Evaluating the long-term future of fine sediment in Lake Powell

CEE 6440: GIS in Water Resources
Term Project

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Contents

Introduction

The Colorado River is paramount to both the development and functioning of the arid West. Its roles are multifaceted: providing water for both municipal and agricultural uses, powering hydroelectric turbines, supporting dynamic ecosystems and associated services, and facilitating recreation and economies (Kennedy et al., 2016; Schmidt et al., 1998). The basin drains approximately 246,000 square miles, through seven states in the United States and two states in Mexico, and is heavily regulated. Water delivery protocols and dam operations are governed by detailed policy, of which undergo revision as management needs change (Bureau of Reclamation). As population growth in the region leads to increased water demand, coupled with climate change exacerbating drought cycles, it is necessary to evaluate and adaptively manage the region's water resources (Jones et al., 2016; Schmidt et al., 2016; Melis et al., 2015; Webb et al., 1999).

Within the United States, the watershed is separated into two classifications: Upper and Lower Basin. The Upper Basin includes Colorado, New Mexico, Utah, and Wyoming. The Lower Basin includes Nevada, Arizona, and California. They are separated at Lees Ferry, which also demarcates Glen Canyon National Recreation Area from Grand Canyon National Park. Though these are imposed parameters from the 1922 Colorado River Compact, they serve as a functional basis for organizing water resources.

Objectives

This analysis had multi-faceted objectives. The first goal was to map and understand catchment characteristics and input of Lake Powell at Full Pool, Minimum Power Pool, and Dead Pool. The second goal was to understand the spatial relationship between substrate type and erodibility rates, using North Wash as a case study. Finally, the third goal was to better understand and integrate the desktop ArcGIS Pro client with web-based providers, such as StreamStats.

Study Area

Lake Powell, the second-largest reservoir in the United States, is a water repository for the Upper Basin (Figure 1). It crosses two states (Arizona and Utah) and four counties (Garfield, Kane, and San Juan Counties in Utah and Coconino County in Arizona). As a part of Glen Canyon National Recreation Area, the lake was created by Glen Canyon Dam, which closed its gates in 1963. This inundated the upstream Glen Canyon reach and fundamentally altered downstream ecosystem characteristics in Grand Canyon (Webb et al., 1999; Topping et al., 2003; Gloss et al., 2005).

As inflow levels fluctuate, sedimentation leads to delta formation (Pratson et al., 2008). Now, much of the sediment that would have been transported through the system, from both major tributaries and smaller slot canyons, is deposited in the reaches of Lake Powell. Though sedimentation rates exist for significant tributary arms (including the San Juan, Dirty Devil and Escalante Rivers), little is understood about associated rates for slot canyons (Griffiths and Topping, 2015, 2017; Pratson et al., 2008). By quantifying sediment accumulation in both slot canyons and tributaries, current reservoir storage capacity can be better understood.

For the purposes of this study, Lake Powell is defined as the area draining upstream from Lees Ferry to Hite, near the confluence of the Colorado River and the Dirty Devil River. North Wash (Figure 2) was selected as a case study due to its upstream location from Glen Canyon Dam, catchment contribution at Minimum Power Pool, and previous work done on its delta and rock strength (Bursztyn et al., 2015; Majeski, 2009).

The maximum extent of the reservoir is Full Pool (3,700 feet above sea level). The additional reservoir levels evaluated in this report are Minimum Power Pool (3,490 feet above sea level) and Dead Pool (3,370 feet above sea level). Minimum Power Pool is the lowest reservoir elevation at which hydropower can be produced, and Dead Pool is the level at which hydropower can no longer be produced.

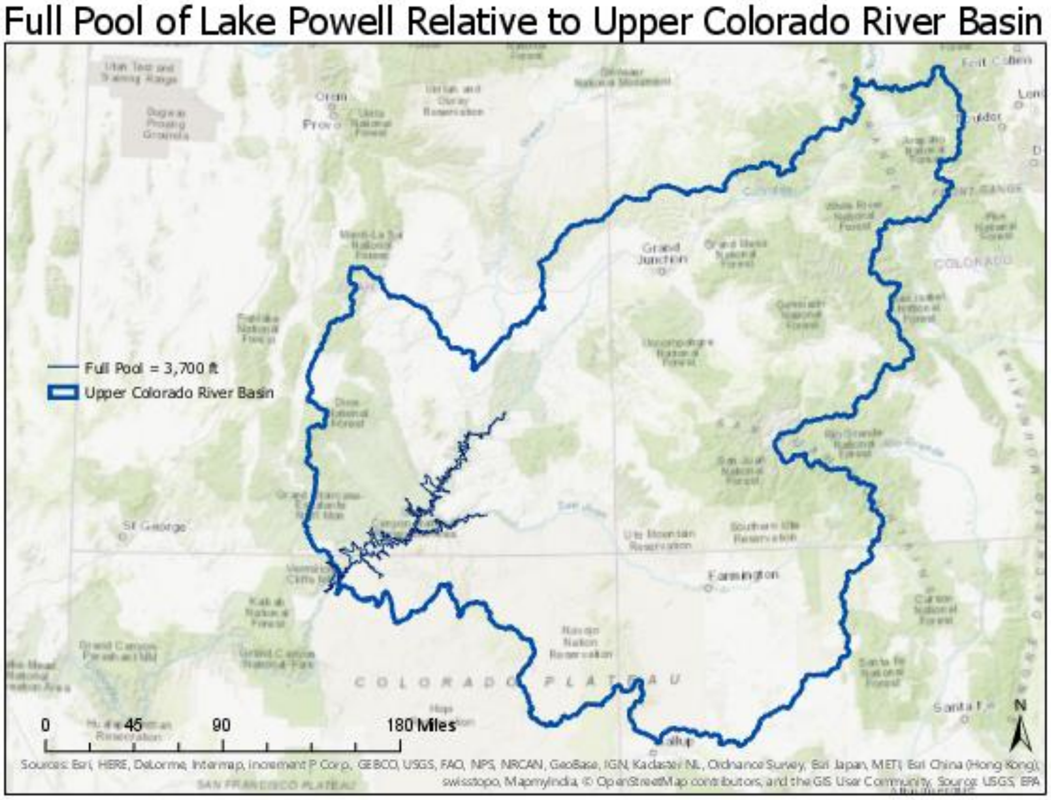
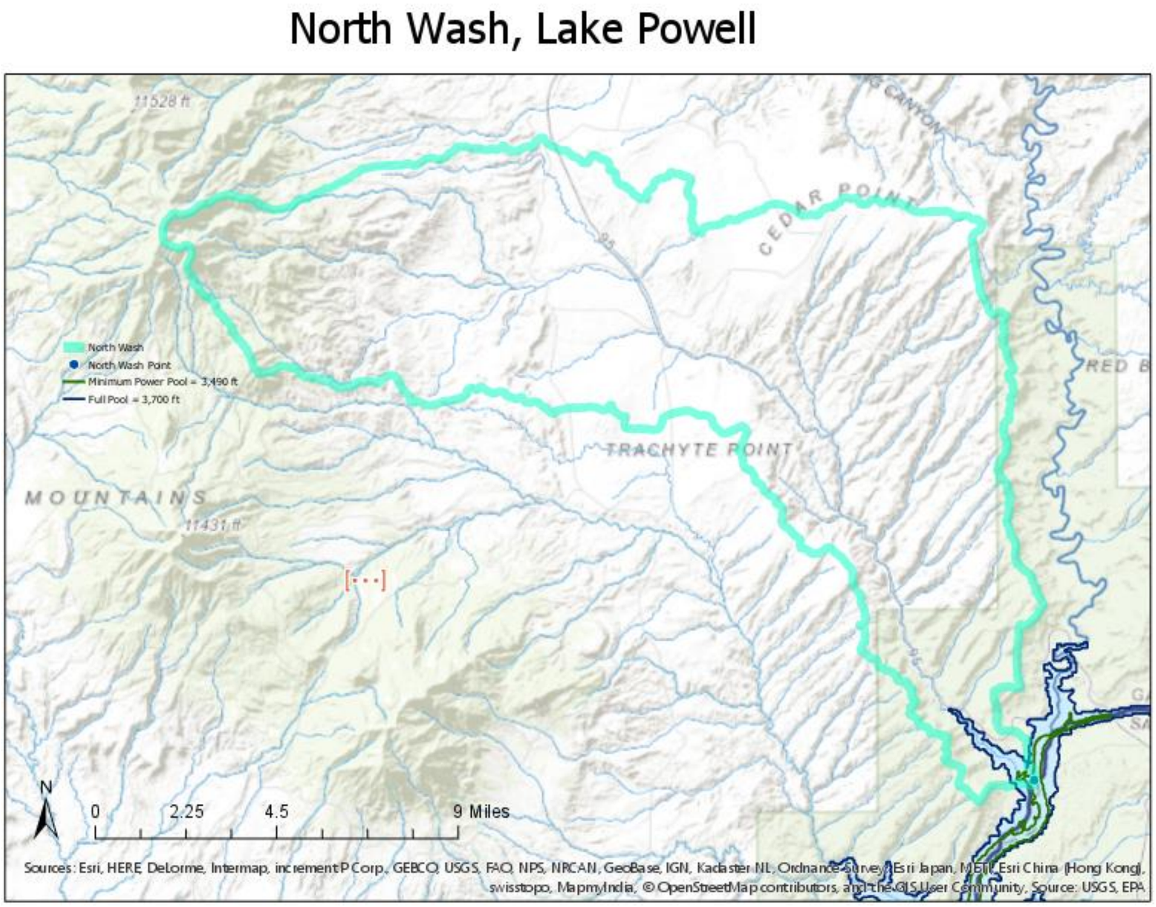


Figure 1. Extent of Lake Powell at Full Pool relative to the Upper Colorado River Basin, based on pre-dam topography of the region.



Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community, Source: USGS, EPA

Figure 2. The North Wash catchment and its flow lines draining to Lake Powell.

Methods

In order to examine the contributing basins to Lake Powell, first physiographic data was gathered. Basins were delineated and hydrologically conditioned so analysis could be completed. The projection WGS 1984 Web Mercator Auxiliary Sphere was used.

Data Sources

Stream data came from NHDPlus Version 2 and StreamStats. Geology data giving substrate type was from the USGS National Geologic Map Database and Utah Geological Survey, with 10-meter DEM from the National Elevation Dataset. Pre-dam topography was from work done to quantify rock strength along the Colorado River (Bursztyn et al., 2015).

Stream Properties and Hydrologic Terrain

The DEMs for both the pre-dam and post-dam were hydrologically conditioned and the catchments were delineated (Figure 3). The tools for Fill, Flow Direction, Flow Accumulation, Stream Link, and Drainage Lines were used. These polygons were then dissolved, and associated elevations were imposed for for Full Pool, Minimum Powel Pool, and Dead Pool. The contributing catchments at these respective elevations were found using Select By Location (Figure 4). The total area, stream length, and drainage density was found and exported to a .csv file in Excel for calculations. For each selected level, the Copy Features tool was used and the Summary Statistics were run.

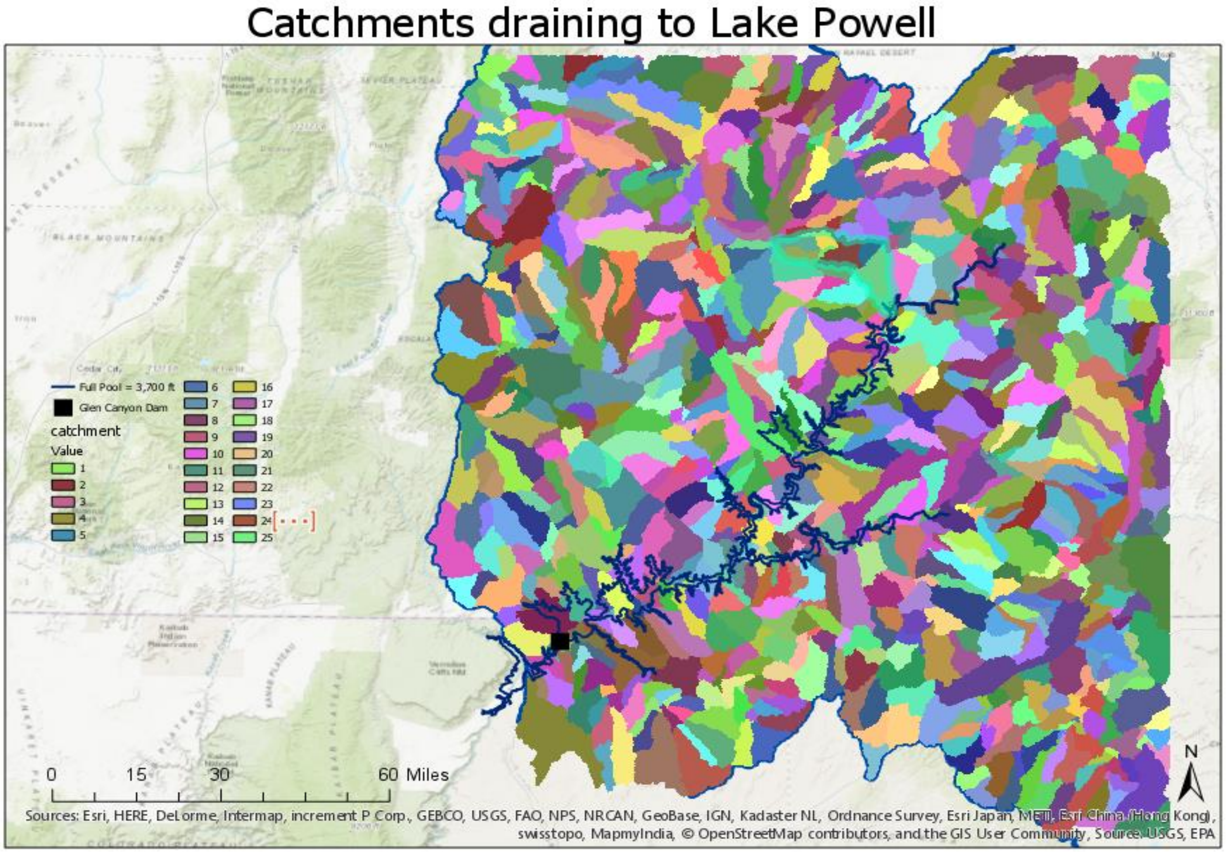
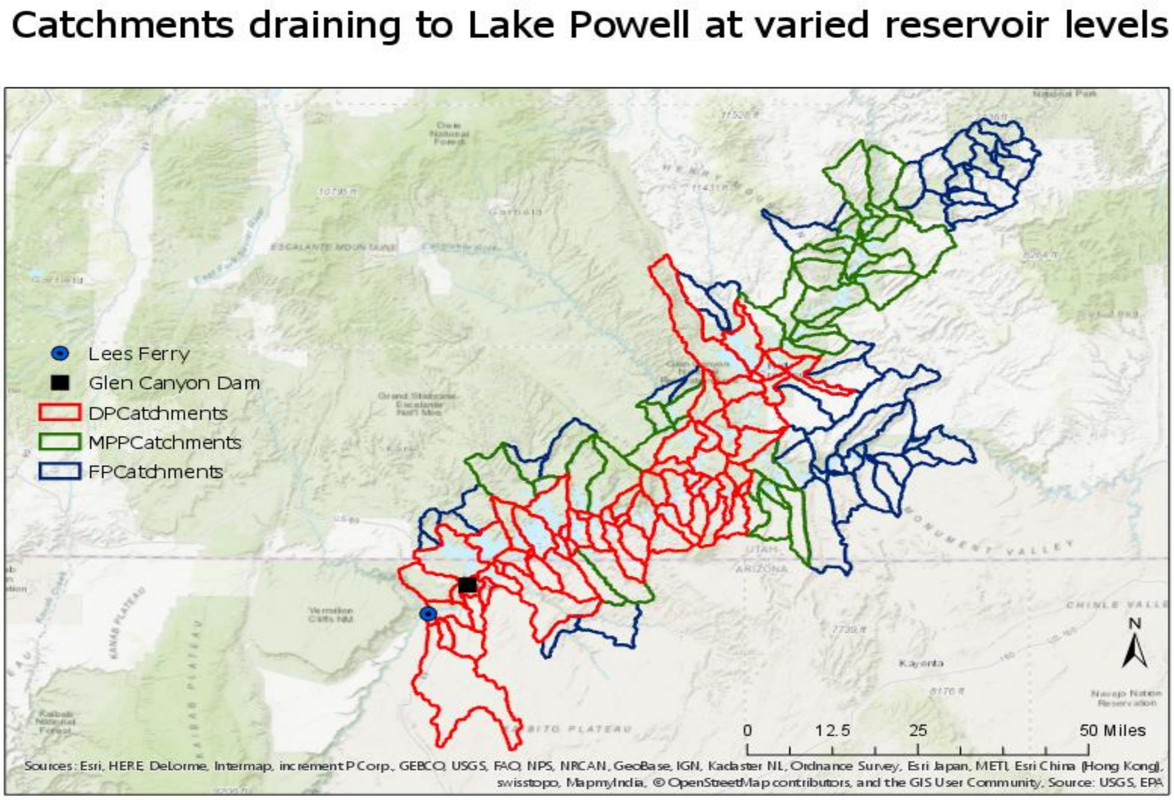


Figure 3. The catchments draining to Lake Powell, utilizing a DEM of pre-dam topography to account for space not yet filled by sediment.

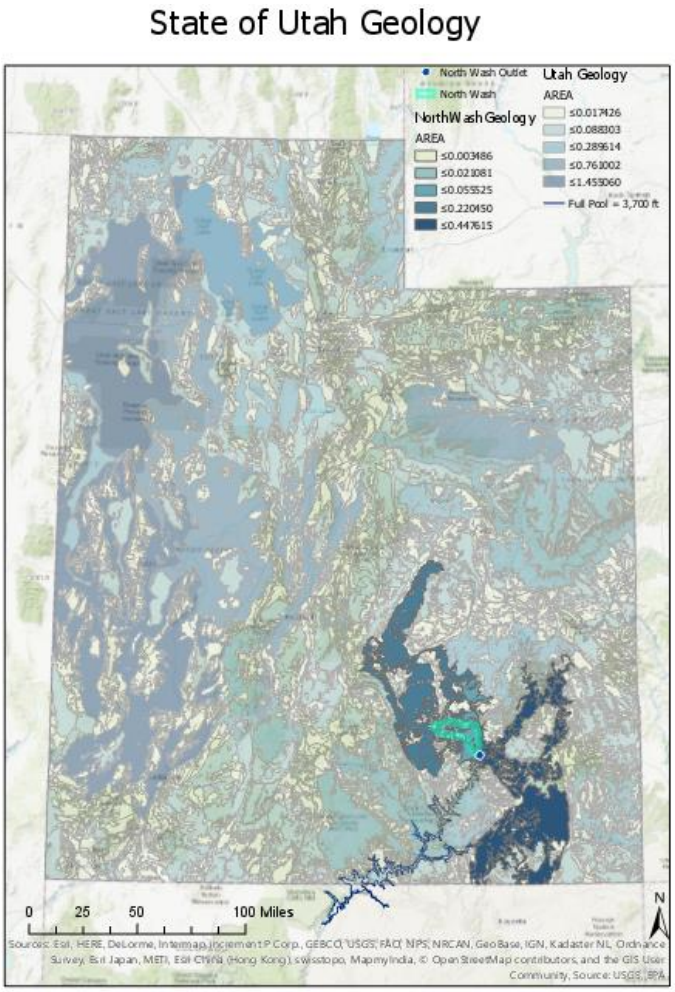

Catchments draining to Lake Powell at varied reservoir levels

Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community, Source: USGS, EPA

Figure 4. Catchments draining to Lake Powell at Full Pool (FP Catchments), Minimum Power Pool (MPPCatchments), and Dead Pool (DPCatchments).

Case Study

For North Wash, the basin was delineated using both ArcGIS Pro and StreamStats, in order to compare statistics. Summary statistics were run using Zonal Statistics, and also imported from StreamStats. Data from StreamStats is presented. In order to connect the delta morphology to the underlying substrate, a raster of the state's geology was used from Utah ARC (Figure 5). Data was then imported from Stream Stats about the ungaged basin characteristics. This was overlaid onto the delineated basin (Figure 6). The spatial extent of the substrates were examined, and the dominant bedrock classified.



Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community, Source: USGS, EPA

Figure 5. State of Utah geology and the extent of Lake Powell at Full Pool.

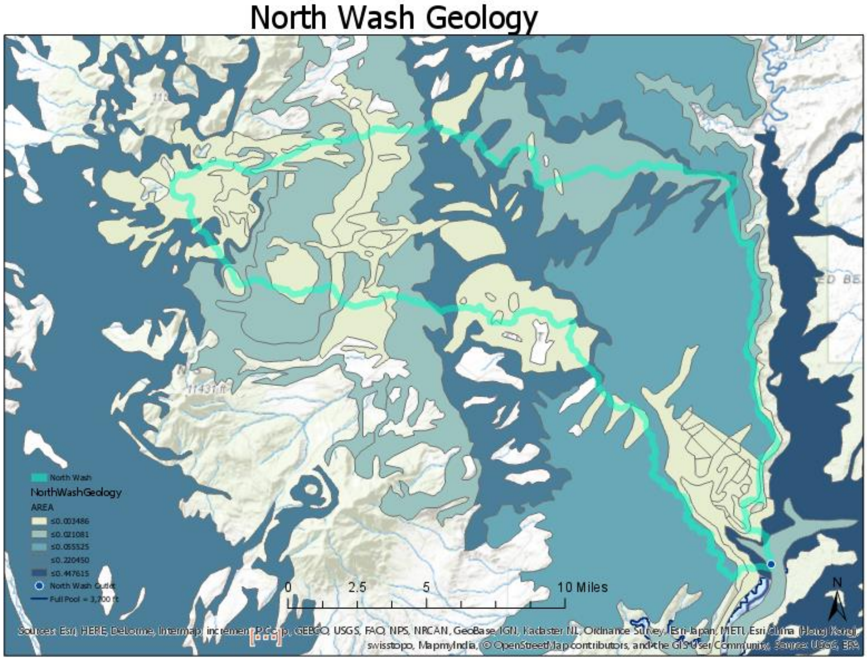


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Figure 6. Spatial extent of North Wash Geology.

Results

At Full Pool, nearly three times the catchment area and length drains to the reservoir than at Dead Pool (Figures 7, 8). The scaling ratio for drainage density is similar for all three levels (Figure 9). The contributing statistics are important because as reservoir levels decline, the deltas have the potential to incise, erode, or be transferred by turbidity currents, further altering their channels.

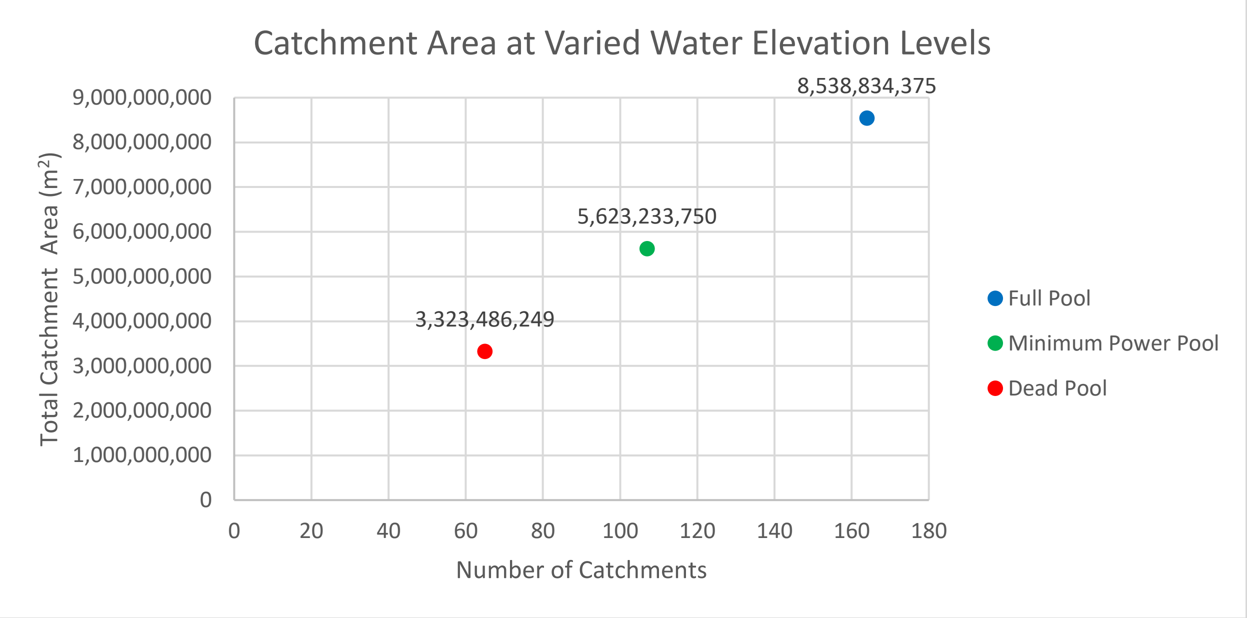


Figure 7. The relative area and catchments for associated reservoir levels.

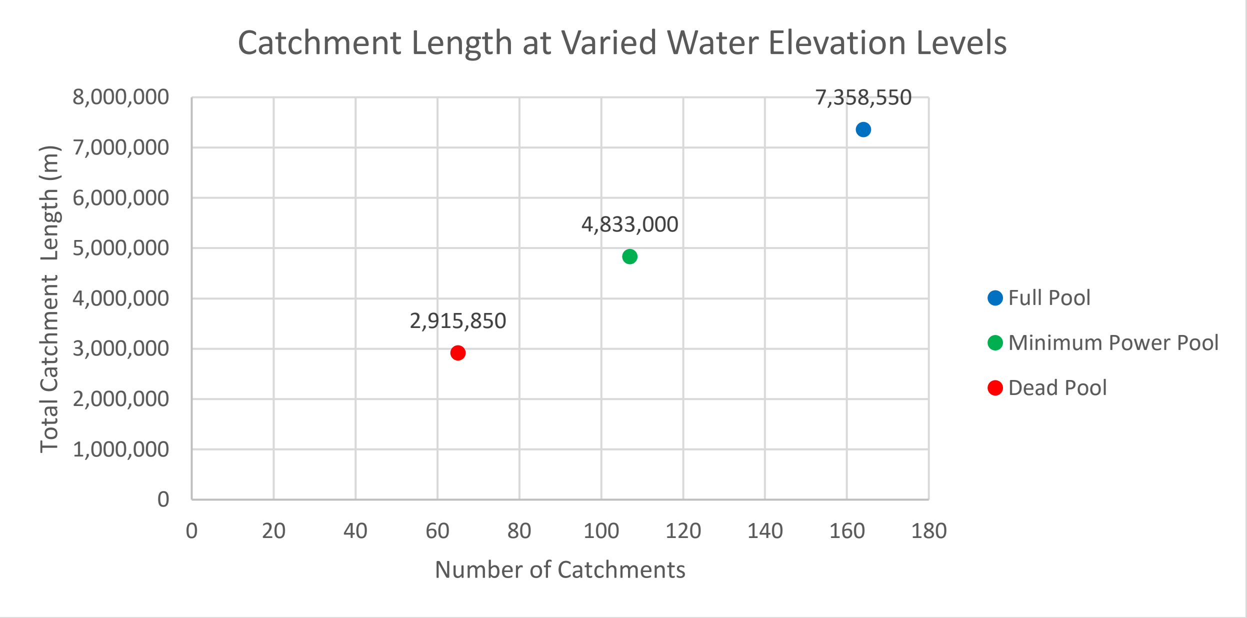


Figure 8. The relative length and catchments for associated reservoir levels.

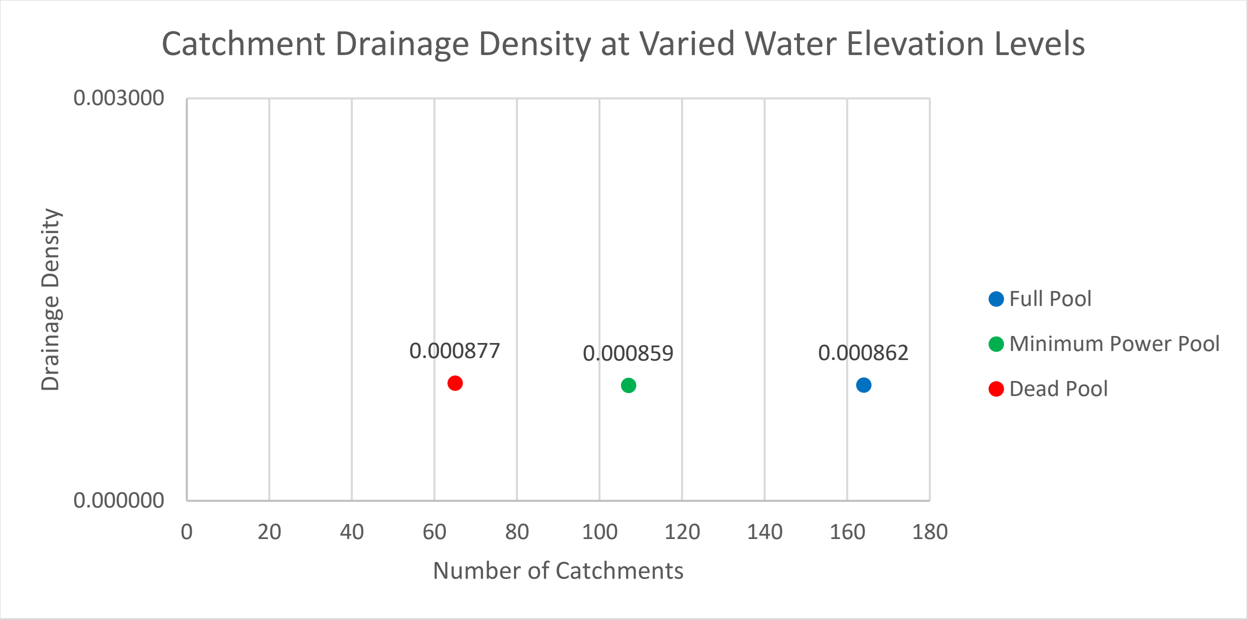
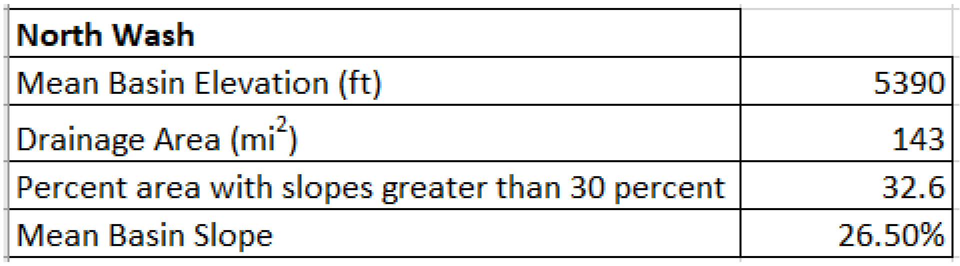


Figure 9. The associated drainage density for each of the selected levels.

Case Study

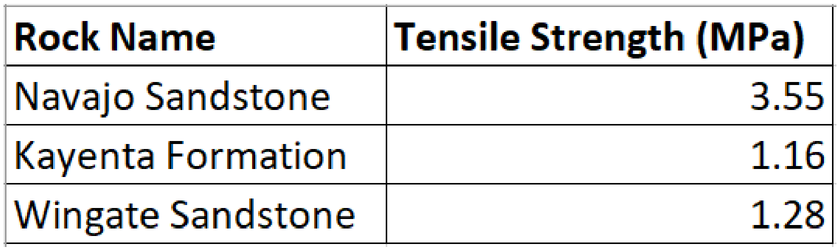
North Wash is one of the upper-most tributaries within Lake Powell. During reservoir level drops between 1999 and 2005, approximately 50% of its delta was eroded (Majeski, 2009). Though upstream, its basin is still within the levels of Minimum Power Pool. Its basin characteristics illustrate the relationship between its relative location in the catchment and its potential for erosion and transport, due to the spatial extent of steep slopes. (Table 1).



North Wash	
Mean Basin Elevation (ft)	5390
Drainage Area (mi^2)	143
Percent area with slopes greater than 30 percent	32.6
Mean Basin Slope	26.50%

Table 1. Summary statistics from North Wash using StreamStats.

The dominant substrate was found to be the Glen Canyon Group. The Glen Canyon Group is a Jurassic-age group, comprised of Wingate Sandstone, Kayenta Formation, and Navajo Sandstone. Once the dominant substrate was determined, this was correlated to erosion rates, which are a non-linear function of sediment supply, grain size, and bedrock tensile strength (Sklar and Dietrich, 2001). For the purposes of this paper, tensile strength and slope were focused on as controlling factors of erosion. (Table 2) (Bursztyn et al., 2015).



Rock Name	Tensile Strength (MPa)
Navajo Sandstone	3.55
Kayenta Formation	1.16
Wingate Sandstone	1.28

Table 2. Tensile strengths of Glen Canyon Group.

Discussion and Future Work

This analysis examined the characteristics of catchment input at various reservoir levels, noting their relationship to fine sediment remobilization. Because erosion is a function of drainage area and channel slope, understanding the characteristics of the catchments that drain to each level is necessary. The outcome of how these deltas will change relative to fluctuations in reservoir levels is determined by numerous controls, including base level change and bedrock strength. As reservoir levels drop, the river erodes a new channel into its delta. At Minimum Powel Pool, most of the accumulated delta sediments are exposed. By using both desktop and online GIS tools to connect these physical data, it was possible to create a framework to understand their interoperability.

For North Wash, a relatively steep basin on the upstream end of the reservoir in erodible rock, there is large potential for remobilization as reservoir levels drop. The process here can be repeated across the entirety of the reservoir in order to understand which tributaries are more likely to evacuate sediment.

In order to better understand the relationship between contributing catchments, stream gradient, and substrate erodibility as reservoir levels change, this project is planned to expand to focus on the total volume available for tributary sedimentation in Lake Powell. The relevant parameters are the levels between Full Pool and Minimum Power Pool, where there is potential for policy discussion and adaptive management.

There are no modern estimates of fine sediment delivery into the reservoir. It has been estimated that delivery rates between 1949 and 1962 were between 54 and 60 million metric tons/year, which is a reasonable assumption for modern rates (Topping et al., 2000). Bathymetric surveys were completed in 1986 and between 2001 and 2005 (Pratson et al., 2008; Ferarri, 1988). Much less of sediment accumulates nearer to the dam, in the deeper regions (Pratson et al., 2008).

By examining the DEMs for pre-dam and post-dam topography, this volume can be calculated. Once this is calculated, each tributary mouth can then be examined for what percentage of its area is filled with sediment relative to the total area. This could be done using 2005 air photos, from when the reservoir was at its lowest level. Understanding these percentages, though underestimates, would help give a formulation of capacity under uncertain inflow and transport rates. Additionally, each of these tributaries will be categorized by their rock type and associated erodibility, as the process was done for North Wash. Then, the total volume filled for erodible versus resistant rock will be compared. Understanding these processes will help inform reservoir management and river restoration.

Conclusion

As the climate changes and demands increase, it is prudent for water managers in the arid Southwest to dynamically adjust and operate within the perspective that drought will continue to be a driving factor in the region. To that end, it is necessary to study the entirety of Lake Powell's interconnected system, including geology, physiography, and climate. This analysis provided a baseline integrative framework of catchment input and geomorphic processes occurring in Lake Powell and North Wash. These findings can be coupled with further analysis of the volume filled by each sediment wedge at ungaged tributary mouths.

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