Sediment Dynamics in the Bear River-Mud Lake-Bear Lake System

Final Project Report
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Cover Photo Credit: NASA Photo of the day from December 11, 2016.
http://earthobservatory.nasa.gov/IOTD/view.php?id=89244
"This bright blue lake, with its tight swirl of a light-toned sediment, caught the eye of an astronaut on the International Space Station. Situated on the Idaho-Utah border, Bear Lake is one of the bigger lakes in the Rocky Mountains. The more diffuse swirls at the north end of the lake (lower right) likely formed from sediment entering from North Eden Creek. This sediment is carried north along the shoreline by lake currents, joining with sediment eroded from the white beaches. When the north-end beach formed, it cut off of Bear Lake from the Mud Lake lagoon. Muddy sediments subsequently collected to form a dark-toned, vegetated wetland now protected as the Bear Lake National Wildlife Refuge."

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1. Executive Summary

The overarching goal of this project was to compile and analyze a variety of existing datasets, and generate several new datasets, to advance our understanding of how the Bear River-Mud Lake-Bear Lake system functions, how it has, or is expected to change, identify which components are degraded or vulnerable to degradation, and determine if/where critical data and/or knowledge gaps exist. We conducted a series of analyses to evaluate changes in hydrology and suspended sediment, collected sediment cores from nine locations in Mud Lake to evaluate how sedimentation rates, sediment sources and water quality have changed over time, and utilized historical air photos and satellite imagery to document changes in Bear Lake's shoreline.

Hydrologic analyses indicate that low, median and high flows have not changed systematically at the Inlet Canal in terms of their long-term averages, since the 1940s. However, all three flow metrics have increased in terms of variability and have experienced longer duration wet and dry periods over the past three decades. We note a paucity of long-term hydrologic datasets for the Bear River-Dingle Marsh-Bear Lake system and additional monitoring would greatly help ensure that we are able to monitor trends throughout the system more carefully. We compiled suspended sediment data from all available sources and concluded, similar to previous studies, that Mud Lake appears to serve as a sediment sink for sediment, but the sediment trapping efficiency appears to vary considerably within and among years. Similar to the flow data, we note an unfortunate paucity of suspended sediment data and strongly recommend more rigorous and continuous monitoring of sediment in all parts of the Bear River-Mud Lake-Bear Lake system. Existing data and monitoring programs are insufficient to identify trends over time.

The nine sediment cores extracted from Mud Lake provide a longer-term perspective on sediment dynamics. Results demonstrate that Mud Lake has historically and continues to serve as a net sediment sink. Two of the six dated cores document continuous deposition over the past 120 years, while the other four cores show truncated profiles in the 1950s. Visual inspection of the cores, as well as analysis of organic, calcium carbonate and mineral fractions occurring in the cores demonstrate highly variable history of sediment sources and water quality conditions in Mud Lake. Analysis of diatom algae species provides more detailed information regarding water quality conditions, indicating that Mud Lake has changed from a planktonic glacial lake, to a cold water, low nutrient environment and has existed as a mesotrophic environment with moderate water quality over the past century. Given the detailed information that diatoms can provide regarding historical water quality, we suggest that a similar diatom study examining the past 150 years in Bear Lake's history could be worthwhile. Elemental analysis of Mud Lake sediments indicate two significant shifts in sediment sources, one coincident with diversion of Bear River into Mud Lake approximately 100 years ago, and a recent shift, within the past 10 years as silver, mercury and rare earth elements have increased considerably.

Analysis of Bear Lake's shoreline from historical imagery shows considerable amount of deposition has occurred in most areas around the lake in the past several decades. The shoreline at low water levels has moved lakeward by 30 to 50 meters (100 to 160 feet) in several locations and as much as 500 m (1600 feet) in the northwest corner of the lake, near St. Charles Creek. Notably, the only location where we document shoreline erosion (i.e., the shoreline moving landward for a given water elevation) is along the eastern edge of the lake, near Porcupine Hollow, Peterson Hollow and Bear Lake State Park. Further, we document that approximately 10% of the beach area in the northwest corner of the lake near St. Charles Creek has transitioned to vegetation cover between 2003 and 2016.

2. Introduction

2.1. General context, overarching project goal, and research questions

Bear Lake is an invaluable natural resource supporting diverse aquatic and terrestrial ecological communities, recreation and tourism, local and downstream water supply, as well as cultural and historical value. The past, present and future water quality conditions of Bear Lake are inextricably linked to the Bear River, which serves as a primary water input to, and output from Bear Lake, as well as Mud Lake, which serves as a buffer between Bear River and Bear Lake. Bear River flows are managed by a series of dams and diversions. Mud Lake is managed as part of the Bear Lake National Wildlife Refuge for pubic recreational activities such as bird watching, hiking, photography, hunting and fishing. And Bear Lake itself is managed for myriad uses, including water storage, a wide range of recreational activities, fisheries, and aesthetic values. As a complex natural and human-managed system, a wide variety of reliable and well-targeted data are needed to monitor the status and trajectory of the system. A considerable amount of such data have been collected by numerous federal, state, industry, and non-profit organizations. The overarching goal of this project was to compile and analyze those diverse datasets and generate several new datasets to advance our understanding of how the system functions, how it has, or is expected to change, identify which components are degraded or vulnerable to degradation, and determine if/where critical data and/or knowledge gaps exist.

Sediment is a prevalent concern in rivers, wetlands and lakes and consistently ranks among the most common causes of water quality impairment in the US (Finlay, 2011; Schwartz, Simon, & Klimetz, 2011; Bilotta & Brazier, 2008; Schwartz, Dahle, & Bruce Robinson, 2008; Wood & Armitage, 1997; Richards & Bacon, 1994). While sediment is a natural component of river, lake and wetland ecosystems, excessive loading of fine sediment to the Bear River, Mud Lake or Bear Lake may have detrimental effects on the water quality, recreational value, regional property values, and ecological communities. Determining the origin of sediment, how much is natural versus human-caused, and which policy and management approaches to implement to reduce sediment loading has proven challenging (Knox, 2001; De Vente et al., 2007; Syvitski and Milliman, 2007; Belmont et al., 2011; Belmont and Foufoula-Georgiou, 2017; Vaughan et al., 2017). With future increases in population and recreation demand in direct conflict with predicted decreases in snowpack and increased losses from evapotranspiration, management of the Bear River-Mud Lake-Bear Lake system will require improved understanding of water and sediment dynamics. We used a combination of techniques to answer the following questions regarding sediment dynamics in the Bear River-Mud Lake-Bear Lake system.

1. Have flows into Dingle Marsh changed systematically over time?
2. Is Mud Lake functioning as a sediment trap?
3. Have sedimentation rates in Mud Lake changed over time?
4. Have sediment sources to Mud Lake changed over time?
5. How has water quality changed in Mud Lake over time?
6. How has Bear Lake shoreline changed over time?
7. How has vegetation along the shoreline changed over time?

2.2. Geologic, climatological and historical context of Bear Lake

Bear Lake sits within a natural depression that formed several hundred thousand to a few million years ago within a Basin-and-Range structure (Reheis et al., 2009; Robertson, 1978). The lake itself resides within an east-ward tilting half-graben, which is bounded by a steep fault (the East Bear Lake Fault) along the eastern margin and a flexural margin (i.e., a margin that acts as a hinge; the Bear River Range) along the western side (Fig. 2.2.1; Colman, 2006; Rosenbaum and Heil, 2009). Block-faulting within the Tertiary period is thought to be responsible for dropping the Bear Lake Valley into the formation of a half-graben (Mansfield, 1927). The eastern fault has experienced 4-6 episodes of significant tectonic displacement within the Holocene, with the most recent being approximately 2,500 years before present and causing approximately 15 feet (4.6 meters) of vertical offset (McCalpin, 2003). The West Bear Lake Fault is capable of significant seismic activity, with past earthquakes on the fault estimated at magnitudes around 6.8 to 7.2.

The lake was able to form within the half-graben because depression rates and water infilling have exceeded sedimentation from surrounding hillslopes. Bedrock within the valley is buried by a thick layer of unconsolidated sediment, presumably eroded from the adjacent ranges based on seismic data and valley borings (Skeen, 1975). The rocks within the eastern formation are primarily limestone and clastic (i.e., formed of large fragments) sedimentary rocks with little dolomite, whereas rocks along the western margin are Paleozoic carbonates that exhibit large quantities of dolomite, quartzite, and limestone (Colman, 2006; Rosenbaum and Heil, 2009). The mineral structure of rocks along the western margin have led to a karst topography, which is characterized by well-developed groundwater structures as preferential weathering has developed flowpaths through the rocks. Through this underground system, water has entered the lake through springs, seeps, and groundwater discharge (Dean et al., 2007).

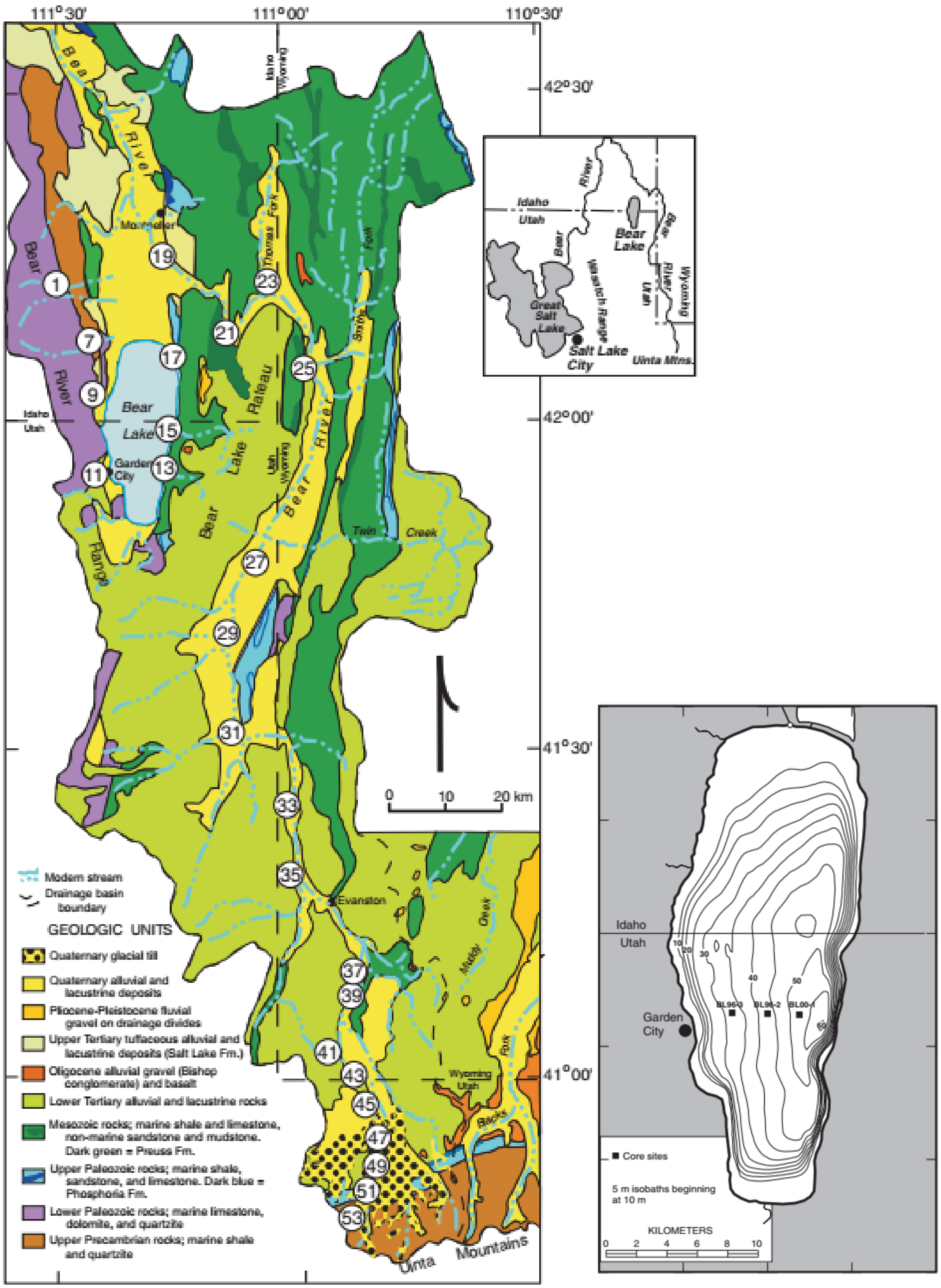


Figure 2.2.1. Two figures extracted from Rosenbaum and Heil (2009). The bathymetry map (lower right inset) illustrates Bear Lake's contrasting bed gradient that reflects the flexural margin (west, to the left) and active normal-fault (east, to the right). To the left, the Bear Lake is shown within the broader context of geologic units and its contributing watershed.

The rich magnesium mineral content within the surrounding rock formations have contributed to the Bear Lake's unique water chemistry that is highly enriched with magnesium (Lamarra, 1980; Rosenbaum and Heil, 2009). Groundwater flow from the nearby catchment is also largely responsible for the oligotrophic (i.e., low productivity due to low nutrient content) and mesosaline (i.e., a specific salinity level derived from land-salt) character of the Lake (Dean et al., 2007). If Bear Lake water supply was limited to the local catchment, the basin- to lake-area ratio would be 4.8:1, which is relatively low (Wurtsbaugh and Leucke, 1997). However, it has also been fed intermittently from the Bear River throughout geologic time, which increases the ratio to 29.5:1 (Dean et al., 2007).

The Bear River was intermittently connected to Bear Lake until about 10,000-8,000 years before present (Lamarra, 1980), but was separated at times due to fluctuating lake levels that captured the lake, tectonic activity that changed the river's course, a natural sandbar that blocked the river, and channel meandering away from the lake. Rosenbaum and Heil (2009) used a geochemical sediment fingerprinting approach to study how sediment sources to Bear Lake have changed over time, taking advantage of the unique chemical properties of each source, which include nearby groundwater, the Bear River headwaters, and lower reaches of the Bear River (Fig. 2). Prior to 20,000 years ago, their study demonstrates cyclical, millennial-scale variation between glacial sediment (from the Uinta headwaters; Fig. 2.2.1, black/yellow spots) and material derived from the local catchment. A peak in sediment derived from the Uinta-based headwaters occurred between 20,000 to 19,000 years ago, followed by a slow decline of Uinta-based sediment and a consistent input of alluvial sediments from lower portions of the Bear River until 17,000 years ago. This period of transition from the Uinta headwaters to lower Bear River was followed by an increase in local catchment sediment input from 17,000 to 15,500 years ago and an increase in Bear River sediments from 15,500 to 14,500 years ago. These dates are important because they provide indicators of 1) changes in the Bear River position and course throughout its delta as well as 2) changes in glacial sediment fluxes reflecting the extent of glaciation. Furthermore, when the Bear River is not connected, the lake will precipitate large amounts of carbonate materials that provide the unique lake environment that is home to four endemic species (Lamarra, 1980). Dean et al. (2007) demonstrated how extended periods of connectivity with the river has resulted in 20-fold reductions in Mg^{2+} content and 50% reductions in lake salinity (discussed in more detail below).

Climate, through long-term changes in evaporation, precipitation, and glaciation, has been a driver behind fluctuations in Bear Lake water levels, and thus, connectivity with Bear River (Dean et al., 2009). The region surrounding Bear Lake is characterized by arid semi-desert conditions (Heinrich, 1975) with dry, short summers (promoting evaporation) and long, cold winters- when the majority of precipitation occurs, as snow. The lake is especially vulnerable to climatic fluctuations due to these dry conditions and its position between multiple atmospheric boundaries that can result in significant changes to the hydrologic balance (Moser and Kimball, 2009). Moser and Kimball, (2009) analyzed diatoms within lake-bed cores (Dean et al., 2006) in order to reconstruct changes in hydrologic and climate regimes influencing Bear Lake. Their results show periods of highly turbid conditions that reflect large input of glacial sediments from 19,100 to 14,600 years ago (roughly similar to results in Rosenbaum and Heil (2009)), followed by greater river inputs for roughly 7,000 years and a subsequent reduction in river inputs and lake levels from 11,000 to 9,000 years ago. Robertson (1978) also provides useful insight regarding climate's influence on the regional setting: moist conditions throughout the late Pleistocene glaciation resulted in Bear Lake's maximum extent into the northern valley, including the area that is now occupied by Dingle Marsh, creating many shallow water environments and sediment deposits throughout the area. Waning moist conditions exposed the deposits to wind-erosion, leading to loess deposits and beach ridges in the area.

Dingle Marsh (71 km^2) is a natural wetland system with several open-water bodies that has served as the primary mode of connectivity for the Bear Lake-Bear River system throughout the majority of their history (Fig. 2.2.2, Allen, 2011). While Dingle Marsh has played a large role in connecting the River and Lake, at times they are thought to have been directly connected, as indicated by channel scars filled by the marsh (Robertson, 1978) and a 2x6 mile (4x10 kilometer) paleo-delta composed of coarse-grained sand found at a depth of 10-25 meters within the bed of Bear Lake (Colman, 2006). Robertson (1978) explains that the Marsh was formed prior to 27,400 years before present (referred to as the 'Ovid Episode') when differential lowering of the Northern Bear Lake Valley promoted marsh and shallow bay formation throughout the area. At the time, the lake and river were at similar elevation to a pediment truncating the river, which caused a 'threshold condition' to govern connectivity between the river and lake (around 5,990 ft). An extended period of time in which the lake did not exceed this threshold would lead to formation of a lake, marsh, and/or bay in the area through preferential deposition. These conditions are reflected in a sequence of deep-water carbonates (indicative of the lake environment) and silty-marsh sediments (lagoon and marsh conditions) that lie in accordance with the elevation threshold described in Robertson (1978). Throughout its existence, Dingle Marsh has acted as a sediment and nutrient filter for flows entering Bear Lake, which is an extremely important natural role due to the drastic differences in salinity, chemical composition, and sediment concentrations found in Bear River flows. Whether Dingle Marsh continues to act as a filter has been questioned on several occasions (Herron, 1985; Bjornn et al., 1989; Lamarra, 1997; Allen, 2011) due to human interference to the natural conditions.

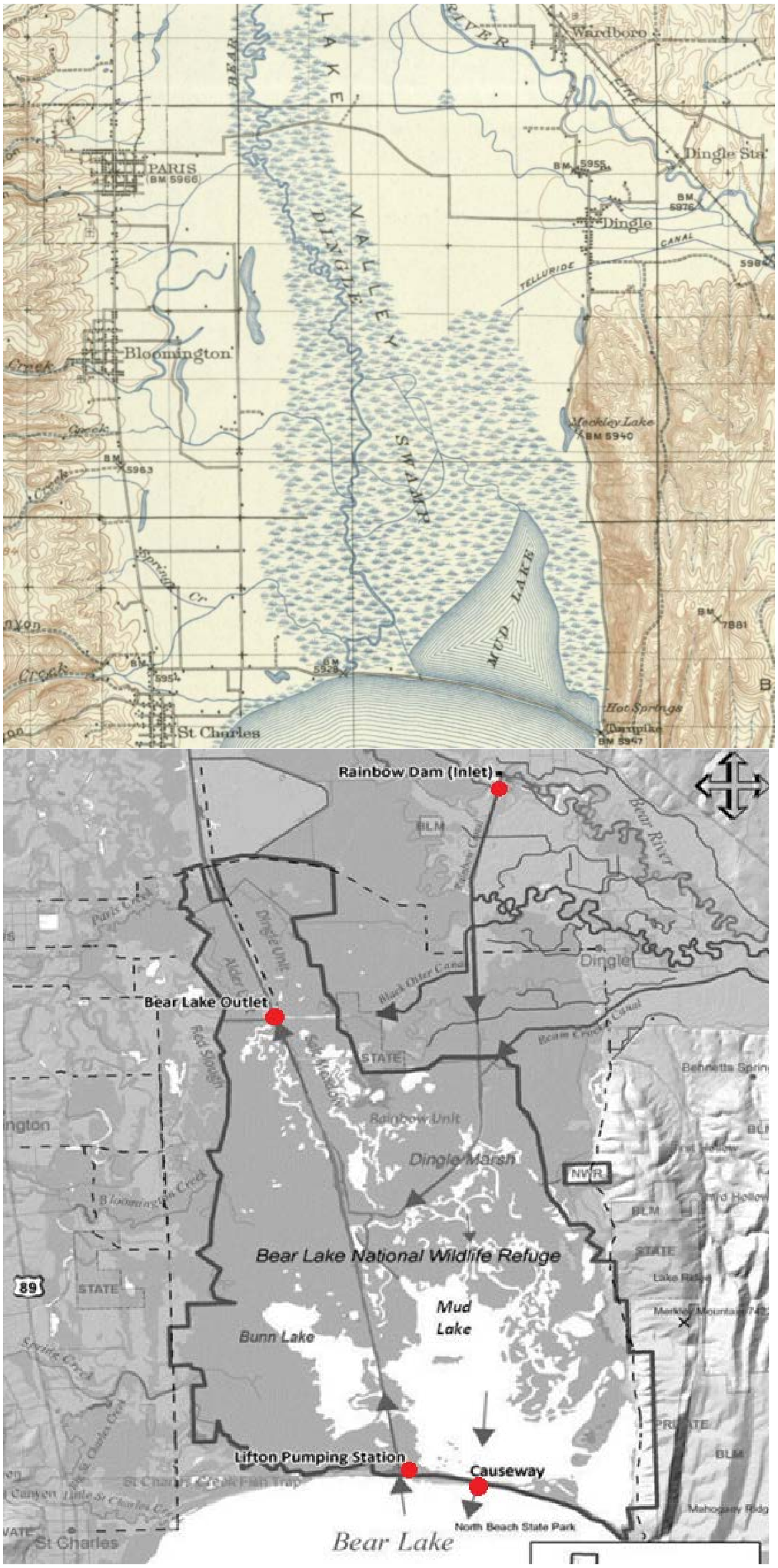


Figure 2.2.2. (Left) Portion of a USGS topographic map depicting the Dingle Marsh and Mud Lake as seen in 1909. Note the natural outlet canal along the western portion of the lake and the partially completed Telluride canal in the NE corner of the map. (Right) Image extracted from Allen (2011) depicting Dingle Marsh and Mud lake as seen in the modern landscape. Note the intricate system of inlet and outlet canals controlled by dams and pumping stations in stark contrast to the 1909 depiction.

2.3. The history and implications of water resources management in and out of Bear Lake

The relevance of whether Dingle Marsh continues to filter sediments and nutrients has drastically increased since 1909, when the 'Bear Lake Project' began under Telluride Power Inc.[1], marking the beginning of construction for a controlled canal system connecting Bear Lake and Bear River through the Dingle Marsh (Hydro SLC, 1999). In the decades prior, there had been multiple attempts and interest in adapting the Bear Lake site for storage for irrigation, including the U.S. Reclamation Service. (20th Annual Report of USGS, AH Newell 1899). Telluride Power's original proposal, in 1902, was rejected but the Right of Way was finally granted in 1907 by the Secretary of the Interior. The canal system, completed in 1917, created the ability to pump out of Bear Lake and subsequently divert Bear River water into Bear Lake for storage and release to accommodate downstream agricultural irrigation and hydroelectric power demands (Lamarra et al., 1986; Hydro SLC, 1999; PacifiCorp, 2000; Smoak and Swarzenski, 2004; Dean et al., 2007; Allen, 2011). Restated for context- the majority of precipitation occurs throughout the winter months as snow, which is delivered as runoff into the spring as the snow melts. Precipitation outside of these months is sparse due to the arid, desert-like conditions (Dean et al., 2007; Allen, 2011). In an attempt to bypass this imbalance in seasonal precipitation and utilize the system for power generation, PacifiCorp (at the time, UPL) obtained rights to sequester water into Bear Lake from the Bear River so that it could be released later in the summer for irrigation. The specifics of these flow regulations have changed over time, but can be characterized in three main phases (Figure 2.3.1, adapted from Allen, 2011):

1. Storage phase- during winter/spring, water is moved from the inlet, to the causeway, and into Mud Lake and Bear Lake.
2. Lake fill & downstream release- during the summer, incoming flows thru the causeway are reduced, flows through the outlet are increased for downstream irrigation. The exact timing depends on downstream water demands.
3. Lake pumping phase- water is moved from the inlet to the outlet and water is pumped out of Bear Lake.

The Bear River provides water to three states with distinct industry and community interests- including environmental concerns (DeRose et al., 2015)- and is host to 6/5 hydroelectric plants owned and operated by PacifiCorp (one has since been decommissioned). L.L. Nunn filed for the storage right on Bear Lake in Idaho 1902, and negotiated delivery contracts with both canal companies and individuals holding irrigation rights below Bear Lake. The Idaho Dietrich Decree of 1920 and Utah Kimball Decree of 1922 settled the many disputes that arose regarding those contracts and affirmed UP&L's storage right. The drought of the Dust Bowl years (1920-1930's) precipitated a federal interstate compact, Bear River Compact of 1958 and Bear River Compact Amendment of 1980. The compacting states agreed to how the water would be divided between them, with Bear Lake operations being a pivotal component, including certain constraints that are based upon the elevation of the Lake. The Bear Lake Settlement Agreement of 1995 and the Amended Bear Lake Settlement Agreement of 2004 instituted voluntary reductions of the annual allocations for irrigation relative to the decline in surface-water elevation of the lake.

The PacifiCorp Agreement of 2000 with the compact states, put into record the power company's "historical practices" and operations of the Bear Lake/Bear River system. These include requirements that during ‘projected high-runoff conditions’ the Lake surface-water elevation should be maintained between 5916’ and 5920’, with the target elevation for April 1 being 5918’. These requirements were established in order to ‘best balance long term contract requirements for Bear Lake Storage Water during sustained drought periods with flood control operation during high-runoff periods. The flows in and out of Bear Lake are therefore directly managed by PacifiCorp in order to meet the requirements of their agreements to multiple parties.

The regulation of Bear Lake water-surface levels were enacted solely to enhance the power and irrigation use of the storage water. There are no regulations of water-surface levels for environmental and habitats of delicate species, nor for recreational or aesthetic opportunities, except below the storage level of 5902 which is preserved by a water right held by the State of Idaho. Drastic water drawdown for irrigation can cause shoreline retreat up to hundreds of feet, which affects fish, bird and vegetation species as well as recreation and aesthetics. Dingle Marsh also serves as an important habitat niche for waterfowl and migratory birds. The Marsh’s significance was recognized decades ago, initially under the US Bureau of Land Management and more recently by the US Fish and Wildlife Service, who entered into agreements with PacifiCorp in 1968 to maintain it as a National Wildlife Refuge in order to preserve and improve the habitat, and in particular, the bulrush that provides important nesting material for waterbirds.

Prior to these diversions, Dingle Marsh was a freshwater system fed by local runoff and multiple groundwater springs (Reeves, 1954), whereas it now contains turbid, mesotrophic flows that are threatening the oligotrophic state of the Lake (U.S. EPA, 1975; Bear Lake National Wildlife Refuge, 2006). Although it is believed that Dingle Marsh continues to act as a net filter of sediments and nutrients, there are periods of net sediment and nutrient loading into Bear Lake during the ‘Lake Fill/Downstream Release’ phase(s) (Fig. 2.3.1). The fluctuations in Figure 2.3.1 are also evident for sediment and temperature. The latter is important because the groundwater fed from the local catchment is considered ‘cold’ water (Dean et al., 2007). With a disturbance to lake temperatures above some threshold, this may influence lake currents and water cycles, which are dimictic (i.e., cycling twice a year; Moser and Kimball, 2009). Distinct increasing trends in sedimentation and phosphorus loading rates are apparent within the lake. Sedimentation in Bear Lake doubled from 1885-1998 (Smoak and Swarzenski, 2004) and phosphorus loading to Bear Lake doubled from 1976-1983 (Lamarra et al., 1986).

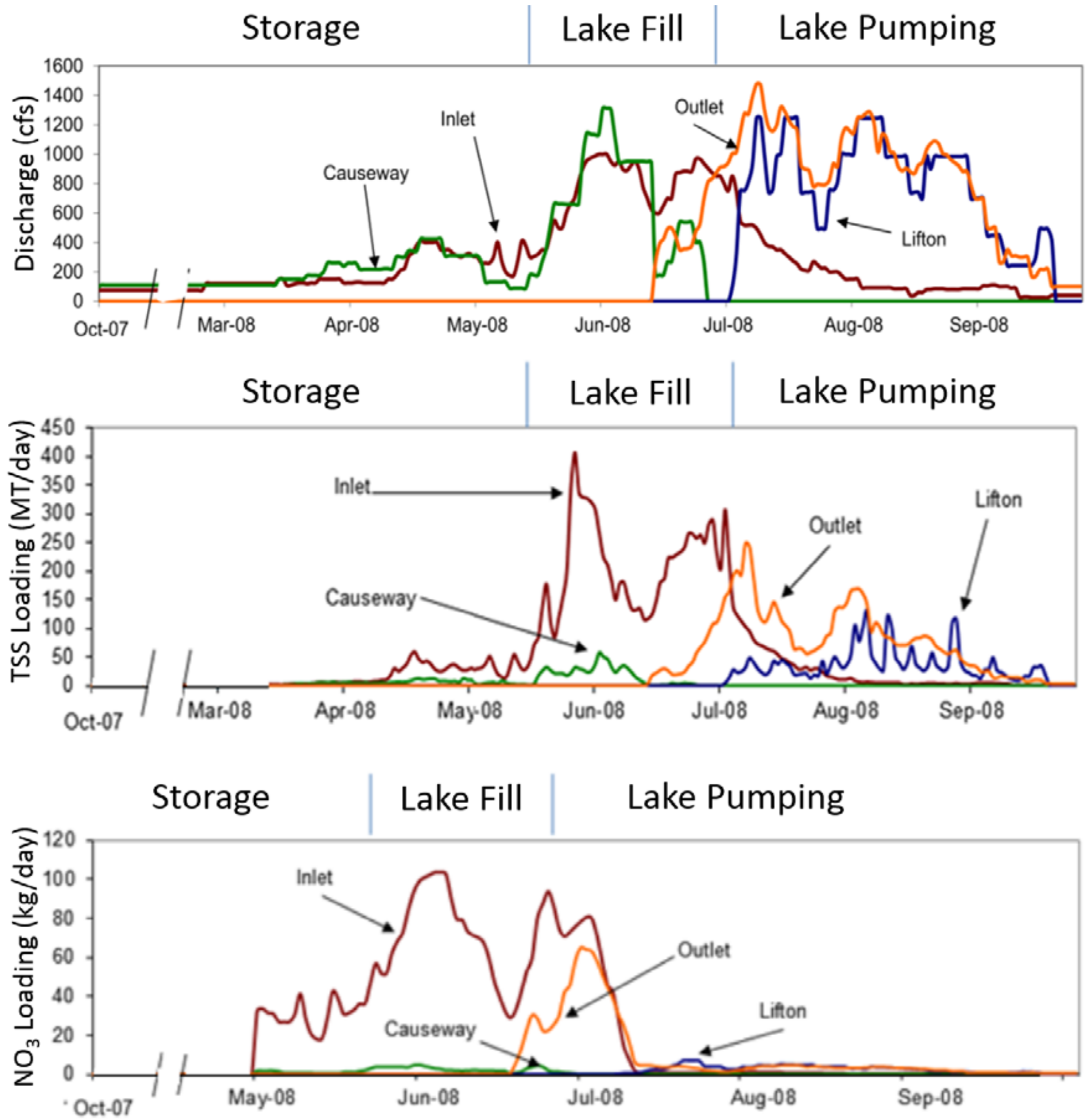


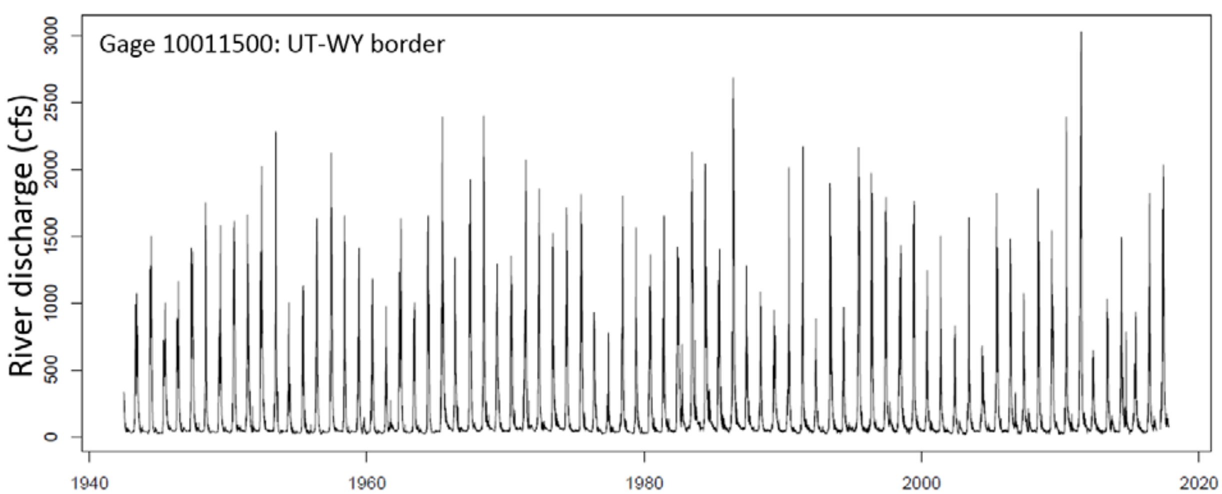
Figure 2.3.1. Adapted figure from Allen (2011) illustrating variable flows (top panel), sediment (middle panel) and nitrogen (bottom panel) loads into Bear Lake throughout the year 2008.

3. Research Questions, Methods, Results, Discussion

3.1. Have flows into Dingle Marsh changed systematically over time?

Flows in large rivers such as Bear River are inherently variable over hourly, yearly and decadal timescales due to fluctuations in weather and climate. However, many river systems throughout the US and world are experiencing systematic increases or decreases in flow, which may have cascading impacts on sediment and nutrient transport, flooding, aquatic habitat and biota, and riparian conditions (Kelly et al., 2017; Call et al., 2017). Thus, it is important to conduct targeted hydrologic analyses that appropriately organize and parse the data in order to extract meaningful metrics. We compiled data from all available stream gages including USGS gage 10011500 near the UT-WY border, USGS gage 10039500 near the WY-ID border, and USGS gage 10046000 at Rainbow Inlet Canal.

Due to the immense variability in river flow over several decades, only minimal insight can be gleaned from viewing the data in raw form (Figure 3.1.1). Therefore, we conducted a number of standard hydrologic analyses that organize the data such that changes in high, moderate, and low flows can be more easily compared (Dingman, 2015; Brooks et al., 2003). All of the flow data compiled for this study are available from our public data archive: https://usu.box.com/v/belmontbearlake



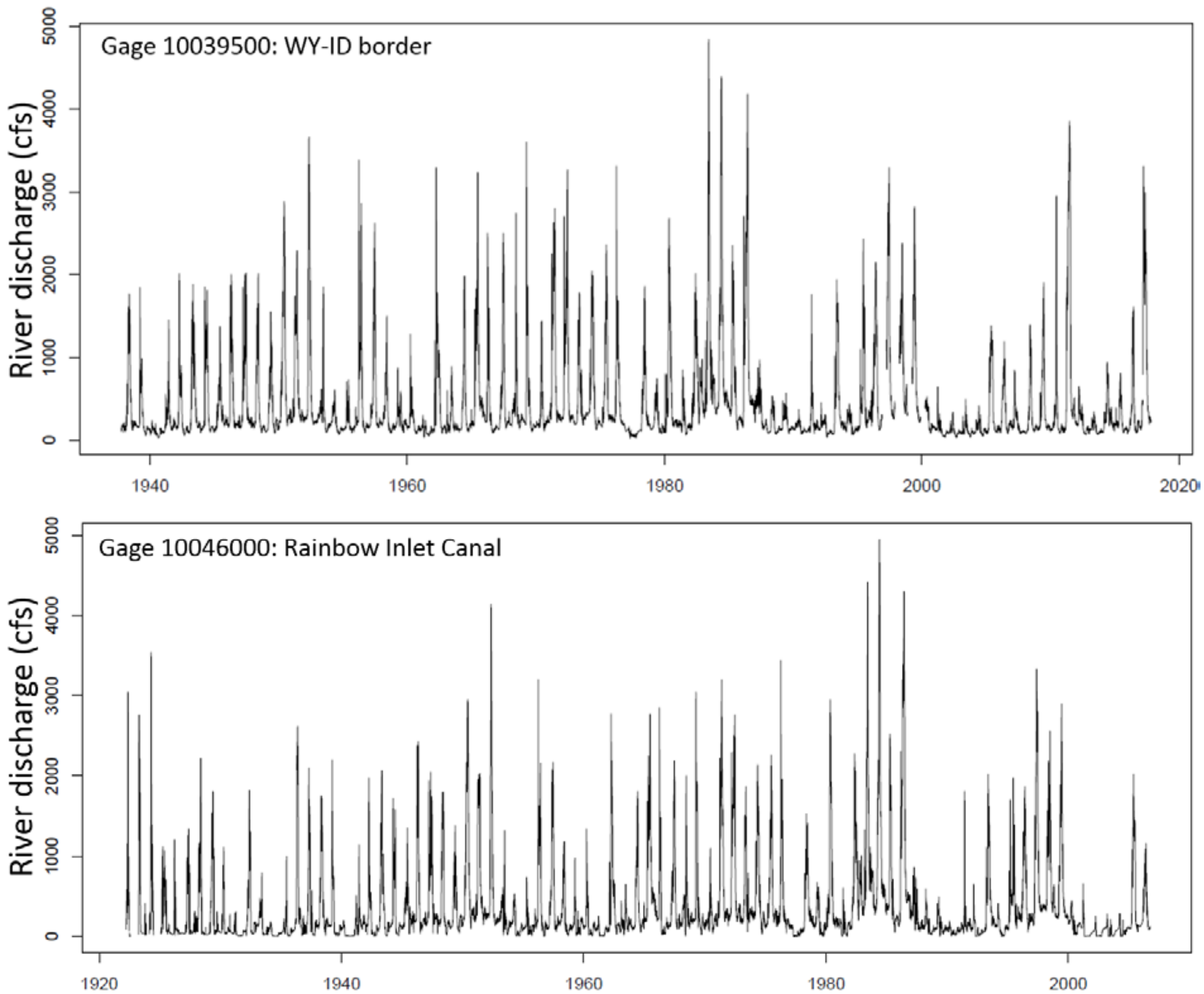


Figure 3.1.1. Hydrographs for the period of record at three gaging stations on the Bear River upstream from Bear Lake, including the gage at the Utah-Wyoming border (top panel, USGS gage 10011500), at the Wyoming Idaho border (middle panel, USGS gage 10039500), and at the Rainbow Inlet Canal (bottom panel, USGS gage 10046000).

The Inlet Canal has been monitored continuously for nearly 100 years. We parsed the data into individual years and computed the flow percentiles for each of the daily discharge measurements (i.e., what percentage of the year was a given flow value exceeded). This technique allows us to compare low flows (i.e., flows that are exceeded 90% of the time in a given year, green line in Figure 3.1.2) for each individual year and separately compare high flows (i.e., flows that are exceeded only 10% of the year, black line in figure 3.1.2) from year to year. We normalized each of the flow percentiles to their long-term average so low flows and high flows can be plotted together. The data show significantly lower flows across the spectrum of flows (low, medium and high) during the 1920s to early 1940s. From the mid 1940s to the early 1980s we see a considerable amount of variability from year to year, but all three flow metrics are varying around a common average value (1 in the plot). Since the early 1980s we have seen more pronounced cyclicity and higher variability. Specifically, during high flow periods (early to mid-1980s and mid to late 1990s) we see all three flow metrics (low, median and high flows) remain high for extended periods of time and are among the highest flows on record. During low flow periods, we see all three flow metrics remain consistently low for extended periods of time and are among the lowest on record. A similar pattern occurs at the gage at the Wyoming-Idaho border. Similar patterns have been observed in other parts of the US (Kelly et al., 2017) and are indicative of the amplified patterns of excessively wet and drought periods associated with climate change.

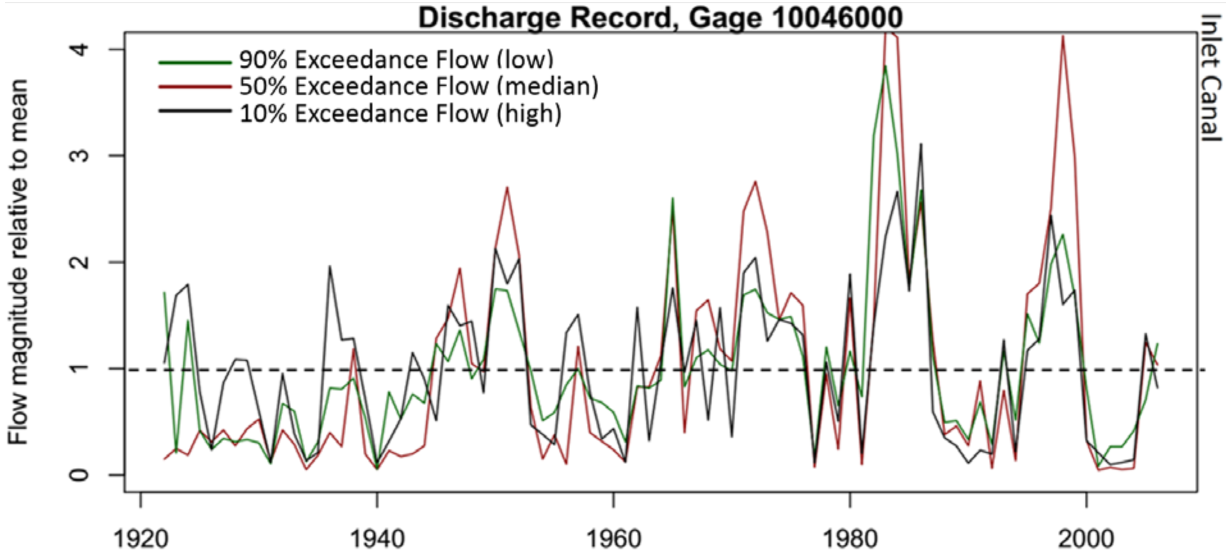


Figure 3.1.2. Flow records coming through the inlet canal over the period of record (1922-2009). Flow percentiles relative to their ensemble mean (i.e., normalized) allow them to be compared to one another for relative changes.

We aggregated the Inlet Canal flow data into monthly time periods and averaged monthly flows over time periods that roughly correspond to major changes in Bear Lake water management policy (i.e., the timing of the Dietrich/Kimball Decrees, Bear River Compact and subsequent modifications). The monthly aggregated data indicate that, despite the significant changes in flow management regulations, the timing of and duration of high flow inputs have not changed systematically (Figure 3.1.3). Monthly averaged flows during the time period 1990-2006 are, in fact, most similar to flows in the 1959-1968 time period and are not much higher than flows in the 1922-1944 time period The 1980s experienced the highest monthly flows on record, but were not too much higher than monthly flows in the 1945-1958 and 1969-1979 time periods.

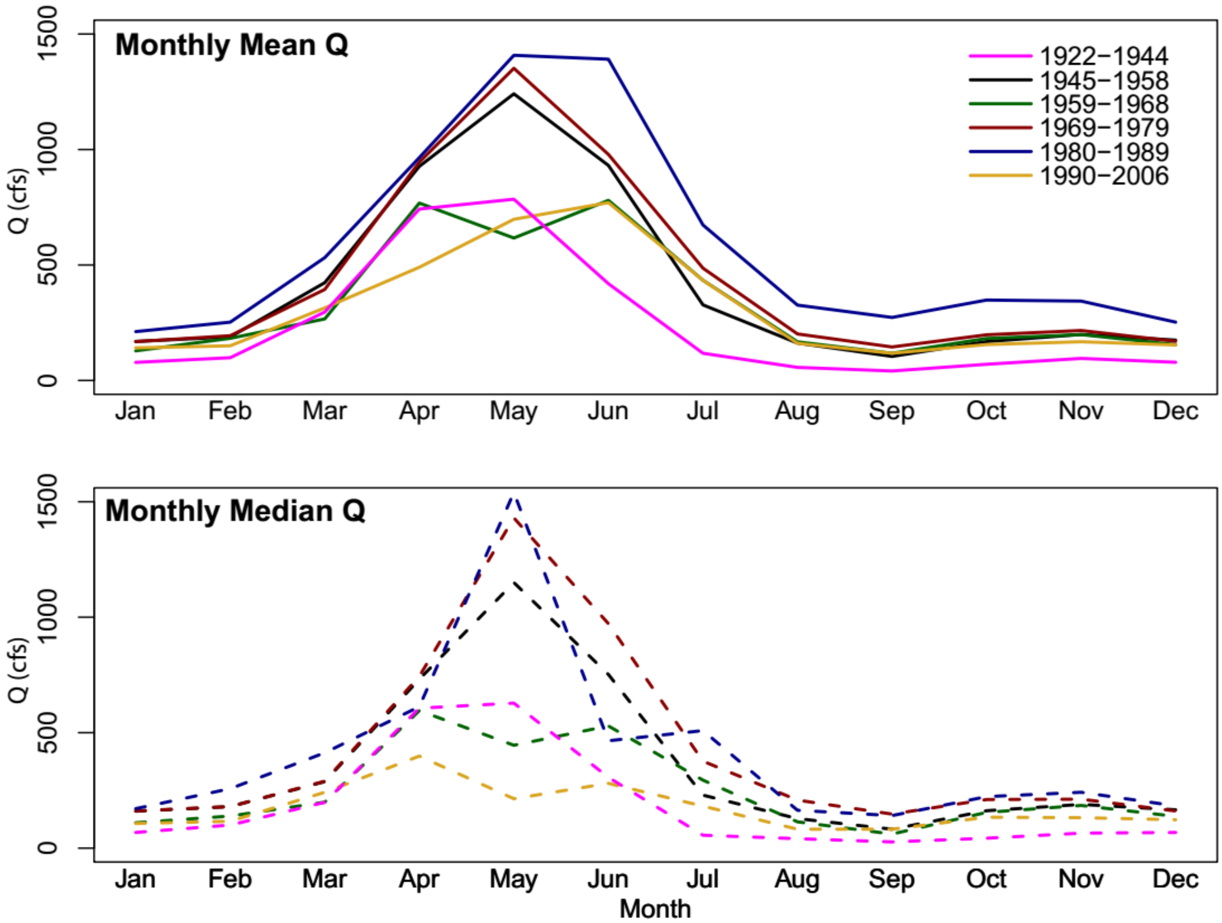


Figure 3.1.3. Seasonal patterns in the mean monthly flows into the inlet canal do not appear to have changed significantly over the gage record. Slightly higher spring inputs occurred from 1969-1989 as a result of higher than average flow conditions.

Section Conclusions and Remarks

The low, median and high flows have not changed systematically at the Inlet Canal in terms of their long-term averages, since the 1940s. However, all three of those flow metrics have increased in terms of variability and have experienced longer duration wet and dry periods over the past three decades. Similarly, flows aggregated at the monthly scale indicate that there has not been any systematic change, though there is a considerable amount of variability, which appears to be driven by decadal-scale variations in climate. We note that there is a paucity of long-term hydrologic datasets for the Bear River-Dingle Marsh-Bear Lake system and additional monitoring would greatly help ensure that we are able to monitor trends throughout the system more carefully.

3.2. Is Mud Lake functioning as a sediment trap?

Mud Lake, defined as the open-water area in the southeast corner of Dingle Marsh, plays a central role in filtering sediment-laden water from Bear River before it enters Bear Lake. It is conceivable that changes in flow magnitudes, seasonality, or flow pathways, or changes in management could alter Mud Lake's sediment trapping efficiency. Several previous studies have quantified Mud Lake's sediment trapping efficiency. Herron (1985) measured the trapping efficiency for phosphorus, the vast majority of which is transported with sediment, and found that Dingle Marsh reduced total phosphorus by 12% in 1981, 34% in 1982. Bjornn et al. (1989) found that Dingle Marsh trapped 70% of total suspended solids, 16% of total phosphorus and 44% of nitrate. Lamarra (1997) found that 75% of turbidity was removed in Dingle Marsh and documented that most sediment loading to Bear Lake occurred during the lake fill/downstream release phase. Cody Allen and Nancy Mesner monitored sediment concentrations at each of the four gages around Dingle Marsh in 2008 (see Figure 2.2.2., Inlet Canal, Causeway between Mud Lake and Bear Lake, Lifton Pumping Station between Bear Lake and the outflow canal, and at the Outlet returning flow to Bear River). They found that approximately 50% of suspended sediments were retained within Dingle Marsh during the 2008 flow year. They further documented a net loss of sediment from Mud Lake as Bear River water is routed through Mud Lake and into the Outlet Canal during the lake pumping phase (Figure 3.2.1), along with 30% of phosphorus and nearly 85% of nitrates. Sediment exported from Mud Lake during this time is routed through the Outlet Canal and back into Bear River. Notably, 2008 was slightly below an average flow year.

Figure 3.2.1.Trapping efficiency of Dingle Marsh throughout the 2008 flow year with the majority of sediment being retained within Dingle Marsh during the low flow time period of October 2007-June 2008 and a net release of sediment from Mud Lake to the Outlet Canal during July-September 2008. Adapted from Allen, 2011.

In an effort to consolidate all available datasets, we downloaded flow and suspended sediment data available online and contacted representatives of relevant state and federal agencies as well as PacifiCorp. Following an extensive search, we found that there is a surprising shortage of suspended sediment data available. Nevertheless, we compiled data from Utah State University, Idaho Department of Environmental Quality, and PacifiCorp. Plots reconfirm what has been demonstrated in previous studies, that Dingle Marsh generally reduces sediment concentrations between the Inlet Canal and the Causeway between Mud Lake and Bear Lake, but we still observe high sediment concentrations flowing into Bear Lake for some samples in the April, May, June time period (Figure 3.2.2). All sediment data compiled for this study are available from our public data archive: https://usu.box.com/v/belmontbearlake

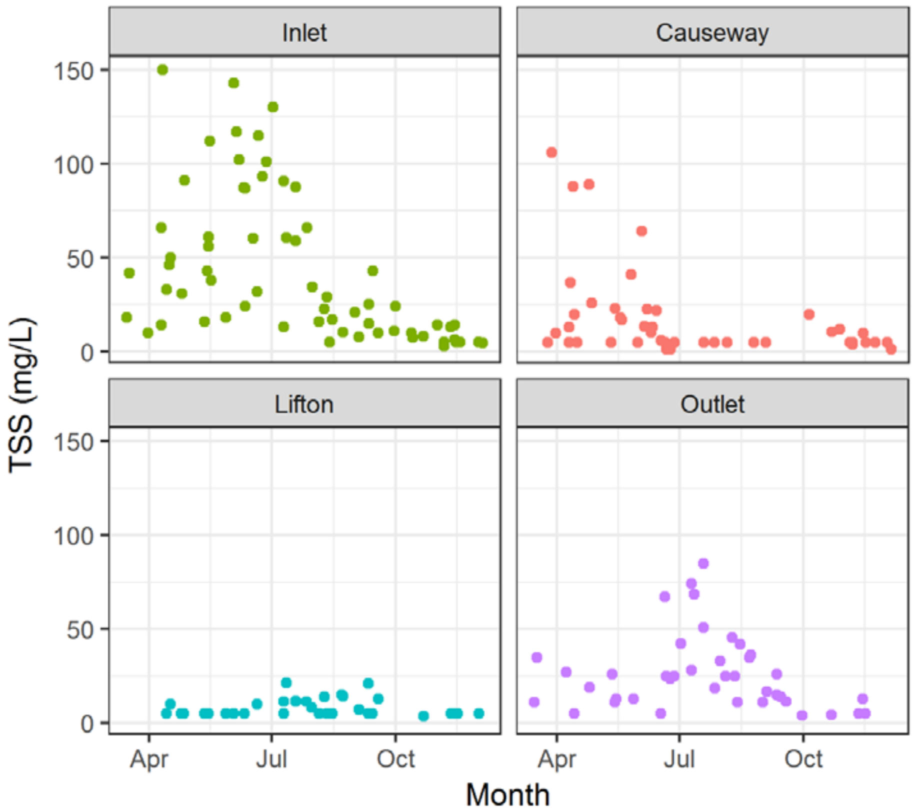


Figure 3.2.2. Data compiled from Utah State University (Allen, 2011), Idaho DEQ, and PacifiCorp at each of the four gages surrounding Dingle Marsh, see Figure 2.2.2 for locations of each gage.

Section Conclusions and Remarks

Suspended sediment monitoring has been sparse and conducted only for short time periods. All previous studies have concluded that Dingle Marsh serves as a sediment trap, but the efficiency of sediment trapping varies considerably on a seasonal basis, with Mud Lake serving as a sediment sink for much of the year and transitioning to a sediment source to the Outlet Canal and Bear River during the Lake Pumping phase. From the few studies that have been completed, we also see that sediment trapping efficiency of Mud Lake varies considerably from year to year, presumably depending on flow and sediment concentrations. However, more frequent and longer-term monitoring of suspended sediment is needed to improve our understanding of sediment storage and release processes and track the trajectory of the system over time.

3.3. Have sedimentation rates in Mud Lake changed over time?

It is useful to know that several previous studies have documented net sediment storage in Dingle Marsh. However, these studies were short-lived, occurred over a range of different flow conditions, documented considerable differences in the proportion of sediment retained within Dingle Marsh, and used a variety of different techniques. To overcome these limitations, we collected sediment cores from Mud Lake to directly measure sedimentation rates over time. We collaborated with the National Lacustrine Core Facility (LacCore) at University of Minnesota to extract a total of nine sediment cores distributed throughout Mud Lake on September 20-21, 2016 (Figure 3.3.1). Mud Lake was near its summer high water level for the coring campaign.

Most cores were 100 to 130 centimeters (3.5 to 4 feet) long. The maximum depth of each of the cores was determined by a hard, very fine-grained layer that we were unable to push the corer through, which occurred at a relatively consistent depth throughout the lake bed. Six of the cores (locations indicated by multi-colored dots and labeled 1-6 on image below) were meticulously ‘extruded’, meaning ‘sliced’, into 1 cm (~ 1/3 of an inch) intervals. Each slice was packaged separately and sent back to the St. Croix Watershed Research Station and University of Minnesota LacCore for dating and additional chemical analyses. The other three cores (locations indicated by purple dots, labeled 7-9) were kept intact and were scanned with a high-resolution camera and other instruments to help elucidate the depositional history of Mud Lake. The sediment cores and samples are archived at University of Minnesota LacCore and are available for additional analysis. All data generated from the sediment cores for this study are available from our public data archive: https://usu.box.com/v/belmontbearlake

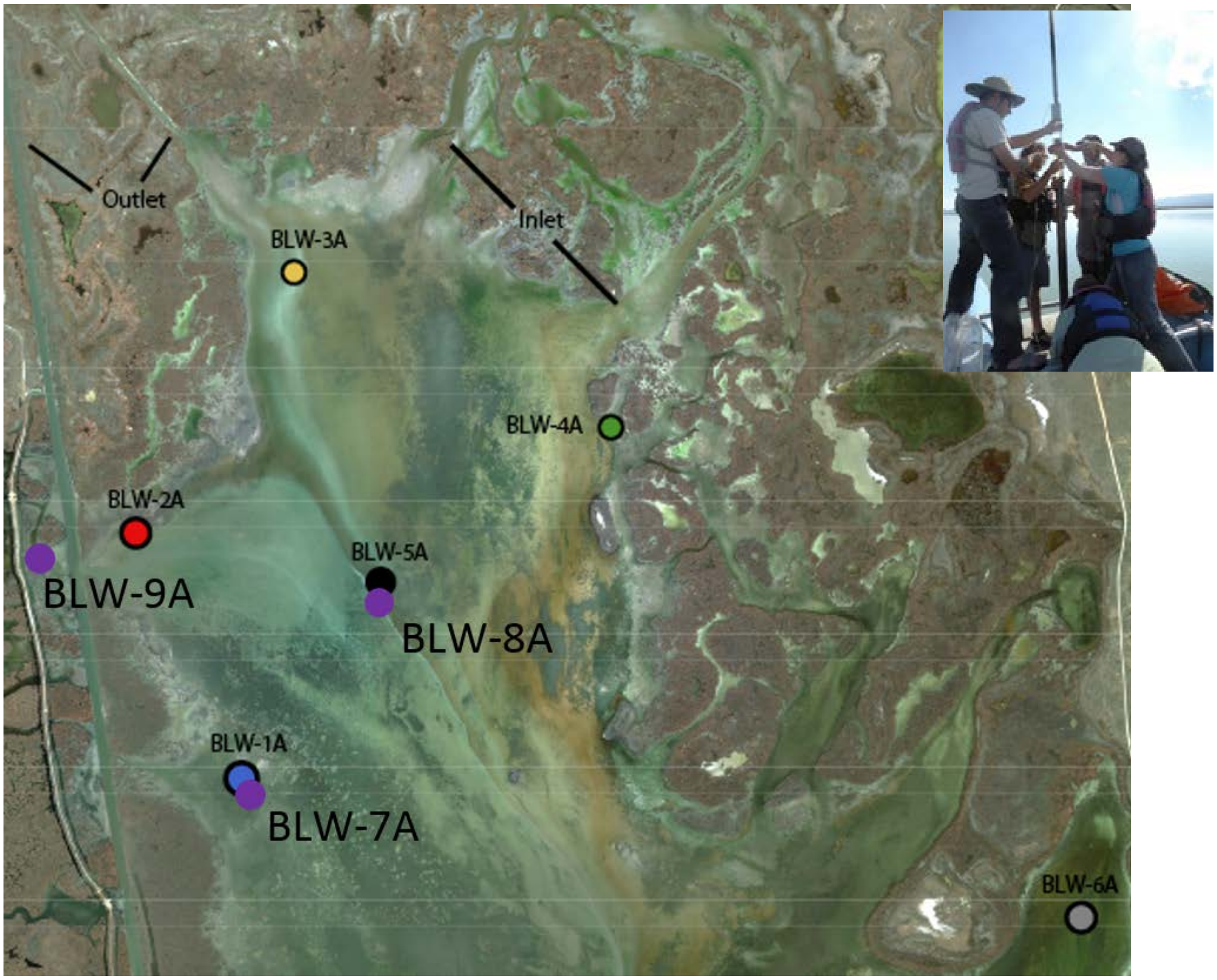


Figure 3.3.1. Locations where nine sediment cores were extracted from Mud Lake in fall 2016. Colored dots labeled 1-6 indicate cores that were sliced into 1 cm (~1/3 inch) increments, to be analyzed for sediment age and geochemical composition. Purple dots (labeled 7-9) indicate cores that were kept intact and sent to University of Minnesota for high-resolution scanning and whole-core analyses.

High resolution scans of the cores show considerable changes in sediment characteristics with depth (Figure 3.3.2). Core 7, the longest core that was kept intact, shows at least seven distinct depositional units. Visual inspection of these cores led us, in collaboration with Bear Lake Watch, to decide to further investigate biological and geochemical changes in the sediments via diatom community composition analysis and elemental analysis, both discussed in the next section.

Figure 3.3.2. High resolution scans of intact cores from locations 7 (left), 8 (middle) and 9 (right). The raw, high-resolution versions of these images are available in our data archive:

https://usu.box.com/v/belmontbearlake

The extruded cores were dated using alpha particle excess-Lead-210 (^{210}Pb) by St. Croix Watershed Research Station. The concentration of ^{210}Pb consistently decreased with depth in each of the cores, as expected due to the fact that ^{210}Pb decays in older sediments, with a half-life of 22.3 years (i.e., the concentration decreases by half every 22.3 years). The decrease in ^{210}Pb concentration with depth is a proxy for the time of deposition and therefore the sedimentation rate. In general, the sediment cores exhibited very low concentrations of ^{210}Pb, which increased uncertainty, especially in the lower portions of the cores (Figure 3.3.3). To improve dating of the cores, the samples were further analyzed for Cesium-137 (^{137}Cs), another radiogenic tracer that resulted from atomic bomb testing in the 1950s.

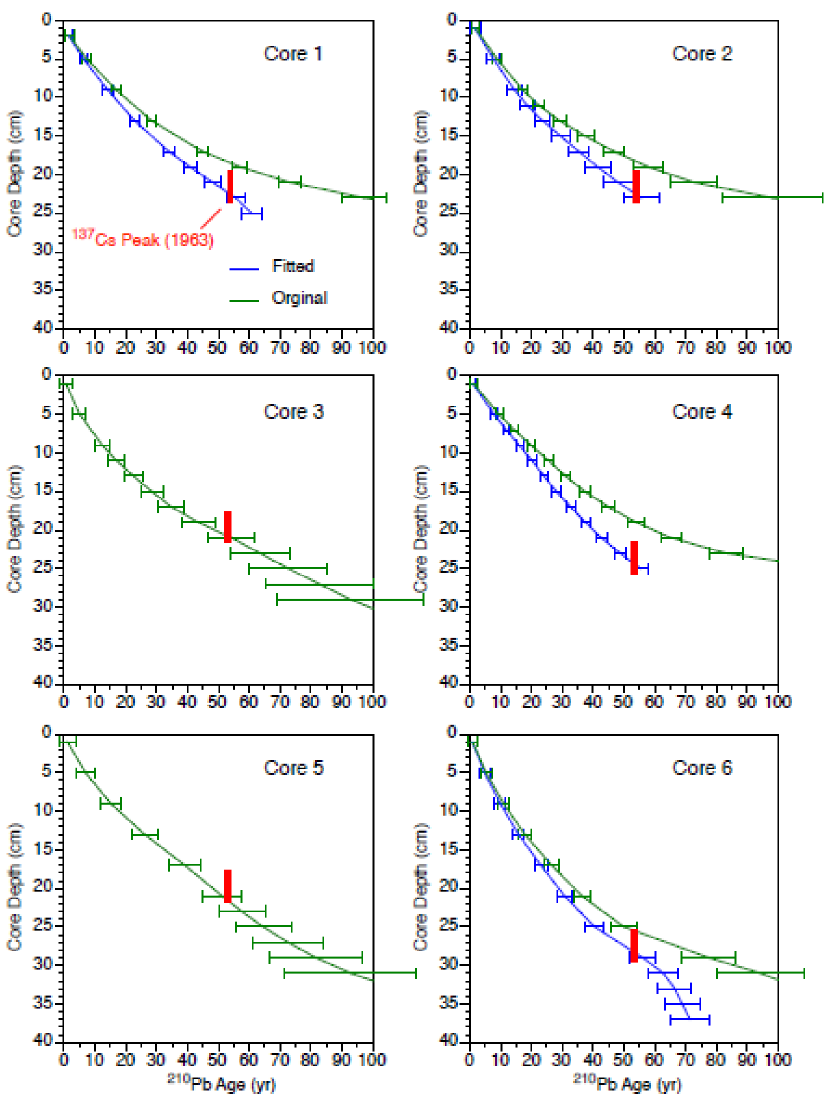


Figure 3.3.3. Sediment deposition ages computed from alpha particle Lead-210 dating (green lines) and Cesium-137 dating (red dot). The two dating techniques provided the same trends in cores 3 and 5, but corrections were applied to the Lead-210 dates for cores 1, 2, 4 and 6, based on the Cesium-137 peak (blue lines). Error bars indicated two standard errors of the dating technique.

Figure 3.3.4 shows computed sedimentation rates for each of the extruded cores from Mud Lake. Sedimentation rates are calculated based on sediment depth, age, moisture content and bulk density. Two of the cores (3 and 5) record sedimentation rates over the past 120 years. Other cores record sedimentation rates over the past 40-60 years. The maximum depth to which

^{210}Pb dates, and therefore sedimentation rates, can be computed is limited by the amount of measurable ^{210}Pb above background concentrations in the core, which typically allows dating of sediments back to 120-175 years. Thus, sediments below the ages at which the profiles are truncated are likely older than 120 years old. The addition of radiocarbon ages would allow us to model sedimentation rates through the full extent of each core. There is considerable variability in sedimentation rates, but in general, rates have remained steady (cores 1, 4, and 6) or increased (cores 2, 3, and 5) over time. These trends indicate that Mud Lake has historically, and continues today, to serve as a sediment trap between Bear River and Bear Lake. Sedimentation rates from all six extruded cores are plotted together in Figure 3.3.5. It is noteworthy that sedimentation rates in our two longest cores (cores 3 and 5) have increased considerably (a factor of two to five) since 1900. This long-term trend may be explained by increased sediment loading from Bear River, or decreased sediment trapping in upstream portions of Dingle Marsh. Prior to construction of the canal system Bear River would have flowed across a broad, shallow marsh system prior to reaching Mud Lake whereas under the current system Bear River water is essentially routed directly to Mud Lake.

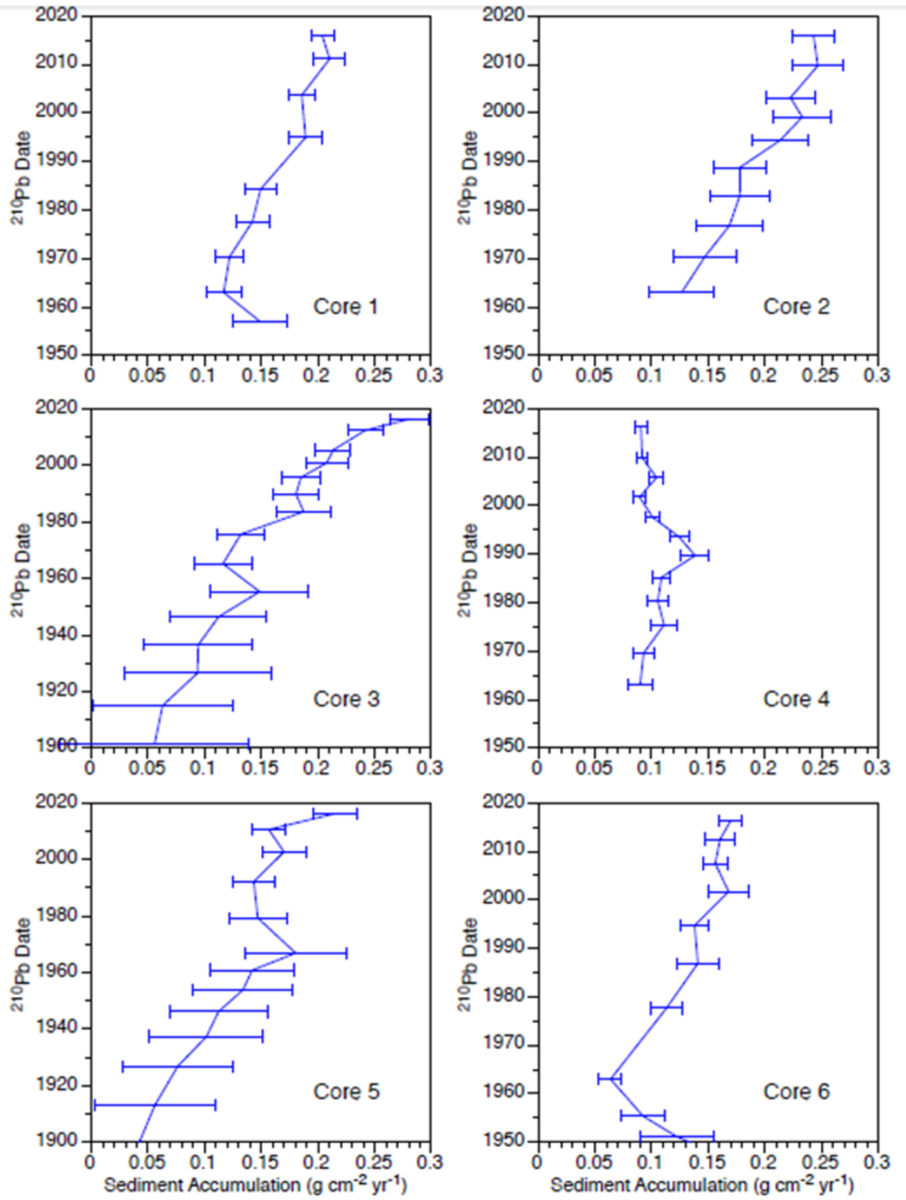


Figure 3.3.4. Sedimentation rates for each of the extruded Mud Lake cores, based on sediment deposition ages and measurements of moisture content and bulk density. Error bars indicate propagated two standard errors.

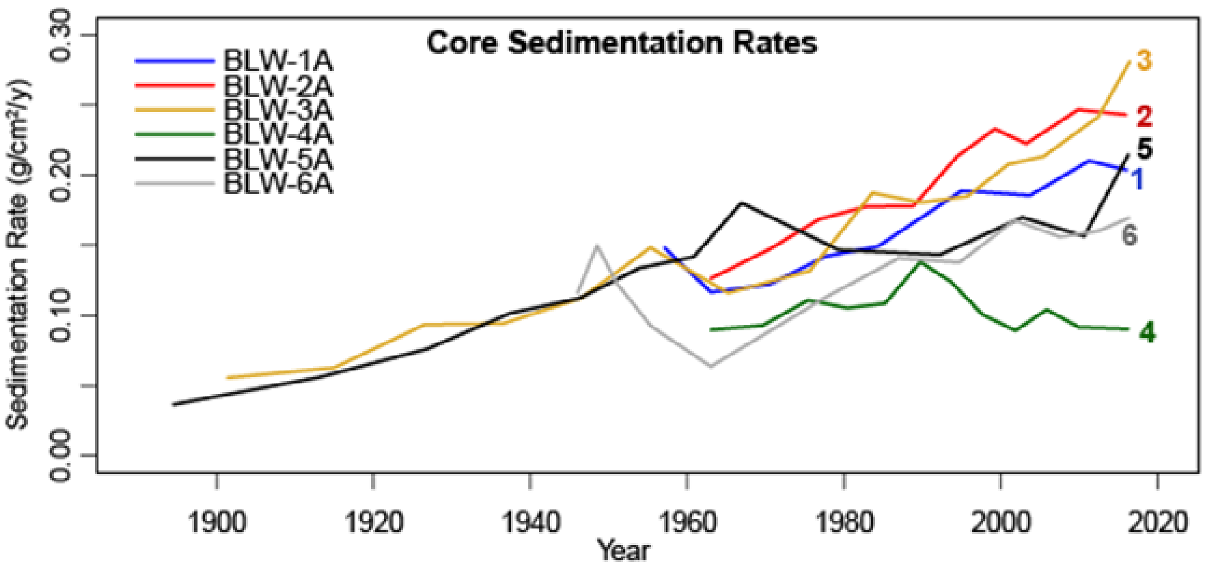


Figure 3.3.5. Sedimentation rates for all six extruded cores from Mud Lake.

The fact that we observe steady or increasing sedimentation rates in every core extracted from Mud Lake does not exclude the possibility that sediment loading to Bear Lake has also increased over time. Mud Lake serves as a buffer between Bear River and Bear Lake, so if sediment loads from Bear River have increased more than the sedimentation rates we observe in Mud Lake, it is possible that sediment loading has increased to both Mud Lake and Bear Lake. Unfortunately we lack the long-term sediment records to determine whether and how sediment loads have changed in Bear River over the past century.

Section Conclusions and Remarks

Qualitative observations of the three intact cores indicate that the sediment characteristics and depositional environment of Mud Lake have changed considerably over time. Sedimentation rates have remained steady or continued to increase in all sampled locations throughout Mud Lake, indicating that it has historically and will continue to serve as a net sediment trap for the foreseeable future. Additional work could analyze Carbon-14 samples from the archived cores to determine the longer-term depositional history of Mud Lake.

3.4. Have sediment sources to Mud Lake changed over time?

Geochemical properties of sediment contain information regarding the source of sediment (Brahney et al., 2010; Davis and Fox 2009; Gellis and Walling 2011; Mukundan et al. 2012; Koiter et al. 2013; Walling 2013; Belmont et al., 2014). There is no universally applicable technique to directly link the geochemistry of sediments in a deposit with specific sediment sources upstream. To determine causality, the geochemistry in Mud Lake and key upstream sediment sources would both have to be measured. However, measuring geochemistry of sediment in Mud Lake allows us to determine whether and when significant shifts in sediment sources have occurred. With that understanding, decisions can be made regarding the value of measuring the geochemical properties of potential upstream sediment sources in an effort to determine causality for any observed shifts.

A common approach to measuring shifts in sediment sources is to measure the mineral, organic, and calcium carbonate ($CaCO_3$) composition of the sediments. We measured all three fractions using loss-on-ignition (University of Minnesota Limnological Research Center standard protocol) in all six extruded sediment cores from Mud Lake, using sub-samples from each 1-cm increment into which the cores were sliced. Figure 3.4.1 shows the percentage of each of the 1 cm increments that is composed of organic material, calcium carbonate, and mineral, or inorganic, matter. The top 25-35 cm of each core, which corresponds to the past 75 to 100 years in each of the cores (see Figure 3.3.3), contains consistently 10-20% organic matter and an additional 30-40% calcium carbonate. Further down, most cores contain several spikes or sustained periods with elevated levels of organic carbon and carbonate. Both organic matter and carbonate decrease near the bottom of each core. The distinct peat layer is most prominent in cores 1A and 2A around 55 and 61 cm depth, respectively, dates for which extend beyond the ^{210}Pb dating timeframe of the last 120 years. Extended periods of high organic matter content are observed in core 6A and 3A and a spike in organic matter content is observed in core 5A, at approximately 80 cm depth. Core 4A, collected from the eastern central portion of Mud Lake, near one of the historical inlet channels appears to be an anomaly. Core 4A was the shortest core we collected because we hit the hard, fine-grained inorganic grey layer at a relatively shallow depth of 70 cm.

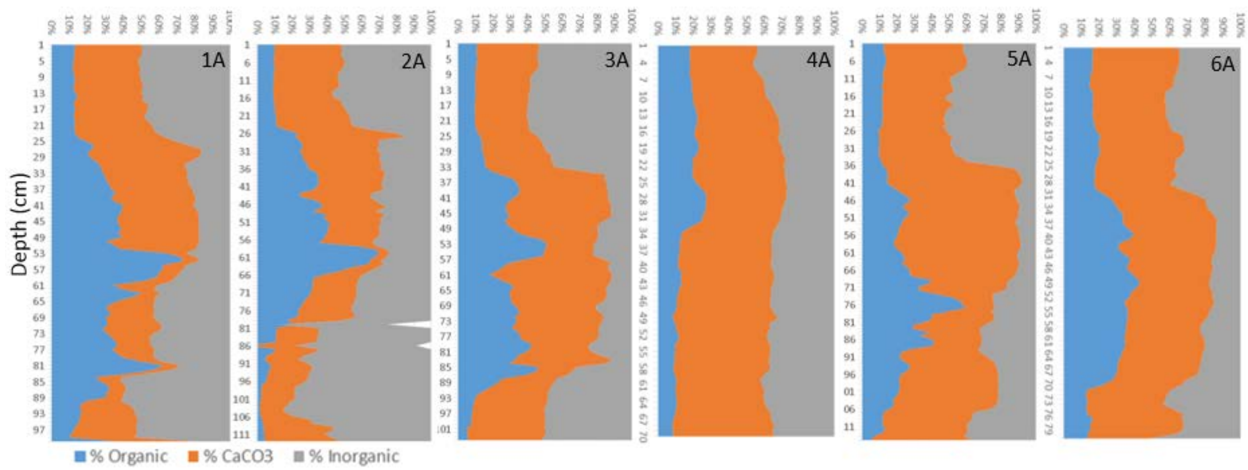


Figure 3.4.1. Measurements of organic (blue), calcium carbonate (orange) and mineral (grey) sediments from each of the six Mud Lake sediment cores, obtained via loss-on-ignition.

More detailed information regarding sediment sources can be obtained from an elemental analysis of the sediment samples. We obtained sub-samples from 25 of the extruded samples spanning the top 45 cm (18 inches) from core 3A and chemically separated the organic material from the mineral content using a technique developed by Dr. Janice Brahney (Brahney et al. 2008, 2010). The samples were then sent to the Spectroscopy and Biophysics Core laboratory at University of Nebraska where they were analyzed by Inductively Coupled Plasma Mass Spectrometry. Data presented are representative of the organic fraction associated with the sediment particles, which is typically bioavailable, rather than bound within the mineral particles themselves. All raw data obtained from the elemental analysis are available from our public data archive: https://usu.box.com/v/belmontbearlake

We parse the data into three distinct chemical groups, Rare Earth Elements, Transition Metals and other metals, and Metalloids and non-metals (Figures 3.4.2, 3.4.3, 3.4.4). We see significant transitions in all three classes around 34 cm deep in the core, corresponding to approximately 100 years ago when Bear River was diverted through Mud Lake. Prior to this time, concentrations of Rare Earth Elements were nearly all negligible except for Uranium-238, which was high prior to 100 years ago and decreased considerably when Bear River was diverted into Mud Lake. We observe a similar trend in Transition Metals and other metals, with concentrations prior to 100 years ago being essentially negligible except for Molybdenum, which exhibits a pattern very similar to Uranium-238. Metalloids and non-metals are more variable, with concentrations of most varying little throughout the core. Concentrations of Selenium are consistently higher post-Bear River diversion and concentrations of Lead-208 initially increase as a result of diversion of Bear River into Mud Lake, and then consistently fall over the past 50-60 years.

Throughout the upper 34 cm of the core, most Transition and other metals and Metalloids and non-metals remain relatively constant. However, we observe another major shift within the top 5 cm of the core, representing approximately the past 10 years. Most Rare Earth Elements increase 2 to 10 fold and Silver (Ag) and Mercury (Hg) increase 5 to 10 fold in this top layer of sediments. Silver and Mercury exhibit particularly interesting trends, as both start to increase gradually around a depth of 20 cm in the core and then spike within the top 5 to 10 cm. It is unclear whether these increases are from changes in suspended sediment sources to the Bear River or if they have been delivered by atmospheric deposition. But the changes in elemental composition are very large and may be reason to investigate further.

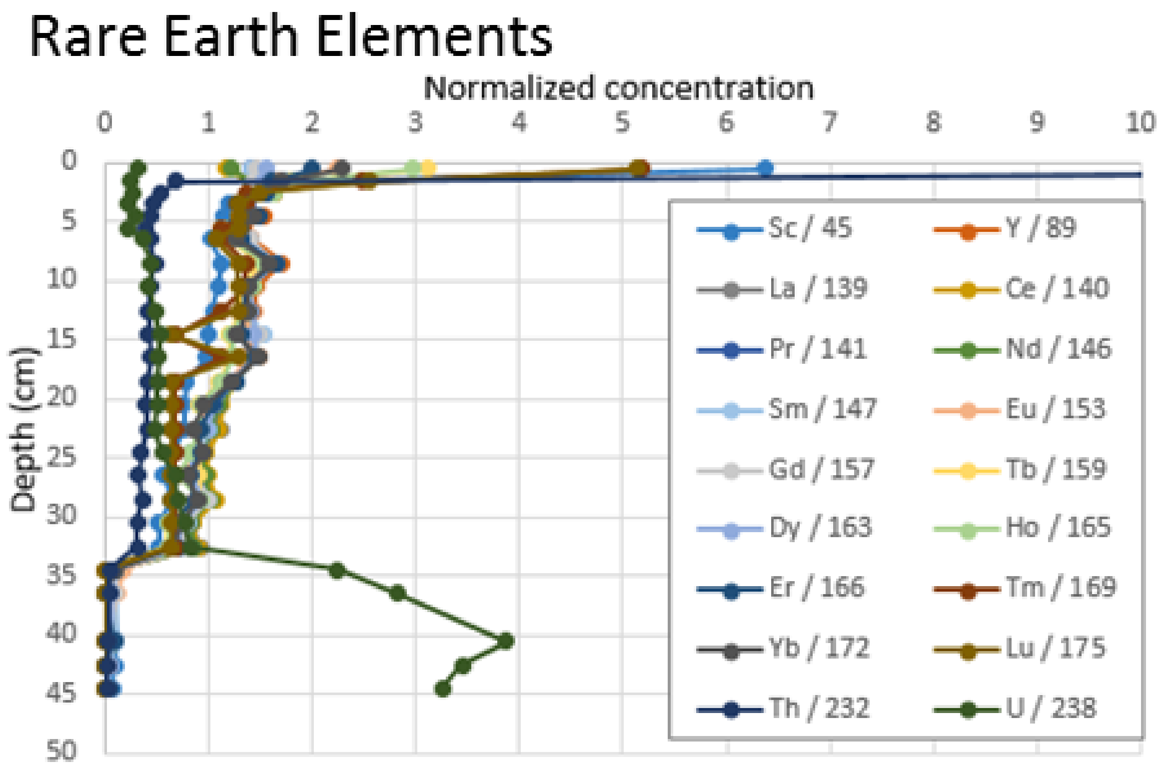


Figure 3.4.2. Elemental analysis of Rare Earth Elements of 25 samples spanning the top 45 cm of core 3A extracted from Mud Lake. Concentrations for each element (in parts per million, billion, or trillion) have been normalized by the average value for the entire core (represented as 1 on the graph) so that they can all be plotted together and relative trends can be evaluated.

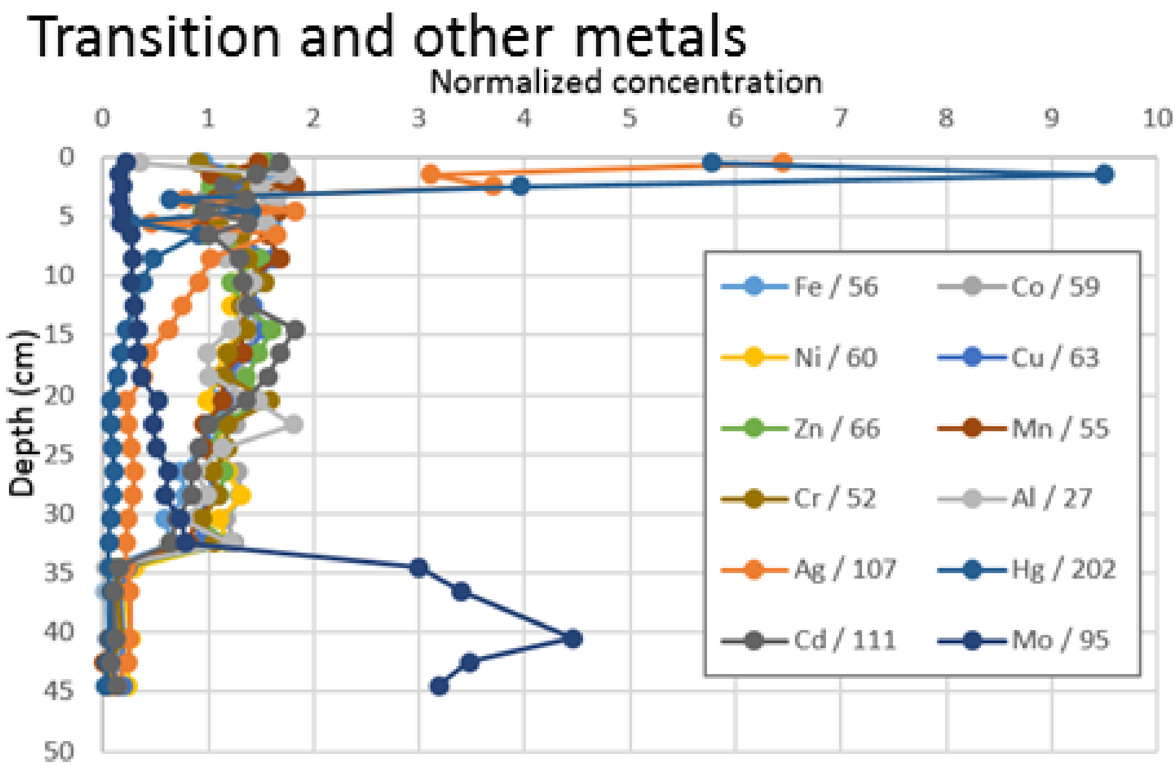


Figure 3.4.2. Elemental analysis of Rare Earth Elements of 25 samples spanning the top 45 cm of core 3A extracted from Mud Lake. Concentrations for each element (in parts per million, billion, or trillion) have been normalized by the average value for the entire core (represented as 1 on the graph) so that they can all be plotted together and relative trends can be evaluated.

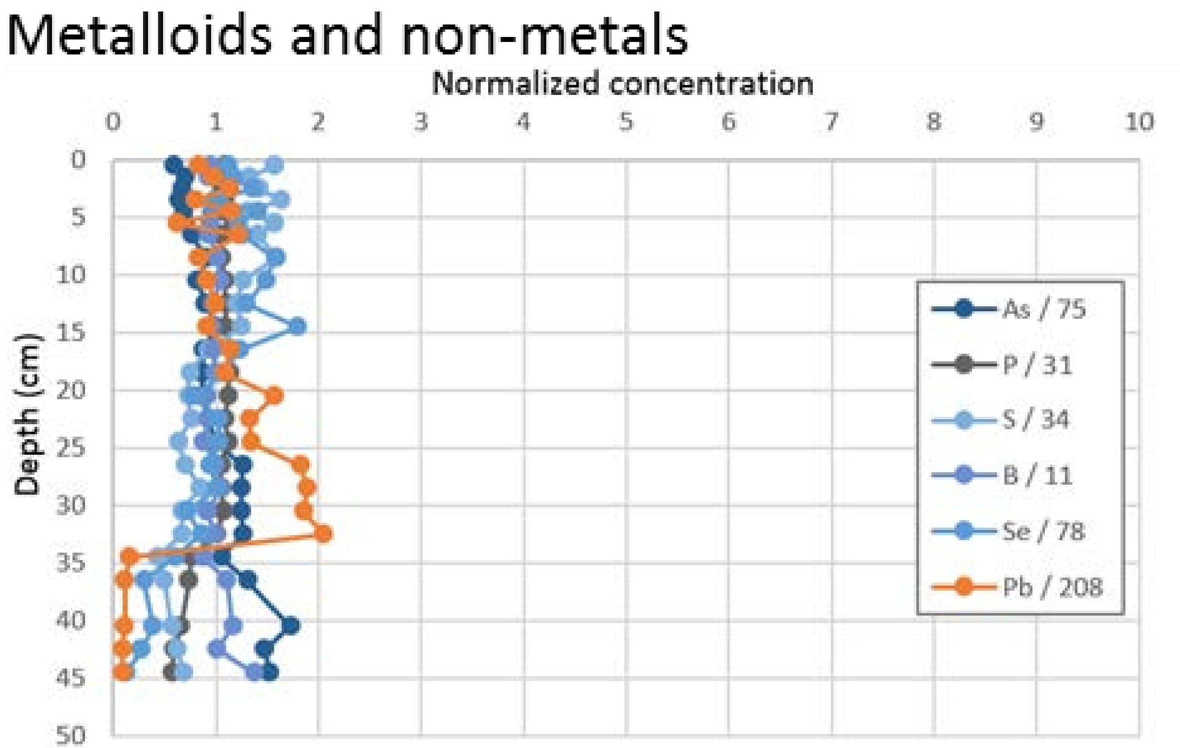


Figure 3.4.2. Elemental analysis of Metalloids and non-metals of 25 samples spanning the top 45 cm of core 3A extracted from Mud Lake. Concentrations for each element (in parts per million, billion, or trillion) have been normalized by the average value for the entire core (represented as 1 on the graph) so that they can all be plotted together and relative trends can be evaluated.

Section Conclusions and Remarks

Analysis of the chemical composition of Mud Lake sediment cores indicates that the sources of sediment have shifted considerably over time. Analysis of organic, calcium carbonate and mineral fractions in each of the cores demonstrates some consistency across cores, including consistent amounts of organic matter (10-20%) and calcium carbonate (30-40%) in sediments from the past 75-100 years. Prior to this time, the cores exhibit considerably more variation in both space and time. Elemental analysis of Mud Lake sediment cores identifies two major shifts in sediment sources, one occurring approximately 100 years ago when Bear River was diverted into Mud Lake and a second shift around 10 years ago, when most Rare Earth Elements, Silver, and Mercury increase abruptly and significantly. This most recent shift is of particular interest and it may be worthwhile to conduct a follow up study to determine what these new sources of sediment are, where the sediments come from (via sediment fingerprinting), the mechanisms by which these sediments are delivered to Mud Lake (via Bear River or atmospheric deposition), and implications for the health of the Mud Lake and Bear Lake ecosystems.

3.5. How has water quality changed in Mud Lake over time?

Water quality is often evaluated on the basis of numerous chemical and physical measurements, including nutrient content, dissolved oxygen levels, temperature, sediment concentrations, etc.. However, such measurements are rarely available for long-term monitoring, are often specific to the location of measurement, and are inherently incomplete metrics for evaluating water quality in a comprehensive manner. However, certain types of algae living in the water, named diatoms, are quite sensitive to water quality conditions. The assemblage of diatom species changes significantly under different water quality conditions and when they die, the diatoms then sink to the lake bed and provide a record of past water quality environments as sediments accumulate (Dixit et al., 1992; Reid, 1995; Kelly et al., 1998).

Dr. Janice Brahney obtained 12 samples from core 3A, spanning the top 90 cm, and counted the abundance of different diatom species in each sample. Note from Figure 3.3.3 that the last 100 years is represented by the top 30 cm of the core, so while we do not have definitive dates on the lower 60 cm of the core, the diatom record extends well beyond the historical record of water management in Mud Lake. Figure 3.5.1 shows the relative abundance of different diatom types (names along top of each plot) with depth through the core (vertical axis, consistent for each of the plots). The left-most plot shows dominance of *Aulacoseira crenulata*, a species common to the planktonic regions of lakes, in the lowest portion of the core. It is possible that these sediments represent a time when Mud Lake was part of Bear Lake and/or an old glacial lake. Amphora species are also common at this time; these are benthic, sand dwelling species (nearshore habitats). Slightly higher in the core we see spikes in abundance of Crysophyte cysts. The Crysophyte cysts are not identified to the species level in this analysis, but in general, these are low nutrient species. Also present at this depth in the core are freshwater sponges that typically grow on rocks or logs. Samples from 60 cm deep in the core show elevated abundance of *Epithemia spp*, which are generally epiphytic, meaning they live on the surface of other algae. *Epithemia* also have the capacity to form symbiotic relationships with blue-green algae (cyanobacteria) and are thus often found in water with low ratios of Nitrate to Phosphorus (N:P) because cyanobacteria are nitrogen fixing algae. *Epithemia* prefer alkaline systems. At around 50 cm we see the emergence of a group of species that are commonly associated with alkali fens. At that same depth/time, we also see emergence of monoraphid species, which are benthic organisms that prefer cold water, low nutrient and low conductance environments. Thus, it appears that during this time Mud Lake was a fen environment with freshwater streams draining to it intermittently. Cymbelloid species tend to dominate around 30-40 cm. These are benthic species, but are found in a wide range of habitats, so without further quantitative analysis we are unable to determine what the dominance of these species is telling us about water conditions of Mud Lake during this time. The top 20 to 30 cm of the core, representing the past 100 years, we see the number of benthic araphid species increase dramatically and become the dominant species, making up nearly 100% of the taxa. These species in general are benthic, alkaliphilous species that are indicative of mesotrophic (moderate water quality) habitats.

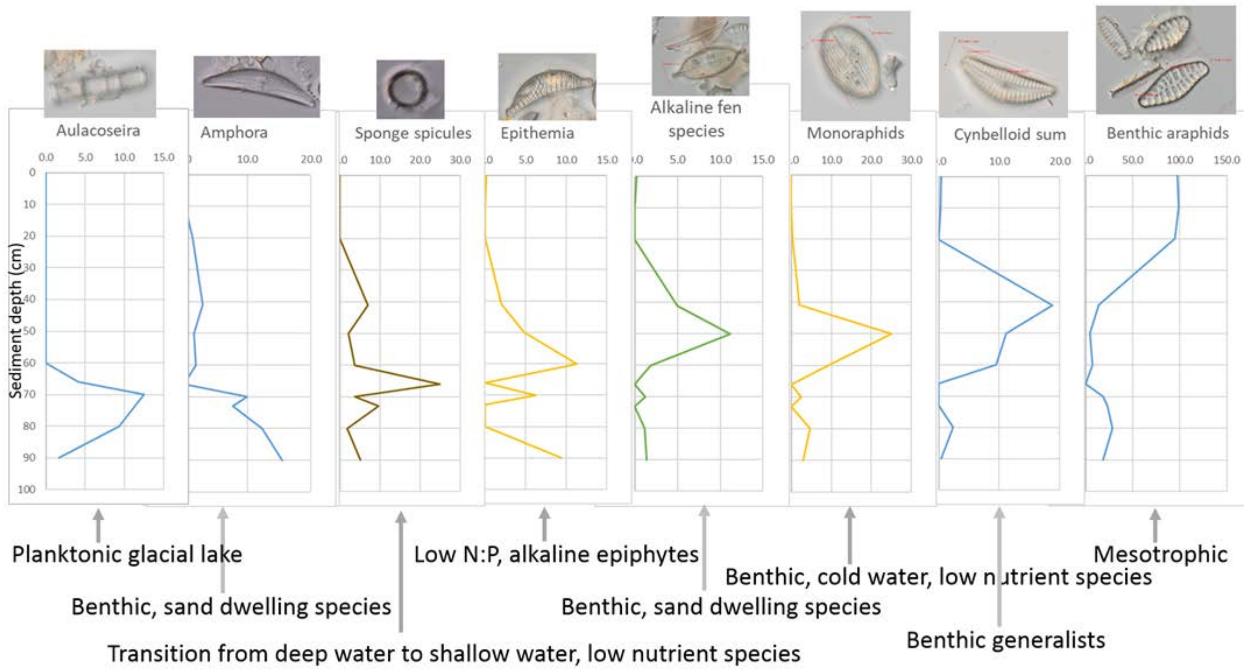


Figure 3.5.1. Preliminary relative counts of different diatom species with depth in Mud Lake sediment cores.

Section Conclusions and Remarks

The different communities of diatom algae found at different depths in sediment core 3 illustrate a wide range of conditions that Mud Lake has experienced over the past several hundred to several thousand years. The different assemblages indicate large and systematic shifts in water quality. Most recently, dominance of benthic araphids indicates that water quality in Mud Lake has been mesotrophic for the past 100 years. This analysis was exploratory and was therefore done at a relatively coarse scale (12 samples over 90 cm of core). More detailed analysis of the Mud Lake diatom assemblages, especially over the past 100 years could provide considerably more insight regarding historical water quality conditions. Furthermore, conducting a similar diatom analysis on sediment cores extracted from Bear Lake could be very insightful as a comprehensive measure of changes in water quality over time. Longer-term diatom studies have been conducted in Bear Lake to evaluate changes in climate and water quality over the past 30,000+ years, at a time scale to coarse to make inferences about the past 150 years. Thus, a higher resolution diatom study on Bear Lake sediment cores focusing on the post-settlement period would be very valuable.

3.6. How has Bear Lake shoreline changed over time?

Shorelines are often very dynamic features in a landscape, as sediment is readily eroded, deposited and transported within the high-energy environments created by currents and wave action. In an effort to evaluate whether and how the Bear Lake shoreline has changed over time we first compiled all available historical air photos and high-resolution satellite images from federal and state agencies. When necessary, we georeferenced and mosaicked individual photos from a given time into a larger image covering as much of Bear Lake shoreline as possible. In total 14 sets of photos were obtained with significant coverage of the lake, primarily from USDA, USGS and NASA, spanning 1980 to 2016 (1980, 1992, 1997, 1993, 2003, 2004, 2006, 2009, 2011, 2012, 2013, 2014, 2015, 2016). We manually delineated the shoreline at the edge of water in each of the photo sets. All imagery compiled for this project is available from our public data archive: https://usu.box.com/v/belmontbearlake

Fluctuating water levels make it impossible to infer erosion or deposition among all of the images. However, we identified the dates on which each image was generated and found the lake water surface elevation on each date. All elevations reference the UP&L datum and are available in the data repository. We found two sets of images with very comparable water surface elevations. The most comparable set of images were from August 28, 1980 and August 11, 2011, which had water levels at 1804.85 meters (5921.4 feet above mean sea level), and 1804.86 (5921.5 feet above mean sea level), respectively (Fig. 3.6.1). Notably, this is an exceptionally high water level. Imagery available for both of these dates spans the northern 40% of Bear Lake's shoreline, predominately the portion of the lake that is in Idaho. Figure 3.6.2 show the extent of analysis (indicated by red and purple lines representing the shoreline in 1980 and 2011, respectively). Results indicated a moderate amount of deposition at this high water level in three areas along the north and western shoreline and a small, but measureable amount of erosion (10 to 20 meters, or 30 to 70 feet) along the eastern shoreline, near Porcupine Hollow, Peterson Hollow and Bear Lake State Park. See also Figures 3.6.3, 3.6.4 and 3.6.5 for detailed views of the areas of significant change between 1980 and 2011.

We conducted a similar analysis with images from 1992 and 2004. Images from both of these dates were available for 90% of the Bear Lake shoreline (Figure 3.6.6). Notably, water levels were approximately a half foot lower in 2004 (5905.67 feet compared to 5906.16 feet in 1992), which slightly biases the measurements to show deposition (net migration of the shoreline lakeward). Assuming a slope of 0.002, which we measured from lidar data near the northwest corner of the lake, a half foot difference in water level translates to the shoreline moving lakeward approximately 250 feet, or 90 meters. However, many of the measurements we made show lakeward migration of the shoreline far exceeds that bias associated with the difference in lake levels. While many locations around the lake do not demonstrate significant deposition at the low lake levels observed in 1992 and 2004, the northwest corner of the lake shows considerable deposition. Figure 3.6.7 shows 200 to 500 meters (650 feet to 1600 feet) of lakeward migration of the shoreline in the vicinity of St. Charles Creek during 1992-2004 at this low lake level. This deposition and lakeward migration of the shoreline at low water levels is likely detrimental to any fish species that migrate between St. Charles Creek and Bear Lake as they would be exposed to higher temperatures and higher amounts of predation from birds.

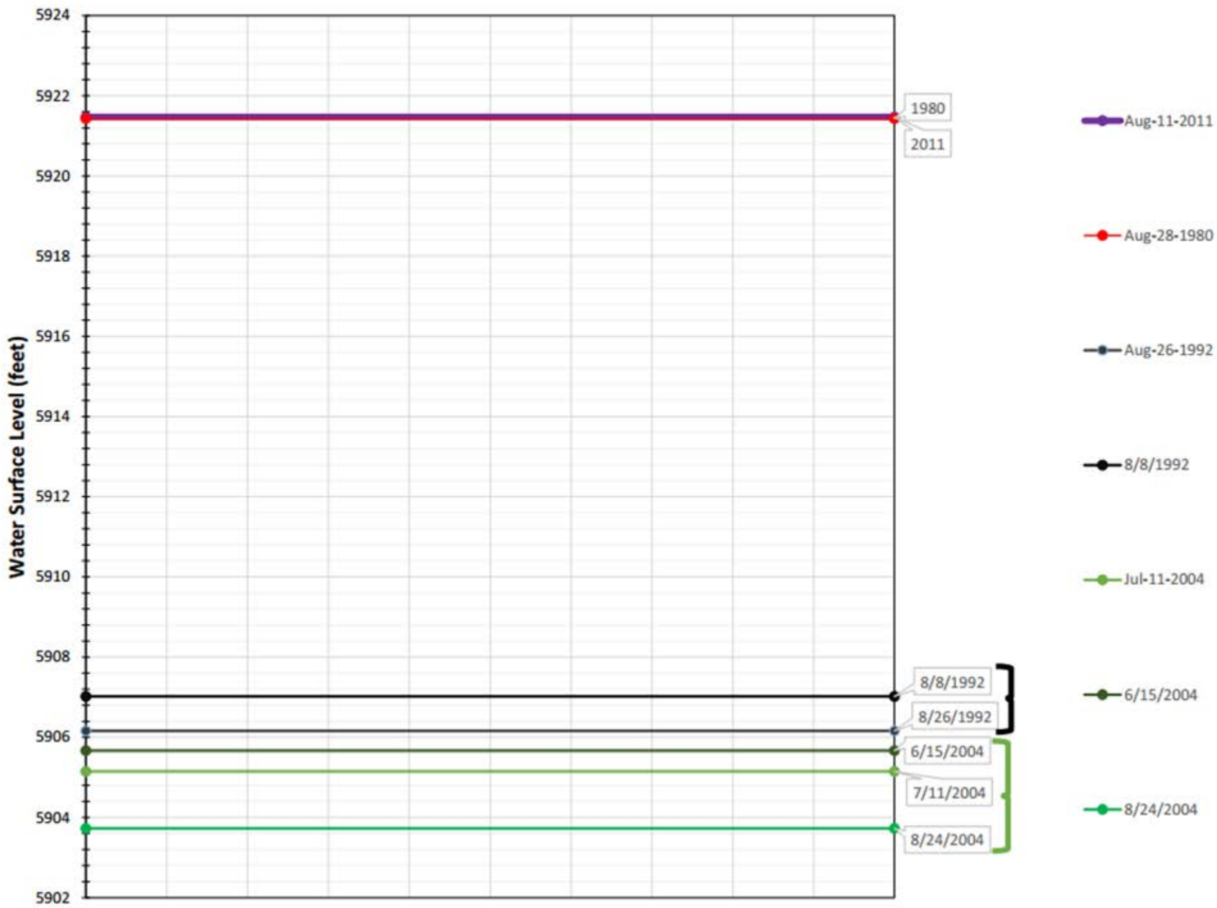


Figure 3.6.1. Bear lake water surface elevations for images acquired during 1980, 2011, 1992, and 2004. Each pair of images (1980/2011, and 1992/2004) were captured with similar water levels, allowing us to detect shoreline erosion and deposition by comparing shoreline delineations from each year.

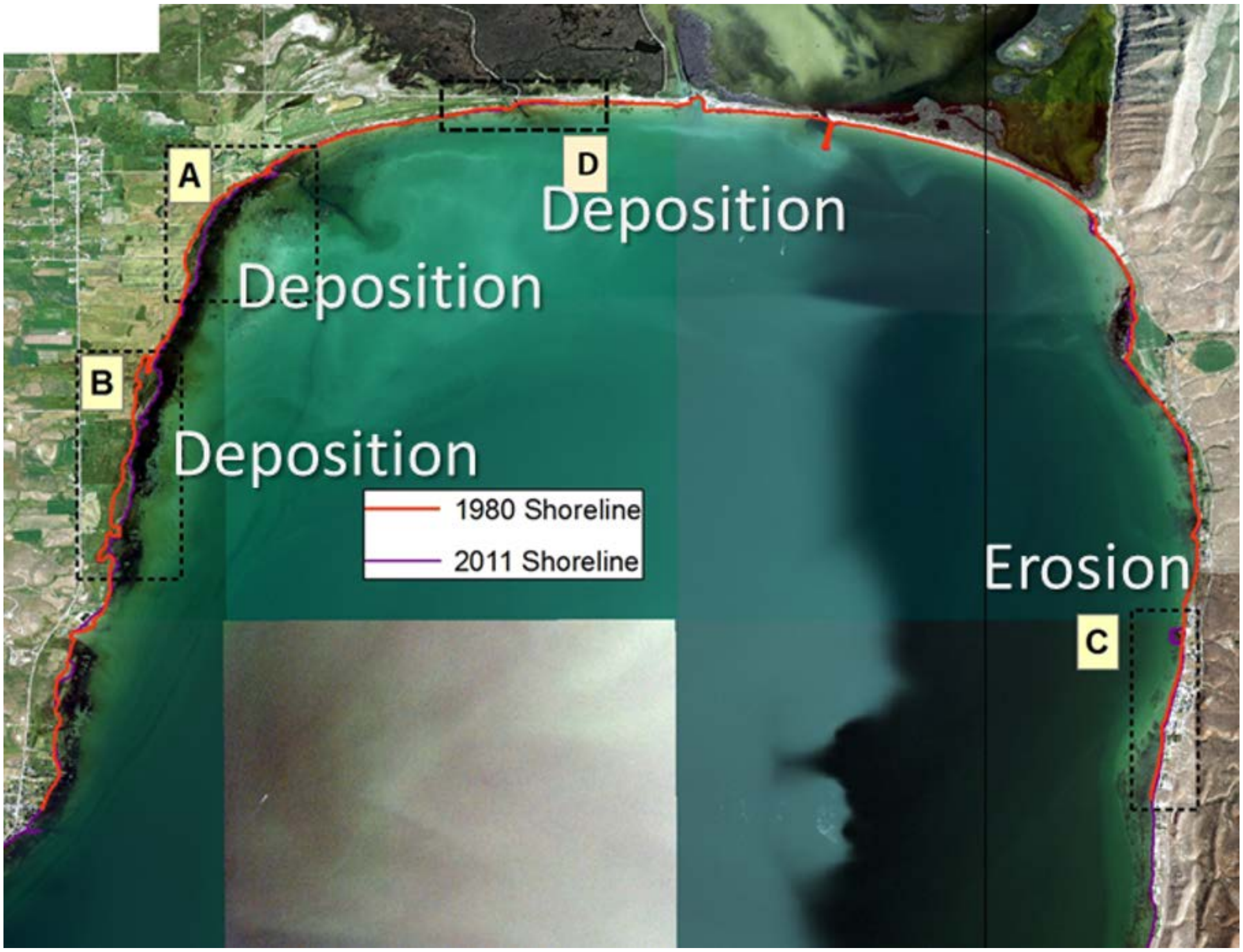


Figure 3.6.2. Lines indicate location of Bear Lake water shoreline in 1980 (red) and 2011 (purple). Image is from 2011. Black dashed boxes indicate locations of significant shoreline change, with the direction of change indicated.

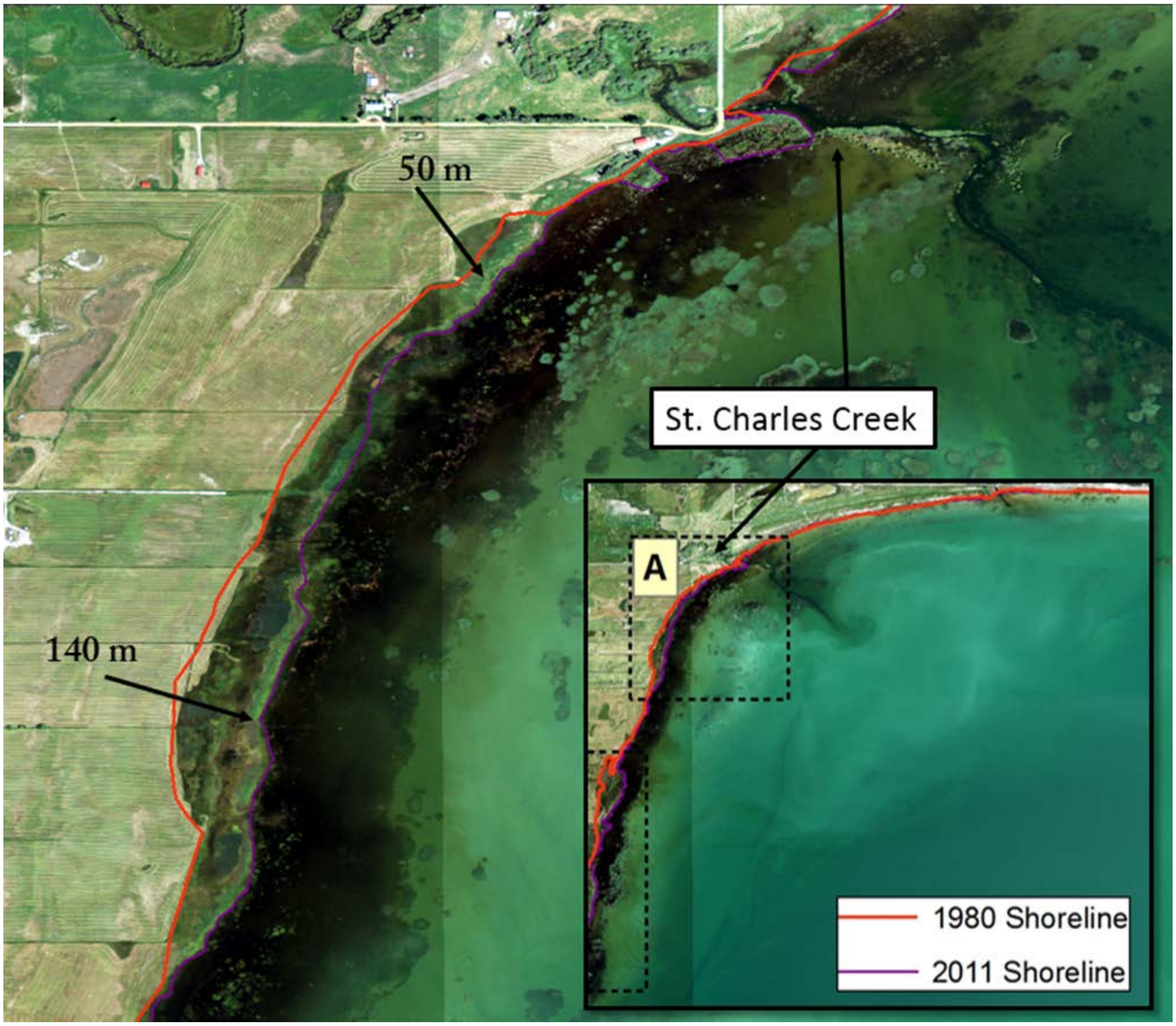


Figure 3.6.3. (Inset) The Northwestern corner of Bear Lake (indicated as area A in Figure 3.6.2), south of the St. Charles Creek tributary. (Main) Overlapping images were used to delineate shorelines for 1980 (red) and 2011 (purple). Comparing shoreline delineations for images with similar water levels allowed us to detect areas of erosion or deposition. Subsequently, we used a lidar-derived DEM to estimate the volume of sediment deposited in this area of most significant change.

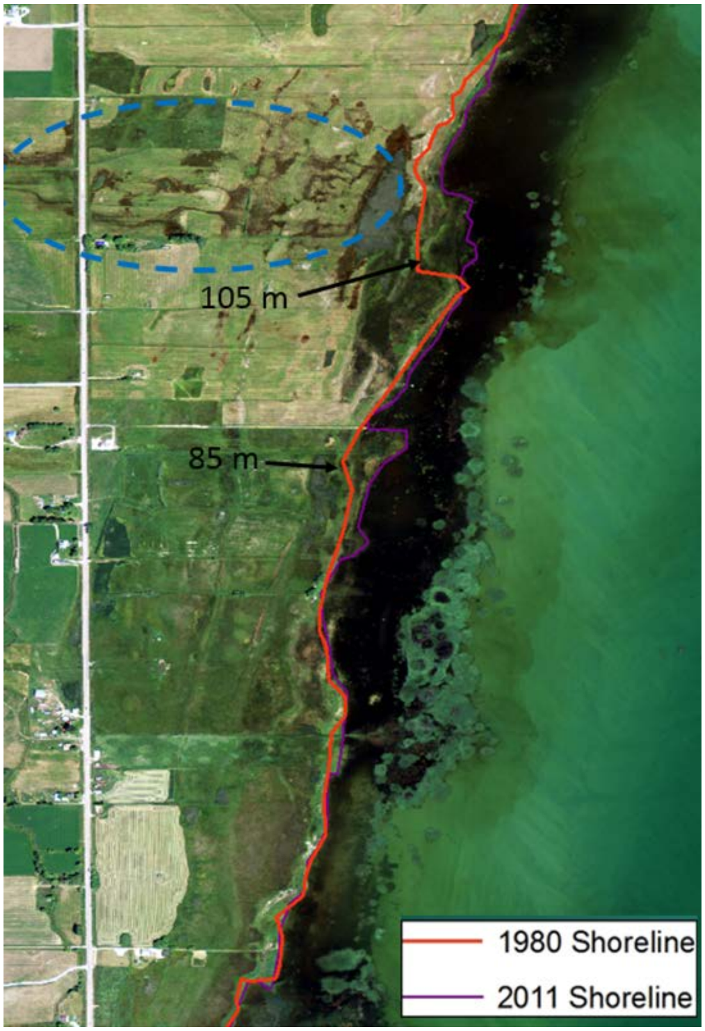


Figure 3.6.4. Deposition has accumulated in localized areas along the western shoreline in this area (indicated as area B in Figure 3.6.2) to the south of the area shown in Figure 3.6.5. Highlighted in blue dashed lines is an area that appears to have experienced erosion, which could be partly responsible for sediment deposited at the shoreline.

Figure 3.6.5. Along the eastern shoreline of Bear Lake (south of the Marina at the outlet of Cooley Canyon, indicated as area C in Figure 3.6.2), there appears to be a long stretch of shoreline that experienced net erosion between 1980 and 2011. This shoreline erosion may be the result of broad-scale flow currents and wind directions, or local human activities built up along the shoreline.

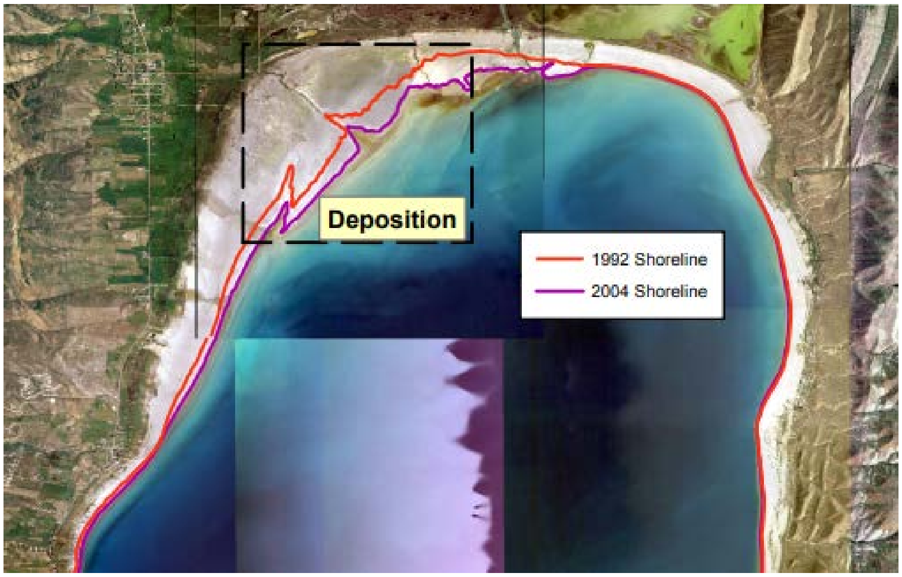


Figure 3.6.6. Lines indicate location of Bear Lake water shoreline in 1992 (red) and 2004 (purple). Image is from 2004. Black dashed box indicates the area with the most significant shoreline change, in the northwest corner of the lake.

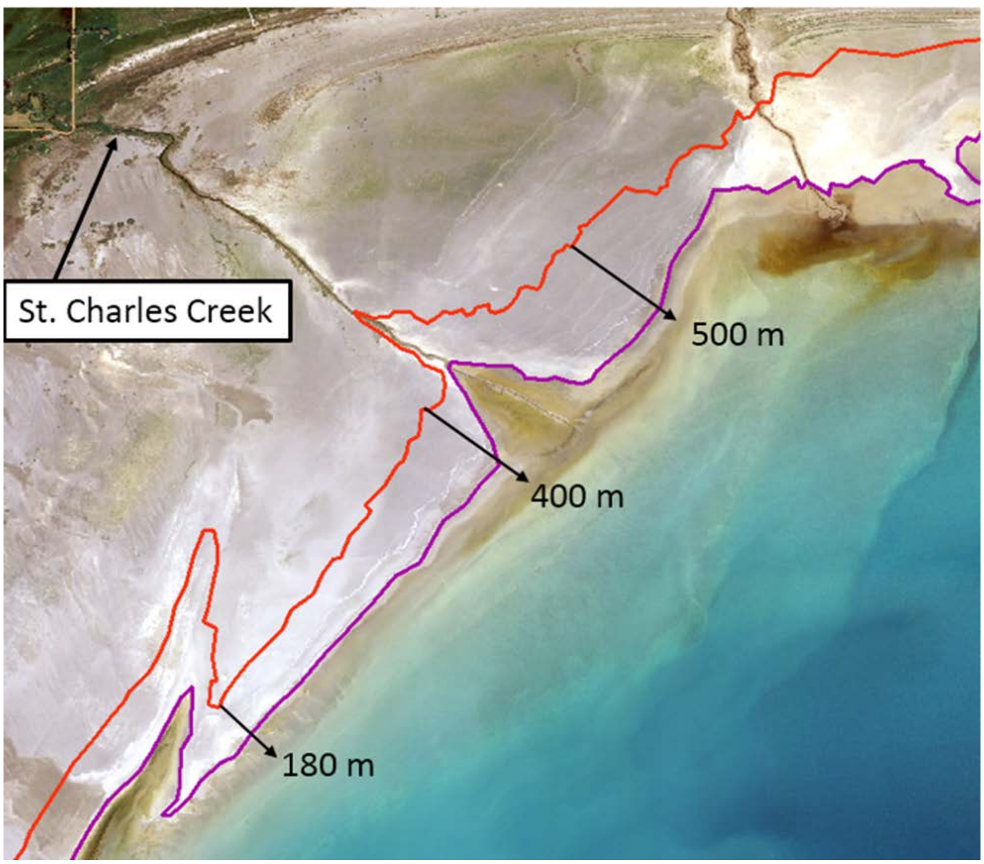


Figure 3.6.7. Deposition along the NW corner (site A in Figure 3.6.6) appears to be considerably larger at lower water elevations. Exacerbated deposition at lower lake levels may indicate that the sediments in this area are primarily fine-, rather than coarse-grained, because they are transported farther towards the lake center before dropping out of suspension.

Section Conclusions and Remarks

The Bear Lake shoreline has moved inward, indicating deposition in various locations around the lake at both high and low lake levels. Lakeward migration of the shoreline appears to be greatest at low lake levels with the shoreline having moved lakeward as much as 500 m (1600 feet) in the northwest corner. Repeat bathymetric mapping would help us track erosional and depositional areas throughout the lake. It was not possible within the scope of this project to determine the grain size or provenance of sediment deposited along the shoreline, but this would provide useful information regarding sediment sources, transport mechanisms, and implications for vegetation and recreational uses of the lake and beaches.

3.7. How has vegetation along the shoreline changed over time?

Vegetation naturally colonizes terrestrial surfaces with appropriate amounts of water, nutrients and oxygen. In lake ecosystems, vegetation near the shoreline can play an important role in nutrient and carbon dynamics. Sand beaches, which are of great recreational value at Bear Lake, are kept free from vegetation by submergence under water during critical times in the growing season, as well as wave action physically removing seeds and plants, as well as human management actions that clear or kill vegetation. Thus, there is a potential conflict between maintaining natural vegetation stands to support wildlife and lake ecosystem processes and the high recreational value placed on unvegetated, sandy beaches. In addition, some vegetation types are invasive and may have detrimental impacts on wildlife and lake ecosystem processes. Thus, it is not the objective of this project to provide a detailed analysis of vegetation type and change over time and cost-benefit analysis of the ecological versus recreational values of vegetation and sandy beach. However, knowing whether and how the extent of vegetation cover has changed over time can serve as a basis for deciding whether or not it would be useful to further investigate beach-vegetation dynamics in order to support future decision regarding beach and vegetation management policies.

To evaluate whether and how vegetation cover has changed, we obtained aerial photographs from 2003, 2006, 2012 and 2016. We focus our analysis on the northwest corner of Bear Lake as that is the region that has experienced the most change in shoreline at low flow conditions, as discussed in section 3.6. We mapped the full extent of unvegetated sand beach area in 2003 during low water stage conditions. Maintaining a consistent boundary on the lakeward side of the area (irrespective of where the water line occurred in each subsequent year), we mapped changes in vegetation along the outer edge of the beach as well as patches of vegetation that colonized areas within the beach polygon. We computed the area of the total beach polygon in each subsequent year and subtracted out area within the polygon that had been colonized by vegetation. Results indicate that between 2003 and 2016 approximately 10% of the sandy beach area mapped in 2003 (approximately 3.7 square miles of beach) had transitioned to vegetation cover by 2016. Due to timing constraints of the project and high water levels we were unable to conduct any field validation of the mapping or determine what kind of vegetation species have colonized these areas. All imagery and GIS shapefiles generated as part of this analysis are available from our public data archive: https://usu.box.com/v/belmontbearlake

Figure 3.7.1. Shows the total extent of sandy beach mapped from the 2003 aerial photo in the vicinity of St. Charles Creek in the northwest corner of Bear Lake.

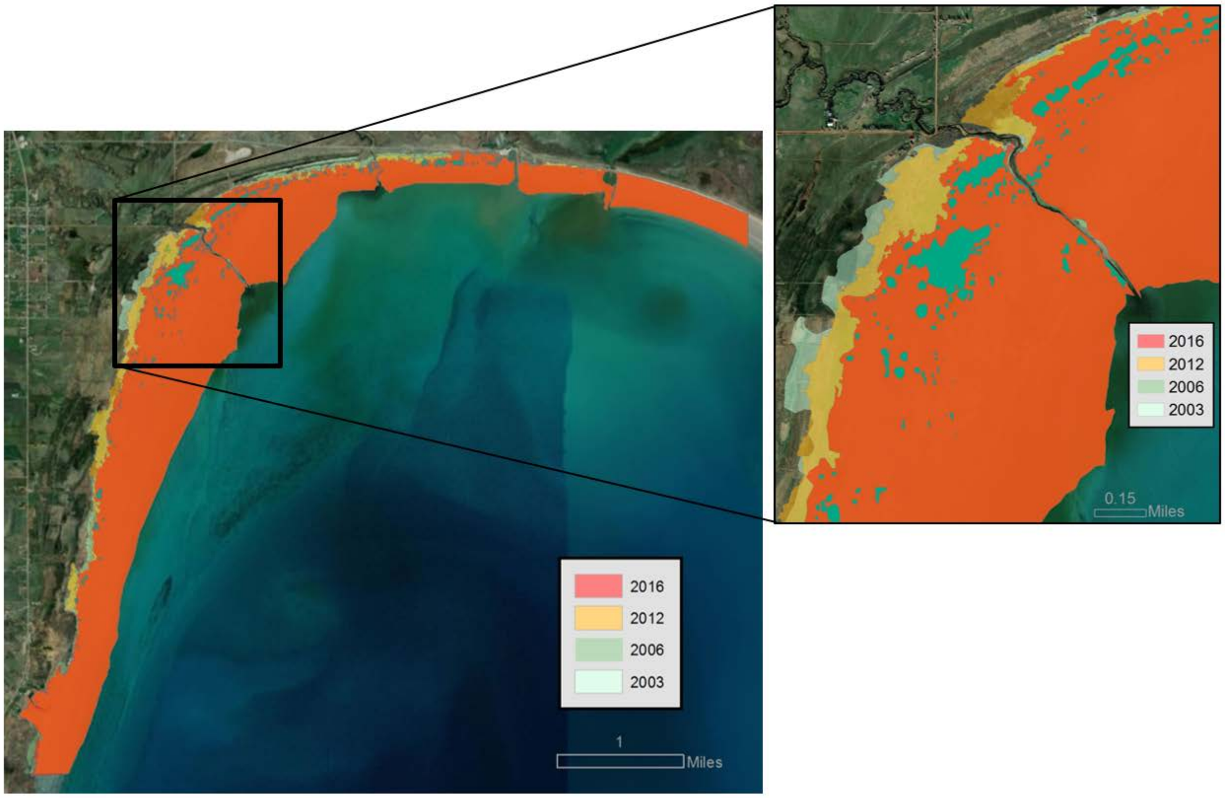


Figure 3.7.2. Shows area mapped as sandy beach for all four air photos. Vegetation encroachment on the beach can be observed at the outer boundary as the vegetation-beach transition moves inward with each subsequent year. Vegetation that colonized areas within the beach are mapped in dark green.

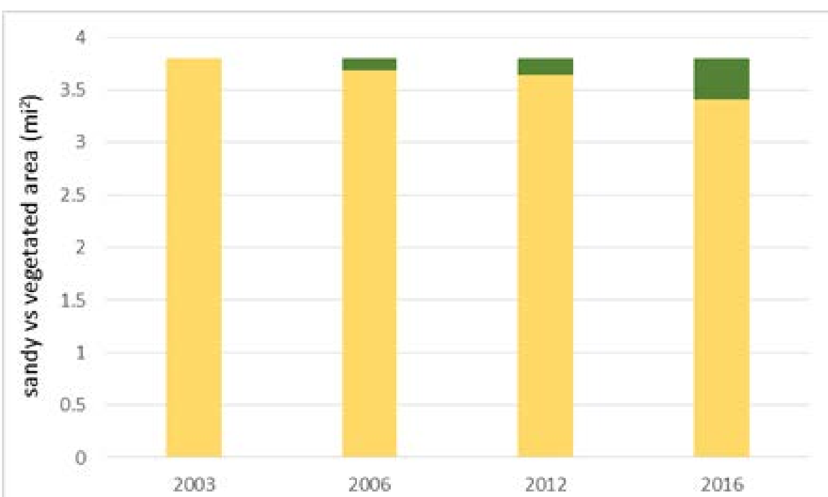


Figure 3.7.3. In total, approximately 10% of sandy beach area (yellow, totaling 3.7 square miles in 2003) transitioned to vegetation cover (green) during 2003 to 2016.

Section Conclusions and Remarks

Approximately 10% of sandy beach area transitioned to vegetation cover during the period 2003 to 2016 in the vicinity of St. Charles Creek in the northwest corner of Bear Lake. This analysis does not place a value judgement on whether that transition is beneficial or detrimental. However, the transition to vegetation is substantial and these data provide some initial information that suggests more careful mapping of vegetation type may be worthwhile. Such additional study could provide insights regarding the costs, benefits and detriments of vegetation-beach dynamics and inform decisions about future vegetation and beach management.

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