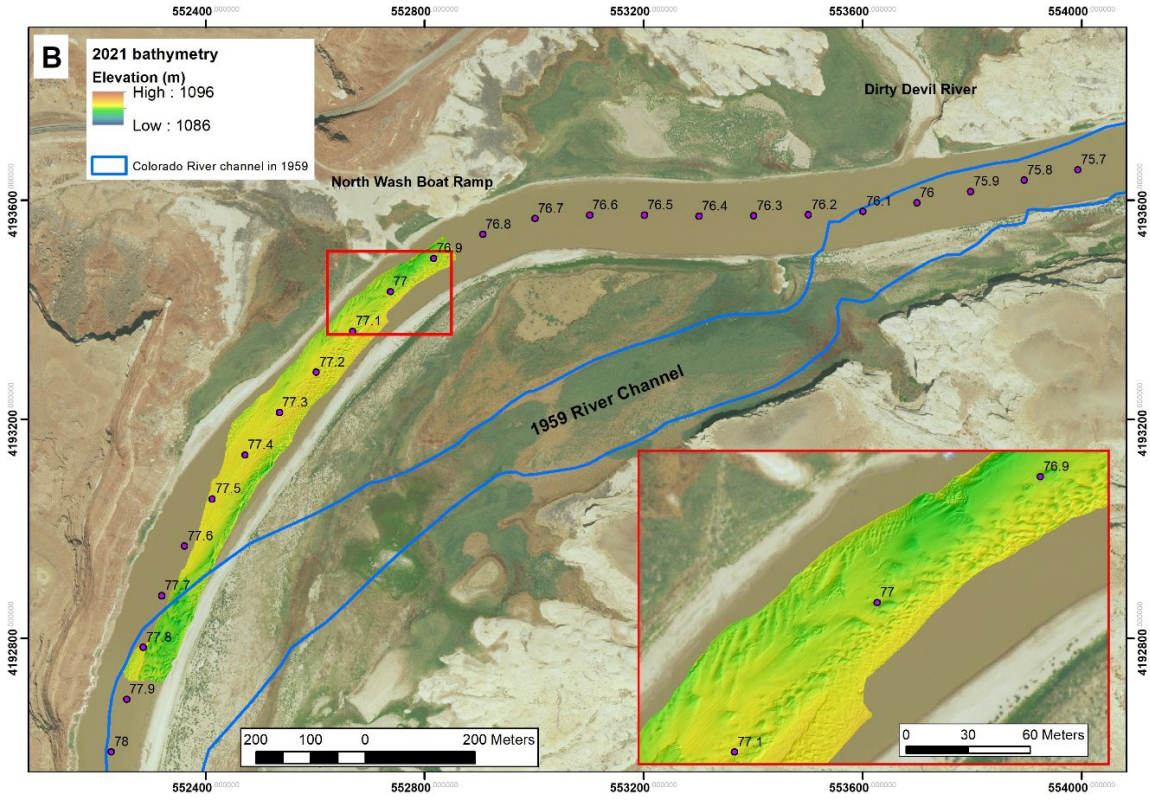
Figure 4. Launching survey vessel at North Wash boat ramp, about 900 m downstream from the mouth of the Dirty Devil River. The incising riverbed has caused the boat ramp to become too steep for safe use with vehicles and boats must be launched and retrieved by mechanical winch.

Results

From the first measurements collected for this study in October 2020 to the most recent field survey in May 2022, the reservoir elevation at Lake Powell dropped from 1095.71 m to 1077.42 m (Figure 1). Over this same period the streamflow gage for the Colorado River at Hite, UT indicates a drop in the stage-discharge relation by 5.6 m for a similar discharge. The last time the backwater effect of Lake Powell controlled water surface elevation at the Hite gage was August 2020 when Lake Powell elevations dropped below 1096.5 m (Figure 1).

The repeat bathymetric surveys document both changes in bed elevation and bed configuration. In October 2020, the river bed was relatively smooth and flat, was covered by very few bedforms, and few erosional features (Figure 5a). One year later the riverbed in the same location was covered by large dunes and contained many scour features (Figure 5b). Because these data were collected at similar discharges (4000 ft^3/s in 2020 and 5000 ft^3/s in 2021), it is likely that these differences represent changes in bed configuration associated with bed lowering and not flow-controlled changes in bed configuration. In May 2022, six months after the October 2021 survey, the bed consisted of a smooth center channel with few bedforms and abundant scour features along the shelf-like channel margins (Figure 5c). This survey was collected during the spring 2022 snowmelt flood at a discharge of about 24,000 ft^3/s and likely reflected both bed lowering and differences in bed configuration associated with the higher discharge.


A
2020 bathymetry
Elevation (m)
High : 1096
Low : 1086
Colorado River channel in 1959
Dirty Devil River
North Wash Boat Ramp
1959 River Channel
552400
552800
553200
553600
554000
4193600
4193200
4192800
200 100 0 200 Meters
0 30 60 Meters


B
2021 bathymetry
Elevation (m)
High : 1096
Low : 1086
Colorado River channel in 1959
Dirty Devil River
North Wash Boat Ramp
1959 River Channel
552400
552800
553200
553600
554000
4193600
4193200
4192800
200 100 0 200 Meters
0 30 60 Meters

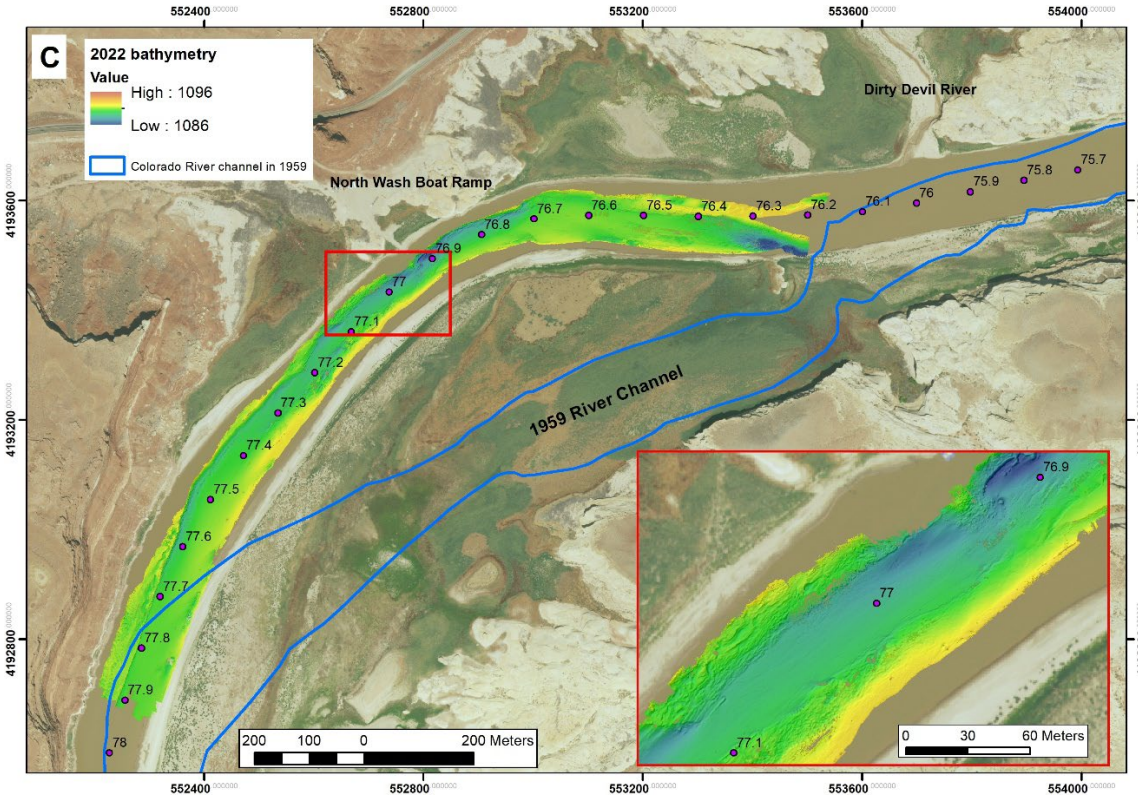
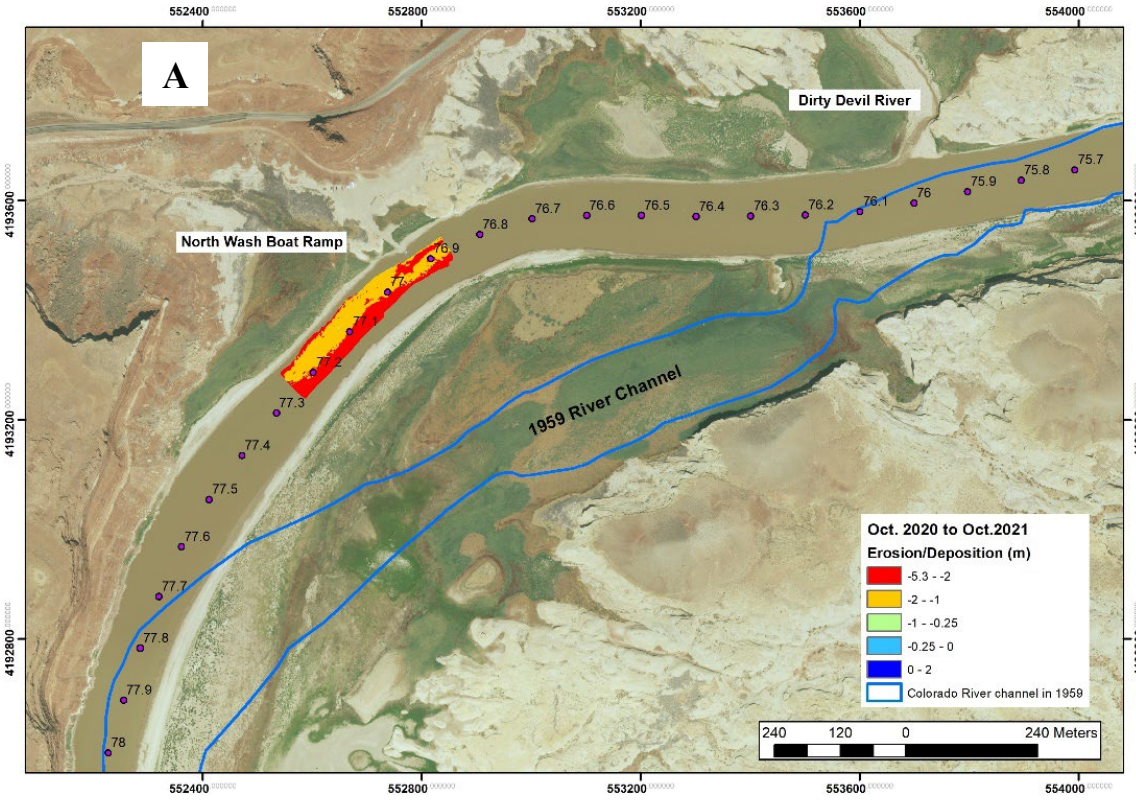
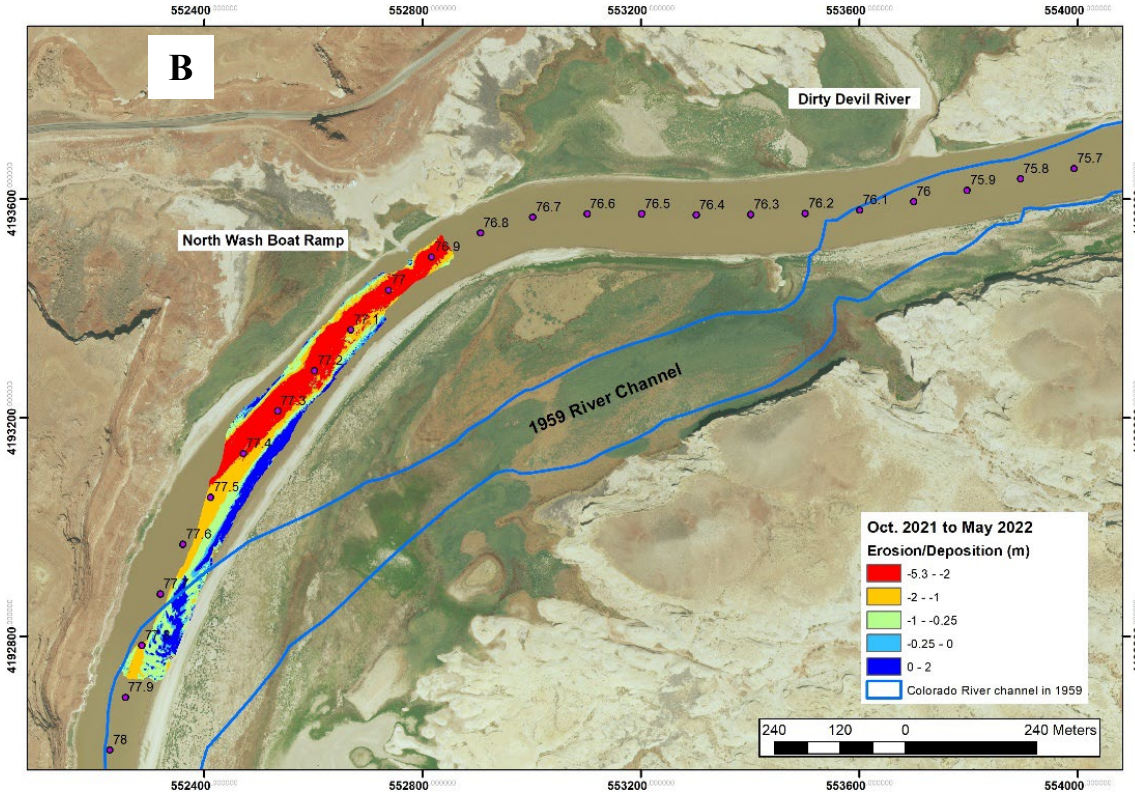


Figure 5. Shaded relief maps of riverbed elevation. Data collected October 23, 2020 (A), October 22, 2021 (B), and May 19, 2022 (C). The blue outline in each panel is the path of the Colorado River in 1959. The labeled points along the channel centerline indicate distance downstream from the Green River confluence, in kilometers. The inset in the red box illustrates the bedforms in the region of the study reach near the North Wash boat ramp.

Comparison of these bed elevation maps reveals the magnitude of bed lowering and confirms that these surveys depict three entirely different river channels. Between October 2020 and October 2021, the bed eroded by up to 4 m with an average decrease over the area of overlap of 2 m. The greatest magnitudes of erosion were along the river left bank. The average decrease between October 2021 and May 2022 was 1.3 m with some parts of the channel eroding as much as 5 m (Figure 6b). Over the area common to the October 2020 and May 2022 surveys, there was up to 11 m of erosion with an average lowering for this period of 4.3 m. The greatest magnitude of erosion occurred near the location where the current river channel departs from the pre-Lake Powell course of the channel (Figure 6c).


A
Dirty Devil River
North Wash Boat Ramp
1959 River Channel
Oct. 2020 to Oct.2021
Erosion/Deposition (m)
-5.3 - -2
-2 - -1
-1 - -0.25
-0.25 - 0
0 - 2
Colorado River channel in 1959
240 120 0 240 Meters
552400
552800
553200
553600
554000
4193600
4193200
4192800


B
Dirty Devil River
North Wash Boat Ramp
1959 River Channel
Oct. 2021 to May 2022
Erosion/Deposition (m)
-5.3 - -2
-2 - -1
-1 - -0.25
-0.25 - 0
0 - 2
Colorado River channel in 1959
240 120 0 240 Meters
552400
552800
553200
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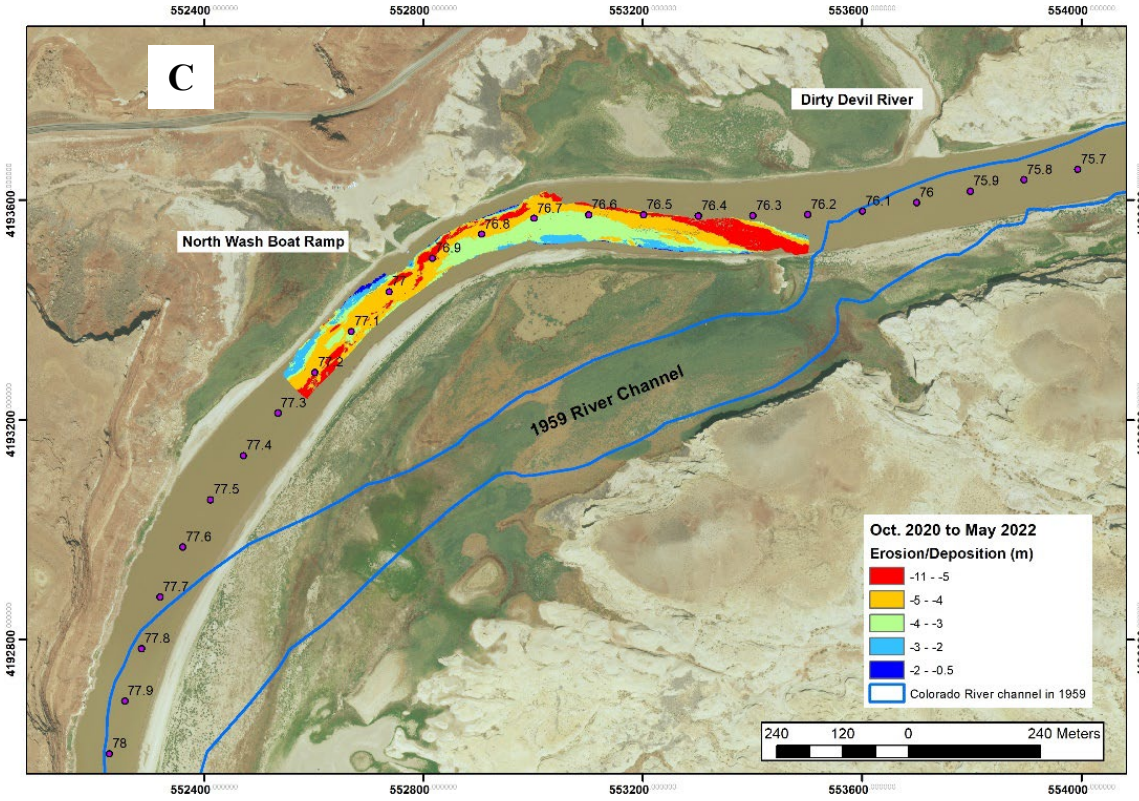

Figure 6. Maps showing erosion and deposition between October 23, 2020 and October 22, 2021 (A), between October 22, 2021 and May 19, 2022 (B), and between October 23, 2020 and May 19, 2022 (C). The blue outline in each panel is the path of the Colorado River in 1959. The labeled points along the channel centerline indicate distance downstream from the Green River confluence, in kilometers.

Discussion and Conclusion

Between October 2020 and May 2022, as the level of Lake Powell decreased 18.3 m, the bed of the Colorado River near the confluence of the Dirty Devil River incised up to 11 m. In this segment of the Colorado River, the channel follows a course different than the pre-Lake Powell Colorado River channel (Figure 3). The difference between the May 2022 bathymetry and the 1959 topographic map (Root et al. 2019) indicates that the channel has incised through the entire thickness of reservoir sediment and into the 1959 topography. This includes erosion of as much as 40 m of reservoir sediment and as much as 15 m into the pre-reservoir topography. Up to 40 m of reservoir sediment remain in parts of the channel where incision has not yet occurred (Figure 7).

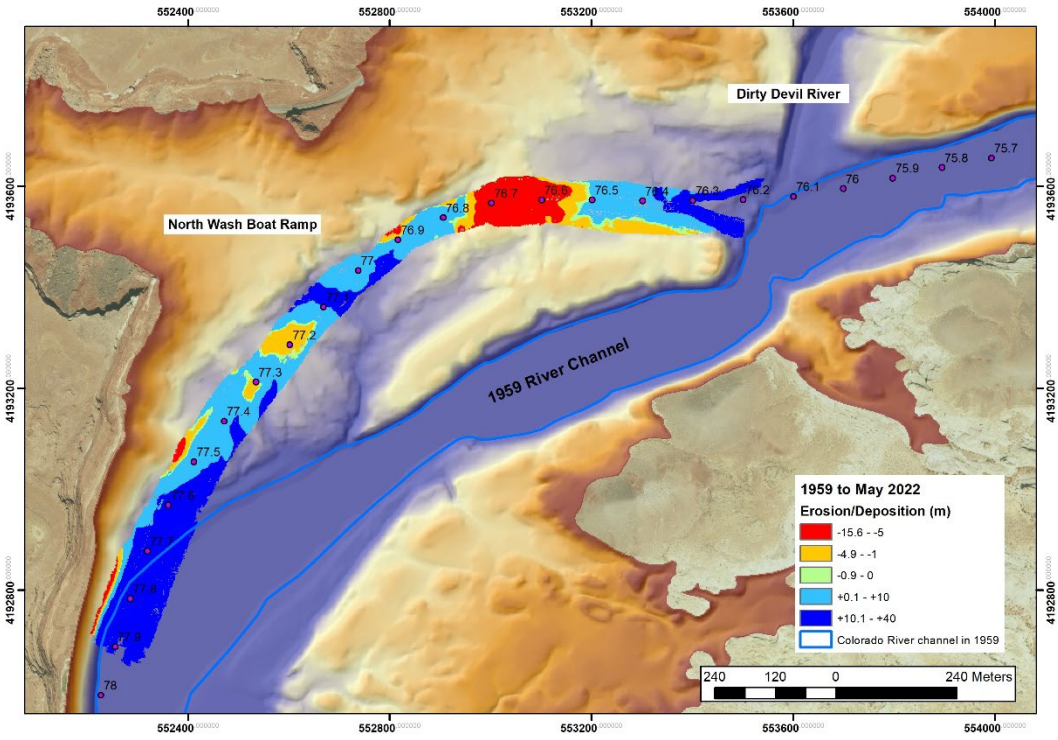

Figure 7. Map showing the difference between the May 19, 2022 bathymetry and the pre-Lake Powell (1959) topography. The shaded relief background image is from the 1959 topography (Root et al. 2019).

Because bed elevations in the study reach are more than 6 m above the current Lake Powell surface elevation, continued incision is likely unless the reservoir refills to levels most recently seen in July 2021. However, we do not yet have enough information to predict the most likely outcome of further incision. The greatest uncertainty is in the competency and structure of the riverbed and underlying material. The geologic map for this region (Orkild 1956) indicates that the perched river channel is flowing over "surficial deposits." The adjacent bedrock is Permian sandstone of the Cutler formation, which must underlie the surficial deposits but at unknown depth. The rapid rates of incision we have measured indicate that the underlying bedrock has not yet been reached. If upon further incision the river encounters bedrock or another resistant layer, it is possible that a rapid or waterfall could form. Depending on the depth of the potential resistant layer and the level of Lake Powell at the time the drop of the rapid or waterfall could be on the order of ~1 m to ~10 m. It is possible that the entire thickness of the riverbed subsurface down to the elevation of the pre-Lake Powell river channel is unconsolidated surficial deposits. In this case, downcutting may continue uninterrupted without forming a major knickpoint.

An alternative possibility is for the river to return to the pre-Lake Powell channel. The entrance to this channel opposite the mouth of the Dirty Devil River is filled by a plug of reservoir sediments that are 30 to 40 m thick. For the Colorado River to avulse and reoccupy that channel would likely require a flood large enough to overtop the river-left bank that is currently ~15-m high and increasing in height relative to the river as downcutting continues. Because of the active incision, there is not a stable stage-discharge relation for the upstream gage and the magnitude of the discharge that would be required to overtop the bank is unknown. For example, the 2022 peak flow of approximately 28,000 ft^3/s only cause the stage to increase by about 1 meter owing to concurrent incision during the 2022 snowmelt flood resulting in a net decrease in stage.

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