8-2020

Visualizing Effects of Changing Base Level on Tributary Resources in Lake Powell Reservoir

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VISUALIZING EFFECTS OF CHANGING BASE LEVEL ON TRIBUTARY

RESOURCES IN LAKE POWELL RESERVOIR

by

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A Plan B paper submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Watershed Sciences

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2020

ABSTRACT

Visualizing Effects of Changing Base Level on Tributary

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by

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Lake Powell reservoir is the second-largest reservoir in the United States. As climate change reduces watershed runoff in the Colorado River Basin, questions arise about the management and even existence of Lake Powell. If lake levels continue to drop, what will the emerging canyon look like and what value will we assign it? Lake Powell traps all incoming fine sediment from the Colorado River, the San Juan River, and many smaller tributaries. What is the fate of this sediment under falling reservoir levels and how will it influence other resources? To support a robust public discourse, we provide an immersive ESRI StoryMap, combining a range of information in a visually compelling, user-friendly digital format. A particular focus of the StoryMap is the configuration and persistence of sediments deposited in the reservoir during previous high stands. In this document, we provide background information for stakeholders and user groups that desire to understand more about the region, reservoir and dam operations, climate change and aridification, and sediment transport. The StoryMap can

be accessed at https://arcg.is/1feGiO or at https://storymaps.arcgis.com/stories/41b5fda81d8b47d0abe8958845fd0194.

(27 pages)

ACKNOWLEDGEMENTS

Just as art is not created in a vacuum, neither is science. I am incredibly grateful to Dr. Peter Wilcock for providing me a path forward to finish my degree in a program and tradition of fluvial geomorphology I am incredibly proud to be a part of. Dr. Belize Lane is a phenomenally supportive committee member who is a tremendous force to look up to as a water resources professional and river guide. Dr. Alan Kasprak was the first person to introduce me formally to the wonderful world of fluvial fun, and I am grateful for his support and technical assistance as a committee member. He was first to propose the creation of the accompanying StoryMap and provided critical context with his work in the Center for Colorado River Studies.

USU is full of compassionate, skilled professionals. I thank my lucky stars for the USU WATS administrative staff, Brian Bailey and Enid Kelley. They cheerfully answered my increasingly complex administrative and bureaucratic questions and I am so grateful. They get things done. Kourtney Austin and Shelby Schmidt from the SAAVI office supported me through tremendous personal challenges affecting my academic progress, as did Dr. Amy Kleiner (CAPS) and Eric Lee (ACT Research Group). Generous support from My Good Fund and Glen Canyon Institute allowed me to conduct research that facilitated the development of this project. Jennifer Speers, Dr. Rich Ingebretsen, and Eric Balken were instrumental in supporting this project. Bill Wolverton was invaluable in the field. Dr. Jack Schmidt directed that work and provided the opportunity to pursue graduate studies at USU.

When I moved to Logan in 2018, I did not realize how much the Cache Valley community would become a home. Thank you to my grad student crew: Karen Bartelt,

Todd Blythe, Natalie Gillard, Jabari Jones, Jenna Keeton, Christy Leonard, Clarissa Ong, Becky Riemann, and Susan Washko. Thank you to community members Makayla Blair (CAPSA), Kim Jeppson, Malacha Leonard, John Luthy (Peck Hadfield), Shaun Peck (Peck Hadfield), Katie Potter, JaNae Sorenson (The Family Place), and Toby Stegman.

Thank you to my people across the land: Keegan Athey, Bridie Carmichael, Curt Chang, Mia Clyatt, Megan Dwyer, Andy Errickson, Colleen Fitzgerrell, Caroline Foley, Alison Holland, Emily Koehn, Seneca Kristjonsdottir, Sarah Mallory, Lauren McCullough, Abby McMurtry, Chantal Mosman, Sofia Nicholson, Kersten Schnurle, Amber Shannon, Sabrina Stein, Rose Triolo, Morris Uebelacker, Emma Wharton, and Jasmine Wilhelm.

Most importantly, thank you to my family: Robert, Christine, and Mercedes Friend; and Mark Beale.

Madeline L. Friend

CONTENTS

LIST OF FIGURES

INTRODUCTION

Lake Powell is the second -largest reservoir in the United States and traps all incoming fine sediment the Colorado River used to transport through Glen Canyon and into Marble Canyon and Grand Canyon. A warming climate is projected to yield less streamflow in the Colorado River and its major headwater tributaries, inevitably leading to persistently less water stored in mainstem reservoirs (MacDonnell et al., 1995; Castle et al., 2014; Udall and Overpeck, 2017; Lehner et al., 2018; Xiao et al., 2018; Milly and Dunne, 2020). Sediments transported into the reservoir by two large interregional rivers (the Colorado and San Juan Rivers), regional rivers (the Escalante and Dirty Devil Rivers), and small local streams now form deltas that partially fill upstream parts of many reservoir arms. During periods of low reservoir level, this fine sediment can be eroded, remobilized, and transported further into Lake Powell. Although bathymetric measurements of sediment accumulation have been made in the largest reservoir arms, little is understood about fine sediment accumulation and evacuation in smaller side canyons that once made Glen Canyon famous. Further, few public-facing, user-friendly tools exist to synthesize what information does exist.

My research draws on aspects of geomorphology concerning erosion and deposition in river channels (Hadley, 1974; Gellis et al., 1991; Church, 2006; Collins and Bras, 2008; Mueller and Pitlick, 2013; Griffiths and Topping, 2017); geomorphology of alluvial valleys and their history of accumulation and evacuation of fine sediment (Bryan, 1925; Bailey, 1935; Antevs, 1952; Patton and Schumm, 1981; Graf, 1983; Harvey and Pederson, 2011); the concept of base level (Powell, 1875; Mackin, 1948; Leopold and Bull, 1979; Majeski, 2009); and delta formation and reworking processes during changes

in base level (Gilbert, 1885; Vernieu, 1997; Pratson et al., 2008; Millares and Moñino, 2018).

By integrating these into an ESRI StoryMap, I aim to provide geomorphic context and insight to better inform stakeholders and public policy concerning Lake Powell and its future. This map will be free and accessible to anyone with a digital device and internet. This digital tool will evaluate three tributary resources (sediment, cultural and recreation sites, and dam operations) at four different reservoir elevations (full pool: 3,700 feet above sea level (fasl); minimum power pool: 3,490 fasl; dead pool: 3,370 fasl; and March 2018 levels: 3,619 fasl).

Study Area

Glen Canyon Dam on the Colorado River forms Lake Powell (Figure 1). More than 40 million people in seven U.S. states and two Mexican states rely on Colorado River water through a complex system of national and international laws, policies, and agreements (Bruce et al., 2018; Maupin et al., 2018; Milly and Dunne, 2020). Spanning nearly 186 miles in Utah and Arizona, the reservoir provides storage for Upper Basin states to meet their flow obligations to Lower Basin states under the 1922 Colorado River Compact (Figure 2) (Bureau of Reclamation, 1966). The region immediately surrounding Lake Powell is primarily underlain by erodible Mesozoic rock (Ferrari, 1988; Chidsey Jr. et al., 2000). The climate is semi-arid, with precipitation primarily occurring in summer and fall during the North American Monsoon (Iorns et al., 1965). As is common on the Colorado Plateau, intense local rainfall leads to overland flow and significant sediment delivery from upland watersheds (Patton and Boison, 1986).

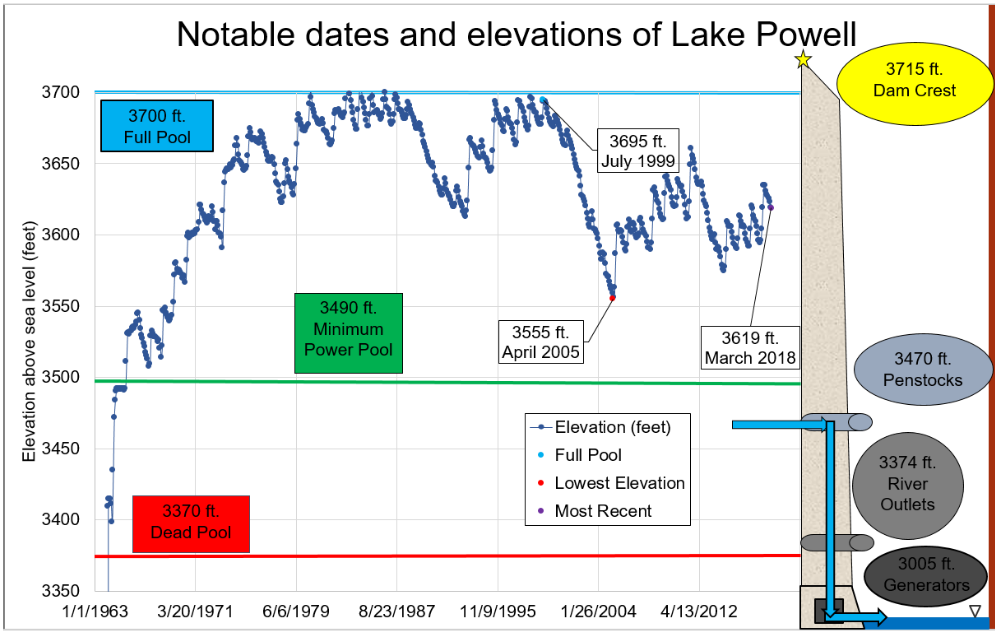

Figure 1. An illustration of Glen Canyon Dam, noting important management elevations and historically significant dates.

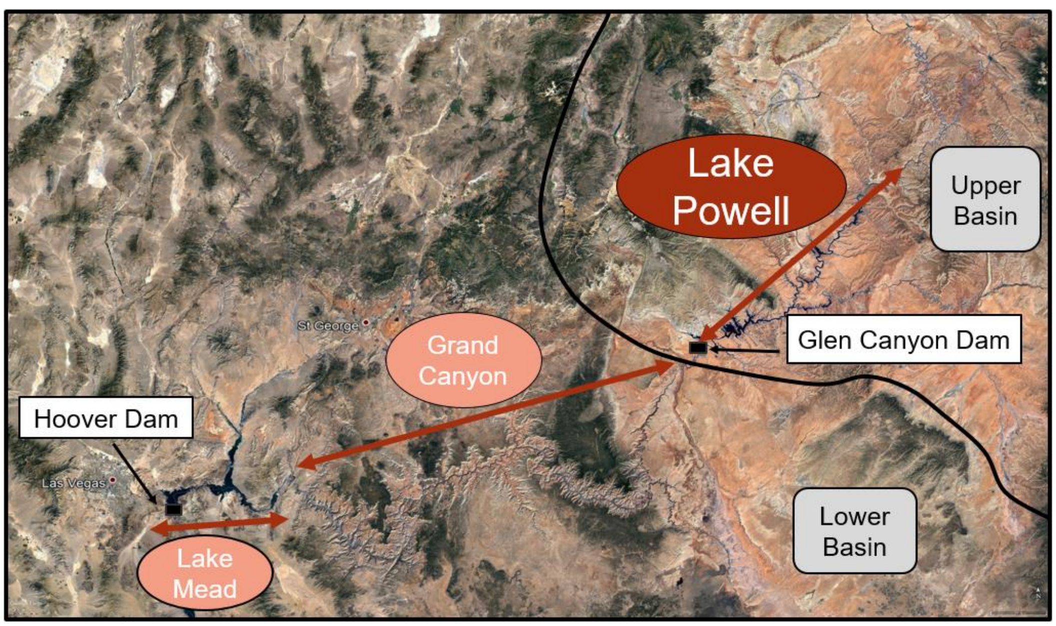

Figure 2. Map of the greater Colorado Plateau region, showing the location of Lake Powell (i.e., Glen Canyon), Grand Canyon, and Lake Mead along the Colorado River.

Local Streams

Most studies of sedimentation rates in Lake Powell have focused on the interregional streams that transport the majority of water and sediment into the reservoir. Ferrari (1988) estimated 14 percent of total reservoir sediment volume is stored in both regional and local stream types. Deposits of tributary sediment during high reservoir elevations form alluvial terraces. Tributary runoff during low reservoir periods, particularly from monsoon-induced flash floods, can subsequently erode these terraces and deliver sediment to lower elevations. Though anecdotal work has shown limited visual evidence of fine sediment remobilization during extended reservoir low stands, there has been no systematic undertaking to comprehensively account for the amount of accumulation and deposition or the controls on erosion patterns.

When a dam perturbs a river, a delta is created where the stream meets the reservoir and the reach upstream from the reservoir generally aggrades (Vanoni, 1975; Liangqing and Galloway, 2009). A typical delta often has thin horizontally topset beds, steeply dipping forset beds, and thin horizontal bottomset beds (Gilbert, 1885; Bates, 1953). Once deltas are formed, they are subject to control from reservoir operations. Reservoir drawdown increases the hydraulic gradient and provides energy for incision (Greimann et al., 2006). As the bed slope increases, so does selective transport of fine sediment (Vanoni, 1975). This eroded sediment can be transported and deposited further downstream, even forming turbidity currents (Greimann et al., 2006; Pratson et al., 2008).

Base Level and Effects of its Fluctuations

On a global scale, rivers erode to the ultimate base level of the ocean, where the hydraulic gradient is zero and potential energy can no longer be transformed into kinetic energy (Powell, 1875). On a local scale, streams draining to the Colorado River in Glen Canyon now adjust their local base level to the fluctuating elevations of Lake Powell (Leopold and Bull, 1979). Majeski (2009) showed that stream adjustment in three streams draining to Lake Powell (Colorado River, Dirty Devil River, and North Wash) is modulated by rate of base-level fall. When there is rapid reservoir draw-down, incision creates narrow, deep channels with minimal widening. They also found rapid base-level fall was a stronger control than sediment type on the potential for channel widening or incision. This finding was contrary to conceptual models predicting shallow and wide channels in incohesive sand.

FILLING AND EVACUTION OF SEDIMENT IN ALLUVIAL VALLEYS

Streams that drain to Lake Powell include a mix of confined bedrock canyons and broad alluvial valleys in which cyclic incision and aggradation of arroyos have occurred. Hydroclimatic variability leading to shifts in flood magnitude and frequency are the most plausible explanation for regional channel incision (Graf, 1986). A major remaining unknown in sediment delivery from tributary canyons to Lake Powell is the importance of arroyo dynamics in sediment sourcing; that is, we do not know whether sediment is delivered to Lake Powell at a fairly constant rate, or if this rate varies with hydro-climatic variability at regional scales. It has been proposed to combine both arroyo cycle and paleoflood approaches to validate whether large floods of unusual frequency, driven by external climate forces, are a major control in cutting arroyos (Harvey and Pederson, 2011; Harvey et al., 2011). This combination could be used to understand the causative mechanisms of fine sediment delivery to the Colorado River, notably if fine sediment delivery to Lake Powell tributary mouths is from bedrock or from terraces and floodplains formed from large swaths of soil and weathered rock. If floods are the dominant drivers in major tributaries, the question remains if this is applicable to smaller side canyons. Additionally, if anthropogenic climate change continues undeterred, will these cycles of aggradation become less frequent or potentially cease? Put another way, even with more erosion, would sediment input to Lake Powell decrease without monsoon-induced flash floods as a transport mechanism?

PREVIOUS LAKE POWELL SURVEYS

Much has been written about fluvial processes downstream from dams, especially the Colorado River downstream from Glen Canyon Dam (Webb et al., 1999; Topping et al., 2000b, 2000a, p. 2; Brandt, 2000; Wright et al., 2005; Schmidt and Wilcock, 2008; Poff and Schmidt, 2016; Hadley et al., 2018; Mueller et al., 2018). Relatively few studies have been completed on the physical processes driving sediment accumulation and scour in Lake Powell. Though some efforts have been made to understand the large interregional rivers (Colorado and San Juan), and smaller regional rivers (Dirty Devil and Escalante), little research has been done on the nearly 100 smaller tributaries (Potter and Drake, 1989; Pratson et al., 2008; Majeski, 2009). Because the Colorado and San Juan Rivers deliver the majority of water and sediment to the reservoir, a comparatively larger body of literature exists on their sediment dynamics as compared to those of the nearly 100 smaller streams and tributaries (Iorns et al., 1965; Potter and Drake, 1989).

The first comprehensive survey of the region since completion of Glen Canyon Dam was conducted by the Bureau of Reclamation (BOR) in 1986, detailed in Ferrari (1988). They established a set of range lines, or transects, on which future monitoring could be based. Their objectives were to record the locations of sediment deposits, understand the rate of sediment deposition, and document the associated loss of water storage capacity. At full pool (3,700 feet above sea level), water storage capacity was reported to be 26,214,861 acre-feet in 1986. A study conducted by BOR in 1962 predicted an average annual sediment accumulation rate of 85,400 acre-feet. Based on data from March 1963 to September 1986, an average annual sediment accumulation rate of 36,946 acre-feet was estimated, approximately 43 percent of the original estimate. At this rate, it would take

more than 700 years for the reservoir to completely fill with sediment to full pool (Ferrari, 1988). The BOR noted they would revisit this survey 30 years later, and in 2017, began a comprehensive monitoring effort with the USGS Utah Water Science Center to collect bathymetric and aerial LiDAR data for the entire reservoir.

Water inflow decreased by almost a factor of two and Lake Powell water elevation fell nearly 145 feet between 1999 and 2005, largely attributed to aridification in the western U.S. (Vano et al., 2013; Udall and Overpeck, 2017; Xiao et al., 2018; Milly and Dunne, 2020). Pratson et al. (2008) used this opportunity to conduct three bathymetric surveys in April 2001, May 2004, and June 2005. They found incision of tributary deposits occurred when base level rapidly dropped, and some sediment was transported long distances via turbidity currents (what they referred to as "plunging subaqueous gravity flows"). In the Colorado River delta near Hite Marina, the river incised the delta top and produced delta progradation and steepening for more than 26 miles downstream. Much of these deposits were then impounded behind rock falls that covered the width of the reservoir floor. The San Juan River delta showed a different pattern of minimal steepening and progradation over approximately 0.5 mile, with eroded sediments being transported by turbidity currents and deposited near Glen Canyon Dam, more than 99 miles downstream. These turbidity currents created deposits within deep reservoir reaches. During these reservoir low stands, subaqueous fans formed at Antelope Canyon and Forbidden Canyon, two of the smaller, ephemeral tributaries. Sediment deposited over 22 years was remobilized and transported to deep lake regions over a five-year period. Pratson et al. (2008) hypothesized the majority of the sediment transported

downstream during low reservoir stands likely came from delta topset beds and not from upstream sources (Pratson et al., 2008).

Majeski (2009) used bathymetric sonar, aerial lidar, and cross-sectional data gathered between 2004 and 2007 to analyze the response to base level drop of the Dirty Devil River, North Wash, and Colorado River. He found the 1986 survey did not provide sufficient evidence when compared to their survey to conclude if there was an increase in sediment delivery. On the Colorado River, they found no evidence that pre-dam morphology was emerging except in extremely localized upstream parts of the delta. On the Dirty Devil River, there were spatially distributed changes in width, with novel, notable widening of 112 to 230 feet spanning from the confluence with the Colorado River to three miles up the Dirty Devil River. However, this was not representative of the entire channel length, where widening was largely not observed. A plug of sediment cuts off North Wash from its confluence at the Colorado River. Therefore, North Wash was essentially a self-contained system with little contribution of sediment to the Colorado River.

Majeski (2009) found the percentage of the total tributary deposit eroded during Lake Powell lowstand was not directly proportional to basin area. North Wash was the smallest of the three systems and eroded nearly half of the sediments deposited between 1963 and 1999. In the same period, the Dirty Devil eroded about 15% and the Colorado eroded about 20% of the sediment deposited over 36 years. He attributed the smaller fraction of eroded sediment to bed armoring and bedrock control on sediment routing on the Dirty Devil and Colorado Rivers. Though North Wash has been incising and widening, the Dirty Devil has been primarily incising. Neither the Dirty Devil nor the

Colorado Rivers have incised to their pre-dam bed elevations. Overall, they concluded the rate of base level fall provided the strongest influence on how the streams adjusted, and whether incision dominated over widening. Notably, Majeski (2009) found that a smaller system is "more capable of removing its accumulated delta and recovering towards its pre-dam condition."

Kasprak and Schmidt (2019) analyzed similar topographic and bathymetric data of sediment deposits in 27 tributary side canyons, comparing surveys from 1959, 1986, and 2017. Notably, they showed how the rates of sedimentation varied in these canyons. Some had no discernable sediment accumulation. Others deposited two feet of sediment per year. By calculating unit stream power and using this as a representative for sediment transport potential, they hypothesized canyons with high unit stream power and low sediment accumulation will show rapid evacuation as reservoir levels decrease (Figure 3).

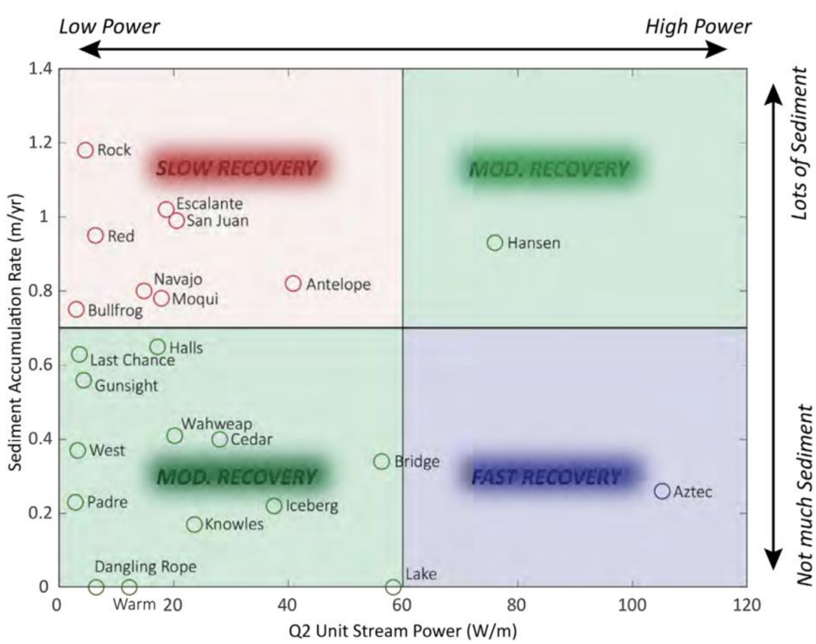

Figure 3. This scatter plot from Kasprak & Schmidt (2019) shows the unit stream power of 23 tributaries in Lake Powell compared to the average annual sediment accumulation rate for those streams from 1959 to 2017.

DAM REMOVAL

As conversations about the nexus of water sustainability, renewable energy, reservoir suitability, hydropower management, and climate change continue in the public sphere, large-scale dam removal as a means of river restoration is gaining traction in the United States (Rand; Morris and Fan, 1998; Pizzuto, 2002; Poff and Hart, 2002; Graf et al., 2010). Though there have been more than 450 small-scale dam removals in the nation, only a few large-scale removal processes have been studied (Skalak and Pizzuto, 2005; East et al., 2015; Harrison et al., 2018). Challenges exist when attempting to predict channel response after dam removal, though some work has shown the re-emergent channel will likely have different sediment and riparian vegetation types than upstream reaches (Pizzuto, 2002). The relative changes in flood magnitude and sediment transport that occur following dam removal may provide insight into whether a given river will aggrade or incise (Schmidt and Wilcock, 2008). Researchers are using these events to understand previously seldom quantified associated effects, such as landscape adjustment to large-scale sediment pulses (East et al., 2015; Harrison et al., 2018). Water is an increasingly valuable and scarce global commodity. In semi-arid regions specifically, erosive processes have externalities with regulated water delivery systems (Millares and Moñino, 2018).

Case studies highlight broad frameworks for how new equilibrium channels are created after dam removal (Pizzuto, 2002; East et al., 2015). On the Elwha River in Washington, East et al. (2015) found that after dam removal, newly deposited sediment was finer than the majority of the pre-dam bed. Similar findings occurred on the Carmel River in California, where there was gradual downstream fining after removal of the San

Clemente Dam (Harrison et al., 2018). On both rivers, bar formation occurred (East et al., 2015; Harrison et al., 2018). On the Elwha, channel braiding index increased nearly by half. Two years after removal, the river began to incise through the sediment deposited from the initial pulse, and most of the released sediment was transported to the river's mouth. The phased-removal processes were characterized by gradual delta progradation instead of the rapid mass movements that have been part of instantaneous dam removals (East et al., 2015).

The role of post-removal floods vary across physiographic provinces (Kondolf et al., 2013; Harrison et al., 2018). Notably, neither the Elwha nor Carmel Rivers have as many ephemeral tributaries as the Colorado River in Glen Canyon. Though their results may create a broad framework for understanding the delta at Hite Marina, where the Colorado River enters the reservoir, it does not provide guidance on what will happen to the deltas at the many side canyons. Additionally, most large-scale dam removals have occurred on gravel-bedded streams, whereas the Colorado River in Glen Canyon is primarily sand-bedded.

DATA MANAGEMENT

The purpose of the abovementioned StoryMap is to provide a comprehensible, open access tool for regional stakeholders and others who desire to learn more about Lake Powell and its resources. The StoryMap is accessible in many different places: directly through ESRI, my website (both link and PDF), via ResearchGate, or by Digital Object Identifier 10.13140/RG.2.2.35885.10727. This is an interactive, living document. I will update as needed. As part of my dedication to stakeholder outreach and community engagement, I will lead talks and presentations with interested user groups, which include Grand Canyon Youth and Grand Canyon River Guides.

FUTURE

Management of the changing Colorado River requires innovative interdisciplinary understanding of policy, fluvial geomorphology, climate change, and more. By creating a robust yet useable digital tool focused on the availability of tributary resources in Lake Powell and the Glen Canyon region at different reservoir elevations, my work will contribute to an increased and more productive discourse between the public, stakeholders, policy makers, and scientists: a conversation I believe will ultimately improve the management of the Colorado River and promote better outcomes for its stakeholder group.

LITERATURE CITED

Antevs, E., 1952, Arroyo-Cutting and Filling: The Journal of Geology, v. 60, p. 375–385, doi:10.1086/625985.

Bailey, R.W., 1935, Epicycles of Erosion in the Valleys of the Colorado Plateau Province: The Journal of Geology, v. 43, p. 337–355, doi:10.1086/624315.

Bates, C.C., 1953, A Rational Theory of Delta Formation as Exemplified by the Present-day Mississippi Delta: Journal of Sedimentary Research, v. 23, http://archives.datapages.com/data/sepm/journals/v01-32/data/023/023002/0132b.htm (accessed November 2018).

Brandt, S.A., 2000, Classification of geomorphological effects downstream of dams: CATENA, v. 40, p. 375–401, doi:10.1016/S0341-8162(00)00093-X.

Bruce, B., Prairie, J., Maupin, M.A., Dodds, J., Eckhardt, D., Ivahnenko, T.I., Matuska, P., Evenson, E., and Harrison, A., 2018, Comparison of U.S. Geological Survey and Bureau of Reclamation water-use reporting in the Colorado River Basin: U.S. Geological Survey Scientific Investigations Report USGS Numbered Series 2018–5021, 50 p., http://pubs.er.usgs.gov/publication/sir20185021 (accessed October 2018).

Bryan, K., 1925, Date of Channel Trenching (arroyo Cutting) in the Arid Southwest: Science, v. 62, p. 338–344, doi:10.1126/science.62.1607.338.

Bureau of Reclamation, 1966, Final Construction Report: Glen Canyon Unit, Arizona-Utah, Middle River Division, Colorado River Storage Project, Volume 1.

Castle, S.L., Thomas, B.F., Reager, J.T., Rodell, M., Swenson, S.C., and Famiglietti, J.S., 2014, Groundwater depletion during drought threatens future water security of the Colorado River Basin: Geophysical Research Letters, v. 41, p. 2014GL061055, doi:10.1002/2014GL061055.

Chidsey Jr., T.C., Sprinkel, D.A., Willis, G.C., and Anderson, P.B., 2000, Geologic lake guide along Lake Powell, Glen Canyon National Recreation Area and Rainbow Bridge National Monument, Utah-Arizona:, http://www.lakepowell.org/documents/Lake%20Powell%20Geologic%20Guide.pdf (accessed October 2017).

Church, M., 2006, Bed Material Transport and the Morphology of Alluvial River Channels: Annual Review of Earth and Planetary Sciences, v. 34, p. 325–354, doi:10.1146/annurev.earth.33.092203.122721.

Collins, D.B.G., and Bras, R.L., 2008, Climatic control of sediment yield in dry lands following climate and land cover change: Water Resources Research, v. 44, doi:10.1029/2007WR006474.

East, A.E. et al., 2015, Large-scale dam removal on the Elwha River, Washington, USA: River channel and floodplain geomorphic change: Geomorphology, v. 228, p. 765–786, doi:10.1016/j.geomorph.2014.08.028.

Ferrari, R., 1988, 1986 Lake Powell Survey: Bureau of Reclamation REC-ERC-88-6, 68 p.

Gellis, A., Hereford, R., Schumm, S.A., and Hayes, B.R., 1991, Channel evolution and hydrologic variations in the Colorado River basin: Factors influencing sediment and salt loads: Journal of Hydrology, v. 124, p. 317–344, doi:10.1016/0022-1694(91)90022-A.

Gilbert, G.K., 1885, The Topographic Features of Lake Shores: U.S. Government Printing Office, 123 p.

Graf, W.L., 1983, The arroyo problem--paleohydrology and palaeohydraulics in the short term: Background to Paleohydrology, v. 1, p. 279–302.

Graf, W.L., 1986, Fluvial Erosion and Federal Public Policy in the Navajo Nation: Physical Geography, v. 7, p. 97–115, doi:10.1080/02723646.1986.10642284.

Graf, W.L., Wohl, E., Sinha, T., and Sabo, J.L., 2010, Sedimentation and sustainability of western American reservoirs: Water Resources Research, v. 46, p. W12535, doi:10.1029/2009WR008836.

Greimann, B.P., Huang, J., and Engineers, H., 2006, One-dimensional modeling of incision through reservoir deposits, *in* Hydraulic Engineers, Sedimentation and River Hydraulics Group, Technical Service Center, US Bureau of Reclamation.

Griffiths, R.E., and Topping, D.J., 2017, Importance of measuring discharge and sediment transport in lesser tributaries when closing sediment budgets: Geomorphology, v. 296, p. 59–73, doi:10.1016/j.geomorph.2017.08.037.

Hadley, R.F., 1974, Sediment yield and land use in southwest United States, http://hydrologie.org/redbooks/a113/iahs_113_0096.pdf (accessed May 2018).

Hadley, D.R., Grams, P.E., and Kaplinski, M.A., 2018, Quantifying geomorphic and vegetation change at sandbar campsites in response to flow regulation and controlled floods, Grand Canyon National Park, Arizona: River Research and Applications, v. 0, doi:10.1002/rra.3349.

Harrison, L.R., East, A.E., Smith, D.P., Logan, J.B., Bond, R.M., Nicol, C.L., Williams, T.H., Boughton, D.A., Chow, K., and Luna, L., 2018, River response to large-dam removal in a Mediterranean hydroclimatic setting: Carmel River, California, USA: Earth Surface Processes and Landforms, v. 0, doi:10.1002/esp.4464.

Harvey, J.E., and Pederson, J.L., 2011, Reconciling arroyo cycle and paleoflood approaches to late Holocene alluvial records in dryland streams: Quaternary Science Reviews, v. 30, p. 855–866, doi:10.1016/j.quascirev.2010.12.025.

Harvey, J.E., Pederson, J.L., and Rittenour, T.M., 2011, Exploring relations between arroyo cycles and canyon paleoflood records in Buckskin Wash, Utah: Reconciling scientific paradigms: GSA Bulletin, v. 123, p. 2266–2276, doi:10.1130/B30374.1.

Iorns, W., Hembree, C., and Oakland, G., 1965, Water Resources of the Upper Colorado River Basin - Technical Report: Geological Survey Professional Paper 441.

Kasprak, A., and Schmidt, J.C., 2019, Sedimentation of Lake Powell Tributary Canyons, 1959 - 2017. Center for Colorado River Studies, Quinney College of Natural Resources, Utah State University, https://qcnr.usu.edu/coloradoriver/files/Kasprak%20Report_Dec20.pdf.

Kondolf, G.M., Podolak, K., and Grantham, T.E., 2013, Restoring mediterranean-climate rivers: Hydrobiologia, v. 719, p. 527–545, doi:10.1007/s10750-012-1363-y.

Lehner, F., Deser, C., Simpson, I.R., and Terray, L., 2018, Attributing the U.S. Southwest's Recent Shift Into Drier Conditions: Geophysical Research Letters, v. 0, doi:10.1029/2018GL078312.

Leopold, L., and Bull, W., 1979, Base level, aggradation, and grade: v. 123, p. 168–202.

Liangqing, X., and Galloway, W.E., 2009, Fan-Delta, Braid Delta and the Classification of Delta Systems: Fan-Delta, Braid Delta and Delta Systems: Acta Geologica Sinica - English Edition, v. 4, p. 387–400, doi:10.1111/j.1755-6724.1991.mp4004004.x.

MacDonnell, L.J., Getches, D.H., and Hugenberg, W.C., 1995, The law of the Colorado River: coping with severe sustained drought: Journal of the American Water Resources Association, v. 31, p. 825–836, doi:10.1111/j.1752-1688.1995.tb03404.x.

Mackin, J.H., 1948, Concept of the Graded River: GSA Bulletin, v. 59, p. 463–512, doi:10.1130/0016-7606(1948)59[463:COTGR]2.0.CO;2.

Majeski, A., 2009, Fluvial Systems Tied Together Through a Common Base Level: The Geomorphic Response of the Dirty Devil River, North Wash Creek, and the Colorado River to the Rapid Base Level Drop of Lake Powell: All Graduate Theses and Dissertations, https://digitalcommons.usu.edu/etd/291.

Maupin, M.A., Ivahnenko, T.I., and Bruce, B., 2018, Estimates of water use and trends in the Colorado River Basin, Southwestern United States, 1985–2010: U.S. Geological Survey Scientific Investigations Report USGS Numbered Series 2018–5049, 75 p., http://pubs.er.usgs.gov/publication/sir20185049 (accessed October 2018).

Millares, A., and Moñino, A., 2018, Sediment yield and transport process assessment from reservoir monitoring in a semi-arid mountainous river: Hydrological Processes, v. 0, doi:10.1002/hyp.13237.

Milly, P.C.D., and Dunne, K.A., 2020, Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation: Science, doi:10.1126/science.aay9187.

Morris, G.L., and Fan, J., 1998, Reservoir Sedimentation Handbook: New York, NY, McGraw-Hill Book Co., http://reservoirsedimentation.com/ (accessed October 2018).

Mueller, E.R., Grams, P.E., Hazel, J.E., and Schmidt, J.C., 2018, Variability in eddy sandbar dynamics during two decades of controlled flooding of the Colorado River in the Grand Canyon: Sedimentary Geology, v. 363, p. 181–199, doi:10.1016/j.sedgeo.2017.11.007.

Mueller, E.R., and Pitlick, J., 2013, Sediment supply and channel morphology in mountain river systems: 1. Relative importance of lithology, topography, and climate: Journal of Geophysical Research: Earth Surface, v. 118, p. 2325–2342, doi:10.1002/2013JF002843.

Patton, P.C., and Boison, P.J., 1986, Processes and rates of formation of Holocene alluvial terraces in Harris Wash, Escalante River basin, south-central Utah: GSA Bulletin, v. 97, p. 369–378, doi:10.1130/0016-7606(1986)97<369:PAROFO>2.0.CO;2.

Patton, P.C., and Schumm, S.A., 1981, Ephemeral-stream processes: Implications for studies of quaternary valley fills: Quaternary Research, v. 15, p. 24–43, doi:10.1016/0033-5894(81)90112-5.

Pizzuto, J., 2002, Effects of Dam Removal on River Form and Process: BioScience, v. 52, p. 683–691, doi:10.1641/0006-3568(2002)052[0683:EODROR]2.0.CO;2.

Poff, N.L., and Hart, D.D., 2002, How Dams Vary and Why It Matters for the Emerging Science of Dam Removal: BioScience, v. 52, p. 659–668, doi:10.1641/0006-3568(2002)052[0659:HDVAWI]2.0.CO;2.

Poff, N.L., and Schmidt, J.C., 2016, How dams can go with the flow: Science, v. 353, p. 1099–1100, doi:10.1126/science.aah4926.

Potter, L.D., and Drake, C.L., 1989, Lake Powell: Virgin flow to dynamo: Albuquerque, NM, University of New Mexico Press, 311 p.

Powell, J.W., 1875, Exploration of the Colorado River of the West and its Tributaries: Government Printing Office, https://pubs.usgs.gov/unnumbered/70039238/report.pdf (accessed October 2018).

Pratson, L., Hughes-Clarke, J., Anderson, M., Gerber, T., Twichell, D., Ferrari, R., Nittrouer, C., Beaudoin, J., Granet, J., and Crockett, J., 2008, Timing and patterns of basin infilling as documented in Lake Powell during a drought: Geology, v. 36, p. 843–846, doi:10.1130/G24733A.1.

Rand, J. Overlooked trade-offs of environmentally protective hydropower operation: Impacts to ancillary services and greenhouse gas emissions: River Research and Applications, v. 0, doi:10.1002/rra.3354.

Schmidt, J.C., and Wilcock, P.R., 2008, Metrics for assessing the downstream effects of dams: Water Resources Research, v. 44, p. W04404, doi:10.1029/2006WR005092.

Skalak, K., and Pizzuto, J., 2005, The Geomorphic Effects of Existing Dams and Historic Dam Removals in the Mid-Atlantic Region, USA: Managing Watersheds for Human and Natural Impacts, doi:10.1061/40763(178)29.

Topping, D.J., Rubin, D.M., Nelson, J.M., Kinzel, P.J., and Corson, I.C., 2000a, Colorado River sediment transport: 2. Systematic Bed-elevation and grain-size effects of sand supply limitation: Water Resources Research, v. 36, p. 543–570, doi:10.1029/1999WR900286.

Topping, D.J., Rubin, D.M., and Vierra, L.E., 2000b, Colorado River sediment transport: 1. Natural sediment supply limitation and the influence of Glen Canyon Dam: Water Resources Research, v. 36, p. 515–542, doi:10.1029/1999WR900285.

Udall, B., and Overpeck, J., 2017, The twenty-first century Colorado River hot drought and implications for the future: Water Resources Research, v. 53, p. 2404–2418, doi:10.1002/2016WR019638.

Vano, J.A. et al., 2013, Understanding Uncertainties in Future Colorado River Streamflow: Bulletin of the American Meteorological Society, v. 95, p. 59–78, doi:10.1175/BAMS-D-12-00228.1.

Vanoni, V. (Ed.), 1975, Sedimentation Engineering: Processes, Measurements, Modeling, and Practice: Reston, VA, American Society of Civil Engineers, doi:10.1061/9780784408148.

Vernieu, W.S., 1997, Effects of Reservoir Drawdown on Resuspension of Deltaic Sediments in Lake Powell: Lake and Reservoir Management, v. 13, p. 67–78, doi:10.1080/07438149709354298.

Webb, R.H., Wegner, D.L., Andrews, E.D., Valdez, R.A., and Patten, D.T., 1999, Downstream Effects of Glen Canyon Dam on the Colorado River in Grand Canyon: A Review, *in* Webb, R.H., Schmidt, J.C., Richardrzolf, G., and Valdez, R.A. eds., The Controlled Flood in Grand Canyon, American Geophysical Union, p. 1–21, doi:10.1029/GM110p0001.

Wright, S.A., Melis, T.S., Topping, D.J., and Rubin, D.M., 2005, The State of the Colorado River Ecosystem in Grand Canyon: Influence of Glen Canyon Dam Operations on Downstream Sand Resources of the Colorado River in Grand Canyon: USGS Circular 1282, https://groups.nceas.ucsb.edu/flow-experiments/documents/flow-experiment-case-studies/Wright%20et%20al%20Influence%20of%20Glen%20Canyon%20Dam%20Operations%20SCORE.pdf/view (accessed May 2018).

Xiao, M., Udall, B., and Lettenmaier, D.P., 2018, On the causes of declining Colorado River streamflows: Water Resources Research, v. 0, doi:10.1029/2018WR023153.