Water Resources Mission Area

Prepared in cooperation with the Bureau of Reclamation

Elevation-Area-Capacity Relationships of Lake Powell in 2018 and Estimated Loss of Storage Capacity Since 1963

Scientific Investigations Report 2022–5017

U.S. Department of the Interior
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Cover:
(Front) Lake Powell, March 25, 2020. Photograph taken by Casey Root.
(Back) Glen Canyon Dam, December 2, 2018. Photograph taken by Casey Root.

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By Jonathan Casey Root and Daniel K. Jones

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	$1{,}233\text{x}10^{-6}$	cubic kilometer (km^3)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988.

Horizontal coordinate information is referenced to the North American Datum of 1983 with the National Adjustment of 2011. Historical data were transformed from the North American Datum of 1927.

Data used in this report are in the Universal Transverse Mercator Zone 12 projection.

All elevations are referenced to the North American Vertical Datum of 1988 unless otherwise noted. The conversion factor from the National Geodetic Vertical Datum of 1929 to North American Vertical Datum of 1988 in this study area is 2.913 feet, as determined using the VERTCON tool produced by the National Oceanic and Atmospheric Administration (https://geodesy.noaa.gov/VERTCON3/) for vertically transforming geospatial data. This conversion was calculated for the U.S. Geological Survey reservoir elevation station (09379900) located at 36.9369326, –111.4837694 (U.S. Geological Survey, 2021).

Supplemental Information

Elevation-area-capacity relationships presented here are not directly comparable to those used in Bureau of Reclamation operations at Glen Canyon Dam.

Abbreviations

CARIS HIPS	Computer Aided Resource Information System Hydrographic Information Processing System
DEM	digital elevation model
EROS	U.S. Geological Survey Earth Resources Observation and Science Center
NOAA	National Oceanic and Atmospheric Administration
Reclamation	Bureau of Reclamation
RMSEz	root mean square error in the vertical direction
STAID	U.S. Geological Survey Station Identifier
TBDEM	topobathymetric digital elevation model
USCS	U.S. customary system
USGS	U.S. Geological Survey

Elevation-Area-Capacity Relationships of Lake Powell in 2018 and Estimated Loss of Storage Capacity Since 1963

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Abstract

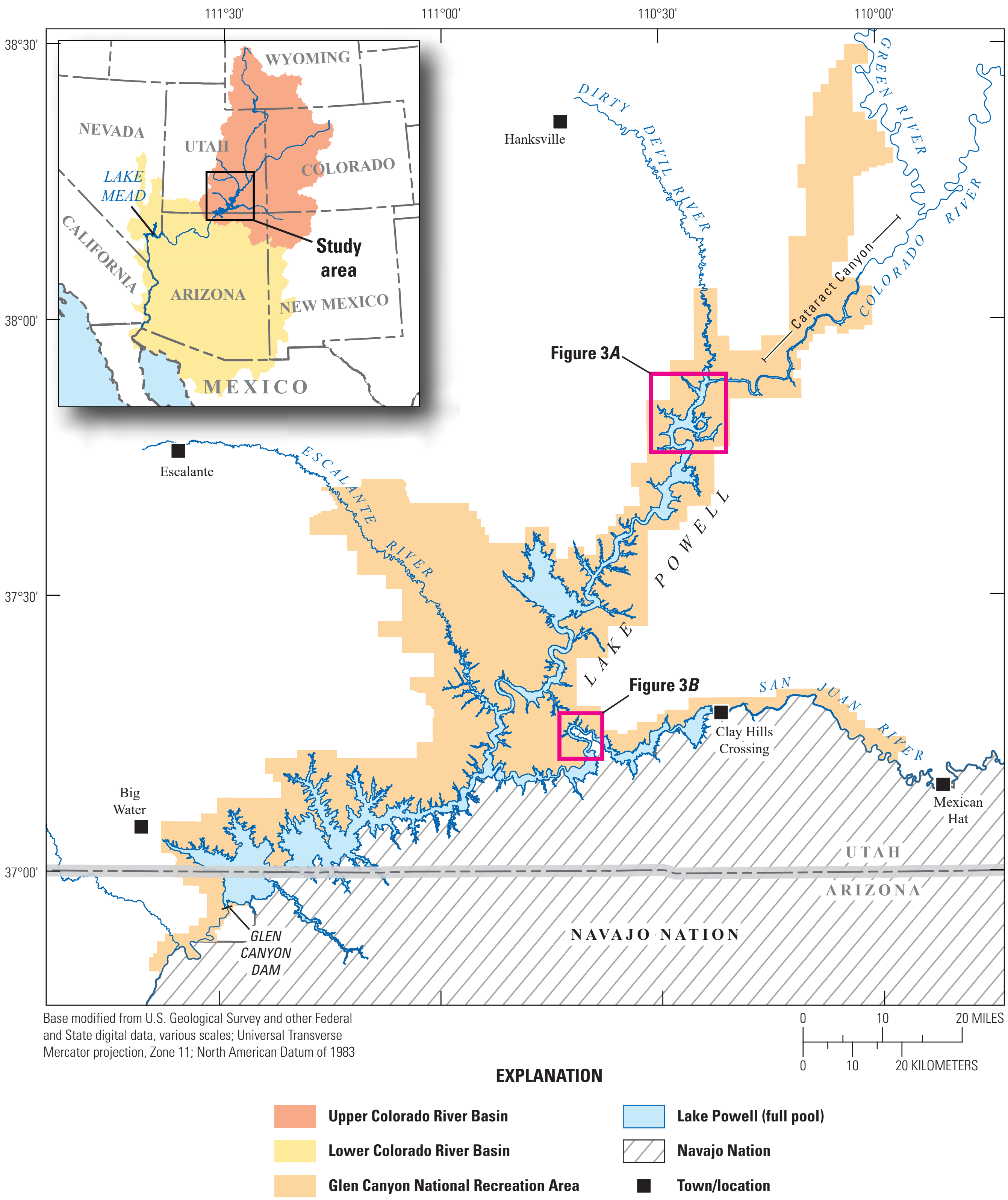
Lake Powell is the second largest constructed water reservoir by storage capacity in the United States and represents a critical component in management of water resources in the Colorado River Basin. The reservoir provides hydroelectric power generation at Glen Canyon Dam, banks water storage for the Upper Colorado River Basin, stabilizes water commitments downstream, and buffers the Lower Colorado River Basin, including Lake Mead, against sedimentation and fluctuations in hydrological conditions. With completion of the dam in 1963, Lake Powell steadily filled with water before reaching full pool in 1980 and has become a popular destination for recreation, welcoming more than 4 million visitors per year. Since the early 2000s, severe drought and increases in water demand have resulted in a significant drop in reservoir elevation and stored water, prompting a heightened level of interest in the current state and future of Lake Powell.

Beginning in 2017, the U.S. Geological Survey, in cooperation with the Bureau of Reclamation, completed topobathymetric surveys of Lake Powell for the first update of elevation-area-capacity relationships since 1986. This report presents results of these surveys and comparisons with estimates from previous surveys. The storage volume and surface area, as of completion of the topobathymetric survey in spring 2018, are calculated at 0.33-foot (0.10-meter) increments for elevations ranging from 3,120.08 to 3,717.19 feet above the North American Vertical Datum of 1988 (NAVD 88). Between 0.33-foot increments, the storage volumes and areas were linearly interpolated at 0.01-foot intervals. Interpolation error in the 0.01-foot interval estimates was assessed at lower (3,160.00–3,161.00 feet above NAVD 88), middle (3,400.00–3,401.00 feet above NAVD 88), and upper (3,700.00–3,711.00 feet above NAVD 88) elevations. The interpolated storage capacity and area estimates are comparable to the measured values with differences ranging from 0.00 to 0.02 percent and from −0.01 to 0.03 percent, respectively.

Current storage capacity at full pool (3702.91 feet above NAVD 88) is 25,160,000 acre-feet. Compared to previously published estimates, this volume represents a 6.79 percent or 1,833,000-acre-foot decrease in storage capacity from 1963 to 2018 and a 4.00 percent or 1,049,000-acre-foot decrease from 1986 to 2018. Areal extent, as of spring 2018, at full pool is 159,200 acres, which represents a 1.33-percent decrease from 1963 to 2018 and a 0.96 percent decrease from 1986 to 2018.

Introduction

The U.S. Geological Survey (USGS), in cooperation with the Bureau of Reclamation (Reclamation), surveyed Lake Powell between fall 2017 and spring 2018 to produce an integrated topobathymetric dataset, which comprises topographic light detection and ranging (lidar) data (land elevation) and multibeam bathymetry (bed elevation of a water body), for the purposes of calculating the elevation-area-capacity relationships in Lake Powell. Lake Powell is located on the Colorado River across the Utah–Arizona border (fig. 1) and was created by the closure of Glen Canyon Dam in March 1963. Nearly 200 miles of the Colorado River has been flooded upstream from the dam. The reservoir storage capacity of Lake Powell is surpassed in the United States only by Lake Mead, which is approximately 300 miles downstream on the Colorado River. Lake Powell is a key component to water management in the burgeoning American southwest. In addition to annually hosting over 4 million visitors to Glen Canyon National Recreation Area (National Park Service, 2021a), Lake Powell supplies water to over 40 million people and supports 16 million jobs within and beyond the Colorado River Basin (fig. 1; James and others, 2014).



Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Universal Transverse Mercator projection, Zone 11; North American Datum of 1983

Figure 1. Location of Lake Powell and the Glen Canyon National Recreation Area, Utah and Arizona. Stream lines and watershed boundaries from U.S. Geological Survey NHDPlus High Resolution dataset (U.S. Geological Survey, 2018). Political boundaries and locations modified from U.S. Geological Survey and other federal and state geospatial data. Horizontal coordinates referenced to the North American Datum of 1983 with the National Adjustment of 2011.

Though the instrumental record of the Upper Colorado River Basin is robust, with daily streamgage monitoring dating to the 20th century (U.S. Geological Survey, 2021), only two published studies have estimated the Lake Powell storage capacity: (1) the original, pre-Glen Canyon Dam elevation-area-capacity tables (Bureau of Reclamation, 1963) that were calculated from contour maps and (2) a reservoir-wide, range-line bathymetric survey that was completed 25 years post-impoundment in 1986 (Ferrari, 1988). Both studies utilized the best-available technology at the time but lacked the precision of current surveying methods. Lake Powell has continuously trapped sediment from the sediment-laden Colorado and San Juan Rivers at the uppermost extents of the reservoir (in other words, the river deltas), diminishing the storage capacity at the highest elevations of the reservoir. Since the early 2000s, extended drought in the American southwest (Woodhouse and others, 2010; Cook and others, 2015; Udall and Overpeck, 2017; Xiao and others, 2018; McCabe and others, 2020; Williams and others, 2020) has resulted in unprecedented drops in reservoir elevation in 2022 (Bureau of Reclamation, 2022), further exacerbating storage losses through declining river flow (Miller and others, 2016; McCabe and others, 2017; Rumsey and others, 2017; Woodhouse and Pederson, 2018; Milly and Dunne, 2020; Miller and others, 2021a; Miller and others, 2021b; Rumsey and others, 2021) and by increasing evapotranspiration rates (Kingston and others, 2009; Helfer and others, 2012; Cook and others, 2015). Because of this storage loss, increasingly high water demands, and ongoing hydrologic and climatic changes to the Upper Colorado River Basin, an updated elevation-area-capacity table utilizing high-precision topobathymetric survey methods is necessary to estimate current storage capacity in Lake Powell.

Purpose and Scope

Bathymetric and topographic lidar surveys were done in 2017 (Andrews and others, 2018) and 2018, respectively, and integrated into a seamless topobathymetric digital elevation model (TBDEM; Poppenga and others, 2020) to determine storage capacity and areal extent of Lake Powell. This report (1) describes the methods used to modify an existing TBDEM of Lake Powell (Poppenga and others, 2020) to eliminate potential biases in storage capacity computations; (2) describes methods used to calculate the elevation-area-capacity relationships derived from the modified version of the TBDEM (Jones and Root, 2021); (3) presents the updated elevation-area-capacity relationships and associated error assessments; and (4) compares these updated elevation-area-capacity relationships with historical datasets and estimates from pre-impoundment (Bureau of Reclamation, 1963) and the 1986 survey (Ferrari, 1988). Herein, our results provide contextual basis for analyzing the expected reservoir life of Lake Powell, though any such presumptions are beyond the scope of this study and are not addressed. Explicit comparisons with operational elevation-area-capacity tables, which are independently calculated, are also not addressed because the calculation methodologies are not directly comparable. Error in elevation-area-capacity relationships is estimated, with vertical accuracy in the 2017 bathymetric dataset providing the most reasonable error for the TBDEM. Additional errors could be due, in part, to differing survey methodologies. Sediment deposition is recognized as the principal cause for storage loss over time; however, modes and rates of sedimentation are not considered.

Study Area

Lake Powell is located on the border of Utah and Arizona, with maximum extents that flood nearly 200 miles upstream on the Colorado River. The lands surrounding the reservoir, the Glen Canyon National Recreation Area, are under the stewardship of the National Park Service and Reclamation (fig. 1). Commissioned in 1956, under the Colorado River Storage Project, the 710-feet (ft) Glen Canyon Dam was completed in March 1963 and rises to its spillway crest elevation of 3,717.91 ft above the North American Vertical Datum of 1988 (NAVD 88), with full-pool storage designated at 3,702.91 ft above NAVD 88. A historic maximum reservoir elevation of 3,708.34 ft above NAVD 88 occurred in spring 1983 when the Glen Canyon Dam spillways were damaged and temporarily closed during a period of particularly heavy runoff and high inflow (figs. 2*A*, *B*). Though the reservoir remained at nearly full pool for parts of the 1980s and 1990s, the elevation has fluctuated for much of Lake Powell's history (fig. 2*A*).

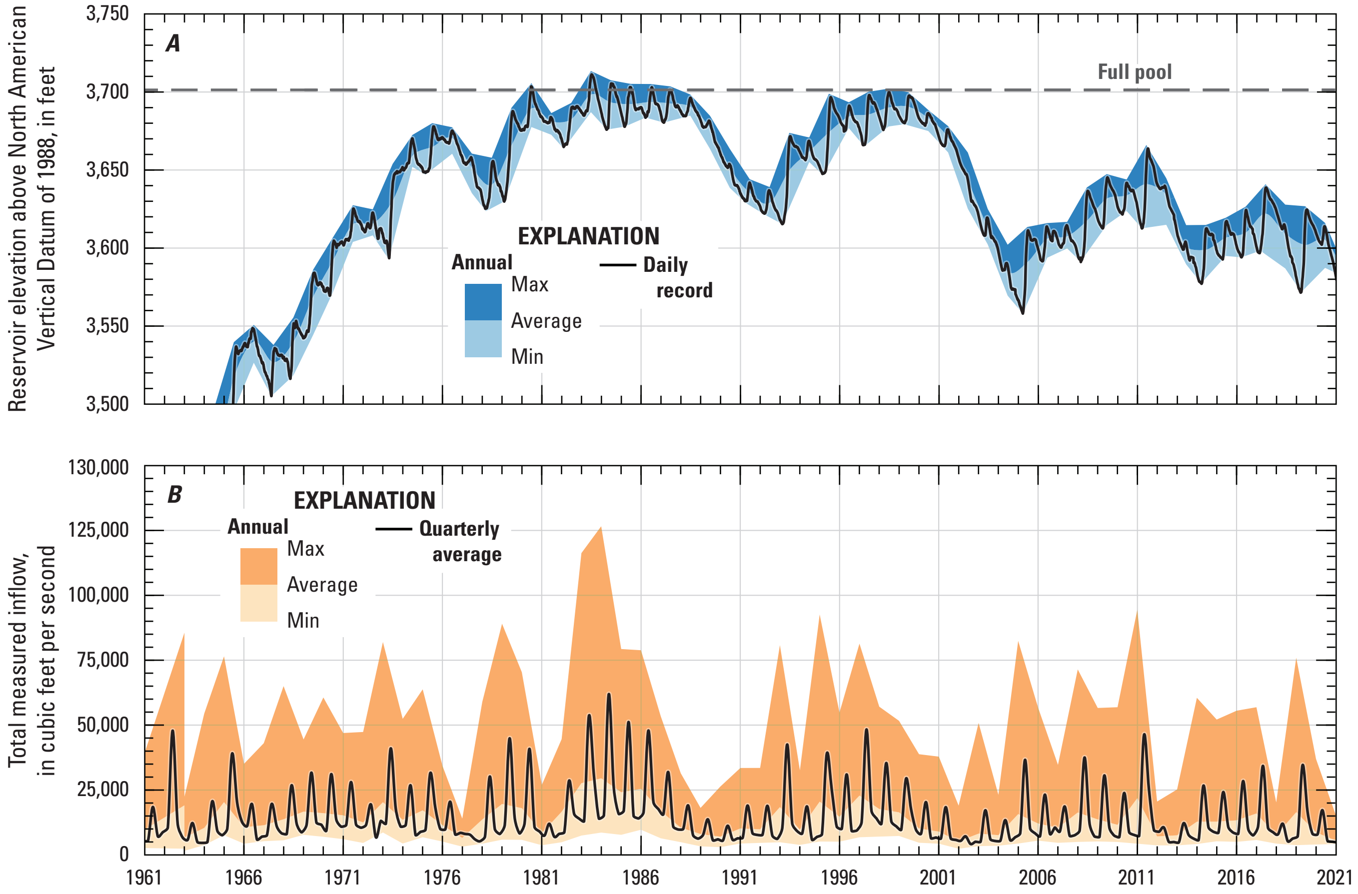


Figure 2. Reservoir elevation and measured inflow by calendar year since 1961. *A*, Daily record of reservoir elevation of Lake Powell (Bureau of Reclamation, 2022), annual maximums and minimums, separated by the annual mean (labeled years represent elevations within calendar year); *B*, Combined quarterly average of the primary water sources to Lake Powell (Colorado, Green, San Juan, Dirty Devil, and San Rafael Rivers) with the annual maximums and minimums separated at the annual mean (labeled years represent January 1 of each year) at U.S. Geological Survey streamgages (U.S. Geological Survey, 2021).

The reservoir elevation for Lake Powell has been reported daily since December 28, 1963, by Reclamation, in addition to other parameters such as storage, inflow, and outflow. Reservoir elevation is recorded hourly, relative to the National Geodetic Vertical Datum of 1929 (NGVD 29), in a stilling well within Glen Canyon Dam, and the last value of each day, at 11:00 p.m. (Mountain Standard Time), is reported (Bureau of Reclamation, 2022; available for download at https://data.usbr.gov/). The USGS deployed a radar-based, water-stage recorder on the bridge next to the west forebay of Glen Canyon Dam on April 18, 2019 (USGS Station ID [STAID] 09379900, available at https://waterdata.usgs.gov/ut/nwis/inventory/?site_no=09379900; U.S. Geological Survey, 2021). Reservoir elevation is recorded at 15-minute intervals relative to NGVD 29 and NAVD 88. Independent survey errors will result in minor differences between reservoir elevations reported by Reclamation and USGS. A formal comparison of data collection methodologies and error quantification is outside the scope of this report; an evaluation of elevation-area-capacity relationships reported herein relative to real-time water surface elevations is not investigated. Additional surveying, which involved examining datums by perpetuating elevation to a variety of objective points from fiducial benchmarks, was done to characterize the differences in datums at Glen Canyon Dam (Gibson and others, 2021). This survey provided additional verification of vertical accuracy in the topobathymetric dataset (Poppenga and others, 2020).

The main tributaries of Lake Powell are the Colorado and San Juan Rivers, with substantially lesser contribution from the Escalante and Dirty Devil Rivers (fig. 1). The USGS has maintained streamgage records for all primary inputs dating to the early 20th century, providing a long-term streamflow record for reservoir monitoring and hydrological context above Glen Canyon Dam (U.S. Geological Survey, 2021). The combined discharges from the nearest gages to Lake Powell for the Colorado (STAID 09180500), Green (STAID 09315000), San Juan (STAID 09379500), Escalante (STAID 09337500), Dirty Devil (STAID 09333500), and San Rafael (STAID 09328500) Rivers approximate an expected total measured inflow (fig. 2*B*) that is independent from derived inflow by Reclamation (2022). Fluctuations in reservoir elevation have been historically proportional to fluctuations in combined discharge.

The current areal extent of the reservoir at full pool is approximately 250 square miles (mi^2), reaching Cataract Canyon on the Colorado River and Clay Hills Crossing on the San Juan River (fig. 1). The reservoir and surrounding Glen Canyon National Recreation Area are classified as arid desert, with an average annual precipitation of 6 inches and summer temperatures up to 110 degrees Fahrenheit (°F; National Park Service, 2021b). Because of the climate and its porous sandstone substrate, losses to evaporation and bank storage are substantial (Myers, 2013; Friedrich and others, 2018). Stable isotope analysis of surface water entering Lake Powell indicates that little evaporation occurs in the upper Colorado River but increases moving downstream, particularly in Lake Powell and Lake Mead (Guay and others, 2006). Reclamation (1950) estimated an annual evaporation rate of 63.0 inches during the planning stages of Lake Powell. Using evaporation data collected between May 1973 and December 1974, the average annual total evaporation at Lake Powell was estimated at 69.48 inches by using mass-transfer methods (Jacoby and others, 1977). Reclamation (1986) estimated annual average evaporation at 68.32 inches for January 1965 through May 1979, incorporating the findings of Jacoby and others (1977) to calibrate its mass-transfer coefficient. Because evaporation at Lake Powell has not been recently studied, estimates at Lake Mead could be used as a proxy at Lake Powell given the reservoirs' proximity and similar reservoir characteristics. Annual evaporation estimates at Lake Mead, using the eddy-covariance method, were 74.07–81.65 inches between March 2010 and February 2012 (Moreo and Swancar, 2013) and 74.65 inches between March 2010 and April 2019 (Earp and Moreo, 2021). Cumulative water loss to bank storage in Lake Powell is estimated at approximately 15,000,000 acre-feet through 2011 (Myers, 2013) or 300,000 acre-feet per year since Glen Canyon Dam closed in 1963. Releases from Glen Canyon Dam to Lake Mead account for approximately 90 percent of the flow into the Lower Colorado River Basin (Ostroff and others, 2017; Lukas and Payton, 2020; McCabe and others, 2020; Tillman and others, 2020).

The distinctive red rocks of the Colorado Plateau characterize the regional bedrock and range in age from Late Pennsylvanian to Late Cretaceous periods (318–66 million years ago). Cliff-forming units, primarily the Navajo Sandstone and Wingate Sandstone of the aptly named Glen Canyon Group, construct the deep and narrow canyons of Lake Powell. Incision of the Colorado River into the bedrock over the last 5 million years formed Glen Canyon (Anderson and others, 2010), which was renowned for its natural beauty (Powell, 1875). The region is culturally significant to Native Americans, and Navajo Mountain, a prominent laccolith south of the confluence of the Colorado River and San Juan River, is an important landmark in Navajo and Hopi history (Luckert, 1977; Bernardini and others, 2021; Navajo Nation Parks & Recreation, 2022).

Previous Reservoir Surveys

Reclamation published two surveys with estimates of elevation-area-capacity relationships of Lake Powell: (1) the original, pre-Glen Canyon Dam storage estimates (Bureau of Reclamation, 1963) and (2) an extensive range-line survey completed in the summer and fall of 1986 (Ferrari, 1988).

Detailed contour maps of Glen Canyon were commissioned during the planning stages of Lake Powell to estimate storage capacity (Fairchild Aerial Surveys, Inc., 1947; Alster and Associates, Inc., 1959; Gessel and Rutledge, 1962). These contour maps were recently digitized and developed into a digital elevation model (DEM; Root and others, 2019). The Colorado and San Juan River arms were separately surveyed and had contour intervals of 10 and 20 ft, respectively. Area and storage capacity estimates were calculated at 1.0-ft and 0.01-ft elevation intervals, respectively. Linear interpolations were used for intermediate intervals in the storage capacity calculations (Bureau of Reclamation, 1963).

A bathymetric survey completed by Reclamation (Ferrari, 1988) used the range-line method, as described by Blanton (1982), to collect 409 bank-to-bank cross-sections of Lake Powell between April 1986 and July 1987. Though previous range-line surveys had been done between 1968 and 1973 (Bureau of Reclamation, 1973), these surveys were limited in their coverage. The 1986 survey produced the first reservoir-wide bathymetric data since impoundment. The complexity of the environment and inherent limitations of early positioning systems warranted the use of a variety of techniques across the reservoir to georeference the measured reservoir depths, which are described in Ferrari (1988). A bathymetric contour map was developed from range-line data and used to calculate elevation-area-capacity relationships with the Reclamation Area-Capacity Computation Program (Bureau of Reclamation, 1985). Abbreviated tables from this study were published at elevation intervals of 20 ft (Ferrari, 1988).

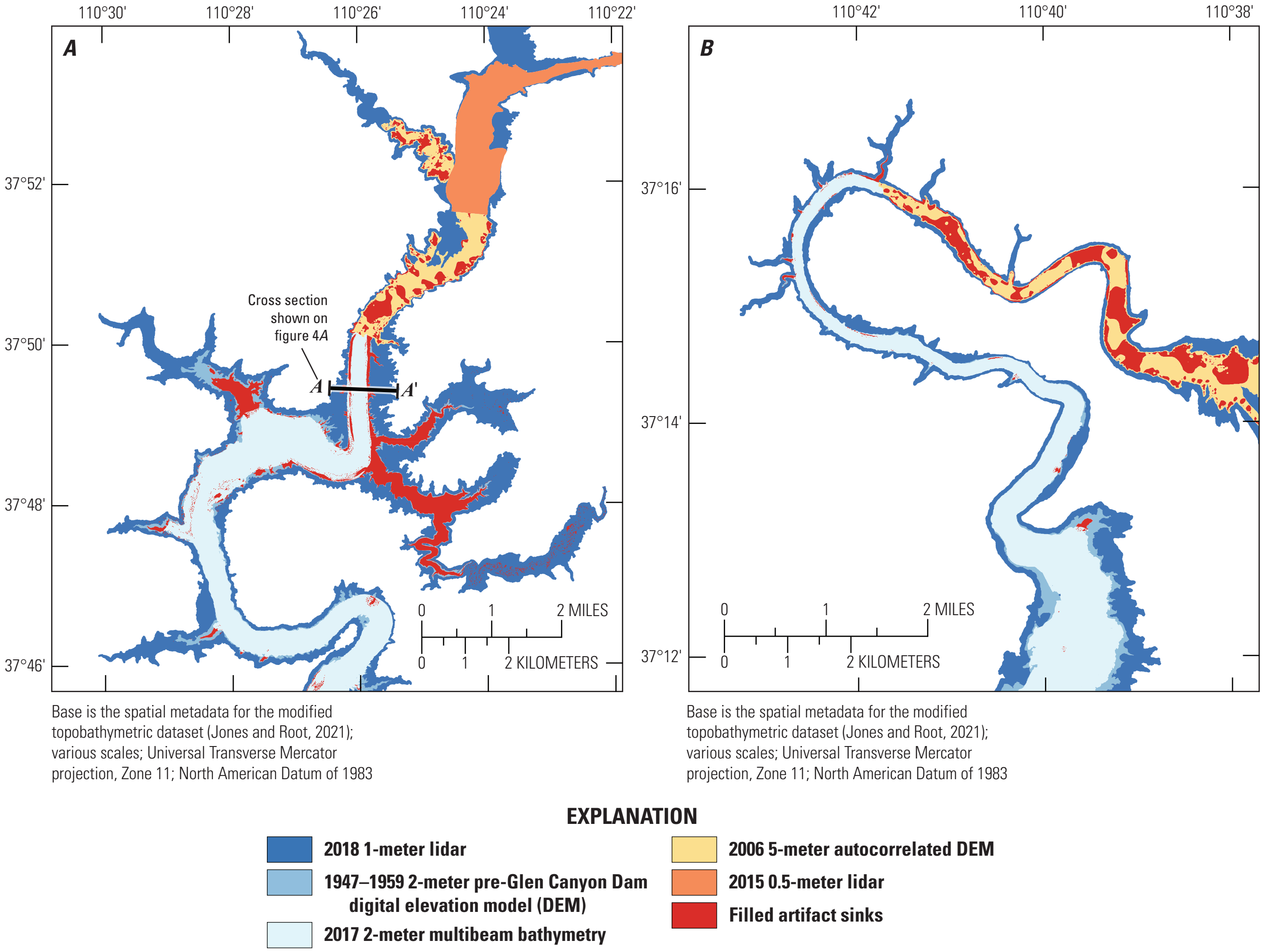
Several studies have been done on sedimentation and storage loss in Lake Powell, though they do not include reservoir-wide estimates for storage capacity. To monitor sedimentation, Reclamation performed a series of sediment monitoring range-line surveys of the deltaic regions of the Colorado and San Juan Rivers between 1968 and 1973 (Bureau of Reclamation, 1973; Lazenby and Nelson, 1976). Other early surveys were done through the Lake Powell Research Project (Spydell, 1975; Condit and others, 1978; Potter and Drake, 1989), a National Science Foundation-funded, interdisciplinary collaboration that included natural and social scientists whose purpose was to observe the effects of water management in the Lake Powell region. As part of sediment and water-chemistry studies in Lake Powell, the USGS completed several single-beam, longitudinal profiles along the river thalwegs (Twichell and others, 2001; Hart and others, 2005; Hornewer, 2014). The first multibeam bathymetric survey was done in 2005 (Clarke and others, 2005; Pratson and others, 2008), though storage capacity estimates were not calculated.

Reservoir Survey 2017–18

A TBDEM is a continuous representation of subaerial topography and submerged bathymetry. Poppenga and others (2020) created a TBDEM of Lake Powell from four data sources: (1) 2017 2-meter (m) multibeam bathymetry (Andrews and others, 2018); (2) 2018 1-m topographic lidar point-cloud dataset contracted by Reclamation; (3) 2-m historical digital elevation model (DEM) interpolated from 1947 and 1959 contour maps (Root and others, 2019); and (4) 10-m interpolated topography where gaps exist between data sources (fig. 3). These datasets were mosaiced together by generating spatial seamlines with a blending width of 5 m. Where overlap between datasets existed, topographic lidar was given the highest priority, bathymetry the second highest priority, historical DEM third highest priority, and interpolated gap-filling topography had the lowest priority. Priority was based on cell size of the source data.

A dual-head Reson T20-P multibeam echosounder was used to collect reservoir-wide high-resolution bathymetry between October 8 and November 15, 2017 (Andrews and others, 2018). Reservoir water surface elevations ranged between 3,629.18 and 3,631.20 ft above NAVD 88 during the bathymetric survey. Differential Global Positioning System (DGPS) data and vessel roll, pitch, heave, and yaw were collected with an inertial navigation system and depth data collected with the multibeam echosounder were integrated during the survey using HYPACK data acquisition software (version 2017, 17.1.3.0; https://www.hypack.com/). Post-survey, the raw depth data were processed with Computer Aided Resource Information System Hydrographic Information Processing System (CARIS HIPS; versions 10.2 and 10.4; http://www.teledynecaris.com/en/products/hips-and-sips/), which included applying an adjustment for changes in sound velocity with depth and removing erroneous points, such as noise, in individual multibeam swaths. The raw DGPS data were processed with POSPac Mobile Mapping Suite software (version 8.1; https://www.applanix.com/products/pospac-mms.htm), which uses Applanix SmartBase technology to improve the horizontal and vertical accuracy of the navigation solution. The improved solution was applied to the depth data in CARIS HIPS. The post-processed bathymetric dataset was exported as 6.6-ft per pixel ASCII files referenced to Universal Transverse Mercator (UTM) Zone 12N, World Geodetic System 84 (WGS 84) and WGS 84 ellipsoidal heights. Vertical accuracy of the post-processed bathymetry dataset is approximately 1 percent of water depth, which ranged between approximately 15 and 500 ft. The inertial navigation system used in the survey has an additional theoretical vertical accuracy on the order of hundredths of an inch. Vertical transformations from WGS 84 to NAVD 88 during post-processing corrections introduced an additional ±3.0 inches of vertical uncertainty. Horizontal positioning of the raw data is accurate to 1.6–6.6 m but may be as accurate as less than 4 inches after post processing.

The lidar topographic data were acquired during a 2-day airborne survey on April 2 and April 3, 2018, and completed by The Atlantic Group, LLC (https://www.atlantic.tech), under contract by Reclamation. This dataset is not independently published as of the release of this report. A Pacific Aerospace PAC750XL (N750VX) outfitted with a Leica ALS70-HP topographic lidar system was used for data collection, with a maximum flying height of 11,500 ft above ground level. The vertical accuracy of the point cloud and bare-earth data were assessed to the American Society for Photogrammetry and Remote Sensing Positional Accuracy Standards for Digital Geospatial Data (American Society for Photogrammetry and Remote Sensing, 2015). There were 28 distributed check points, including 21 non-vegetated and 7 vegetated, with ground-cover classifications that included open terrain, urban terrain, bare earth, brush, and high grass) measured to assess the accuracy of the lidar data. Vertical error of all check points at the 95-percent confidence level ranged between 0.092 and 0.134 m (0.3018–0.4396 ft) and root mean square error in the vertical direction (RMSEz) ranged between 0.048 and 0.068 m (0.1575–0.2231 ft). In the inundated river and delta regions, where lidar did not penetrate, the DEM was hydro-flattened so that the water surface behaved like a lake rather than a river with a gradient. A constant elevation value of 3,612.76 ft above NAVD 88, representing the water surface elevation of the reservoir during the survey, was applied to these areas.



Base is the spatial metadata for the modified topobathymetric dataset (Jones and Root, 2021); various scales; Universal Transverse Mercator projection, Zone 11; North American Datum of 1983

Base is the spatial metadata for the modified topobathymetric dataset (Jones and Root, 2021); various scales; Universal Transverse Mercator projection, Zone 11; North American Datum of 1983

Figure 3. Select locations in Lake Powell that display data sources for the original (Poppenga and others, 2020) and modified topobathymetric digital elevation models (TBDEMs; Jones and Root, 2021). *A*, Spatial metadata for the TBDEM in the Colorado River delta region. Cross-section A–A′ is referenced in figure 4*A*; *B*, Spatial metadata for the TBDEM in the San Juan River delta region.

Gaps between the 2017 bathymetry and 2018 lidar datasets were inevitable in shallow regions of the reservoir where the multibeam vessel was incapable of accessing and lidar could not penetrate the water surface. Interpolation errors in the TBDEM appear at the location of those gaps because of a lack of topographic or bathymetric data. To create a continuous surface, the gaps were seamlessly assimilated with the U.S. Geological Survey Coastal National Elevation Database methodology of interpolation (Danielson and others, 2016) or filled with a pre-Glen Canyon Dam DEM (Root and others, 2019). Additionally, a hydro-flattened elevation of 3612.76 ft above NAVD 88 was applied to the water surfaces of the Colorado and San Juan Rivers upstream from the deltas where water was too shallow for the multibeam vessel to access and lidar data recovery was poor. The hydro-flattened water surface in the rivers was not corrected by Poppenga and others (2020) because there was no alternate data source and further manipulation of topography would introduce additional error; thus, the hydro-flattened surface was the most transparent and decipherable solution.

Root and others (2019) digitized the pre-Glen Canyon Dam contour maps (Fairchild Aerial Surveys, Inc., 1947; Alster and Associates, Inc., 1959) and created a DEM of Glen Canyon prior to the impoundment of Lake Powell. The Colorado River arm, from the site of Glen Canyon Dam to Cataract Canyon, was surveyed in 1958 and 1959 at a contour interval of 10 ft. The San Juan River arm was surveyed in 1947 at a contour interval of 20 ft from the confluence of the San Juan and Colorado Rivers through Mexican Hat, Utah. Horizontal data were transformed from the State Plane Coordinate System, based on the North American Datum of 1927 (NAD 27), to Zone 12N of the Universal Transverse Mercator coordinate system, North American Datum of 1983 with the National Adjustment of 2011. Vertical data were transformed from the NGVD 29 to NAVD 88 using the correction rasters developed for the National Oceanic and Atmospheric Administration (NOAA) VDatum vertical datum transformation tool (National Oceanic and Atmospheric Administration, 2019). A hydrologically corrected, 2-m DEM was created from the digitized contours with the Topo to Raster tool in ArcMap (version 10.6.1; https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview). Vertical accuracy with respect to the original contour maps was reviewed, though a formal error analysis was not performed. The vertical error in this dataset is, at least, equal to the contour interval (10 or 20 ft) that represents that area of the DEM.

The 2017 bathymetry and 2018 lidar topography do not always overlap or abut. Sizeable gaps between the datasets were filled with interpolated topography to create a continuous surface. The edges of the bathymetry and lidar topography were converted to points and then interpolated within the gaps at a 33-ft (10-m) cell size using ArcGIS Topo to Raster. This methodology was primarily utilized in the northeast region of the dataset. Poppenga and others (2020) include spatial metadata of source inputs, and Jones and Root (2021) include an updated version of this metadata with the modified TBDEM.

Methods

The datasets and methods used to calculate elevation-area-capacity relationships in Lake Powell are described in this section. The TBDEM created by Poppenga and others (2020) required modifications for the purpose of this study. This section describes the modifications that were made to the original TBDEM (Poppenga and others, 2020) and the alternate sources of data that were incorporated into a modified TBDEM (Jones and Root, 2021). Discussion is provided for vertical datum conversions because previous storage capacity estimates of Lake Powell were made prior to the adoption of the NAVD 88. Calculations for elevation-area-capacity relationships of the modified TBDEM at 0.33-ft (0.10-m) intervals and linear interpolations at 0.01-ft intervals and error estimates also are detailed.

Modifications to the 2017–18 Topobathymetric Digital Elevation Model

The assimilation of interpolated data, incorporation of historical data, and hydro-flattening technique into the TBDEM provides the topobathymetric surface in the absence of data but will cause inconsistencies with the true bathymetric surface that are difficult to quantify. Though these inconsistencies may misrepresent a small fraction (less than 10 percent) of the total TBDEM area, these regions are expected to have the largest volumetric change due to sedimentation at the river deltas. In context of extensive sedimentation observed in the Colorado and San Juan River deltas and inflows (Lazenby and Nelson, 1976; Condit and others, 1978; Ferrari, 1988; Potter and Drake, 1989; Hart and others, 2005; Ferrari, 2006; Pratson and others, 2008; Hornewer, 2014), further modifications were made to the original TBDEM (Poppenga and others, 2020) prior to calculating storage capacity relationships (table 1; Jones and Root, 2021). Specifically, these modifications (1) address gaps in the dataset where the historical DEM (Root and others, 2019) was incorporated and where sediment has since been deposited and (2) replace the constant, hydro-flattened elevation in the river channel upstream from the Colorado and San Juan deltas with alternate topographic data sources.

Regions of the topobathymetric data that incorporated the historical DEM were modified with a reasonable expectation of sedimentation in Lake Powell. In many places in the reservoir, particularly where steep cliffs are predominant, the historical DEM was an acceptable substitution for data gaps. In other regions, with shallower topography or near the river deltas, the historical DEM does not account for large volumes of accumulated sediment. Steep, sharp drop-offs at the interface between bathymetry and lidar data are most pronounced at the edges of the thalweg where the reservoir narrows into the river channel, creating artifact trenches nearly 165 ft deep where they are, in fact, filled with reservoir sediment. To create a surface that best represents the topography in these areas, these artifacts were individually identified in the delta regions and filled using the Fill tool in ArcMap (version 10.6.1; fig. 4).

Table 1. Datasets incorporated into the modified topobathymetric digital elevation model (TBDEM). Resolution is provided in published units (SI).

[mi^2, square miles; USGS, U.S. Geological Survey; m, meters; DEM, digital elevation model; USGS, U.S. Geological Survey; Reclamation, Bureau of Reclamation; UDNR, Utah Department of National Resources; NPS, National Park Service; UGRC, Utah Geospatial Resource Center; n/a, interpolated data does not have acquisition date]

Data source	In-text reference	Source	Data type	Year(s) acquired	Published resolution	Coverage (mi^2)
Lake Powell Arizona-Utah bathymetry	Andrews and others (2018)	USGS	Multibeam bathymetry	2017	2 m	129.6
Lake Powell Arizona-Utah lidar	Poppenga and others (2020)	Reclamation	Topographic lidar	2018	1 m	150.3
Pre-Dam Lake Powell DEM	Root and others (2019)	Reclamation/ USGS	Historical DEM	1947, 1959	2 m	19.1
Lake Powell TBDEM, hydro-flattened	Poppenga and others (2020)	USGS	Hydro-flattened	n/a	10 m	3.3
Modified TBDEM, filled sinks	Jones and Root (2021)	USGS	Void fill areas	n/a	2 m	3.0
Colorado, Green, Yampa River lidar	Utah Geospatial Resource Center (2017)	UDNR/NPS	Topographic lidar	2015	0.5 m	4.8
Utah statewide auto-correlated DEM	Utah Geospatial Resource Center (2007)	UGRC	Topographic lidar	2006	5 m	2.9

Two substitute elevation datasets were incorporated into the modified TBDEM to replace the zones in the original TBDEM where the river thalwegs are represented with a hydro-flattened elevation value of 3,612.76 ft above NAVD 88 (fig. 4). The first dataset is a 0.5-m DEM derived from lidar data acquired in October and November 2015 by the Utah Division of Forestry, Fire And State Lands and the National Park Service (Utah Geospatial Resource Center, 2017). The dataset covers 152 mi^2 of the Colorado, Green, and Yampa river channels in Utah and Colorado, with a sampling density of eight points per square meter. The vertical accuracy of the 2015 DEM was assessed with 72 total check points, including 40 non-vegetated and 32 vegetated. For non-vegetated check points, the 95-percent confidence level was 0.4406 ft (0.1343 m), with a RMSEz of 0.2247 ft (0.0685 m); for vegetated check points, the 95-percent confidence level was 0.1367 m (0.4485 ft), with a RMSEz of 0.0697 m (0.2287 ft). The second dataset is a 5-m DEM created from lidar that was collected in July 2006 (Utah Geospatial Resource Center, 2007) when the lake was at a comparable elevation to the TBDEM datasets (Poppenga and others, 2020). Vertical accuracy was tested on 190 check points, which resulted in 2 check points being removed due to unacceptable accuracy. The 95-percent confidence level is 12.64 ft (3.854 m), with a RMSEz of 6.453 ft (1.967 m). The course of the San Juan River, over subaerially exposed reservoir sediment, is similar to present day based on satellite imagery. The vertical difference of the water surface elevation of the San Juan River as it incises the reservoir sediment (since 2006) is unknown because other elevation datasets that could improve this estimate were not available for the region.

Using the TBDEM spatial metadata as a mask to exclude areas where modifications were not necessary (Poppenga and others, 2020), the substitute elevation datasets were mosaiced over the hydro-flattened regions of the unmodified TBDEM using the ‘Mosaic to New Raster’ tool in ArcMap (version 10.6.1). Source inputs were not reassembled due to processing capacity limitations. A 10-m buffer accounted for the difference in cell size between the input datasets. Because the reservoir had not flooded this region between acquisitions of the 2015 and 2018 lidar (fig. 2), the full extent of the 2015 dataset, including areas outside of the hydro-flattened zone, was used to avoid potential conflicts with the 2018 TBDEM related to changes in topography over time. The resulting raster was matched by cell coordinate location to the original TBDEM, and the substitute datasets were resampled using a cubic convolution to conform with the 1-m cell size. The 2006 5-m DEM primarily is used on the San Juan River arm and had several anomalous sinks that were adjacent to vertical cliffs; these sinks were individually filled.

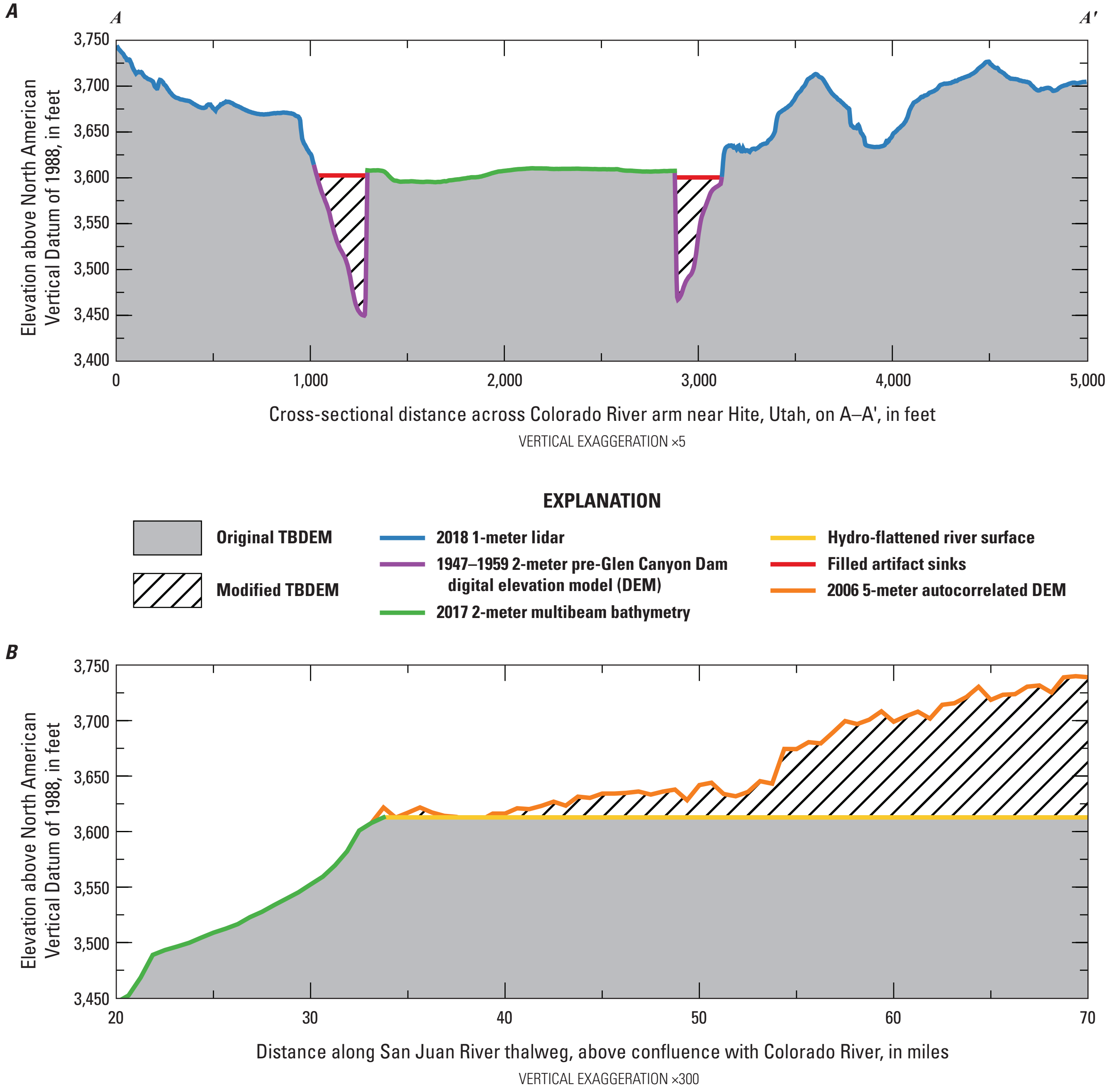


Figure 4. Select locations in Lake Powell that highlight modifications made on the topobathymetric digital elevation model (TBDEM; Poppenga and others, 2020). Colors represent topographic, bathymetric, and interpolated data sources for the TBDEM. *A,* Topobathymetric cross section across the Colorado River arm of Lake Powell on line A–A′ (see fig. 3*A* for location), with modified regions that account for sedimentation (diagonal lines). These trenches are unfilled in the unmodified TBDEM (gray); *B,* Longitudinal profile of the San Juan River thalweg across the delta during the 2017 bathymetric survey. The unmodified TBDEM (gray) represents the top of the delta with a constant, hydro-flattened elevation of 3,612.76 ft above the North American Vertical Datum of 1988 that does not capture upstream sediment accumulation nor river gradient. Using alternate data sources (see table 1), the modified TBDEM (diagonal lines) provides a more reasonable estimate of river channel elevations.

Calculation of Elevation-Area-Capacity Relationships

Elevation-area-capacity relationships were derived from a script written in the Python coding language (Python Software Foundation, Python Language Reference, version 2.7, available at http://www.python.org) that utilizes Esri's Storage Capacity tool, part of the Spatial Analyst Supplemental Toolbox (version 1.4, https://www.arcgis.com/home/item.html?id=3528bd72847c439f88190a137a1d0e67). The script requires three inputs: (1) a DEM, (2) a polygon boundary of the spatial extent of the computation, and (3) the elevation range and interval to calculate the elevation-area-capacity values within. Starting at the minimum elevation value provided, the script iteratively tabulates the total area and volume within the provided polygon extent below each elevation increment. Due to the computational requirements of the analysis, the script was adapted for use on the Yeti high performance computing cluster at the USGS Advanced Research Computing Center in Denver, Colorado (https://www.usgs.gov/core-science-systems/sas/arc). The inputs used to compute elevation-area-capacity relationships for Lake Powell included the modified TBDEM (available for download through ScienceBase at https://doi.org/10.5066/P9H60YCF; Jones and Root, 2021) and a reservoir mask that excludes areas below the Glen Canyon Dam.

Units of the original TBDEM (Poppenga and others, 2020) are in the International System of Units (SI). Primary storage capacity calculations were made in SI, with an elevation range of 950.98–1,133.03 m above NAVD 88 (3,120.01–3,717.29 ft above NAVD 88) at increments of 0.10 m (0.33 ft). These results were then converted to the U.S. customary system (USCS), in accordance with Reclamation operational standards at Glen Canyon Dam and historical estimates of storage capacity. All subsequent calculations were done with USCS results.

Resulting 0.33-ft (0.10-m) relationships were used to generate elevation-area-capacity values at 0.01-ft increments by linearly interpolating values between each 0.33-ft (0.10-m) incremental pair. The 0.01-ft interpolated interval was calculated at the request of Reclamation.

Additional storage capacity calculations were done for error assessment at matching 0.01-ft increments for lower (3,160.00–3,161.00 ft above NAVD 88), middle (3,400.00–3,401.00 ft above NAVD 88), and upper (3,700.00–3,711.00 ft above NAVD 88) elevations. Values were generated following the same procedures outlined for the original 0.33-ft (0.10-m) increment calculations, thereby providing a one-to-one comparison dataset against the linearly interpolated values for these discrete elevation bands.

Vertical Datum Conversions

The TBDEM is referenced to the NAVD 88 using the Geoid12B geoid and horizontally referenced to the North American Datum of 1983 with the National Adjustment of 2011, UTM Zone 12 projection (Poppenga and others, 2020). Historical data (Root and others, 2019) were referenced to NGVD 29 and have been transformed to NAVD 88. Transformation from NGVD 29 to NAVD 88 is determined by adding a constant conversion value to elevations in NGVD 29 for the area of interest. Correction values are stored in a georeferenced grid (0.05 decimal-degree cell size) developed for the NOAA VDatum (v4.0) vertical datum transformation tool (National Oceanic and Atmospheric Administration, 2019). The conversion value for elevations at the dam used in this study is +2.913 ft from NGVD 29 to NAVD 88 and was selected from the land surface east of Glen Canyon Dam using the NOAA VERTCON tool (National Oceanic and Atmospheric Administration, 2021). This conversion was calculated for the USGS reservoir elevation station (09379901) located at 36.9369326, −111.4837694.

Results

This section details elevation-area-capacity relationships in Lake Powell derived from the 2017–18 reservoir survey, along with associated low, middle, and high elevation band error assessment results. These results are compared with previously published estimates of storage capacity and areal extent of Lake Powell by Bureau of Reclamation (1963) and Ferrari (1988). A table of summarized elevation-area-capacity relationships and graphs that show change in storage capacity between surveys are presented in this section. The modified TBDEM is available as a USGS ScienceBase data release at https://doi.org/10.5066/P9H60YCF (Jones and Root, 2021). The complete elevation-area-capacity tables and error analysis of linear interpolations are available as a USGS ScienceBase data release at https://doi.org/10.5066/P9O3IPG3 (Jones and Root, 2022).

Elevation-Area-Capacity Relationships and Comparisons With Previous Surveys

Results from the 2017–18 survey indicate that the total storage capacity and areal extent at full pool (3,702.91 ft above NAVD 88) are 25,160,000 acre-feet and 159,200 acres, respectively. These values represent a decrease in storage capacity of 1,833,000 acre-feet or 6.79 percent from 1963 to 2018 and a 1,048,000 acre-ft or 4.00 percent decrease from 1986 to 2018. The decrease in areal coverage is 2,142 acres or 1.33 percent from 1963 to 2018 and 1,536 acres or 0.96 percent from 1986 to 2018. The elevation-area-capacity relationships are summarized in figures 5, and 6, and table 2. Calculated elevation-area-capacity relationships at 0.33-ft (0.10-m) calculated increments and 0.01-ft interpolated increments are available for download at https://doi.org/10.5066/P9O3IPG3 (Jones and Root, 2022).

Error analysis of the interpolated relationships was performed at 0.01-ft intervals across three elevation bands: (1) lower (3,160.00–3,161.00 ft above NAVD 88); (2) middle (3,400.00–3,401.00 ft above NAVD 88); and (3) upper (3,700.00–3,711.00 ft above NAVD 88). The interpolated values are comparable to the calculated values, with differences ranging from −0.01 to 0.03 percent and 0 to 0.02 percent for area and storage capacity calculations, respectively. The error analysis for all interpolated values is available for download at https://doi.org/10.5066/P9O3IPG3 (Jones and Root, 2022).

Intermediate reservoir elevations include critical benchmarks for the management of Lake Powell and operations at Glen Canyon Dam. The dead storage elevation (3,372.91 ft above NAVD 88), which is the reservoir level below all hydroelectric penstocks and other outlet works, has decreased in storage capacity by 152,900 acre-feet or 8.11 percent from 1963 to 2018 and 27,100 acre-feet or 1.54 percent from 1986 to 2018. The inactive storage level (up to 3,492.91 ft above NAVD 88) represents the lowest reservoir elevation that all hydroelectric penstocks are submerged. Storage capacity at the inactive storage level has decreased by approximately 599,900 acre-feet or 9.84 percent from 1963 to 2018 and 333,000 acre-feet or 5.72 percent from 1986 to 2018.

These results reflect the elevation-area-capacity relationships determined in this study and are not directly comparable to values used for operations at Glen Canyon Dam. Direct comparisons to Reclamation operational relationships are outside the scope of this report.

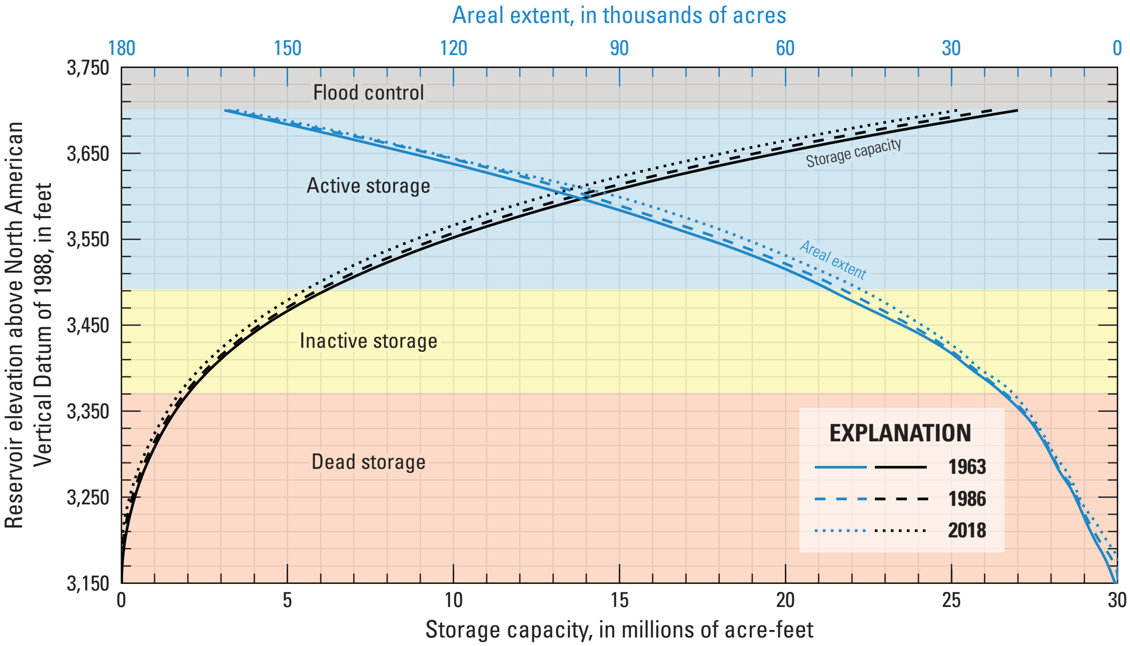


Figure 5. Storage capacity (bottom axis, black lines) and areal extent (top axis, blue lines) of the reservoir calculated from the modified topobathymetric digital elevation model (Jones and Root, 2021, 2022) at 0.1-meter intervals. Values were linearly interpolated at 0.003048-meter intervals between the calculated areas and volumes. Previous estimates of storage capacity and areal extent (Bureau of Reclamation, 1963; Ferrari, 1988) are shown for comparison. Benchmark elevations related to dam operations include the levels for flood control (grey), active storage (blue), inactive storage (yellow), and dead storage (red).

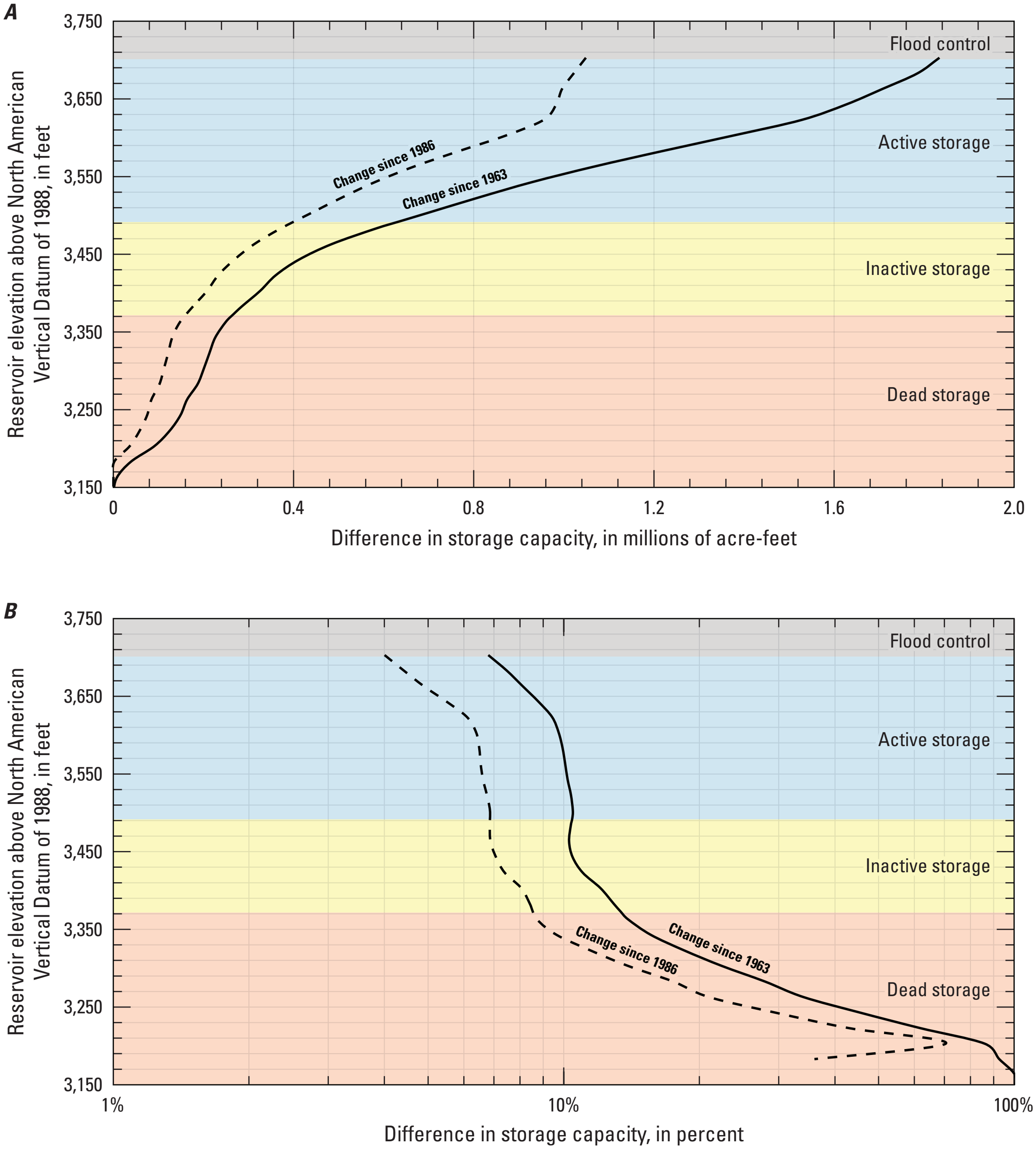


Figure 6. Difference in storage capacity by *A*, absolute storage capacity; and *B*, percent from 1963 (solid line) and 1986 (dashed line) to 2018 (Jones and Root, 2021; Jones and Root, 2022). Benchmark elevations related to dam operations include the levels for flood control (grey), active storage (blue), inactive storage (yellow), and dead storage (red). A 100-percent difference in storage capacity would indicate a complete loss of storage capacity. A sharp decrease in percent difference between 1986 and 2018 is present at low elevations; this deflection from the trend toward 100-percent storage loss likely reflects error that exceeds storage capacity at the lowest elevations.

Table 2. Summary of previous and current elevation-area-capacity relationships in Lake Powell (including benchmark elevations; in feet above NGVD 29: full pool, 3,700; inactive storage, 3,490; dead storage, 3,370).

[ft, feet; NGVD 29, National Geodetic Vertical Datum of 1929; NAVD 88, North American Vertical Datum of 1988; acre-ft, acre-feet; n/a, area and storage capacity for given elevation are not published]

Elevation (ft) NGVD 29	Elevation (ft) NAVD 88	1963[1]		1986[2]		2017–18[3]		Loss of capacity, 1963–2018 (percentage)[4]	Percentage of capacity at full pool[5]
		Area (acres)	Storage capacity (acre-ft)	Area (acres)	Storage capacity (acre-ft)	Area (acres)	Storage capacity (acre-ft)		
3,700	3,702.91	161,390	27,000,000	160,784	26,214,861	159,248	25,166,112	6.79	100.00
3,680	3,682.91	147,490	23,914,000	145,647	23,150,551	144,148	22,128,694	7.47	87.93
3,660	3,662.91	134,280	21,097,000	130,899	20,385,098	130,204	19,389,066	8.10	77.04
3,640	3,642.91	121,510	18,540,000	118,054	17,895,574	117,446	16,912,555	8.78	67.20
3,620	3,622.91	109,690	16,229,000	105,929	15,655,745	103,666	14,700,802	9.42	58.42
3,600	3,602.91	98,470	14,148,000	95,387	13,642,587	90,587	12,770,822	9.73	50.75
3,580	3,582.91	88,150	12,284,000	85,667	11,832,048	80,358	11,064,223	9.93	43.96
3,560	3,562.91	78,810	10,616,000	75,981	10,215,568	71,295	9,548,005	10.06	37.94
3,540	3,542.91	69,700	9,133,000	67,206	8,783,697	63,339	8,202,881	10.18	32.59
3,520	3,522.91	61,750	7,820,000	59,476	7,516,870	56,052	7,009,771	10.36	27.85
3,500	3,502.91	54,790	6,656,000	52,386	6,398,246	49,057	5,959,757	10.46	23.68
3,490	3,492.91	51,600	6,124,000	n/a	n/a	45,864	5,485,084	10.43	21.80
3,480	3,482.91	48,590	5,623,000	46,275	5,411,639	43,040	5,041,128	10.35	20.03
3,460	3,462.91	42,110	4,717,000	40,361	4,545,281	37,852	4,232,898	10.26	16.82
3,440	3,442.91	35,830	3,938,000	34,699	3,794,678	32,902	3,526,543	10.45	14.01
3,420	3,422.91	30,650	3,275,000	30,045	3,147,240	28,472	2,914,717	11.00	11.58
3,400	3,402.91	26,680	2,704,000	26,062	2,586,177	25,019	2,378,132	12.05	9.45
3,380	3,382.91	22,480	2,213,000	22,102	2,104,540	20,442	1,927,743	12.89	7.66
3,370	3,372.91	20,640	1,998,000	n/a	n/a	18,915	1,731,287	13.35	6.88
3,360	3,362.91	18,970	1,800,000	18,504	1,698,475	17,424	1,550,496	13.86	6.16
3,340	3,342.91	15,990	1,452,000	15,698	1,356,447	15,124	1,225,879	15.57	4.87
3,320	3,322.91	13,870	1,155,000	13,603	1,063,436	13,129	941,803	18.46	3.74
3,300	3,302.91	12,110	897,000	11,906	808,350	11,482	696,244	22.38	2.77
3,280	3,282.91	10,490	671,000	10,299	586,303	9,240	484,015	27.87	1.92
3,260	3,262.91	8,460	482,000	8,044	402,872	7,592	318,506	33.92	1.27
3,240	3,242.91	6,960	329,000	6,752	254,905	6,148	180,056	45.27	0.72
3,220	3,222.91	5,600	203,000	5,114	136,241	3,910	77,944	61.60	0.31
3,200	3,202.91	4,100	106,000	3,381	51,290	2,013	15,199	85.66	0.06
3,180	3,182.91	2,370	42,000	1,249	4,995	76	3,199	92.38	0.01
3,160	3,162.91	1,050	8,000	0	0	0	0	100.00	0.00

[1] From Bureau of Reclamation (1963).

[2] From Ferrari (1988).

[3] Calculated from modified topobathymetric digital elevation model (TBDEM; Jones and Root, 2021) after Poppenga and others (2020).

[4] Percent change in storage capacity from 1963 to 2017–18 surveys.

[5] Percent of current storage capacity at full pool for a given elevation according to the 2017–18 TBDEM.

Sources of Error in Topobathymetric Dataset

Sources of error in the TBDEM and elevation-area-capacity calculations are difficult to identify and quantify. Random errors in topographic and bathymetric surveying are small and are ignored here. Systematic errors are difficult to identify, though each dataset was independently assessed for error prior to being assembled into the TBDEM. Interpolation errors are quantifiable, but this was not calculated because of the number of datasets and range of acquisition dates for each survey.

Because the TBDEM comprises sources with different resolutions, coverages, and known errors, the vertical error can be reasonably quantified. The data sources that most represent the TBDEM by area are the 2017 bathymetry (Andrews and others, 2018) and 2018 lidar. The bathymetry includes a majority of storage capacity in Lake Powell below the minimum reservoir elevation during the survey (3629.18 ft above NAVD 88). This elevation corresponds to 61.05 percent storage capacity at full pool. The remaining volume is primarily defined by the 2018 lidar, with a minority contribution from the historical DEM and interpolated topography. The vertical error of the bathymetry is 1 percent of water depth or up to 5 ft of error at the maximum water depth (approximately 500 ft). The average water depth of the bathymetric survey, using the highest reservoir elevation to difference the bathymetry, is 142 ft. This average depth equates to a 1.42 ft error but is likely to vary with location in the reservoir. Vertical error of the lidar at 95-percent confidence level is less than 0.5 ft. The greatest vertical error all associated datasets is in the 2006 statewide auto-correlated DEM (Utah Geospatial Resource Center, 2007), with a 95-percent confidence level of 12.64 ft and RMSEz of 6.453 ft. These errors are substantial but only representative of approximately 3.44 percent of the TBDEM area and only in select regions where hydro-flattened topography was used (see spatial metadata for Jones and Root, 2021). Thus, the bathymetric dataset is most likely to provide a reasonable error for elevation-area-capacity relationships. Conservatively, a vertical error in reservoir elevation of ±1.42 ft is suggested for the results provided here. At full pool (3,702.91 ft above NAVD 88), this error approximately corresponds with storage capacity between 24,940,671 and 25,392,938 acre-feet or a range of 452,267 acre-feet.

Discussion on Rates of Storage Loss

Between 1963 and 2018, the average annual loss in storage capacity was approximately 33,270 acre-feet per year. Deposition at the deltas of the sediment-laden Colorado and San Juan Rivers is the primary cause of storage loss in Lake Powell (Bureau of Reclamation, 1973; Condit and others, 1978; Ferrari, 1988; Potter and Drake, 1989; Vernieu, 1997; Ferrari, 2006; Pratson and others, 2008). Using the elevation-area-capacity data available from the two previous survey and storage capacity studies (Bureau of Reclamation, 1963; Ferrari, 1988), the average annual storage loss was similar. From the closing of Glen Canyon Dam in March 1963 through September 1986, Lake Powell had lost 33,390 acre-feet in storage capacity per year; from September 1986 through the April 2018, 33,180 acre-feet per year was lost. The interplay between new sediment entering the reservoir and the remobilization of previously deposited sediment from higher elevations may bias these rates and is not considered here.

Advancements in bathymetric survey technology over time has allowed for greater spatial coverage, accuracy, and density of bathymetric data which reduces the need to interpolate over large survey errors in the final DEM. The range-line (Bureau of Reclamation, 1973; Ferrari, 1988) and single-beam (Twichell and others, 2001; Hart and others, 2005; Hornewer, 2014) surveys represent two-dimensional bathymetry in a specific location. The modern multibeam bathymetric survey (Andrews and others, 2018) represents the most comprehensive and high-resolution survey of Lake Powell to date. Comparisons between the storage capacity estimates derived from the pre-Glen Canyon Dam topographic survey, the 1986 range-line bathymetry, and 2017 multibeam bathymetry and 2018 lidar datasets are complicated because the error is different for each survey used to estimate storage capacity. An assessment of error in storage capacity estimates because of different survey methodologies, which would include a combination of independent survey and interpolation errors that are difficult to quantify, was beyond the scope of this study.

As a first-order approximation, the average annual loss of storage loss in Lake Powell indicates the remaining volume at full pool will be filled in approximately 750 years. However, the reservoir fills laterally, from the deltas toward Glen Canyon Dam, and would likely cease to be useful sooner. Estimating the remaining useful life of Lake Powell is multifaceted and beyond the scope of this study. This approximation would need to include accounting for benchmark elevations at Glen Canyon Dam, dynamic river discharge and sedimentation rates, the spatial distribution of sediments, climate sensitivity, and potential sediment mitigation activities such as dredging.

The distribution of absolute storage-capacity change since 2018 at reservoir elevations is not linear, with the greatest changes in storage capacity observed in elevations ranging between approximately 3,250–3,350 and 3,600–3,700 ft above NAVD 88 (fig. 6). In the lowest elevations, the initial (in other words, pre-Glen Canyon Dam) storage capacity is comparatively small and was largely filled by sediment prior to the 1986 survey; though the percent loss is high, the absolute volume loss is comparatively small to that observed at higher elevations. Also, these elevations were likely impounded by coffer dams that were installed in 1960 to divert the Colorado River around the Glen Canyon Dam construction site and may have been accumulating sediment at a rate similar to that at the deltas during construction. Storage losses observed between approximately 3,600 and 3,700 ft above NAVD 88 include the highstand, or period of high reservoir level, of the late 1970s through early 2000s and lowstand, or period of low reservoir level, from the early 2000s to present day.

Summary

The completion of Glen Canyon Dam by the Bureau of Reclamation (Reclamation) in 1963 created Lake Powell and provided the means to supply water to a growing population in the American southwest. A bathymetric survey of the reservoir was completed in 1986 to measure the change in storage capacity since impoundment. In 2017 and 2018, the U.S. Geological Survey and Reclamation completed extensive surveys of the reservoir utilizing high-resolution multibeam bathymetry and lidar. These data were merged into a seamless topobathymetric dataset, which was subsequently revised to calculate new elevation-area-capacity relationships. This collaborative effort provides a revised and high-resolution estimate of storage capacity in Lake Powell and an updated topobathymetric surface to support water availability studies amidst prolonged drought. The preceding report summarizes the updated elevation-area-capacity relationships, describes the surveying methods and elevation-area-capacity calculations, and provides comparisons of the updated elevation-area-capacity relationships with previous estimates.

Storage capacity and areal extent of Lake Powell was determined for a range of elevations from 3,120 to 3,717.20 ft above the North American Vertical Datum of 1988 (NAVD 88). The updated elevation-area-capacity relationships indicate Lake Powell has lost 1,833,000 acre-feet or 6.79 percent of its storage capacity at full pool (3,702.91 ft above NAVD 88) since construction was completed in 1963 through 2018. With consideration to potential error in the topobathymetric dataset, the loss of storage capacity ranges between 1,607,000 and 2,059,000 acre-feet. The reduction in storage capacity is attributed to sedimentation at the deltas of the Colorado and San Juan Rivers. Decreases in storage capacity were largest for the reservoir at elevations above 3,600 ft above NAVD 88, which coincide with frequent reservoir elevations since the 1970s. Historical surveys were limited by comparatively coarser survey techniques than those used for the 2017–18 topobathymetric digital elevation model, though the average annual storage loss between surveys remained similar since impoundment in 1963. With increasing demands on water in the Colorado River Basin amidst a decadal-scale drought, these results provide critical information to support water resource management in Lake Powell and beyond.

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Glossary

Active storage This range of reservoir elevations, from 1,064.6 to 1,128.65 meters (3,492.91–3,702.91 feet), represents the levels that all penstocks and river outlets at Glen Canyon Dam are submerged.

Area-Capacity Computation Program Software developed by the Bureau of Reclamation to determine elevation-area-capacity relationships that are independent from the results in this report.

Coastal National Elevation Database topobathymetric digital elevation model (TBDEM) interpolation Methodology for developing TBDEMs that assimilates topographic and bathymetric data sources into a seamless surface.

Datum conversion Datasets published prior to 1988 are originally referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29); for clarity, all elevations have been converted to the North American Vertical Datum of 1988 (NAVD 88), unless otherwise noted, with a conversion factor of +0.887 meter (2.91 feet) from NGV29 to NAVD 88.

Dead storage This benchmark elevation, at 1,028.06 meters (3,372.91 feet), represents the lowest level that water can be released through Glen Canyon Dam.

Elevation-area-capacity relationship The cumulative areal extent and storage capacity, or volume, at a given reservoir elevation.

Flood-control stage As Glen Canyon Dam crests at 1,133.22 meters (3,717.91 feet), all reservoir levels above 1,128.65 meters (3,702.91 feet) are considered a risk to overflowing the dam.

Hydro-flatten Hydro-flattening is post-processing of topographic data to reflect flat-water surfaces. In this report, the regions of the topobathymetric digital elevation model that are active rivers (that is, upstream from the surveyed reservoir but within the reservoir limits) were hydro-flattened and do not reflect the river gradient.

Inactive storage This range of reservoir elevations, from 1,028.06 to 1,064.6 meters (3,372.91–3,492.91 feet), represents the levels that penstocks and river outlets at Glen Canyon Dam begin to be subaerially exposed and limit generation of hydroelectric generation.

Pre-Glen Canyon Dam digital elevation model (DEM) A DEM derived from pre-Glen Canyon Dam topographic surveys in 1947 for the San Juan River arm and 1959 for the Colorado River arm.

Range line A form of bathymetric surveying that consisted of measuring existing sediment profiles with an echosounder, typically from bank to bank in a reservoir.

Reservoir lifespan The expected amount of time a reservoir can reasonably maintain its ability to functionally store water.

Sedimentation rate The rate that sediment is deposited as a volume or mass per unit time. This report does not investigate sediment or modes of sedimentation and referencing loss of storage capacity as a sedimentation rate is not advised.

Storage Capacity tool for ArcGIS A tool packaged with the Spatial Analyst Supplemental Toolbox for ArcGIS by Esri. This tool creates a table of surface area and storage capacity, or volume, for an input surface raster at desired elevations. The script was modified for use on the Yeti supercomputer.

Topobathymetry An integrated, multi-source dataset of topographic and bathymetric elevation data.

Yeti High-performance computing cluster at the U.S. Geological Survey Advanced Research Computing in Denver, Colorado, that was used to calculate the elevation-area-capacity relationships for Lake Powell.

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