A PALEOLIMNOLOGICAL INVESTIGATION OF HISTORICAL ENVIRONMENTAL CHANGE IN EAST CANYON RESERVOIR

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

East Canyon Reservoir is located 32 km east of Salt Lake City, Utah, and serves as a resource for irrigation, culinary water, and recreation. This research used paleolimnology and historical records to investigate the impacts of multiple stressors, including land clearance, dam construction and enlargement, and climate warming on East Canyon Reservoir. Recently, blue green algal blooms, typically indicative of eutrophication, have been increasing at East Canyon Reservoir despite reductions of nutrients from point sources, so part of the impetus for this study was to understand the forcing mechanisms of these blooms. A multiproxy analysis of three sediment cores retrieved from the reservoir determined changes in nutrient concentrations and sediment composition over time. Percent organics, magnetic susceptibility, and diatom analyses of ^{210}Pb dated cores were compared to measurements of temperature and precipitation as well as records of historical land use, which were determined using remote sensing. Percent organics and magnetic susceptibility showed changes related to dam construction and increased development. Fossil diatom assemblages indicated that East Canyon Reservoir had been eutrophic since origination; however, principal components analyses of the diatom data indicated that the canyon became more P-enriched following dam construction and increased development. Recent increases in *Cyclotella* diatoms indicate changes related to warming temperatures, and we speculate that this warming is also what is causing blue-green algal blooms to increase.

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CHAPTER 1

INTRODUCTION

1.1 EPA Standards for Water Quality

There are two main threats to water resources in Utah: drought and eutrophication. Drought reduces water quantity, and in Utah, which is the second-driest state in the country, this is particularly true (Utah Department of Agriculture and Food, 2010). Water resource shortages can be detrimental to private, commercial, and industrial agencies. Eutrophication, which is the degradation of water quality as a result of increased nutrients, is also prevalent in Utah owing to a variety of human activities (Utah Division of Water Quality [UDWQ], 2002). The EPA has designed a strategy to assess the quality of water bodies in the United States. This includes an assessment of water quality and an assessment of the use of water, called beneficial use. Total maximum daily load (TMDL), a regulatory term in the U.S. Clean Water Act (CWA), describes the maximum quantity of pollutant that a body of water can receive and still meet water quality standards (Virginia Cooperative Extension, 2009).

Water resources provide drinking water and recreational opportunities, sustain wildlife, and support agricultural activities. The state—in this case, Utah—assesses the quality of its surface water resources by measuring nutrients, such as phosphorus, dissolved oxygen, and nitrogen on an annual or biannual basis (UDWQ, 2002). The data are compared to state water quality standards that are determined by Utah Division of Water Quality (UDWQ) Ambient Water Quality Criteria Recommendations, which are the standards of acceptable nutrient levels in a water body within the United States, set to ascertain beneficial use support (Environmental Protection Agency [EPA], 2000). The beneficial support categories are predetermined, and a water body is protected for its use for the long term. The beneficial use of water is defined under federal law in the Clean Water Act as the following: (a) sustainability of a water resource as a water supply source; (b) a water resource's ability to support fish and shellfish; (c) the ability of a water resource to support its wildlife habitat; (d) the ability of a water resource to be used as a recreational source (primary contact recreation, sport fishing, boating, and aesthetic enjoyment); (e) the ability of a water resource to support commerce and navigation activities; and (f) the water resource's ability to be aesthetically pleasing (EPA, 2010).

Eutrophication is increasingly becoming a problem for lakes and reservoirs, and East Canyon Reservoir is no exception. It is reported that pollution in East Canyon Reservoir has increased due to the stresses of drought. Nutrients are concentrated as water levels decrease and water residence time increases. The continuous drought of the 1990s and a 52% increase in population and development over the last decade placed tremendous stress on this watershed. Urban growth, along with predicted 80% growth for the future, particularly in Park City and Jeremy Ranch, could cause East Canyon Reservoir to deteriorate further from its current state (UDWQ, 2000). As a result of these multiple stressors, a TMDL was developed for East Canyon Reservoir.

A TMDL assesses an aquatic ecosystem's basic biological, chemical, and physical factors. By regulation, a TMDL is defined as a calculation concentrating on one specific area of a water body and one pollutant (Shipp & Cordy, 2005). However, this assessment has been expanded to refer to entire watersheds and multiple pollutants. Water-quality data collected over the short term year are used to determine the TMDL. Beneficial-use and watershed-specific factors determine other parameters including, but not limited to, bacteriological issues from water and sediments (Commission on Geosciences, Environment and Resources [CGER], 2001). The current nutrient and historical data gathered for the TMDL are used to raise awareness of water quality issues within communities that surround the water resources; identify impaired waters; and establish water quality goals for restoring and/or protecting water quality (EPA, 2010). This report is used to determine the nutrient levels for discharge permits and to assure that the permit requirements are being met for point sources.

The TMDL determines the approximate amount of pollution input at point and nonpoint sources. Point sources are direct sources of pollution into a water body permitted by the National Pollutant Discharge Elimination System, and nonpoint sources are indirect sources of pollution such as grazing, sediment input, and agricultural runoff. In Utah, the Department of Water Quality (UDWQ) then takes the TMDL nutrient concentrations and the standards set by the Clean Water Act and the UDWQ to determine acceptable nutrient levels in the water body for nonpoint and point sources, the natural background, and an additional measure for safety (Virginia Department of Environmental Quality [VDEQ], 2007). Using those data, a management plan aimed at returning the water body to acceptable nutrient levels is developed and implemented (EPA, 2010). The weakness of this approach is that it is independent of knowledge of the natural variability and baseline conditions of the system. Paleolimnology and remote sensing can provide a historical perspective that is rarely available from actual measurements of water quality, owing to an absence of long-term monitoring. Knowing the history of the reservoir will also provide more realistic goals for watershed remediation (Smol, 2008).

1.2 The State of Knowledge of East Canyon Reservoir

East Canyon Reservoir is located in the Wasatch Range, part of the Rocky Mountains, and extends from central Utah northward into Idaho (UDWQ, 2000). There are no previous historical assessments of East Canyon Reservoir, but access to the lake provided by funding from the Utah Bureau of Reclamation and the availability of historical remote sensing coverage for the reservoir make East Canyon Reservoir an ideal candidate for using a combination of sources, paleolimnological and remote sensing data, to determine the causes of recent eutrophication.

In 1998, East Canyon Reservoir and East Canyon Creek, the main tributary of the reservoir, were placed on the EPA's list of impaired waters for total phosphorus and dissolved oxygen (UDWQ, 2000). This action by the EPA mandated a TMDL analysis for the impaired water body. The TMDL analysis for East Canyon Reservoir indicated that optimal total phosphorus concentrations in the reservoir were 0.025mg/L, but East Canyon Reservoir's average lake concentration based on measurements taken at monitoring station 4925160, closest to the dam, from 1994–1997 was 0.117mg/L (Judd, 1999). The TMDL suggested acceptable nutrient concentrations for East Canyon Reservoir; however, a lack of long-term monitoring meant that there was no information on natural variability or baseline conditions to assess whether this "acceptable" concentration was a realistic goal.

The impacts resulting from increased nutrients include degraded water quality, increased algal blooms, and a reduction in trout population. Since 1994, blue-green algae have been increasing, and the Trophic State Index (TSI), a measure of water quality, has been in the low 50s (UDWQ, 2000). TSI is based on total phosphorus, Secchi depth, and chlorophyll a values, and a value of greater than 50 indicates a eutrophic state. The Clean Lakes study (Olsen & Stamp, 2000) indicated that dissolved oxygen is significantly depleted in the lower portions of the water column in East Canyon Reservoir most of the year. The increased nutrients, resulting anoxia, and warmer temperatures decreased the rainbow trout population by 46% from 1988–1993 (UDWQ, 2000). In order to repair the damage to East Canyon Reservoir, the causes of the pollution and increased nutrients must be identified.

In East Canyon Reservoir, nutrients come from both point and nonpoint sources. The single point source for the reservoir is the East Canyon Waste Water Treatment Plant, located at the top of East Canyon just north of I-80. In 2001, the plant upgraded its facility by adding a membrane filtration system to decrease its contribution of phosphorus to the reservoir (Mike Luers, personal communication, 2004), which improved the removal of microorganisms (“High and Dry,” 2002). The nonpoint sources are runoff from agriculture, grazing, storm water, urban waste, and recreation. Of these, storm water runoff from construction sites contributes the most nutrients (UDWQ, 2008). The Snyderville Bureau of Water Reclamation has implemented stipulations to help reduce runoff and decrease nutrients, specifically phosphorous input into East Canyon Creek and Reservoir (East Canyon Watershed Committee, 2004).

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1.3 Paleolimnology

Paleolimnology, the study of past lake conditions and processes, is a multidisciplinary field that uses various biological, physical, and chemical indicators in lake sediments to understand environmental change (Last & Smol, 2001). Can these same techniques be as effective when applied to reservoirs? Sedimentation rates for most natural lakes are 0.05 to 10mm/yr $^{-1}$, and reservoir sedimentation rates are approximately 20mm/yr $^{-1}$ (Shotbolt, Thomas, & Hutchinson, 2005). The greater sedimentation rate limits the effects of postdepositional mixing, diagenesis, and preservation of a more detailed chronological record (Bradbury & VanMetre, 1997). The disadvantages of using paleotechniques in reservoirs are the relatively short histories and problems with aeration and dam building that can disturb records. Therefore, careful consideration of coring locations and a thorough understanding of the reservoir's history and management are required. Paleotechniques including percent organics, magnetic susceptibility, and diatom analysis can be used to track changes in the lake over time as a result of changing human activity in the lake catchment. In order to document past human activities, historical records and remote sensing are used to inventory and monitor natural resources and land use changes on local and regional scales (Campbell, 1996; Lillesand, Kiefer, & Chipman, 2004). In this study, remote sensing images from 1960–2000 along with paleolimnology will be used to try to better understand the links between landscape change and eutrophication in East Canyon Reservoir.

1.4 Research Questions

The research presented here provides information on water quality for East Canyon Reservoir from its original construction in 1896 to the present. A paleolimnological, multiproxy approach of three sediment cores retrieved from the reservoir is used to provide a greater understanding of the processes causing the reservoir to become eutrophic.

The hypotheses are as follows:

1. (H_0) Erosion and nutrients at East Canyon Reservoir have increased over time.

   (H_1) Erosion and nutrients at East Canyon Reservoir have not increased over time.

   Magnetic susceptibility will be used to track erosion and percent organics, and diatom analyses will provide records of productivity and nutrients.
2. (H_0) If erosion and nutrients have increased, this is due to increased development in the catchment.

   (H_1) If erosion and nutrients have increased, this is not due to increased development in the catchment.

   Landscape changes inferred from remote sensing images will be compared to water quality determined from diatoms.

CHAPTER 2

STUDY AREA

2.1 Geography and History

East Canyon Reservoir is located approximately 32 km southeast of Salt Lake City, Utah, USA (40^{o}47'N 111^{o}57'W). The reservoir is located in the Wasatch Range, which is part of the Rocky Mountains and extends from central Utah northward into Idaho. East Canyon Creek Watershed spans both Morgan and Summit Counties (UDWQ, 2000). Elevation of the reservoir is 1,707 m; however, south of the reservoir, elevations reach 3,048 m. Original construction of the dam was in 1896 followed by four enlargements in 1900, 1902, 1916, and 1966. In 1896, the capacity of the dam was 3,850 acre-ft, and in 1900 it was enlarged with 25 ft of additional rock-fill, increasing the capacity to 9,800 acre-ft. In 1902, an additional 12 ft of rock-fill was added, increasing the capacity to 14,000 acre-ft. In 1916, the rock-fill dam was left in place and a concrete dam was built, increasing the capacity to 25,790 acre-ft. In 1966, the 1916 concrete dam was left in place and a concrete, thin-arch dam was constructed, increasing the capacity to the present-day amount of 51,200 acre-ft (Sadler & Roberts, 1994; Figures 1, 2, and 3). The current East Canyon Dam is constructed of a concrete arch with a concrete volume of 35,716 cu yd. The crest elevation is 5715.0 ft, with a length of 436 ft and thickness of

Figure 1: East Canyon Dam, Fall 2004.

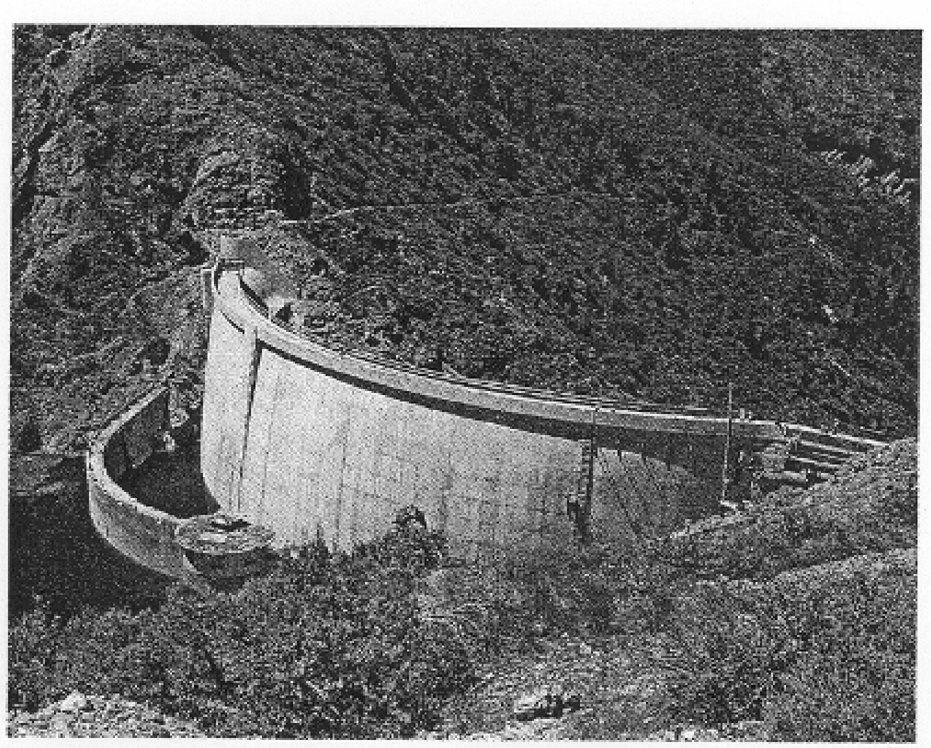


Figure 2: The 1915 and 1964 East Canyon dams. From *The Weber River Basin: Grass Roots Democracy and Water Development*, by R. W. Sadler and R. C. Roberts, 1994, Logan: Utah State University Press.

Figure 3: The construction of East Canyon Dam in 1964 and 1966. From *The Weber River Basin: Grass Roots Democracy and Water Development,* by R. W. Sadler and R. C. Roberts, 1994, Logan: Utah State University Press.

7 ft. Structural height of the dam is 259.8 ft, and total water storage is 51,200 acre-ft. Presently, East Canyon Reservoir's average depth is 75 ft, with a maximum depth of 197 ft and a surface area of 684 acres (U.S. Bureau of Reclamation [USBR], 2009).

The Utah Department of Transportation does not have any supporting documents to indicate the exact dates of construction of State Route 65. The aerial photography acquired indicates that it was likely paved in the 1960s. The road is closed between November and March, dependent on weather conditions, on an annual basis. Road maintenance includes salting the road during the winter months and general maintenance.

Like most reservoirs, East Canyon was stocked with fish within 2 years of being built. Rainbow and tiger trout are the species of preference for the reservoir. Tiger trout did not thrive when introduced in the summer months, so they are introduced in the fall with rainbow trout. Sockeye salmon once thrived in East Canyon, but when the water quality deteriorated, so did this species. In recent years, sockeye salmon have not been spotted in sampling nets. In 2001 and 2002, small-mouthed bass and croupy were illegally introduced into the reservoir. Historically, the water quality has pushed the fish into the metalimnion, where they are plagued by a parasite, *Lernaea,* an anchor worm (UDWQ, 2006).

In 1979, construction of East Canyon Resort began, which is located on 9,600 acres surrounding the southern portion of the reservoir. The facility began operations in 1982 and operates year round. The resort consists of 32 condominiums and 84 RV hookups. There are recreational activities, including ATV and horse riding trails and a small fishing pond (East Canyon Resort, personal communication, 2010)

There have been significant flooding and drought events in Utah. Flooding has occurred in Morgan and Summit Counties three times, specifically in 1965, 1983, and 1986. In 1965 and 1986, there was flooding and flash flooding. In 1983, this event, along with severe thunderstorms, caused major damage, and a state of emergency was declared. The recorded droughts were statewide and occurred in 1930–1936, 1953–1965, 1974–1978, 1988–1993, and most recently, 1999–2004 (Hazards & Vulnerability Research Institute, 2010).

2.2 Geology

The bedrock in the area is composed of Norwood Tuff and Echo Canyon Conglomerate. The Norwood Tuff originated during the Oligocene and Eocene time periods and is composed of white to gray tuff, volcanic sandstone, and conglomerate with some lahars and thin flow breccias. This formation is 1000 m thick and located in the deepest part of the East Canyon Graben at the south end of Morgan City. The Echo Canyon Conglomerate is upper-Cretaceous-aged, composed of 800 m of pale-red, yellowish-gray cobble conglomerate that is composed of discontinuous lenses of coarse-grained sandstone. Intermittent intervals of gray sandstone, siltstone, and claystone are present throughout this formation (Bryant & Nichols, 1990). East Canyon Dam is located in a narrow canyon where East Canyon Creek has cut through massive beds of the Echo Canyon conglomerate. Two faults are located in the vicinity of the dam: An inactive fault is located 91 m upstream, and the Wasatch fault is located approximately 19 km west of the dam (USBR, 2009)

2.3 Climatology

Temperatures in the East Canyon Reservoir catchment vary with altitude; the mountains have cooler temperatures, whereas the lower areas have higher temperatures. There is about a 6–8 ºC decrease in mean annual temperature for each 305 m increase in altitude. The mean annual winter temperature is -7 °C, and the mean annual summer temperature is 16 °C (Western Regional Climate Center, 2006). In the area of the Wasatch Range, there is heavy precipitation, with an average annual snowfall of up to 1,270 cm (Powell, 1992). Average annual precipitation in the East Canyon Creek watershed ranges from 112 cm at the highest elevations located in the southern parts to 49 cm at lower elevations immediately adjacent to the reservoir (Brooks, Mason, & Susong, 1998). During the winter months of October to April, approximately 65% to 75% of the annual precipitation occurs in the form of snow (UDWQ, 2000). Stream flows for the watershed generally peak between March and June as the snow melts. The flows are mostly derived from groundwater discharges other times of the year (UDWQ, 2000; Western Regional Climate Center, 2006).

2.4 Hydrology

East Canyon Watershed is a subbasin of the Weber River Basin, which encompasses a significant amount of the Uinta and Wasatch Mountain Range. The Weber River originates in Summit County near Reid’s Peak in the western part of the Uinta Mountain range and continues 201 km to the northwest to the Great Salt Lake. East Canyon Watershed is located in the southwestern part of the Weber River Basin and drains 232 km of mountainous terrain. East Canyon Creek is the principal drainage flowing into East Canyon Reservoir; McLeod Creek, which flows from Park City into Kimball Creek, joins East Canyon Creek near Interstate 80. Additionally, smaller intermittent streams—Sawtooth Creek, Dry Pine Creek, and Taylor Hollow—surround the reservoir and contribute to the reservoir throughout the year (Terra Server USA, 2010).

2.5 Limnological Data

Dissolved oxygen and temperature, nitrogen (NO_3 + $N0_2$), phosphorous, chlorophyll a, salinity, and Secchi depth were measured by the Utah Division of Water Quality. East Canyon Reservoir's nutrient measurements were taken at Midlake Station (4925170) near the extraction site of Cores 2 and 3 (Figures 4 and 5). Nutrient data collection is dependent on the budget and reservoir significance for any given year and therefore was intermittent. An average of May–September values for all datasets was used, as those months would be most important to understanding biological changes at East Canyon Reservoir. It is important to note that the number of measurements for any given year varied, and that the timing of measurements was not consistent (Figures 6 and 7). Owing to the inconsistent collection of samples, it is difficult to compare measurements from one year to the next and identify trends. However, these data do provide some indication of the general condition of East Canyon Reservoir.

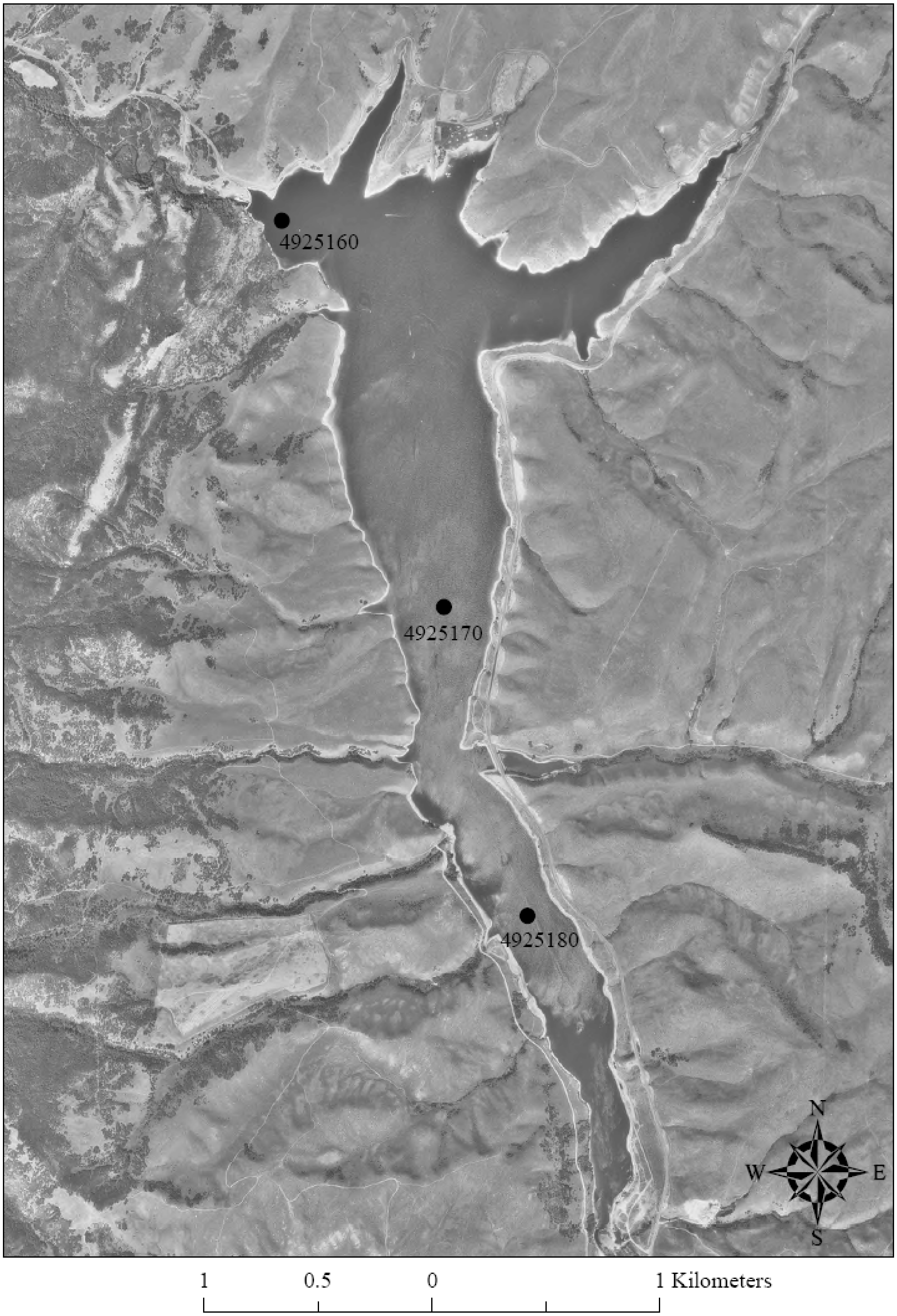
2.6 Vegetation

Sagebrush dominates the reservoir catchment, but there are a variety of shrubs, such as rabbit brush, that are dominant at elevations between 1219 m and 1524 m. In

Figure 4: East Canyon Reservoir sampling sites used to monitor nutrients in order to track water quality over time.

Figure 4 cont.

East Canyon Reservoir Nutrient Sampling Sites

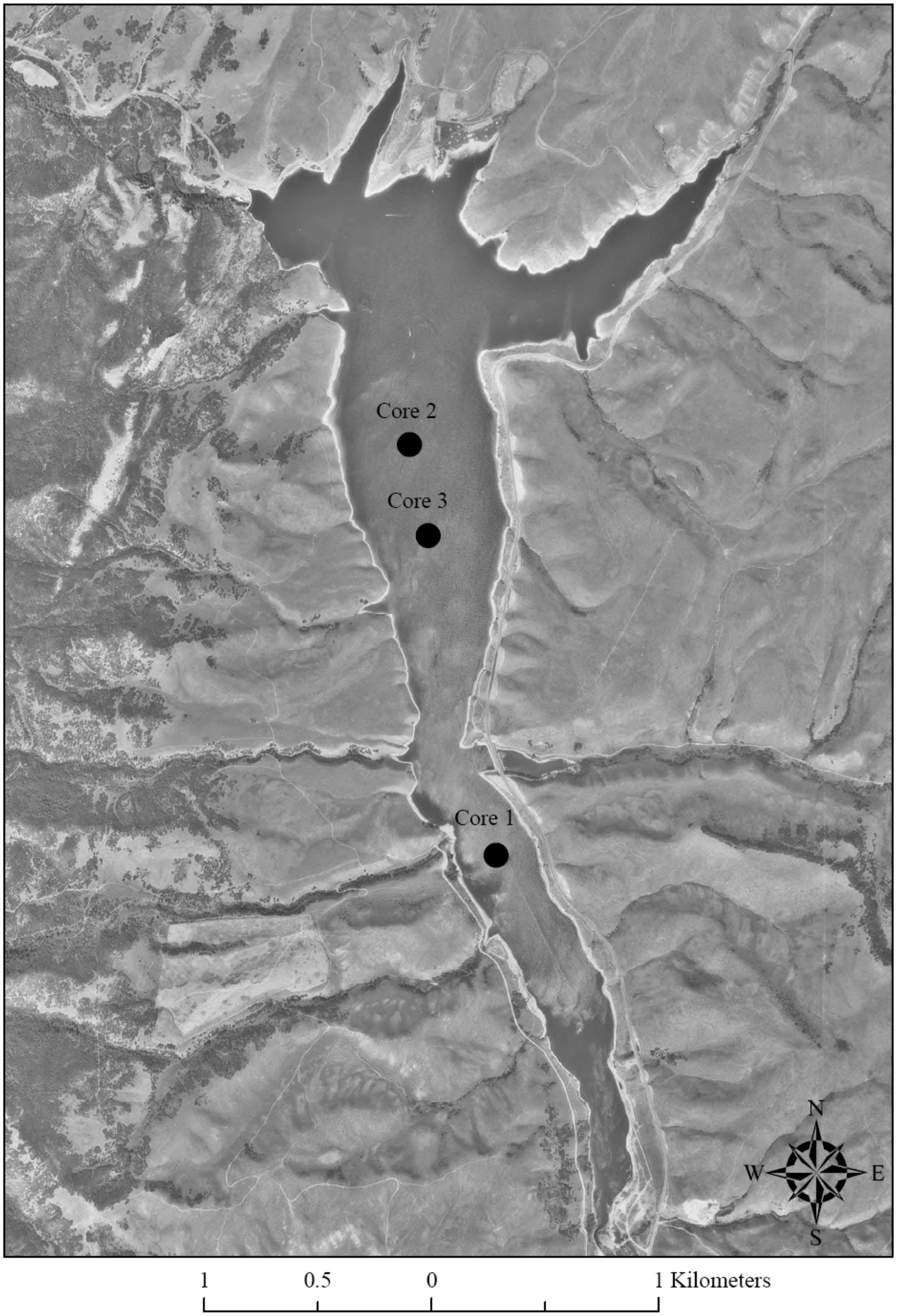


Data Source: Environmental Protection Agency and AGRC, 1997.

Figure 5: East Canyon Reservoir lake core extraction sites 1–3.

Figure 5 cont.

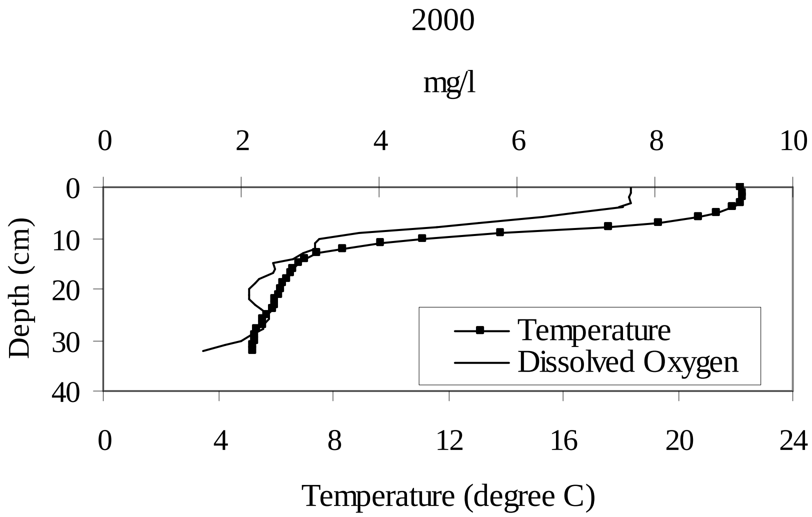
East Canyon Reservoir Lake Core Extraction Sites

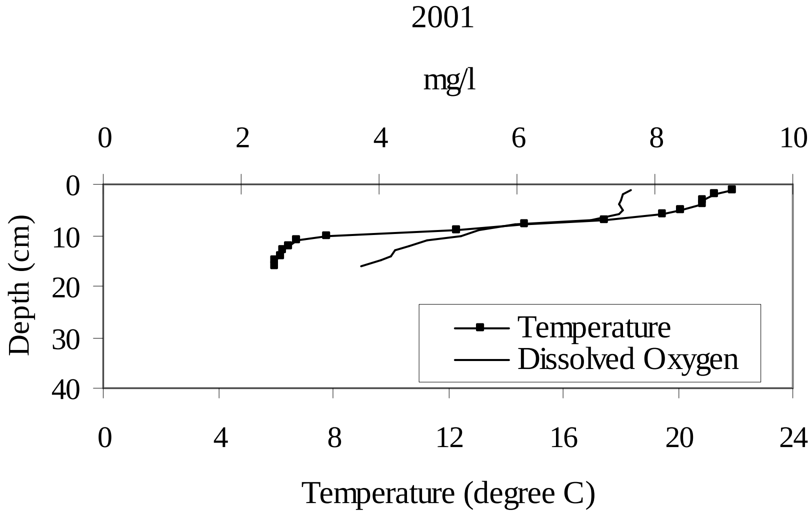


Data Source: Environmental Protection Agency and AGRC, 1997.

Figure 6: Temperature and dissolved oxygen plots of May–September averages for East Canyon Reservoir taken from Midlake Station # 4925170. The East Canyon Reservoir is thermally stratified in the summer but oxygen values in lower waters do not decrease to 0 mg/l. Oxygen curves for 2005 and 2006 indicate biological activity occurring at ~12 m; the peak in dissolved oxygen is likely related to a deep water phytoplankton population. Measurements taken by the Utah Department of Water Quality.

Figure 6 cont.





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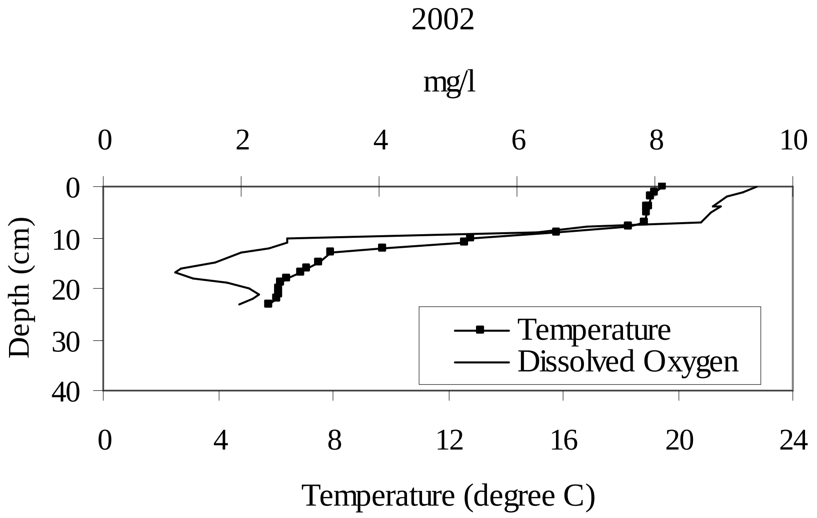

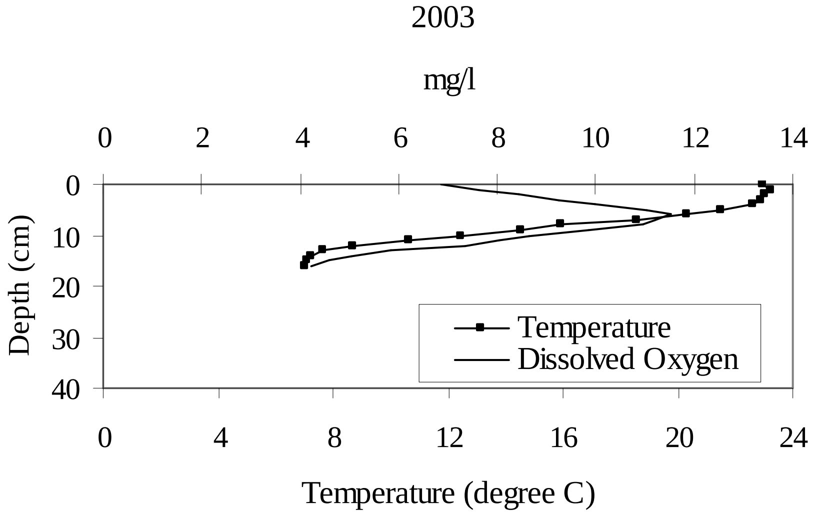

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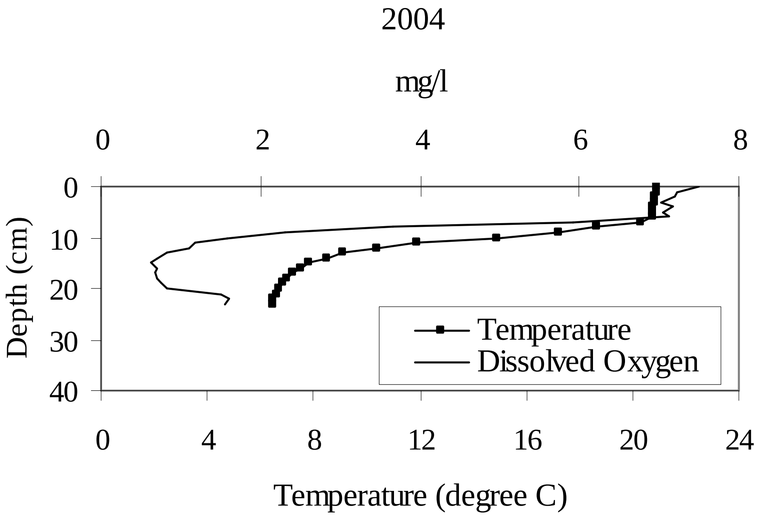
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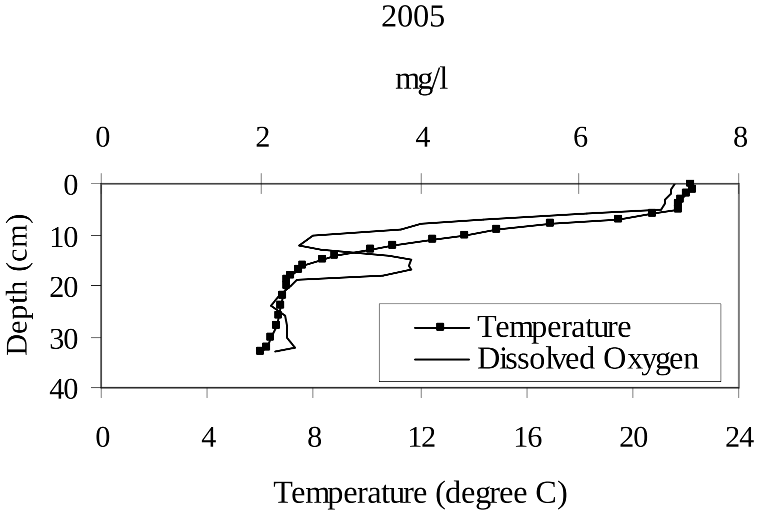
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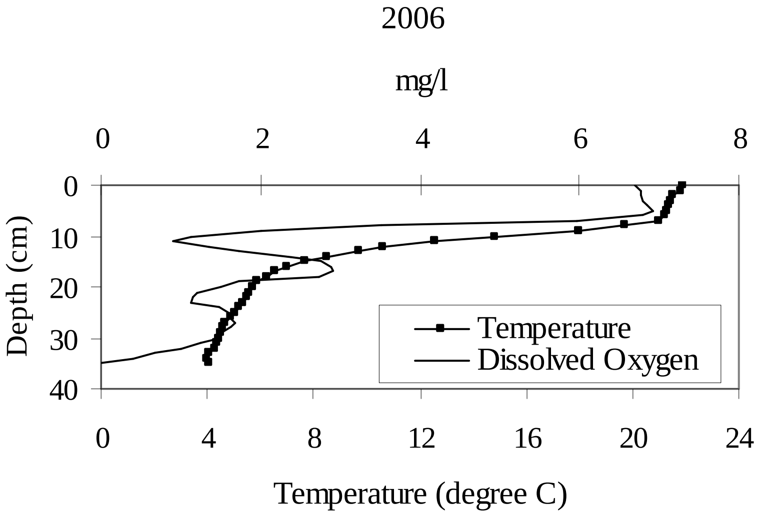
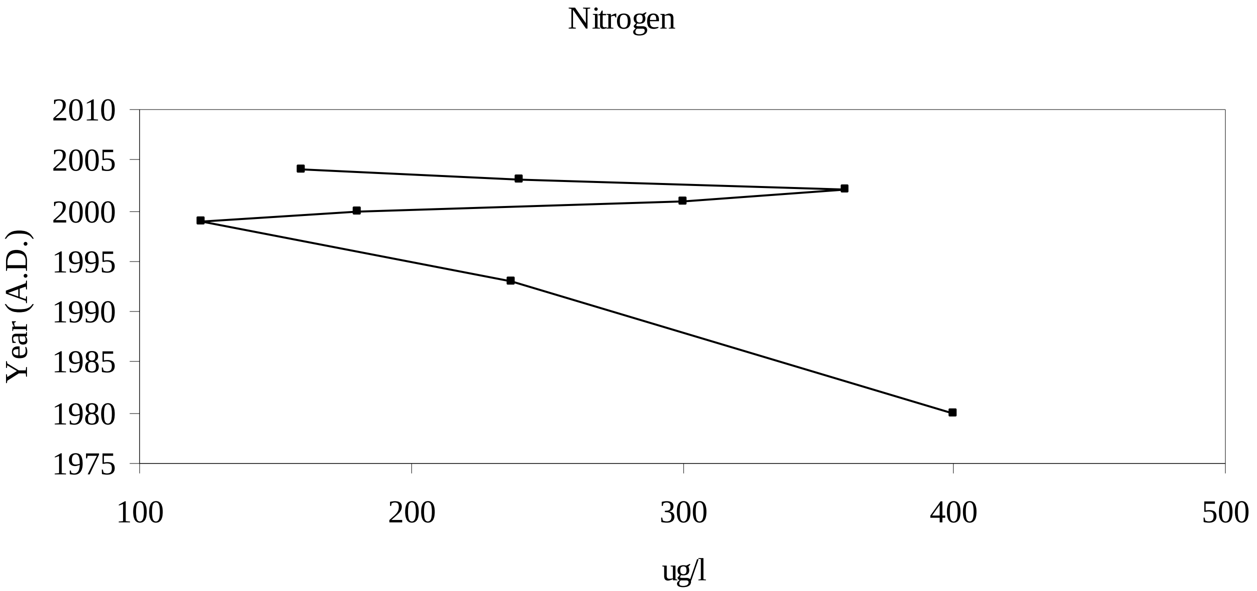


Figure 7: Variations in May-September averages for nitrogen, suspended phosphorus, chlorophyl a, secchi disk and salinity. Measurements were taken from East Canyon Reservoir Midlake Station # 4925170 by the Utah Department of Water Quality.

Figure 7 cont.



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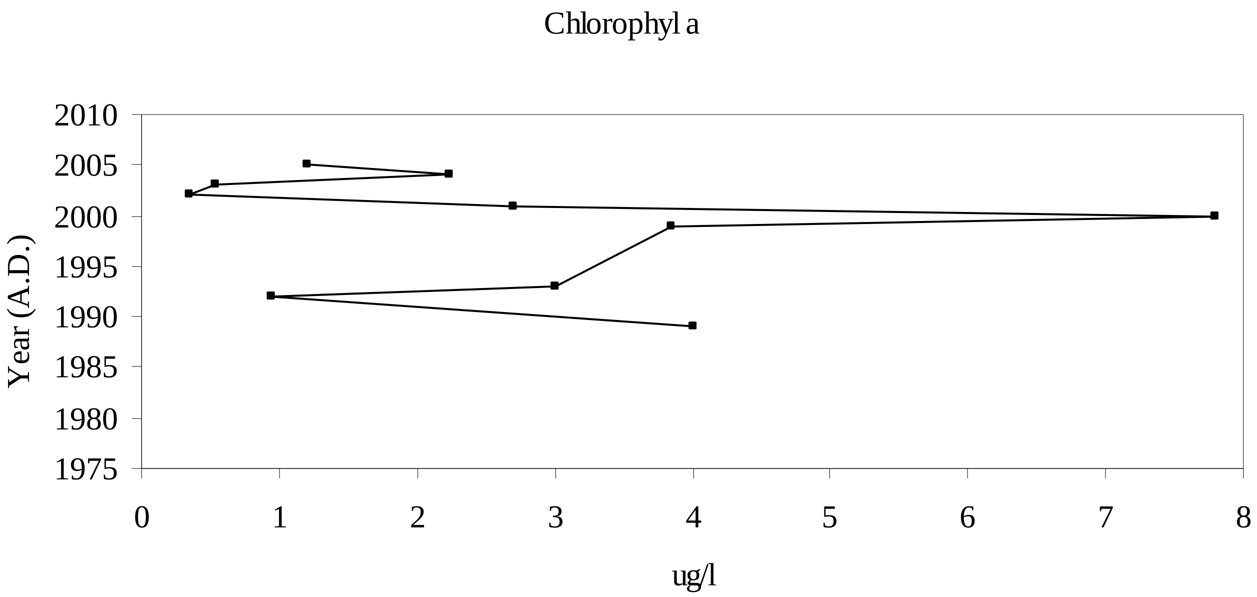

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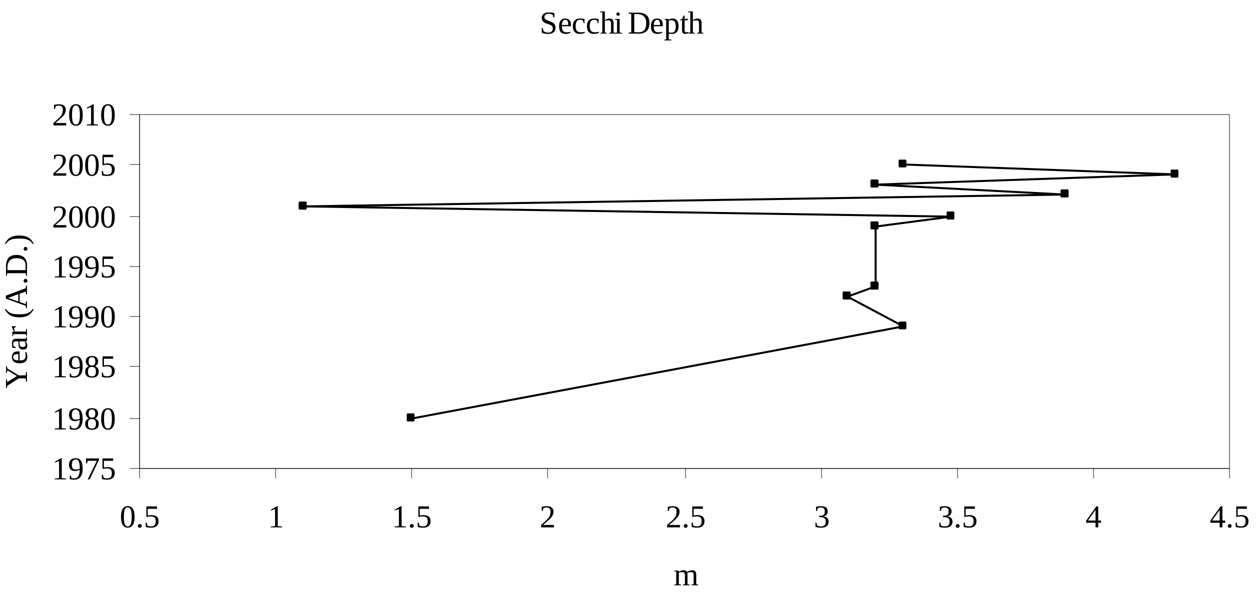

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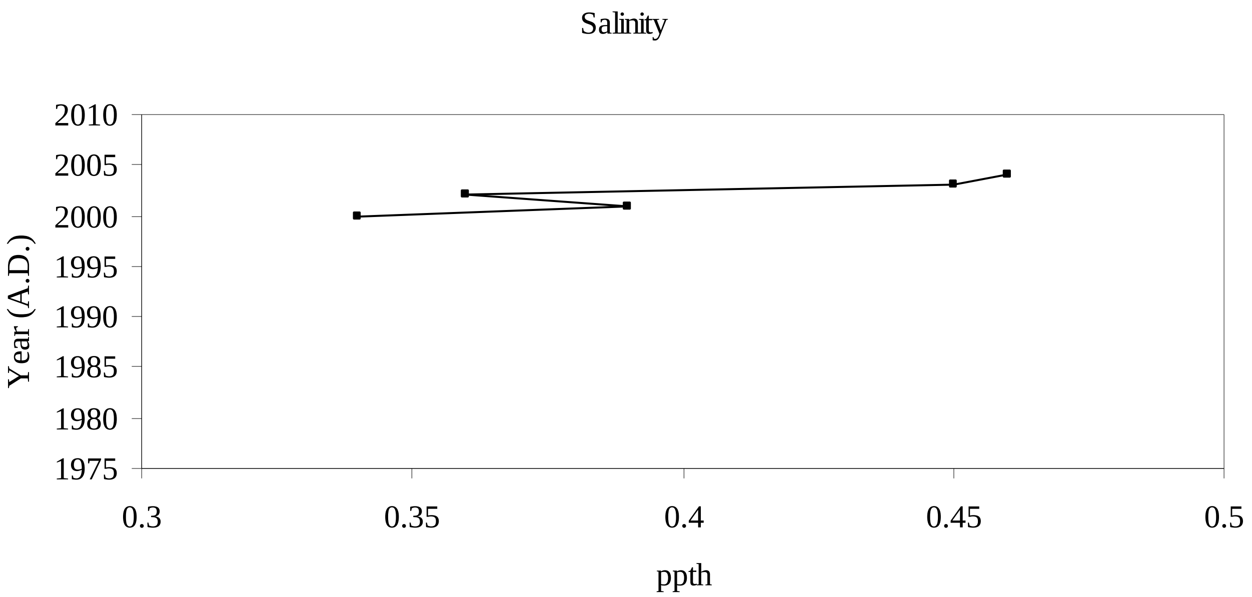


close proximity to the East Canyon Reservoir, the principal vegetation consists of Big Mountain Sagebrush and Antelope Bitter Brush and a variety of perennial and annual grasses. Cheatgrass, Japanese Brome, and Bulbous Bluegrass are the typical annual grasses, and the perennial species consist of Kentucky Bluegrass, Great Basin Wildrye, Sandberg Bluegrass, and Intermediate Wheatgrass (Utah Division of Wildlife Resources, 2010).

2.7 Recreation and Water Uses

East Canyon Reservoir is a significant resource for humans and wildlife. Recreational uses, which are diverse and go on throughout the year, include cross-country skiing, fishing, ice fishing, sailboarding, swimming, water skiing, picnicking, and camping. Hunting for deer and elk is very prevalent during the fall season. In 1992, the state park recorded 108,395 visitors, ranging from 252 in December to 25,716 in June (UDWQ, 2006; U.S. Department of Agriculture [USDA], Soil Conservation Service [SCS], & Forest Service [FS], 1974). Additionally, the reservoir supports local farming downstream with water for irrigation (90%) and, to a lesser degree, culinary water (10%) (UDWQ, 2006).

CHAPTER 3

METHODS

3.1 Climate Measurements

3.1.1 Temperature and Precipitation Data

Temperature data from two SNOTEL sites, Horseridge and Hardscrabble Canyon (1971–1985 and 1971–1994), with a range in elevation from 2210 m to 2286 m, and from the National Climatic Data Center (NCDC; 1895–2004, a statewide average) were analyzed. Both temperature and precipitation data for NCDC (2010) and SNOTEL National Resources Conservation Service (NRCS) national water and climate data can be found at their corresponding websites. The Hardscrabble Canyon SNOTEL site, data for which cover 1994–2005, is more proximal to East Canyon Reservoir but is ~610 m higher in elevation. Temperature data for the state of Utah are from NCDC for 1895–2004 from an average of 75 stations throughout Utah (NCDC, personal communication, 5/1/2004). Comparing the SNOTEL data to the NCDC data, one sees similar trends; however, because of elevation differences, the SNOTEL temperatures were generally 6–8 ºC lower, and precipitation was greater. The NCDC has the longest historical record, and because the trends are comparable between the two datasets, the NCDC data will be used herein.

Precipitation data were available from the SNOTEL and NCDC sites, and for reasons described above, the NCDC data were used. So that the temporal resolution of the precipitation data would be comparable to that of the paleolimnological data**,** a 5-year running average for temperature and precipitation data was calculated.

3.1.2 Reservoir Volume

Reservoir volume data were acquired from the Bureau of Reclamation. The measurements were made in acre-feet and recorded intermittently from 1932 to 2003. A 5-year running average was applied to these data to make the temporal resolution comparable to that of paleolimnological data.

3.2 Field Methods

On October 30, 2004, three cores were taken from East Canyon Reservoir—Core 1 at a depth of 13 m, and Cores 2 and 3 at a depth of 33 m—using a KB-corer, which ensures that the sediment water interface is collected intact (Glew et al., 2001). The specimens were collected from a motorboat provided by the U.S. Bureau of Reclamation, and their locations were identified using a detailed bathymetric map. The cores were sectioned at 1-cm intervals in the field using a portable sectioner (Figure 8; Glew et al., 2001), and samples were kept cool while transported back to the Environmental Change Observatory (ECO) at the University of Utah. Owing to the more central location and greater core lengths of Cores 2 and 3, these specimens likely contain more complete records, so the remainder of the thesis will only include results from these cores.

3.3 Chronology

Lake sediments are widely used to study environmental history; however, accurate environmental reconstructions are only possible with precise dating. Cores are

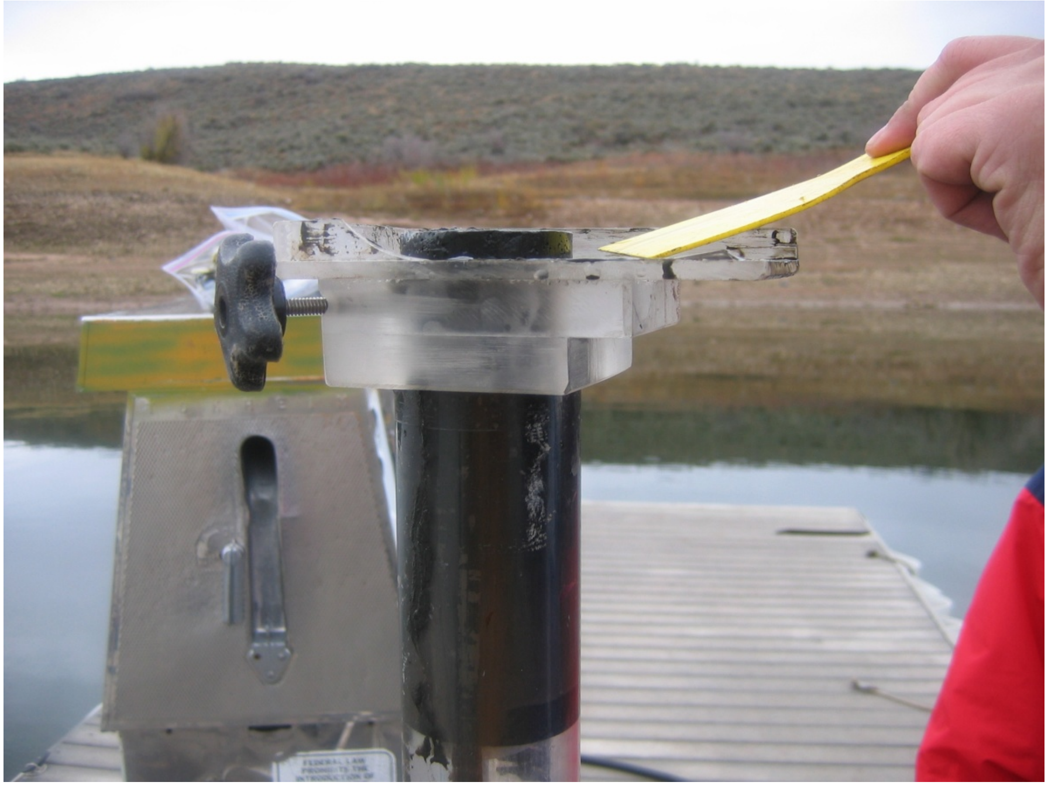


Figure 8: Actual East Canyon Reservoir core and the portable sectioner used to section the cores at 1 cm intervals.

usually dated with two goals in mind: (a) to establish the timing of past environmental change and (b) to determine the accumulation of materials over time. ^{210}Pb is the dating technique most often used when addressing questions regarding the impacts of humans because ^{210}Pb is the most effective dating method for lake sediments that are 1–150 years old (half life is 22.26 +-0.22 years; Olsson, 1986). The following procedures were followed:

- Samples were subsampled from a homogenized section of the core. Large pieces of debris materials were removed prior to sampling for Pb^{210} analysis.
- Samples of 0.1 g dry weight were used for sections between 0 cm and 10 cm, and samples of 1.0 gram were used for samples at depths > 10 cm.
- Samples 1–10 cm in depth and weighing 0.1 grams were dried for 1 hour. Samples > 10 cm and weighing 1 gram were dried for 2 hours.
- Samples were cooled prior to grinding to a grain size that could pass through a 100-mesh-size screen with a mortar and pestle.
- Samples were weighed and then placed into 15-ml centrifuge tubes and sent to MyCore laboratory in Canada for Pb^{210} analysis.

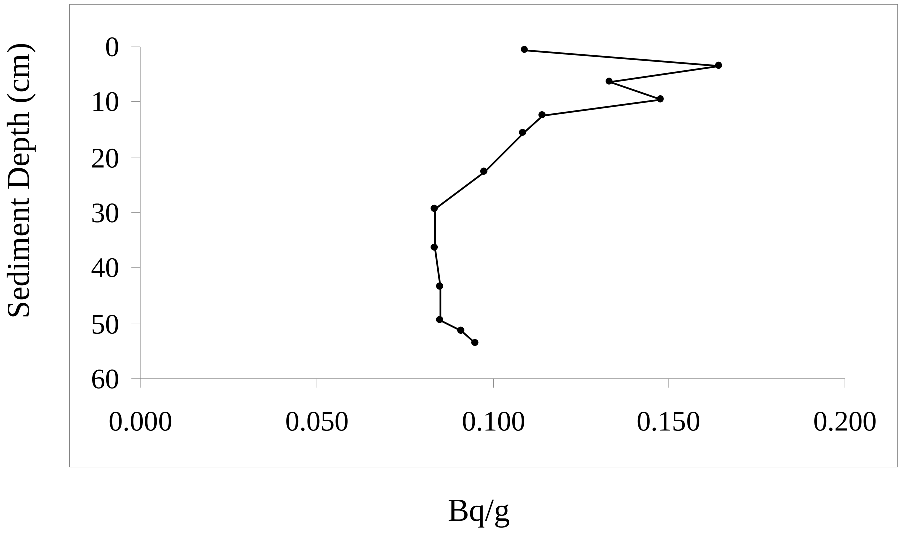
A total of 13 samples were dated from Core 2, and 15 samples were dated from Core 3. Five samples were taken from the top 15 cm from both cores, two samples were taken from between 15 cm and 24 cm, and six and eight samples were taken from below 24 cm for Cores 2 and 3, respectively.

Sediment accumulation rates were derived by MyCore using a constant rate of supply (CRS) model. The CRS model assumes a constant ^{210}Pb flux. Both ^{210}Pb and ^{226}Ra exist in radioactive equilibrium; therefore, excess ^{210}Pb in a system is determined by the ^{226}Ra concentration (Appleby & Oldfield, 1983). Sediment rates were graphed against the average depth of ^{210}Pb samples. In order to compare the timing of sediment changes with historical data and remote sensing data, an age-based model was developed for Cores 2 and 3 (Figure 9). ^{210}Pb dates determined by MyCore were plotted against depth, and a polynomial was fit to the points. Typically, a nonlinear equation best fits the points and helps to correct for the compacting of the sediment within the core (MyCore, personal communication, April 01, 2005).

3.4 Magnetic Susceptibility (MS)

There is significant climatic activity within a lake catchment that can influence the aquatic environment. Fire or heavy precipitation events can increase erosion and influence the input of allochthonous material. Allochthonous material contains magnetic minerals that, once deposited into the lake or reservoir, are recorded as an increase in magnetics. Magnetic susceptibility (MS) is a means to measure magnetics and is useful in correlating cores (Shouyun, Chenglong, Appel, & Verosub, 2002). It is a straightforward technique, and more importantly, it is a nondestructive process and has been used to identify paleoclimate (Thompson, Battarbee, O'Sullivan & Oldfield, 1983; Rummery, 1983; Shouyun et al., 2002). The greatest limitation of MS is that many processes can influence erosion other than magnetic minerals, such as in lake sediments including biogenic magnetism, postdepositional dissolution of magnetic materials under reducing conditions, and in situ authigenesis/diagenesis of magnetic materials (Shouyun et al., 2002). Interpretation of MS data is best done along with other paleolimnological proxies and should be done with caution.

Core 2



Core 3

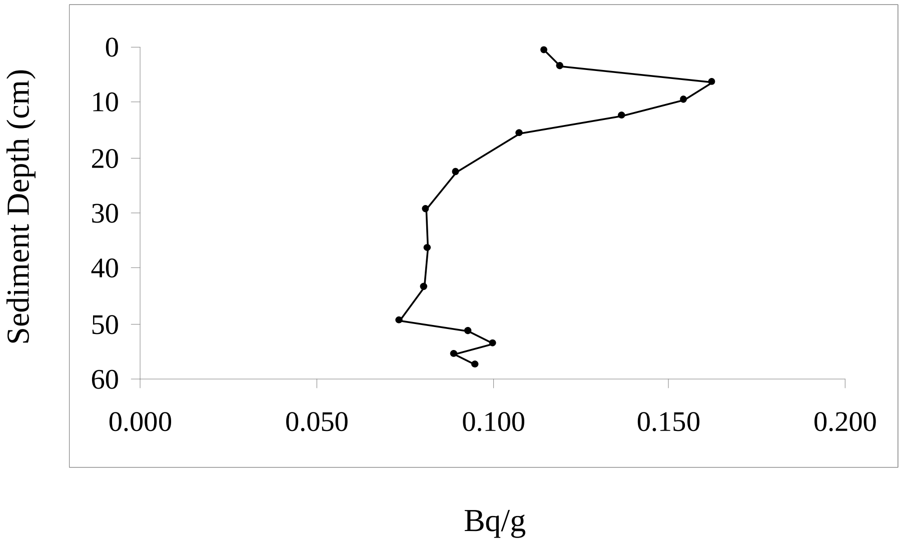


Figure 9: The ^{210}Pb measurements for East Canyon Core's 2 and 3 extracted by MyCore from the original samples.

The Bartington Instruments Multisus program was used to determine the MS on both Cores 2 and 3 at 1-cm intervals. The following lab procedures were used:

- Sediment was placed in a 7.18-ml container until ¾ full.
- The samples were then placed into the same room as the Bartington Instrument and allowed to reach room temperature for approximately 24 hours.
- The MS of each sample was then measured using the MS2B Dual Frequency Sensor.

A 7.18-ml container used for sediment samples allows for 2% accuracy with the Bartington program. The MS measurement was taken to .1 MS2 meter range with the MS2 meter units being SI. To get accurate readings for samples, the air before and after each sample was measured to correct for the current magnetic conditions in the environment. This process was followed for all samples to ensure accurate and consistent results.

3.5 LOI

Loss on ignition (LOI) is often used to estimate the organic content of sediments, particularly in paleolimnological studies (Beaudoin, 2003; Santisteban et al., 2004). It can determine the percentage of organics and carbonate carbon in geologic materials and can be a good qualitative indicator of percent organics (Dean, 1974; Santisteban et al., 2004). LOI is a straightforward and inexpensive process that can be done in most labs that have a muffle furnace. There are several factors that affect percent organics, including in-lake productivity, inorganic inputs, and allocthonous inputs of terrestrial plants and animals (Shuman, 2003). The technique itself has been subject to criticism, and studies have indicated it to be a valuable tool if the procedures are followed correctly (Beaudoin, 2003; Dean, 1974; Heiri et al., 2001). Percent organics was determined at 1-cm intervals following the procedures outlined by Dean (1974) and Heiri, Lotter, and Lemcke (2001).

- 1 cm^3 from each sample was measured and placed in a preweighed ceramic crucible.
- The samples were then placed in a muffle furnace at 95 °C for 1 hour to evaporate all water. The samples were cooled for 30 minutes in a dessicator and weighed.
- The samples were then heated to 550 °C for two hours in a muffle furnace. The samples were cooled for 45 minutes in the dessicator and weighed.
- The following calculation was done for all samples to determine percent organics:

$$LOI_{950} = ((DW_{100} - DW_{550})/DW_{100})*100 \qquad (1)$$

where DW = dry weight

Steps were taken to minimize errors: (a) crucibles were only handled with tongs; (b) constant sample sizes were used throughout the core; (c) the times exposed to 100 °C and 550 °C were consistent with every sample from each core, and (d) cool-down temperatures were also held constant for continuity (Heiri et al., 2001).

3.6 Diatoms, Simpson's Diversity Index, and PCA

Diatoms (*Bacillariophyceae*) are microscopic, unicellular algae with siliceous cell walls that can survive in almost any aquatic habitat as planktonic and benthic species (Battarbee et al., 2001; Moser, MacDonald, & Smol, 1996). Genus-level identification of diatoms is relatively simple, and species-level identification is usually possible based on morphology and size, as well as by examining particular characteristics such as the raphe structure and striae arrangement on their silica walls (Moser et al., 1996; Round, Crawford, & Mann, 1990). The diatom assemblage in lake or reservoir sediments gives valuable information about environmental conditions; analyzing the changes in diatom community composition from different sediment layers can show how lake environments have changed over time (Moser, 2004). Diatom species have specific ecological tolerances, and their short lifespans enable them to respond rapidly to changes in their environment; these characteristics make them excellent indicators of environmental change (Cunningham, Stark, Snape, McMinn, & Riddle, 2003; Solovieva, Jones, Appleby, & Kondratenok, 2002**)**. The type and concentration of diatoms found in a lake are dependent upon the physical and chemical conditions of the lake, including temperature, light availability, habitat availability, water levels, water column mixing, nutrient availability, pH, and salinity (Battarbee et al., 2001; Moser, 2004; Moser et al., 1996; Rühland & Smol, 2002).

East Canyon Reservoir sediment samples were processed following standard procedures outlined in Battarbee et al. (2001). Only samples from Core 2 were analyzed, and these analyses were done at 1-cm intervals between 0.5 cm and 16.5 cm, 21.5 cm and 22.5 cm, 31.5 cm and 37.5 cm, 52.5 cm and 53.5 cm, and then every 4 cm to 5 cm between 22.5 cm and 26.5 cm, as well as 42.5 cm and 52.5 cm. These intervals were chosen based on Pb^{210} dating requirements and enabled a more complete interpretation without having to date the whole core. The samples were washed in a 10% hydrochloric acid solution to remove any carbonate material present. They were then washed with a solution of 50:50 molar sulfuric and nitric acid to eliminate organics. Eliminating organics was expedited by placing samples in a hot water bath for 2 hours at 94 ^{0}C. Samples were then aspirated and diluted with distilled water daily until neutralized, approximately 14–21 days. Once the slurries reached a neutral pH, they were evaporated and placed onto a coverslip. Coverslips were then mounted onto a microscope slide using Naphrax®. Diatoms were identified to species level using a Nikon light microscope equipped with Nomarski optics and a 100x (N.A. = 1.4) oil immersion objective (total magnification was x1000). Approximately 300 to 900 diatoms were counted, and then the counts were converted to percentages (Table 1). Tilia was used to plot these data (Grimm, 1990)

Simpson’s Diversity Index calculates the biodiversity of a habitat and considers both the number of species present as well as the abundance of each species, which are measures of species richness and evenness, respectively (Gauch & Singer, 1982; Hill, 1973; Payne, Schindler, Parrish, & Temple, 2005). The following equation was used to calculate Simpson’s Diversity Index:

$$D = 1- [\sum (n / N)2] \tag{2}$$

where D = Simpson’s Index of Diversity

n = the total number of a specific species

N = the total number of all species

Table 1

Sediment Interval and Total Diatoms Counted in One Transect Per Centimeter Depth

Depth (cm)	Diatoms counted per cm
0.5	368
1.5	402
2.5	511
3.5	583
4.5	487
5.5	565
6.5	353
7.5	648
8.5	764
9.5	650
10.5	539
11.5	380
12.5	401
13.5	460
14.5	505
15.5	469
16.5	429
21.5	462
22.5	385
26.5	489
31.5	465
32.5	445
33.5	473
34.5	429
35.5	613
36.5	528
37.5	693
42.5	488
47.5	591
52.5	932
53.5	385

Using this equation, index values have a range of 0–1, with 0 representing the least diversity and 1 representing the greatest diversity.

Multivariate statistics were used to determine the main changes in diatom community composition over time. Specifically, principal components analysis (PCA), an indirect gradient technique, was used to determine the amount of change between samples in terms of diatom community composition. CANACO 4.0 was used for PCA analysis, and the sample scores were plotted such that the distance between sample points approximated Euclidean distances and therefore reflected the amount of dissimilarity between samples with respect to diatom community composition (CANACO, n.d.). Species data were square root transformed and centered to keep the dominant species important.

3.7 Remote Sensing

Remote sensing has been an indispensable tool in the past for a variety of uses such as topography, political boundaries, and pedologic, geologic, and hydrologic data (Campbell, 1996). It has also been used to inventory and monitor natural resources and land use changes on local and regional scales (Campbell, 1996; Lillesand et al., 2004). The fields of limnology and paleolimnology have begun to use remote sensing to aid in interpreting past environments. The following studies show how remote sensing has been used to document phytoplankton blooms on surface waters, their migration patterns, and more recently, their presence on the upper portion of a sediment core. Black Sea surface waters were monitored for phytoplankton blooms, specifically coccolithophore blooms, over a 6-year period (Cokacar, Oguz, & Kubilay, 2004). Recent papers have highlighted a difference in spectral characteristics of phytoplankton in surface waters, which led to developing new bio-optical algorithms to distinguish diatom communities (Pemberton, Reese, Miller, Raine, & Joint, 2004; Sathyendranath et al., 2004). Other papers examined the use of remote sensing as a new technique in analyzing the migration of benthic diatom communities during tidal and diurnal cycles (Consalvey, Paterson, & Underwood, 2004; Paterson et al., 1998). Hyperspectral reflectance was measured on the surfaces of sediment cores (5 mm) collected from a variety of habitats. Those reflectances and quantified photosynthetic and photoprotective pigments within the microalgae were compared to see if microalgal biomass could be determined (Stephens, Louchard, Reid, & Maffione, 2003).

This study will use remote sensing to correlate the land cover/land use (LCLU) change on aerial photos with the Pb^{210}dates and changes in diatom assemblages within the cores on a decadal scale. The remote sensing data set was acquired for East Canyon Reservoir Watershed from the U.S. Department of Agriculture (USDA), Aerial Photo Field Office (APFO), Farm Service Agency (FSA); the Utah Automated Geographic Reference Center (AGRC); and the Snyderville Basin Water Reclamation District (SBWRD; Table 2). While there was substantial coverage for East Canyon Watershed from 1959 to 2005, the counties’ image extents varied. Therefore, the imagery for both Summit and Morgan Counties was combined by decade to get full coverage of the East Canyon Watershed Boundary.

The images from the USDA were in 10 x 10 inch paper prints for the years 1959, 1962, 1967, and 1978 and were scanned into a digital format at 500 dpi. The remaining years of 1987, 1993, 1997, 2003, and 2005 were downloaded in electronic format from

Table 2

East Canyon Reservoir Watershed Available Imagery and Their Sources

Agency	Year	Morgan County coverage	Summit County coverage	Type
USDA	1959	X	X	Aerial photos
APFO	1962		X	
FSA	1967	X		
	1978	X		
AGRC	1987	X	X	NAPP
	1997	X	X	Digital Ortho Quads
SBWRD	2003	X	X	SIDFile
	2005	X	X	
	2006	X	X	

Note. Morgan and Summit County do not have full coverage for the 1960s and 1990s. The year 2000 had full coverage but there were “no fly areas” that had to be filled in with other years.

their respective sources (Table 2). Decadal imagery for 1962 and 1967, 1993 and 1997, and 2003 and 2006 was georeferenced and then mosaicked together to complete each decade, along with 1978 and 1987 images using Microstation V7. All of the images were then cropped to the East Canyon Watershed Boundary. Aerial photo analysis focused on Summit County within the East Canyon Reservoir Watershed Boundary for the reasons mentioned above and because the most rapid growth influencing the reservoir is occurring in Summit County.

The urban roads, the interstate, and the East Canyon Reservoir waterline were digitized using ArcMap V 9.3 and ArcGIS. Road length is a good indicator of development and is easily quantified. The total length for each year and the difference in length between the years were calculated to see the trends in development throughout the watershed (Table 3). The East Canyon Reservoir waterline was also digitized to compare the water levels with corresponding trends within the paleolimnological record.

Table 3

Summit County Digitized Urban and Highway Lengths in Kilometers within the East Canyon Reservoir Watershed, Boundary, Utah

Year	Urban roads (km)	Highway/interstate (km)	Total (km)	Year to Year change (km)
1960	41.04	15.42	56.46	46.62
1970	179.90	39.08	218.98	162.52
1980	250.39	39.08	289.48	70.50
1990	300.2	39.08	339.28	49.80
2000	365.42	39.08	404.56	65.23

Note. There is significant change from 1960 to 1970 which correlates with an increase in development is evident in historical documentation.

CHAPTER 4

RESULTS

4.1 Climate Data

4.1.1 Temperature and Precipitation

Temperature generally increases beginning about 1960 (Figure 10). The annual temperature mean from 1920 to 1959 was 18.1 °C. This is slightly lower than the annual mean for 1960–2004 (18.5 °C) and even lower than the annual mean for 1997–2001 (19.1 °C). This is consistent with the findings of a recent report that showed that the Western United States, and Utah in particular, warmed significantly after 1970 (Saunders, Montgomery, Easley, & Spencer, 2008).

Precipitation has generally increased over time, particularly from 1962 to 2004 (Figure 10). The mean annual precipitation for 1920–1959 (220 mm) was lower than the mean for 1960–2004 (240 mm). Dry periods were determined as those that fell below the mean for 1962–2004 (231 mm) and include 1932–1936, 1948–1962, 1970–1978, 1988–1992, and 2000–2004. There is good correlation between the analysis of the NCDC climate data and historical local and statewide drought events documented by the University of South Carolina Hazards and Vulnerability Research Institute (2010) for 1930–1936, 1953–1965, 1974–1978, 1988–1993, and 1999–2004.

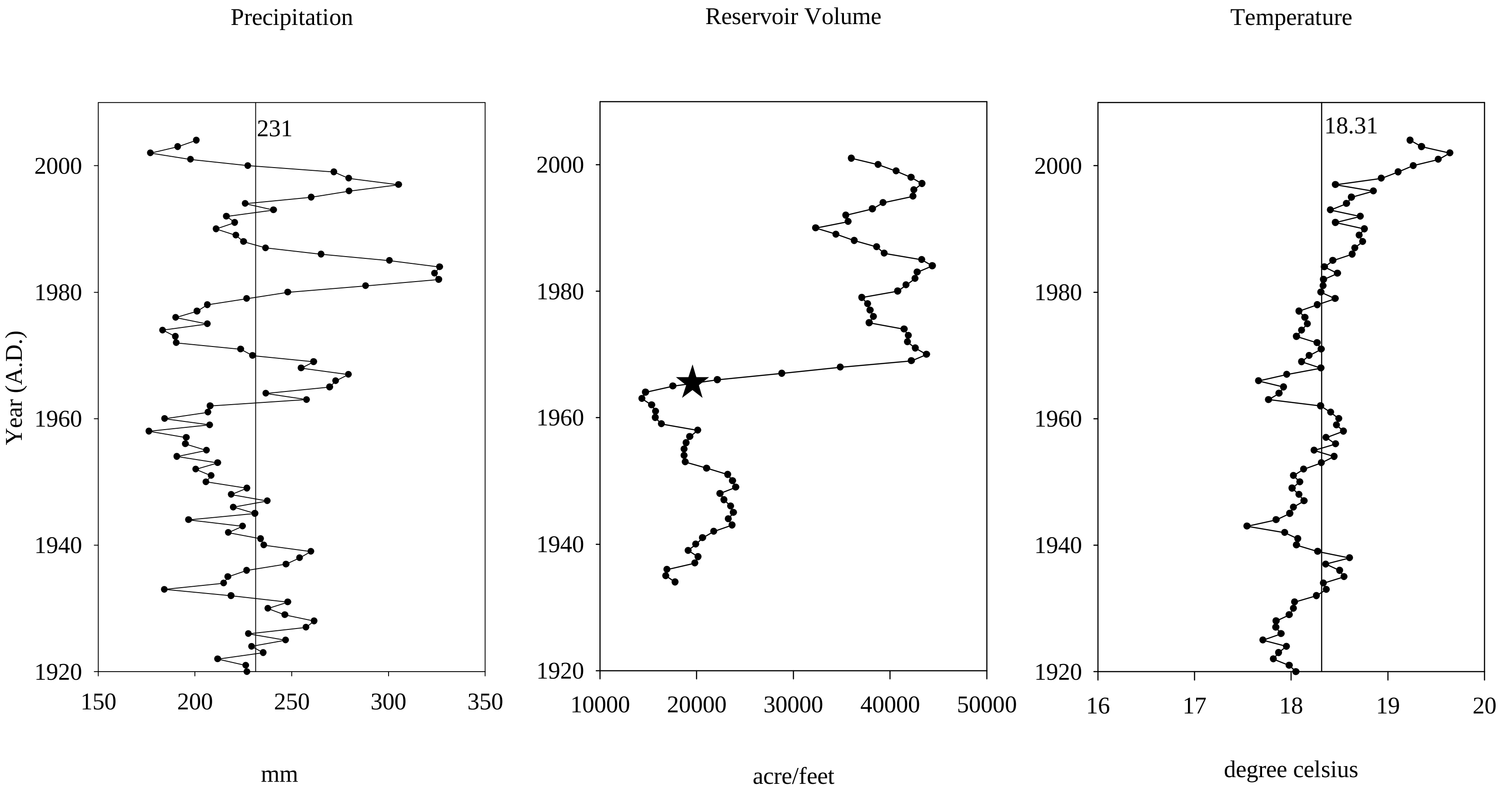


Figure 10: Annual 5 year running average for temperature, reservoir volume and precipitation data from ca. 1920-2004. The mean of temperature and precipitation data are shown as a vertical line on the plots. Dam enlargement occurred in 1966 and is indicated by a star on the y axis on the Reservoir Volume plot.

4.1.2 Reservoir Volume

The reservoir volume trends are similar to those described for precipitation (Figure 10). Prior to 1963, reservoir volume was low, ranging from ~14,000 acre-ft to ~24,000 acre-ft. The largest change in reservoir volume, an increase from 25,790 acre-ft to 48,110 acre-ft, corresponds with an enlargement of the dam between 1963 and 1966. The peaks and troughs described for the precipitation data following 1960 are evident in reservoir volume (Figure 10).

4.2 Sediment and Core Descriptions

Core 2, 54 cm in length, was taken from the center of the lake (Figure 5). The top 0 cm to 0.5 cm of Core 2 contained brown, flocculent organics. The sediments from 0.5 cm to 29 cm were composed of black organics and clay. Between 29 cm and 38 cm, a tan and black laminated section occurs; the tan layers were a mixture of clay and fine sand. The remaining sediment in the core from 39 cm to 54 cm was similar to the first 0.5 cm to 29 cm and was composed of black organics and clay (Figure 11). Core 3 was taken ~244 meters north of the location of Core 2 (Figure 5). The top of Core 3, from 0 cm 0.5 cm, contained brown, flocculent organics. The sediments from 0.5 cm to 31 cm were composed of black organics and clay. The tan and black laminated layer observed in Core 2 was also noted in Core 3 between 31 cm and 39 cm. The remaining sediment in Core 3, from 39cm to 58 cm, was similar to the first part of the core and was composed of organics and clay (Figure 11).

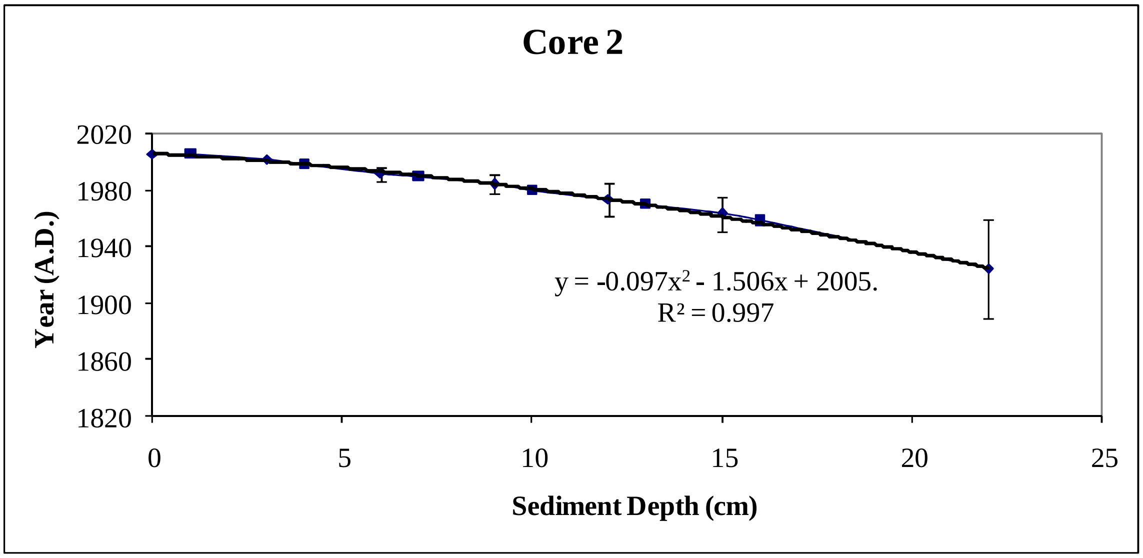
Figure 11: Photographs showing sediment cores retrieved from East Canyon Reservoir on October 2004. From top, clockwise: Core 1, Core 1 close-up, Core 3, Core 2. Only Cores 2 and 3 will be discussed further, but pictures of Core 1 are included to show the well-preserved sediment water interface. For specific core collection sites see Figure 5.

4.3 Chronology

^{210}Pb analyses were made of Cores 2 and 3, as these were anticipated to be least affected by mixing as a result of their deeper locations. The ^{210}Pb beta counts are provided in Figure 9.

These profiles show background levels in the lower portion of the cores and exponential increases toward the top, as would be expected. ^{210}Pb dates for Cores 2 and 3 were consistent with one another (Figure 12). Errors on dates below 22.5 cm are relatively large: ±35 years (Core 2) and ±80 years (Core 3; Figure 12). The strong agreement between the two cores, however, suggests that these errors are over estimated and are due to a statistical propagation of errors, which occurs because of an assumption that there is no correlation between the core data. Some of the error can also be explained by generally low unsupported ^{210}Pb concentrations, suggesting either little input from the atmosphere and/or some dilution by the inflow of sediments into the reservoir. Additionally, there is evidence of a slight radon effect at the bottom of the cores, which is typical in lakes with a high ^{210}Pb background (supported) such as this reservoir (background = 0.08 Bq/g).

Historically, it is unclear what the environment was before the formation of East Canyon Reservoir. Based on this age model, the initial dam construction at 1896 is represented by sediment deposited at 26.5 cm. This is followed by several enlargements that occurred at 1900, 1902, and 1916, which are represented by sediments deposited at 26 cm, 25 cm, and 23.5 cm, respectively. The remaining organic sediment suggests that the environment prior to the dam was more than a creek and was a lake/pond or that there were long periods of standing water due to flooding and drainage of the canyon.



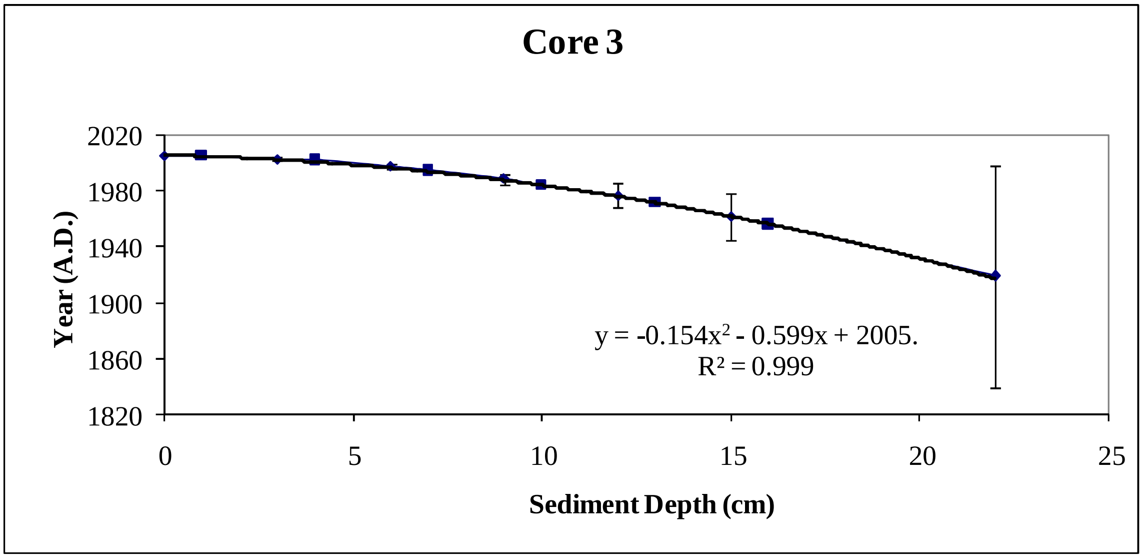


Figure 12: ^{210}Pb activity and ages against depth for Core 2 and 3 from East Canyon Reservoir. Ages below 22 cm were estimated by fitting a polynomial through the data points. The polynomial equation R2 values are shown on the plots.

The sediment accumulation rates (SAR) determined for East Canyon Reservoir are greater than is typical for lakes but are lower than is usual for reservoirs (MyCore, personal communication, December 15, 2004). The sediment accumulation rates (SARs; Figure 13) for Cores 2 and 3 show similar trends. SAR values are relatively low for Core 2 between 22.5 cm (AD 1922) and 3.5 cm (AD 1998), with an average of 606 g/m^2/yr. SAR values increase from 3.5 cm (AD 1998) to the present, reaching maximum values of 2223 g/m^2/yr (AD 2004). In Core 3, between 22.5 cm (AD 1918) to ~6.5 cm (AD 1995), SARs are also relatively low, with an average of 444 g/m^2/yr, and increase rapidly from 6.5 cm (AD 1995) to maximum values of 1460 g/m^2/yr (AD 2004) at the top of the core (Table 4).

4.4 Magnetic Susceptibility (MS) and Loss on Ignition (LOI)

4.4.1 Magnetic Susceptibility (MS)

MS trends for Cores 2 and 3 are similar, although the values in Core 2 are an order of magnitude lower than in Core 3. In order to compare the two cores, the values for Core 3 were multiplied by 10 for comparison to Core 2. The higher MS values in Core 2 may be related to the location of Core 2 closer to inflowing streams (Figure 5), which would wash in allocthonous inorganics and therefore would be higher in magnetic minerals. There are three zones identified in the MS values from Cores 2 and 3: (a) Zone 1, spanning from 53.5 cm (pre-AD 1900) to 23.5 cm (AD 1916), where values were generally high and increasing (average for Core 2 = 18.1 and average for Core 3 = 14.7); (b) Zone 2, extending from 23.5 cm (AD 1916) to 15.5 cm (AD 1958), where values were generally decreasing to less than 10; and (c) Zone 3, extending from 15.5 cm (AD 1958)

Figure 13: Plots showing sediment accumulation rate, percent organics (determined using loss-on-ignition), and magnetic susceptibility values for East Canyon Reservoir.

Figure 13 cont.

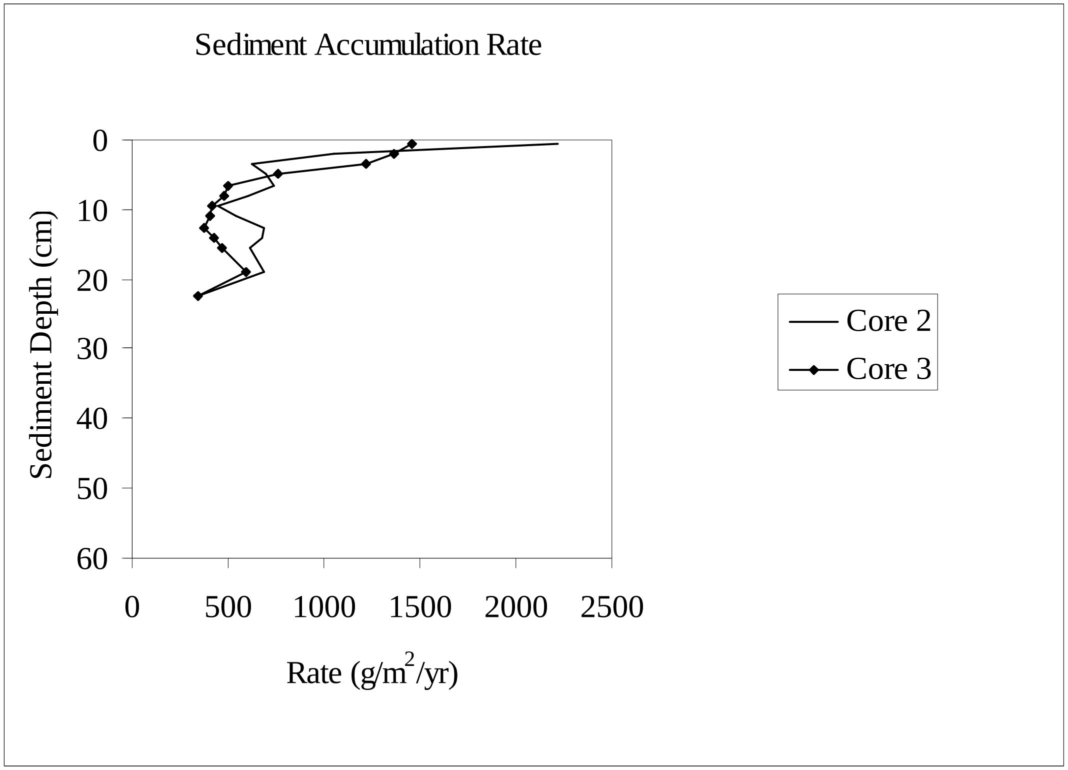


Figure 13 cont.

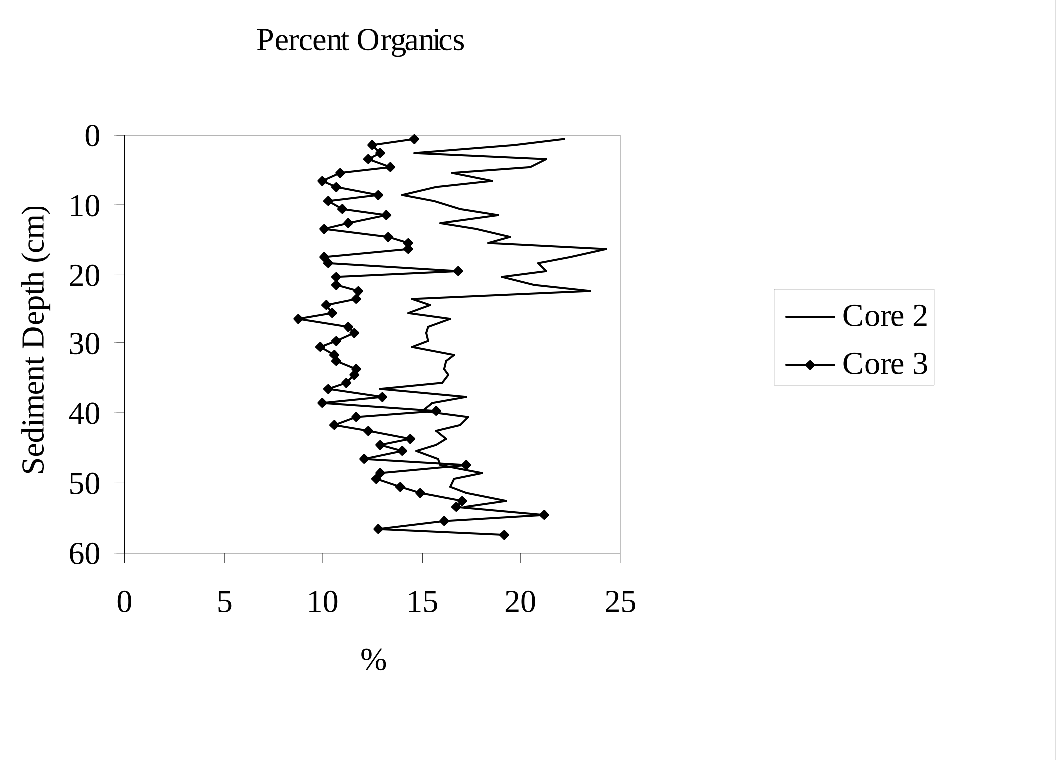
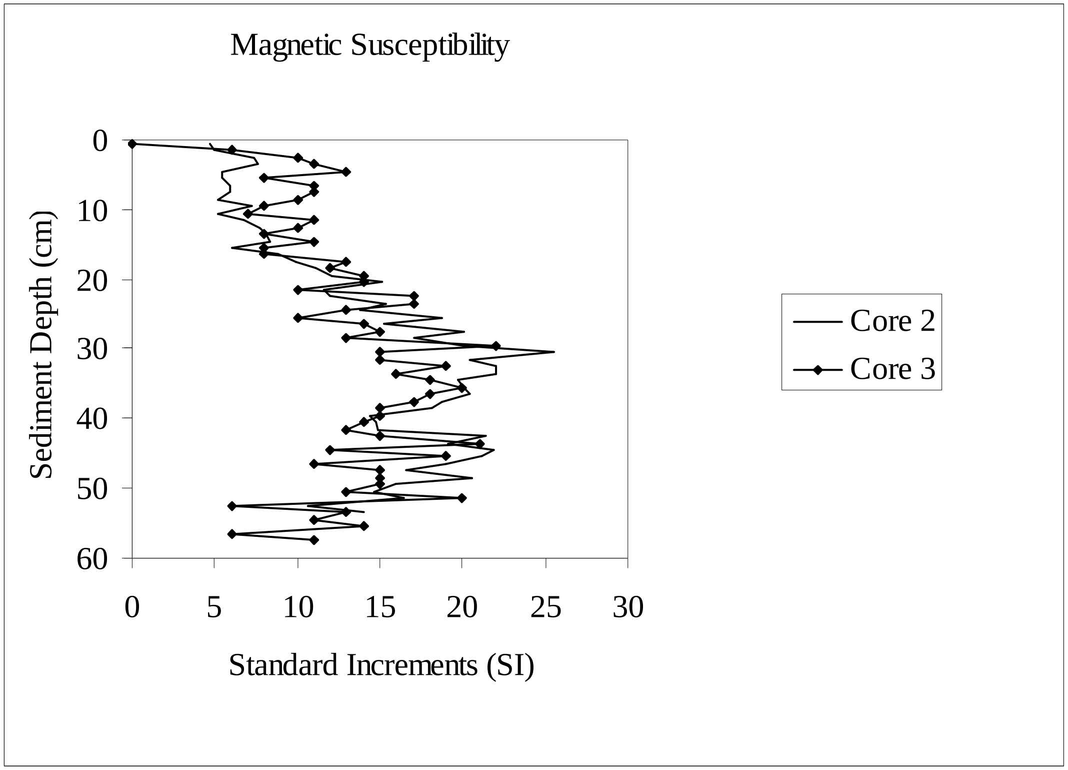


Figure 13 cont.



to 0.5 cm (AD 2004), where values were relatively stable and continued to be low (Core 2 average = 10.2 and Core 3 average = 12.4; Table 4).

4.4.2 LOI

In general, in Cores 2 and 3, percent organic values are similar (average for Core 2 = 16.7% and average for Core 3 = 14.3%). There are four zones identified in the percent organics for Cores 2 and 3: (a) Zone 1, which spans the same interval as Zone 1 for MS, 53.5 (pre-AD 1900) to 23.5 cm (AD 1916), where the values decrease from 24% to 14% in Core 2 and from 21% to 12% in Core 3; (b) Zone 2, which spans the same interval as Zone 2 for MS, 23.5 cm (AD 1916) to 15.5 cm (AD 1958), where the values increase in Core 2 (average = 21%) but remain relatively unchanged in Core 3 (average = 12%); (c) Zone 3, which comprises the lower section of Zone 3 for MS, 15.5 cm (AD 1958) to 7.5 cm (AD 1988.5), where the values decrease in Core 2 (average = 17%) and remain low in Core 3 (average = 12%), and (d) Zone 4, which overlaps with the upper section of Zone 3 in MS, 7.5 cm (AD 1988.5) to 0.5 cm (AD 2004.5), where the values increase slightly in Core 3 (average = 19%) and remain low (average = 12%; Figure 13).

4.5 Diatoms, Simpson’s Diversity Index, and PCA

Diatoms are only analyzed in Core 2, so comparisons between all paleolimnological indicators are limited to this core (Tables 4 and 5). There were a total of 39 diatom species identified in Core 2. The diatom community composition has remained relatively unchanged in the history of the reservoir and has been dominated by planktonic diatoms, which are free-floating organisms that require some turbulence to

Table 4

Core 2 Zones and Relationships Between, SAR, MS, % organics Diatoms and PCA.

Zone	Sub-zone	Sediments	SAR	MS	% organics	Diatoms
1 (53.5-23.5 cm)	1a (53.5-36.5 cm)	Black organics	N/A	Increasing to greatest values	Decreasing values	Highest abundances of *Aulacoseira granulata* (lowest PCA sample scores on axis 1)
	1b (36.5-23.5 cm)	Laminated sediments; alternating light and dark layers				Reduced *Aulacoseira granulata* and increases in *Stephanodiscus niagarae* and some non-planktonic diatoms(gradual increase in PCA sample scores on axis 1)
2 (23.5-15.5 cm)	N/A	Black organics	Increasing to decreasing values	Decreasing values	High values	Further reduction in abundance of *Aulacoseira granulata* and increase in *Stephanodiscus medius* (rapid increase in PCA sample scores on axis 1)
3 (15.5-0.5 cm)	3a (15.5-7.5 cm)	Black organics	Increasing to greatest values	Low values	Low values	Continuation of zone 2 (decreasing PCA sample scores on axis 1). First appearance of *Cyclotella bodanica* var. *lemanica*
	3b (7.5-0.5 cm)				High values	Reduction in abundance of *Stephanodiscus medius* and increase in abundance of *Aulacoseira granulata and Diatoma vulgaris* (variable PCA sample cores on PCA axis 1; sample 1 is the highest score)

Table 5

Core 2 Zones and Relationships Shown Between Sediment Core and Historical Anthropological Events

Zone	Subzone	Age of upper boundary	Human activity
1 (53.5-23.5 cm)	1a (53.5-36.5 cm)	36.5 cm = 1820	Ranching, hay/field crops, mining, lumbering.
	1b (36.5-23.5 cm)	23.5 cm = 1916	Dam built in 1896; Portland Cement Produced Limestone, enlargements 1900 and 1902
2 (23.5-15.5 cm)	N/A	15.5 cm = 1958.5	decrease in dev. during the early 1950's; Increase in dev., farming, ranching, tourism and golf course late 1950's and early 1960's; 1916; drought 1930-1936 and 1953-1965
3 (15.5-0.5 cm)	3a (15.5-7.5 cm)	7.5 cm = 1988.5	Increase in dev. In 1980's same as the early 1960s; final dam enlargement 1966; 1988-1993 drought; 1983 flash flooding (state of emergency called)
	3b (7.5-0.5 cm)	0.5 cm = 2004 .5	2001 upgraded waste water treatment facility; 2001 upgraded waste water treatment facility; 1999-2004 droughts; Development increases/ tourism etc.

remain in the water column (Hall & Smol, 2001). The dominant planktonic diatoms were *Asterionella formosa* Hassall, *Aulacoseira granulata* Ehrenberg and Simonsen, *Fragalaria crotonensis* Kitton, *Stephanodiscus hantzschii* Grunow, *Stephanodiscus medius* Hakansson, *Stephanodiscus minutulus* Kutzing, *Stephanodiscus niagarae* Ehrenberg, and *Stephanodiscus parvus* Stoermer and Håkansson (Figures 14, 15, and 16). These taxa are typical in alkaline waters (Ramstack, Fritz, Engstrom, & Heiskary, 2003; van Dam, Mertens, & Sinkeldam, 1994). *Asterionella formosa, Aulacoseira granulata*, *Fragalaria crotonensis*, *Stephanodiscus hantschii*, *Stephanodiscus medius*, *Stephanodiscus minutulus, Stephanodiscus niagarae*, and *Stephanodiscus parvus* have similar ecologies and are usually associated with eutrophic or hypereutrophic waters (van Dam et al., 1994). *Asterionella formosa* and *Fragalaria crotonensis* are indicative of increased phosphorous and more eutrophic conditions, and in alpine settings they are indicative of an increase in nitrogen (Yang, Pick & Hamilton, 1996; Interlandi, Kilham, & Theriot, 1999; Saros et al, 2005). Finally, the dominant species described above are typically associated with water temperatures of ~15–30 °C (van Dam et al, 1994; Yang, Duthie, & Delorme, 1993).

Although changes are subtle, three zones are noted in the diatom stratigraphy (Figure 14, Tables 4 and 5). Zones 1 and 3 are divided into two subzones. Zone 1a extends from ~53.5 cm to ~36.5 cm (pre-AD 1900) and is characterized by relatively high abundances of *Asterionella formosa* and *Fragalaria crotonensis* and low abundances of *Stephanodiscus niagarae*. The presence of these three diatoms suggests that nitrogen and phosphorus are not limiting (Tilman, Kilham, & Kilham, 1982).

Figure 14: Core 2 fossil diatom stratigraphy for East Canyon Reservoir indicating that the dominant diatoms are planktonic and associated with eutrophic conditions.

Figure 14 cont

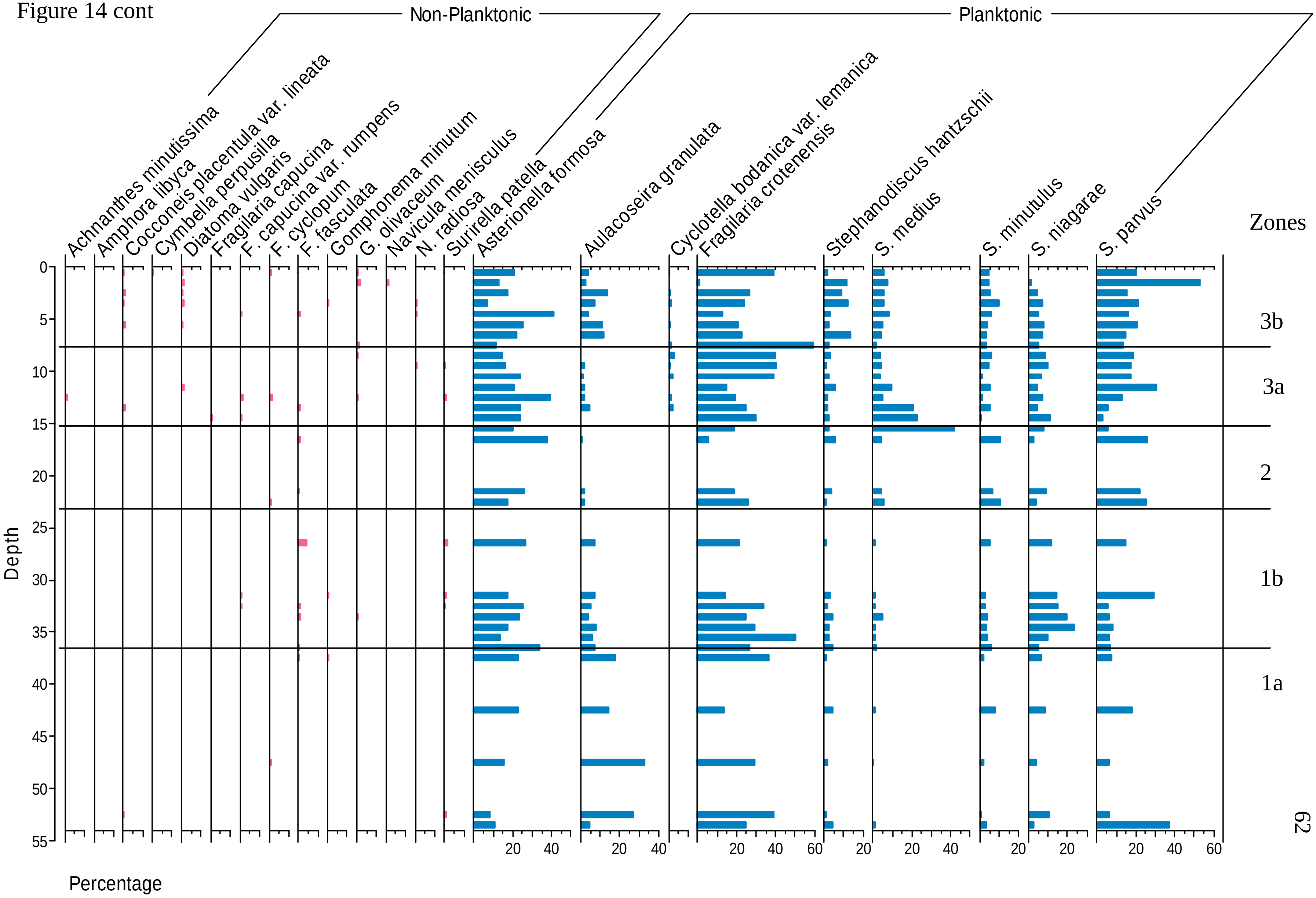
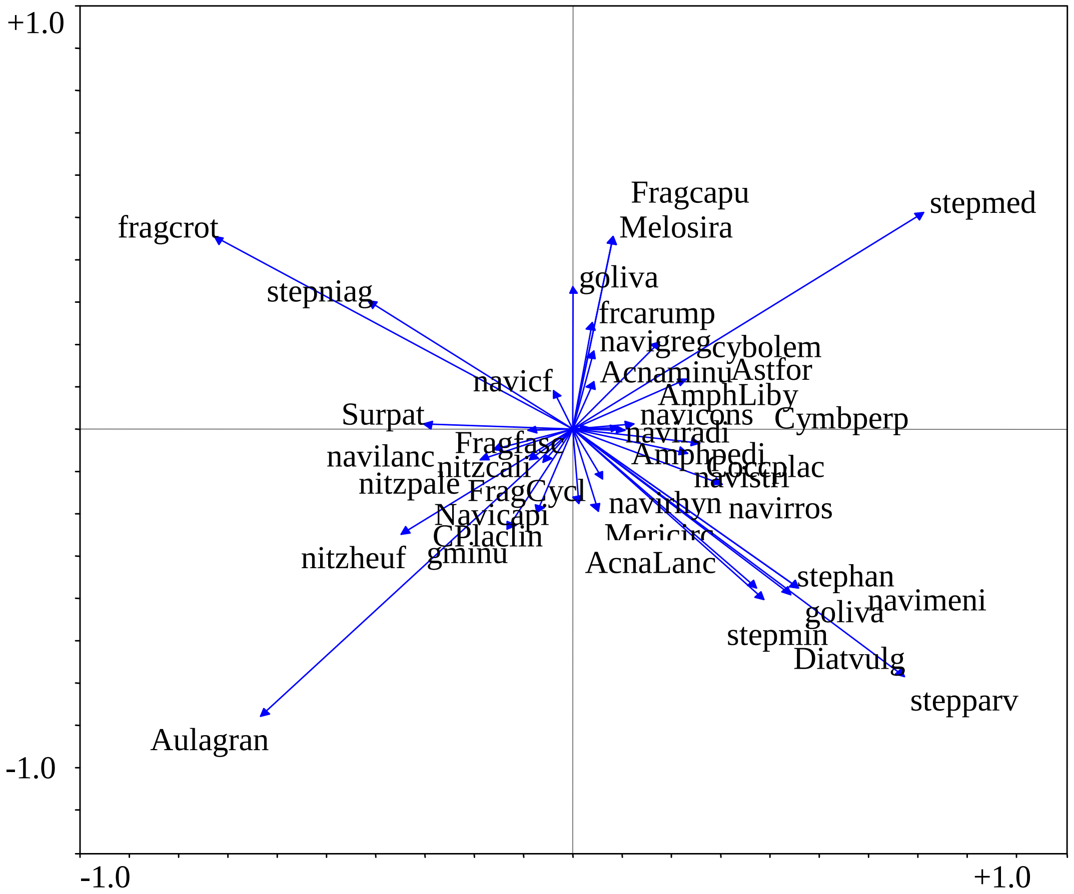


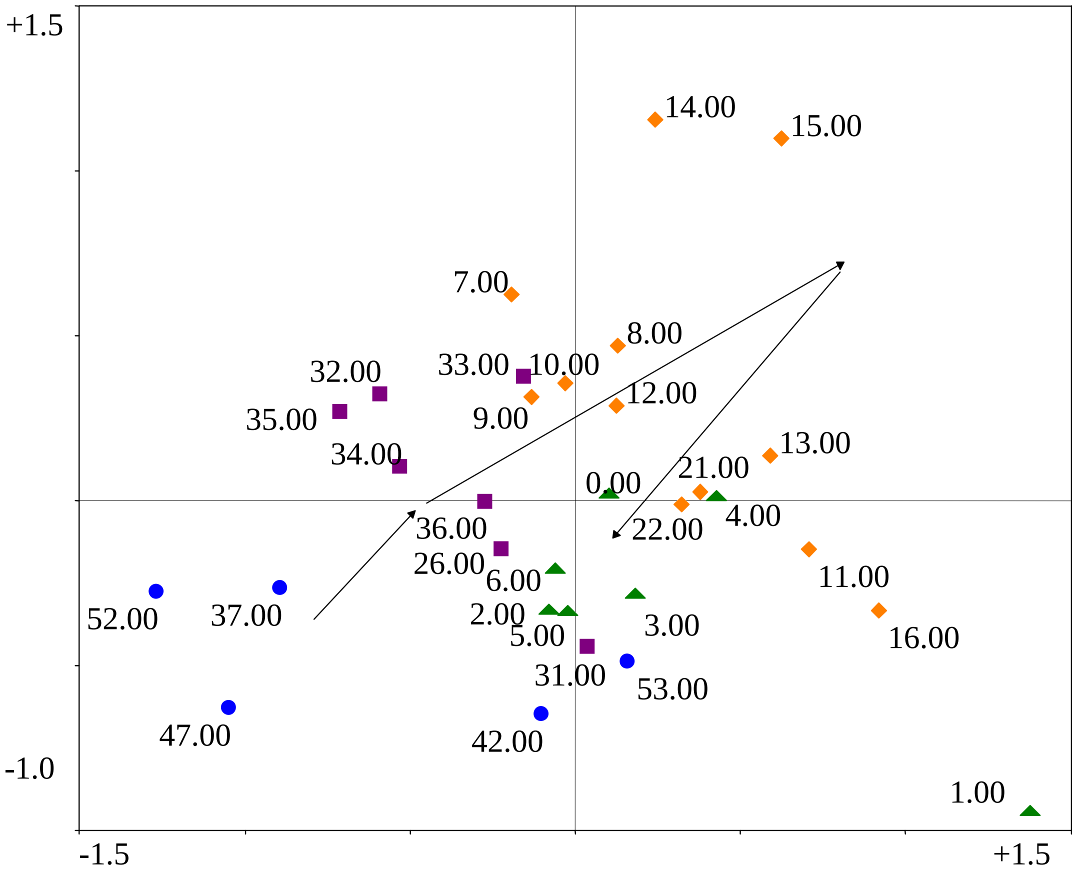
Figure 15: Comparison of PCA sample biplot (A) and species plot (B).

Figure 15 cont.

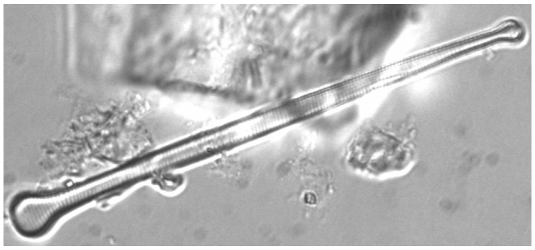


A. PCA sample biplot

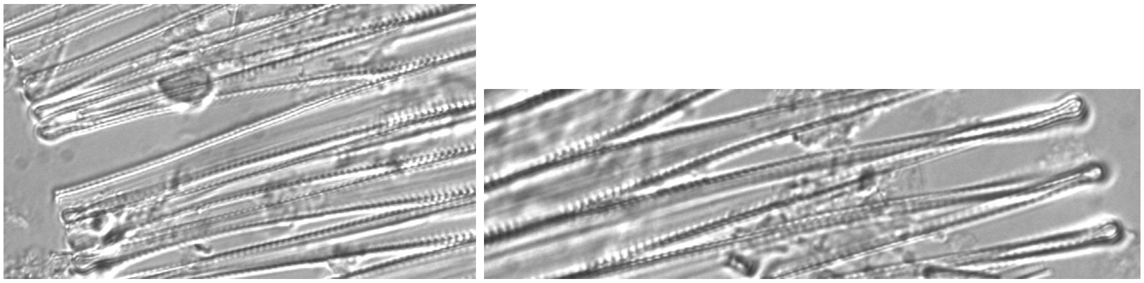
Figure 15 cont.



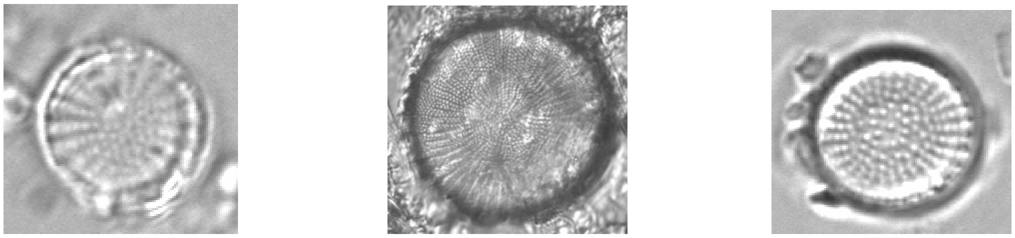
B. Species plot



Asterionella Formosa

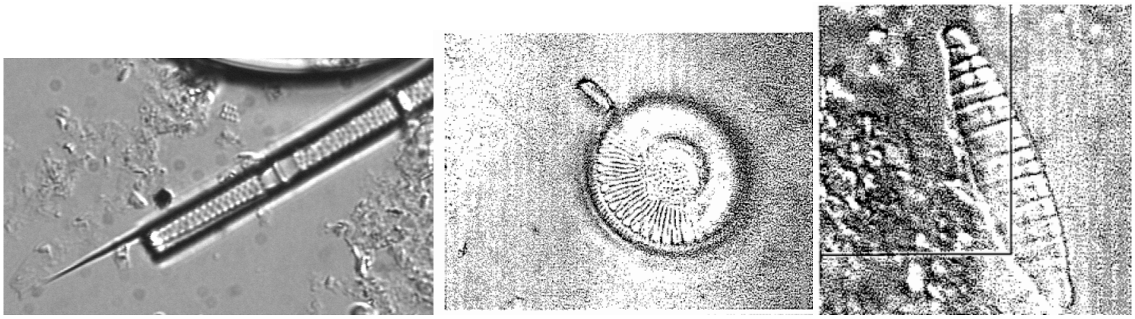


Fragalaria crotonensis



Stephanodiscus parvus *Stephanodiscus niagarae* *Stephanodiscus minultulus*

Stephanodiscus medius Not available from study



Aulacoseira granulate *Cyclotella var bodanica* *Diatoma vulgare*

Figure 16: Samples of the dominant diatoms found in East Canyon Reservoir Core 2.

This zone is distinct from all other zones by having the greatest abundance of *Aulacoseira granulata*, which is a heavily silicified diatom that is limited by Si and requires turbulence to stay in the photic zone (Hotzel & Croome, 1996; O'Farrell, Guillermo, & Podlejski, 2001). Previous studies have suggested that *Aulacoseira granulata* are adapted to low light and fluctuating turbulence based on cell size and morphological variation (Kilham, Kilham, & Hecky, 1986; O'Farrell et al., 2001).

Zone 1b, which extends from ~36.5 cm (AD 1820) to ~23.5 cm (AD 1916), is distinguished from Zone 1a by decreasing abundances of *Aulacoseira granulata* and *Stephanodiscus niagarae* and increasing abundances of some small nonplanktonic species, which could indicate a reduction in turbulence and light and an increase in phosphorus (Kilham et al., 1986; Valdez, Vilaclara, Caballero, & Rodriguez, 2005). Interestingly, this diatom Subzone 1b is roughly coincident with the laminated layer in the sediment. Zone 2 extends from ~23.5 cm (AD 1916) to ~15.5 cm (AD 1958.5) and is characterized by a further reduction in the abundance of *Aulacoseira granulata* (Table 4), suggesting a further reduction in turbulence but also a decrease in Si:P ratio (Hotzel & Croome, 1996; O'Farrell et al., 2001). Zone 3a, which extends from ~15.5 cm (AD 1958.5) to ~7.5 cm (AD 1988.5), is characterized by the first appearance of *Cyclotella bodanica var. lemanica* and *Stephanodiscus medius*. *C. bodanica var lemanica* is associated with ogliotrophic lakes but has been found in eutrophic conditions in temperate lakes, requires sufficient light, is a low nitrogen specialist, and has the ability to regulate its buoyancy (Hall & Smol, 2001; Interlandi et al., 1999). *Stephanodiscus medius* is a eutrophic diatom that is P-limited (Kienel, Schwab, & Schettler, 2005). Zone 3b extends from ~7.5 cm (AD 1988.5) to ~ 0.5 cm (AD 2004.5) and is characterized by an increase *Aulacoseira granulata* and *Diatoma vulgare* and a reduction of *Stephanodiscus medius*, suggesting an increase in turbulence but also an increase in Si:P ratio (Hotzel & Croome, 1996; O'Farrell et al., 2001).

There is almost no change in diversity as indicated by the Simpson Diversity Index. Most of the variance in the PCA is explained by the first two axes. The eigenvalue for Axis 1 is $\lambda = 0.30$ and for axis 2 is $\lambda = 0.21$. The species biplot (Figure 15) shows that PCA Axis 1 is negatively correlated to *Aulacoseira granulata* and *Fragalaria crotonensis* and positively correlated to *Stephanodiscus ssp.*, which suggests that Axis 1 is related to phosphorus because *Aulacoseira granulata* outcompete *Stephanodiscus* when Si:P ratios are high (Tilman et al., 1982) and *Fragalaria crotonensis* is a good competitor at high N:P ratios in an alpine setting (Saros et al., 2005). This suggests that high positive scores on Axis 1 indicate that P values are high.

PCA Axis 2 is negatively correlated with *Aulacoseira granulata* and *Diatoma vulgare* and positively correlated with *Fragalaria crotonensis* (Figure 15). As stated previously, *Aulacoseira granulata* requires light to stay in the photic zone and is adapted to higher Si concentrations (Alameida da Silva, Train, & Rodrigues, 2005; Davey, 1986; Hotzel & Croome, 1996; Kilham et al., 1986; O'Farrell et al., 2001). There is less documented about the ecology of *Diatoma vulgare*; however, this diatom is associated with higher N:P ratios and small amounts of turbidity and suspended sediment (Marks & Power, 2001). *Fragalaria crotonensis* indicates an environment with some turbidity and light and is a good competitor in environments with high N:P ratios (Interlandi et al., 1999; Tilman et al., 1982). Although there is some uncertainty in what Axis 2 is representing, with the ecological data available, it is most likely N:P or light availability, although more ecological information is required to confirm this. The PCA sample plot shows that there is considerable overlap between the zones identified in Figure 14; however, the same general trends observed in Figure 14 are also recorded in Figure 15. In the PCA sample biplot (Figure 15), the lowest core samples (~52 cm to ~26 cm, representing AD 1663 to 1896) plot in the lower left hand quadrant as a result of higher amounts of *Aulacoseira granulata*. Samples that represent more recent time periods plot more and more toward the upper right hand quadrant as a result of decreasing amounts of *Aulacoseira granulata* and increasing *Stephanodiscus medius* and *Cyclotella bodanica var. lemanica.* At ~ 6 cm (AD ~1993), there is a shift back toward the lower left quadrant as a result of increasing *Aulacoseira granulata*, *Diatoma vulgare*, and *Cocconeis ssp.* Based on the ecology of these diatom species, these changes indicate that the earliest samples have the highest Si:P ratios and that the water was likely characterized by greater turbulence or light. As dams were constructed, the Si:P ratio and light or mixing decreased. This continued until recently, when there was an increase in the Si:P ratios and an increase in mixing or light.

4.6 Remote Sensing and Other Historical Data

The total road length data shows a gradual increase in urban roads from the 1960s through the 2000s (Figure 17). The historical rate of change is evident, with the most significant change noted from 1960 to 1970 (Figures 17 and 18). Total urban road length increased by 139 km with the interstate increasing 24 km for a total increase of 162 km between 1960 and 1970 (Figure 17). An increasing trend continues from 1970 through 2000, although with a slower rate of change. The average decade-to-decade change of total road length increased 62 km during this time (Figure 17). Although increased roads would be predicted to result in increased erosion and therefore cause a decrease in the percent organics and an increase in MS, in general there are no clear relationships between the MS and percent organics and road length.

Digitizing the reservoir waterline from 1960 to 2000 provides a temporal evolution of the reservoir level for comparison to the paleolimnological data. The two highest waterlines were in 1960 and 1990 (Figure 19). The 1960s imagery was taken in 1967 and illustrates the largest capacity of the reservoir corresponding to the dam enlargement in 1966. The imagery from the 1990s was from 1997 between two drought periods (Figure 19). The lowest water level occurred in 1987, which corresponded to a statewide drought from 1988 to 1993.

Another proxy used with the remote sensing data was population reports for Morgan and Summit Counties from 1900 to 2000 from the U.S. Census Bureau (Table 6). There was a significant increase by ~23,857 in population growth from 1970 to 2000 in Summit County, and although the population of Morgan County steadily increased from 1960 to 2000, the actual numbers were not as drastic as in Summit County, probably due to Morgan County being a more rural community.

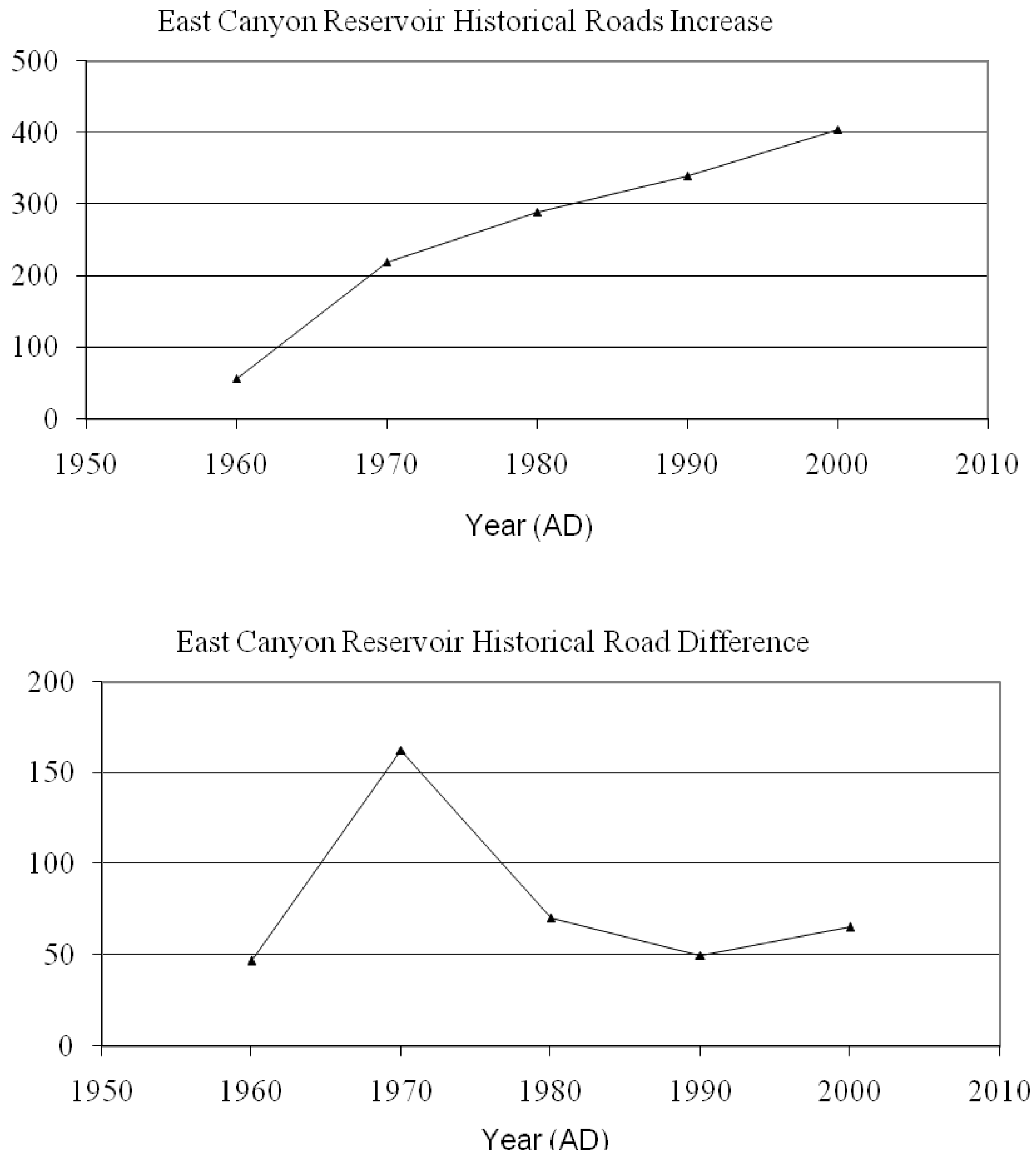
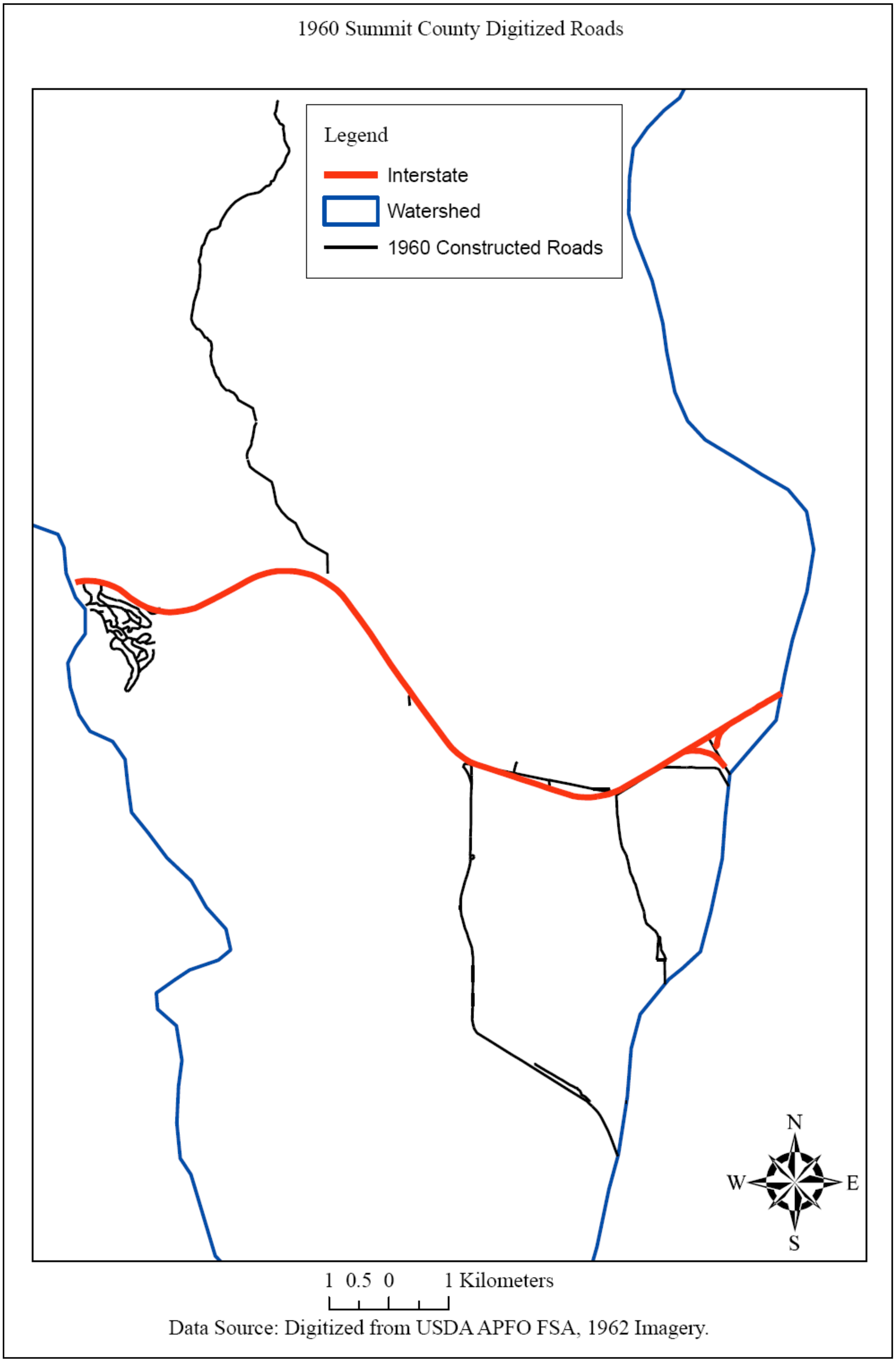


Figure 17: East Canyon Reservoir historical road increase and road difference, 1960–2000, in Morgan and Summit Counties. There has been a steady increase in development from the 1960s.The most distinct difference being from 1960 to 1970, when the greatest increase in development occurred. It was during the 1960s that there was an increase in ranching, farming and tourism industries in Summit County.

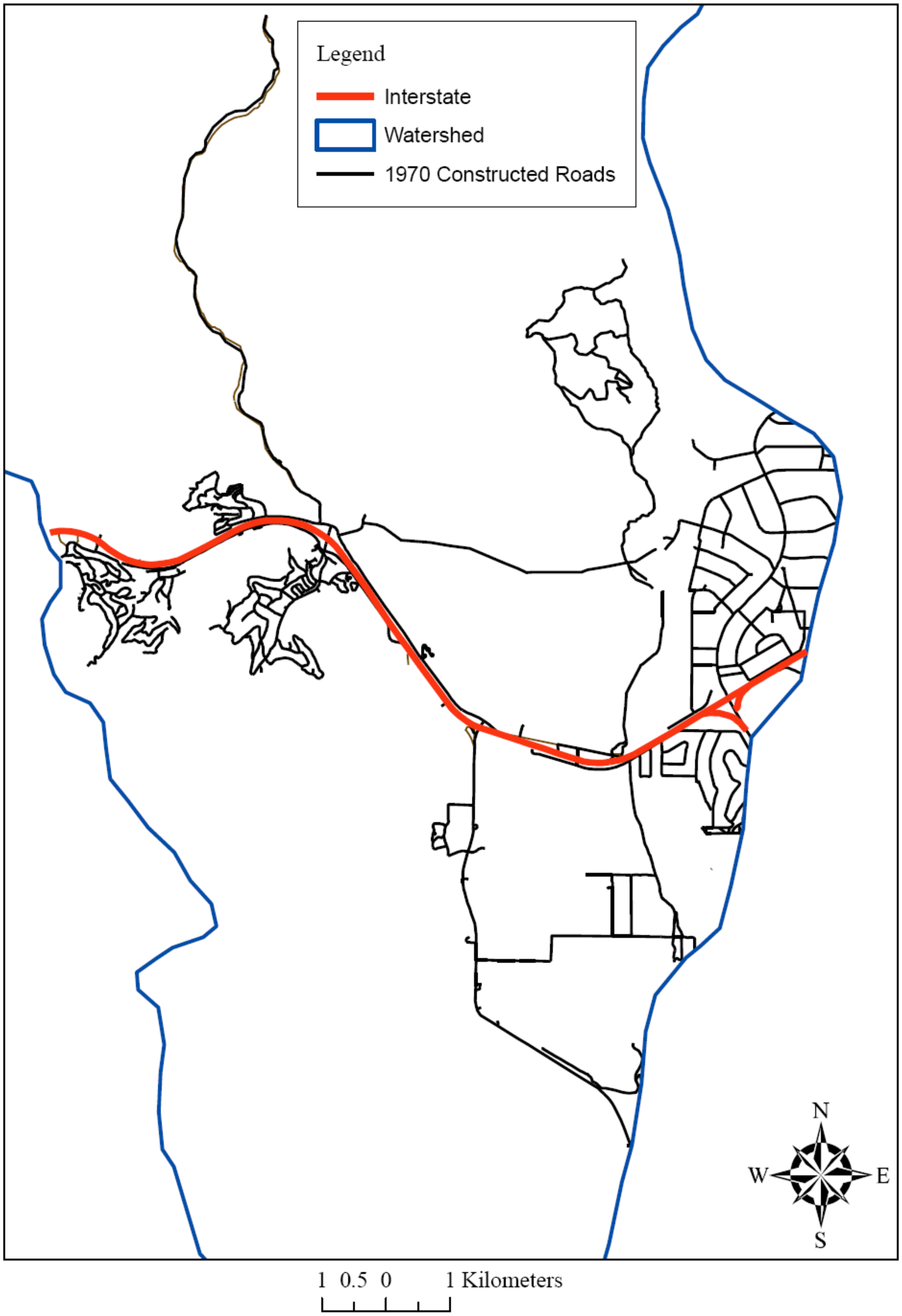
Figure 18: New road growth digitized by decade indicating significant changes in population from 1960 to 2000 in Summit County, Utah.



Data Source: Digitized from USDA APFO FSA, 1962 Imagery.

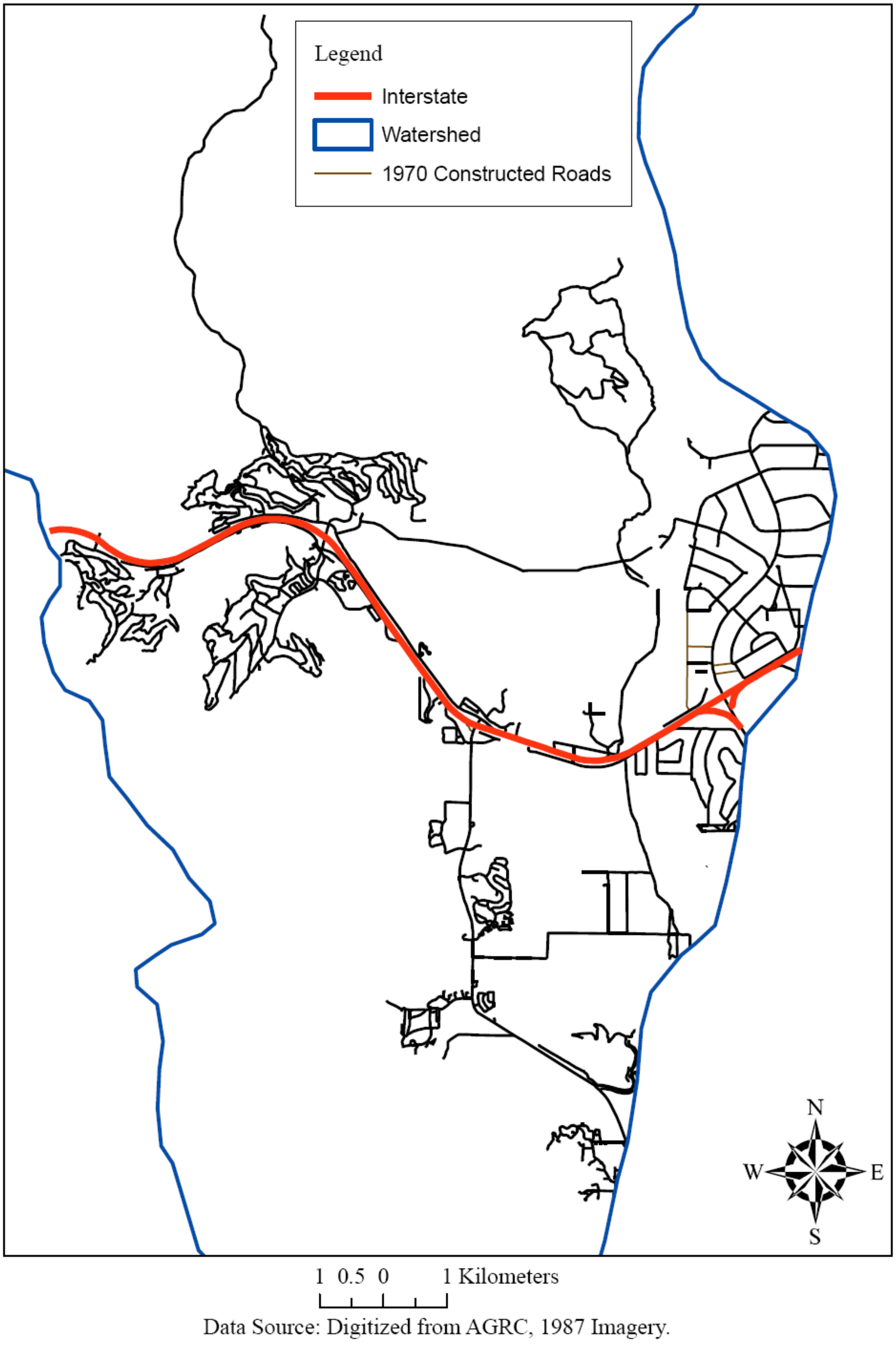
Figure 18 cont.

1970 Summit County Digitized Roads



Data Source: Digitized from USDA APFO FSA, 1978 Imagery.

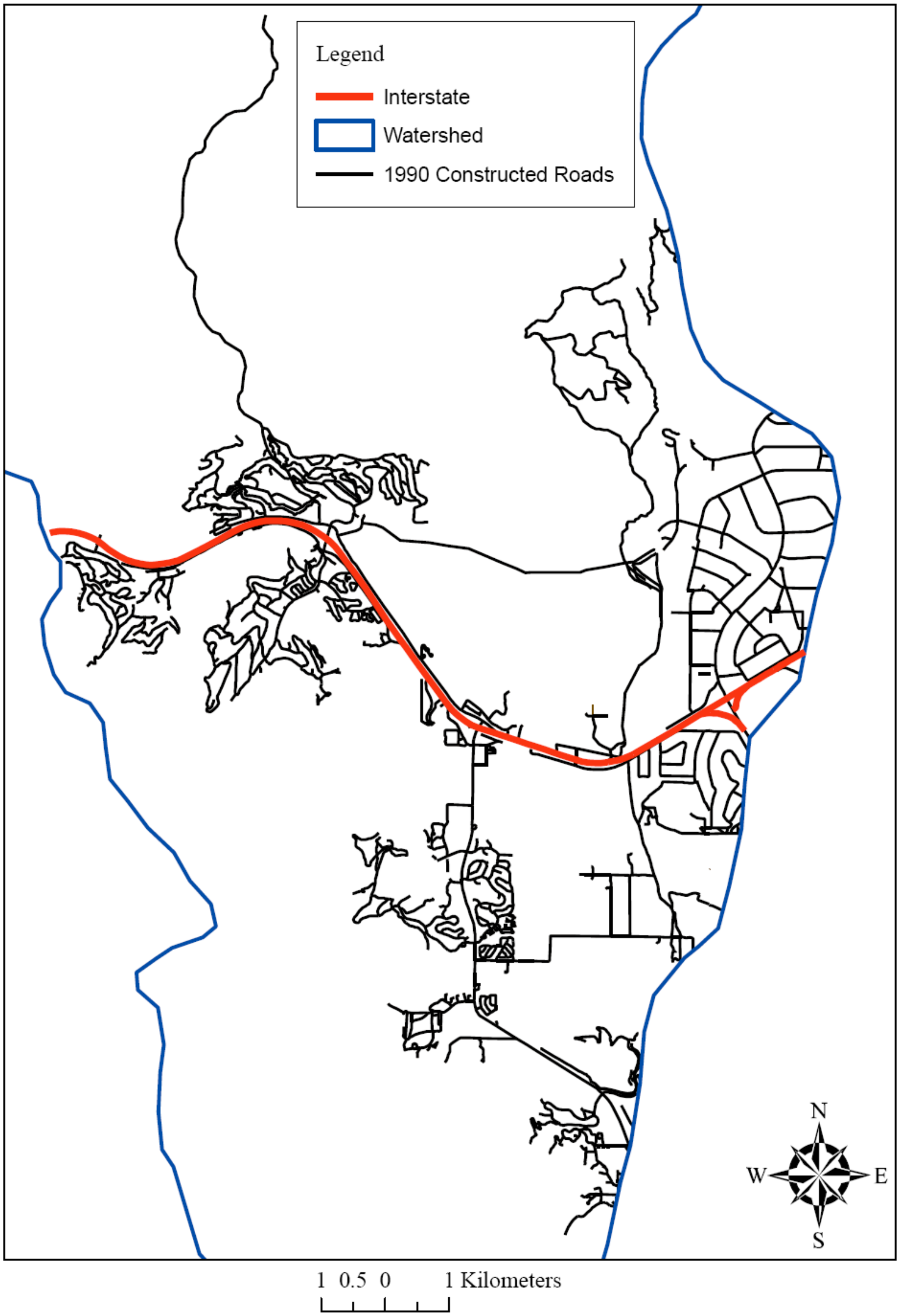
1980 Summit County Digitized Roads



Data Source: Digitized from AGRC, 1987 Imagery.

Figure 18 cont.

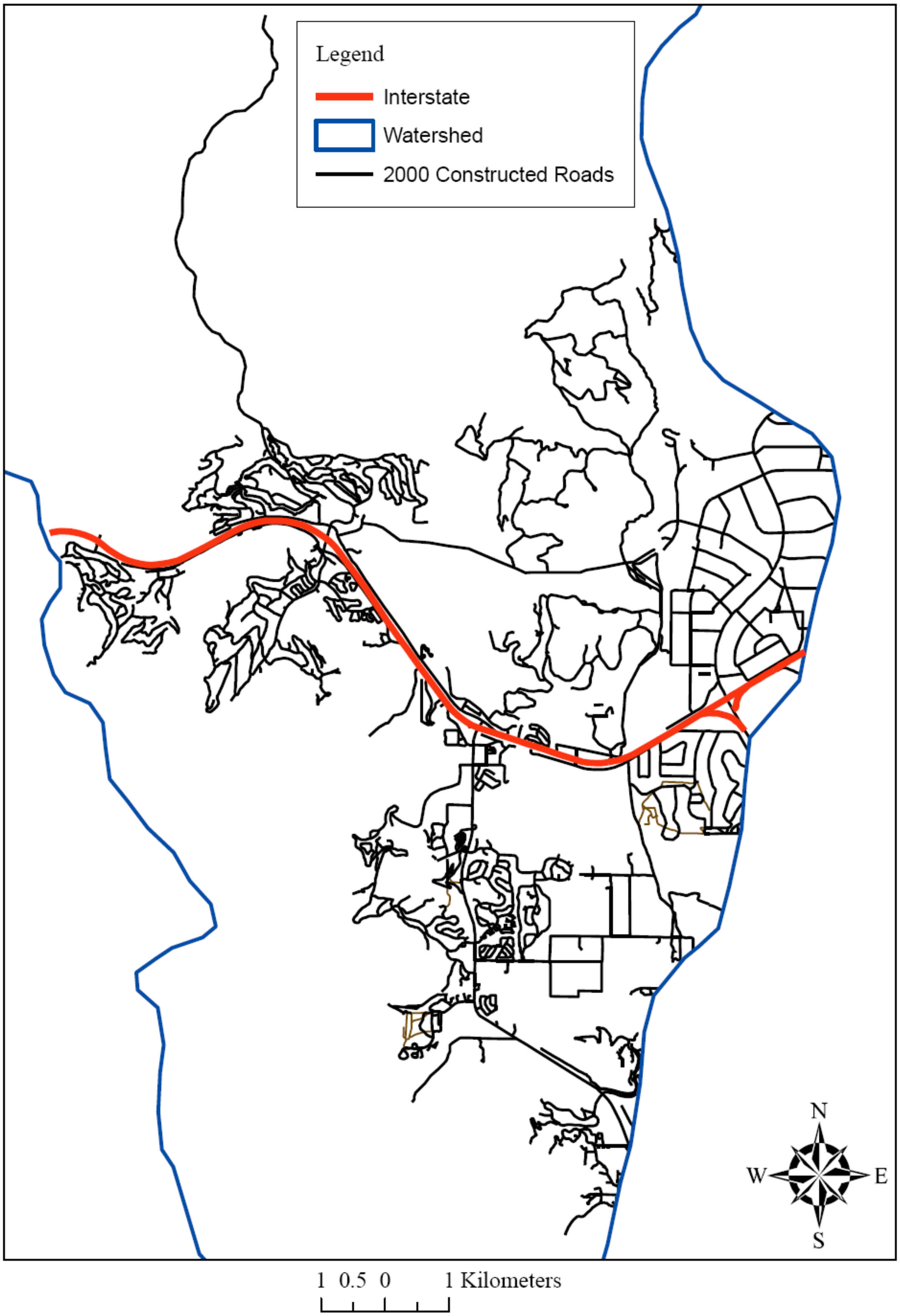
1990 Summit County Digitized Roads



Data Source: Digitized from AGRC, 1997 Imagery.

Figure 18 cont.

2000 Summit County Digitized Roads

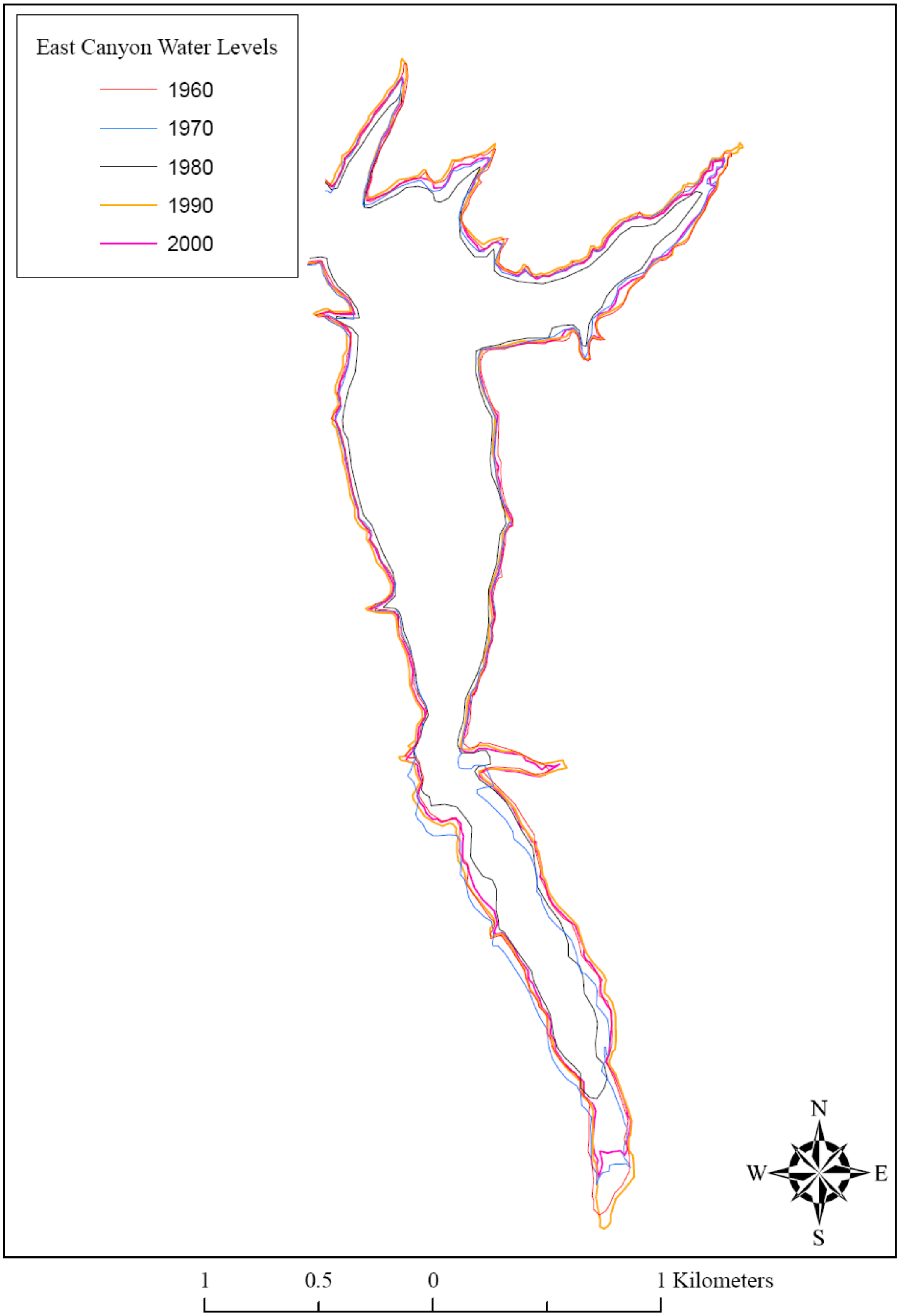


Data Source: Digitized from SBWRD, 2005 Imagery.

Figure 19: Historical East Canyon Reservoir water levels indicating the high and low shifts from 1960-2000.

Figure 19 cont.

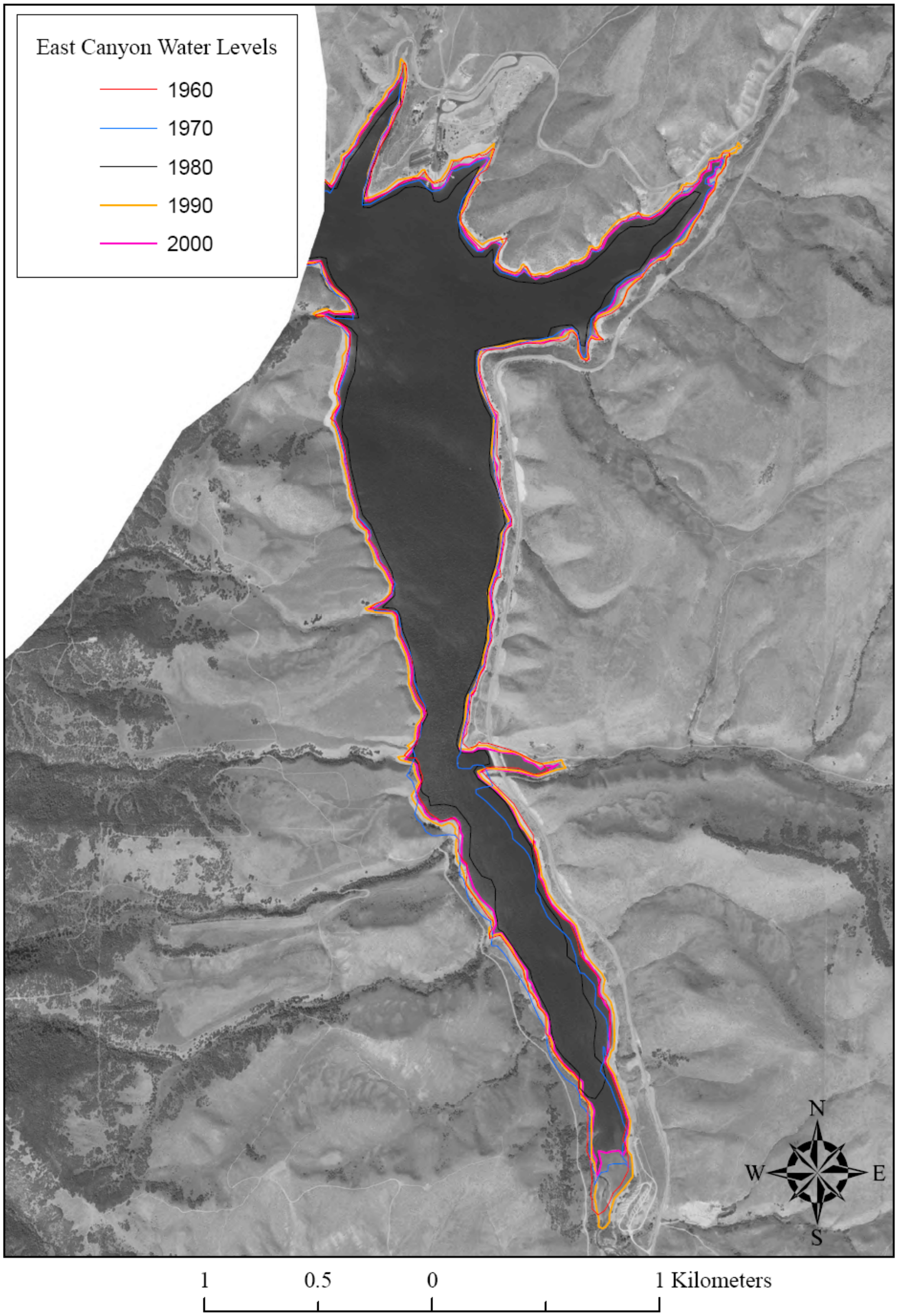
Digitized Reservoir Water Levels from 1960-2000.



Data Source: USDA APFO, AGRC,SBWRD, 1959, 1962, 1978, 1987, 1997, 2005.

Figure 19 cont.

Digitized Reservoir Water Levels from 1960-2000.



Data Source: USDA APFO, AGRC,SBWRD, 1959, 1962, 1978, 1987, 1997, 2005.

Table 6

Population growth of Morgan and Summit County, 1960–2000

Year	Morgan County	Summit County
1900	2045	9439
1910	2467	8200
1920	2542	7862
1930	2536	9527
1940	2611	8714
1950	2519	6745
1960	2837	5673
1970	3983	5879
1980	4917	10198
1990	5528	15518
2000	7129	29736

Note. Adapted from the U.S. Census Bureau (www.censusscope.org).

CHAPTER 5

DISCUSSION

The goal of this thesis was to determine if erosion and nutrients at East Canyon Reservoir have increased over time, and if they have increased, whether they have done so as a result of development. Based on this study, the reservoir's environmental conditions have not changed significantly since before 1900, although there have been subtle changes that have coincided with dam construction, enlargement, and increased development (Table 4).

5.1 The Impacts of Dam Construction, Enlargement, and Land Development on East Canyon Reservoir

With the initial dam construction in AD 1896 (26.5 cm), MS increased (Table 4, Figure 20). Increasing MS values are expected with the increased erosion that would have occurred with land clearance for agriculture and dam construction and enlargement. The increase in MS values was accompanied by a decrease in percent organics (Table 4 and Figure 20). Previous studies have shown that an increase in erosion and inorganic inputs dilutes the percent organics (Almquist et al., 2001; Kirby et al., 2004; Lavoie & Richard, 2000). There is also evidence that land clearance and initial dam construction may have been catalysts for increasing phosphorus levels, as seen in the decrease of

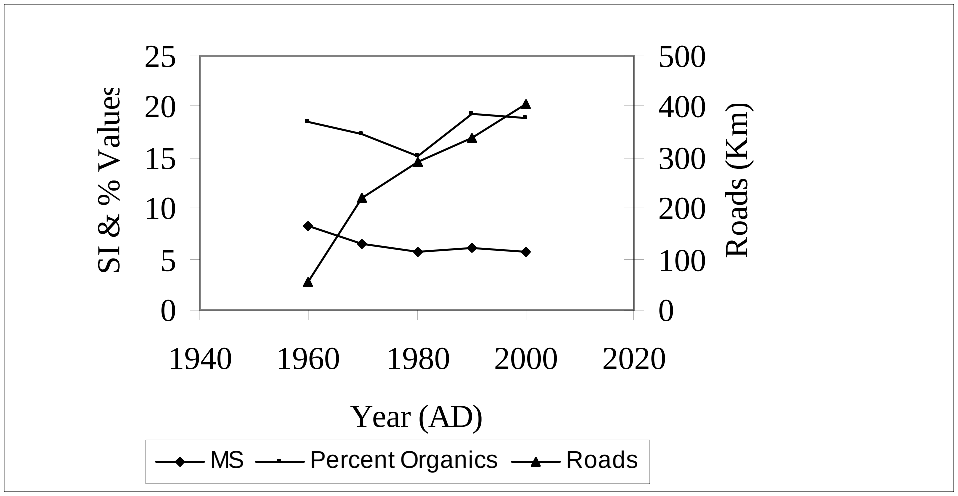


Figure 20: Historical road increase from 1960–2000 in comparison to the decadal average 1960–2000 of magnetic susceptibility and percent organics. This data shows no relationship between magnetic susceptibility, percent organics, and historical road increase within Summit County.

Aulacoseira granulata and the increase in *Stephanodiscus spp*. (Figures 14 and 15). This trend of increasing phosphorous after construction of a dam has been termed *trophic upsurge* caused by the release of phosphorus from flooded organic matter and soil and vegetation decomposition (Schallenburg & Burns, 1997).

Increasing organics from AD 1916 (~23.5 cm) until ~AD 1960 (~15 cm) to a high value of 21% were probably due to trophic upsurge immediately following the significant dam enlargement from 14,000 acre-ft to 25,700 acre-ft in 1916. The concomitant decrease in MS values was the result of dilution from the increase in percent organics but could also indicate a reduction in delivery of inorganics with dam enlargement and the coring sites becoming further from the main stream inflow with the enlargement (Figure 5). However, the continuation of increasing organics well after 1916 is undoubtedly related to increasing nutrients as a result of drought events (1930–1936 and 1953–1965) and an increase in development. This interpretation is supported by changes in diatom assemblages. After AD 1916 (23.5 cm), there was further reduction of *Aulacoseira granulata ssp.* and an increase in *Stephanodiscus ssp.* evident with the 1916 dam enlargement (Table 4). This indicates an environment that is increasing in phosphorous and is supported by continually increasing levels of organics. The increase in development was due to the combination of an economic slow period due to decreasing silver prices, which led to a decrease in population (Figure 21), and a change in economic focus to tourism (UDWQ, 2008). The focus on recreation and tourism resulted in an increase in ski resorts and golf courses in Summit County from the 1930s to the 1960s (Table 4). These activities could have increased the runoff of sediments, increasing phosphorous inputs from the Meade Peak Member (UDWQ, 2008). The Meade Peak

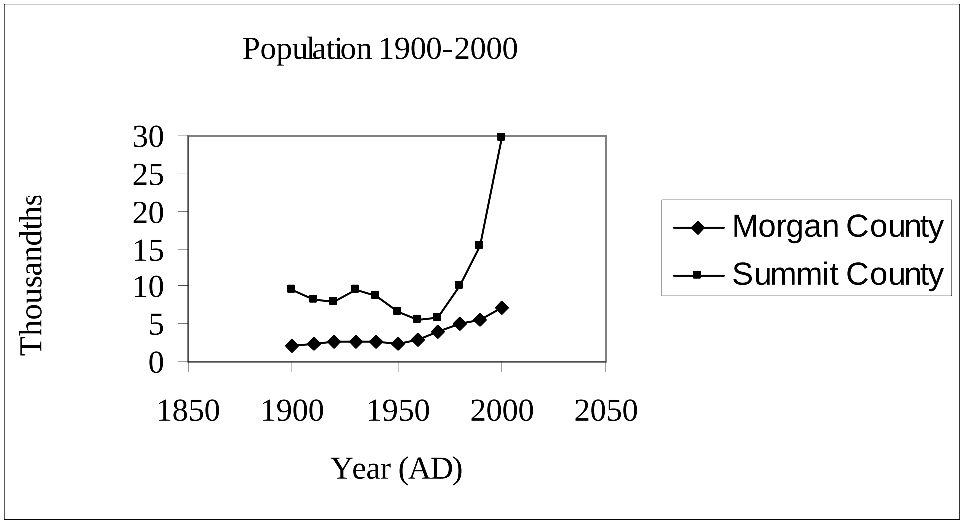


Figure 21: Population of Morgan and Summit County from 1900 to 2000.

Note. Adapted from the U.S. Census Bureau (www.censusscope.org).

Member, which is a primary source of total phosphorus in the watershed, is located near Park City in the southeastern corner of the watershed (UDWQ, 2008). Phosphatic shale areas have been disturbed by development, contributing to the phosphorus loading into East Canyon Reservoir and Creek through erosion (Olsen & Stamp, 2000).

Following the last dam enlargement in 1964, percent organics, MS, and SARs remained low and relatively unchanged (Figure 13). This is surprising, given a dam enlargement that increased capacity from 25,790 acre-ft to 48,110 acre-feet. Increased development should also have led to a change in these variables. Remote sensing imagery from 1960 to 1970 shows the greatest difference in terms of road increase (Figures 17 and 18). A significant population increase also occurred beginning in 1970 (U.S. Census Bureau, 2010; Figure 21). With these marked increases in development, MS and SAR should be amplified in the sediment record due to increased erosion, but they are not (Figure 13; Kirby et al., 2004). Some factors, such as dam enlargement in 1964, might have adjusted East Canyon Creek's sediment bedload, resulting in its deposition farther away from the core sites and an increase in water levels from ~25,000 acre-ft to ~48,000 acre-ft diluting the incoming allochthonous material (Almquist et al., 2001; Lavoie & Richard, 2000; Figure 13 and Table 5). The signal in the core would then be dampened.

The continuation of similar trends in diatom assemblages from Zone 2 to Subzone 3a, in tandem with the final dam enlargement of 1966 (~14 cm; Subzone 3a), indicates a further reduction in turbulence but also indicates a decrease in the Si:P and N:P ratios.

MS remains relatively unchanged, and SARs increases only slightly in Subzone 3b. MS is most likely being diluted by the increase in percent organics, as discussed in relation to Zone 2 (Table 4). Remote sensing imagery shows that there is an increase in road length (Figure 17) from the 1970s to 2000, and the U.S. Census Bureau shows a significant increase in population growth from 1970 to 2000 (Figure 21) in Summit County while Morgan County remained relatively unchanged. These two factors explain the increasing SAR in East Canyon Reservoir from East Canyon Creek (Figure 13).

There is a shift in diatoms to greater abundances of *Aulacoseira granulata* and *Diatoma vulgare* from relatively high abundances of *Stephanodiscus ssp* (Table 4). An increase in nonplanktonic diatoms and diatom diversity in this zone continuing to the present may be associated with increased habitats in the littoral zone as water levels became more stable after the last dam enlargement (Figure 14 and Table 5). The species biplot shows that there is a shift back to the lower left quadrant (Figure 15), which suggests a return to predam conditions.

Figure 22 shows a strong connection between diatom PCA axis 1 and percent organics, supporting the link between increased nutrients and increased productivity.

5.2 Recent Changes: Paleolimnological Data Compared to Limnological Data

My record indicates relatively small changes in East Canyon Reservoir related to dam construction, land clearance, and drought. The recent record suggests that the reservoir may be returning to predam conditions, whereas recent algal blooms suggest a worsening of conditions, despite improved treatment of sewage waters (UDWQ, 2008). Why are algal blooms increasing when mitigation plans are in place and diatoms suggest improving conditions?

Figure 22: Comparison of PCA 1, PCA 2, temperature, and percent organics in Core 2.

Figure 22 cont.

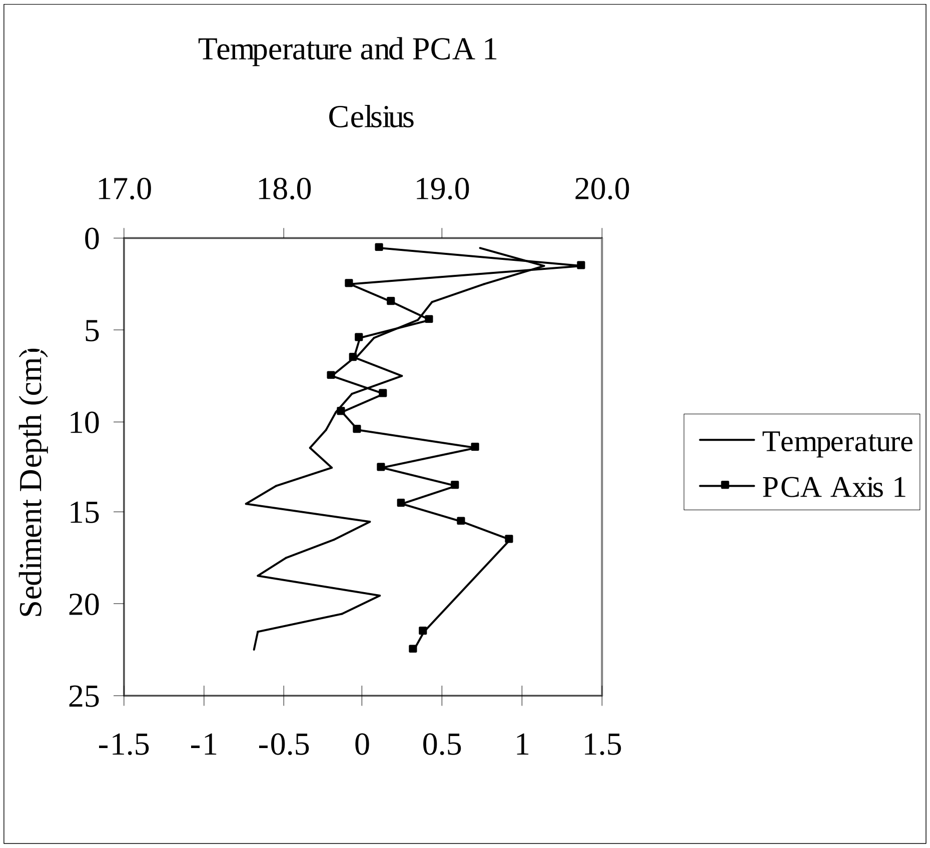


Figure 22 cont.

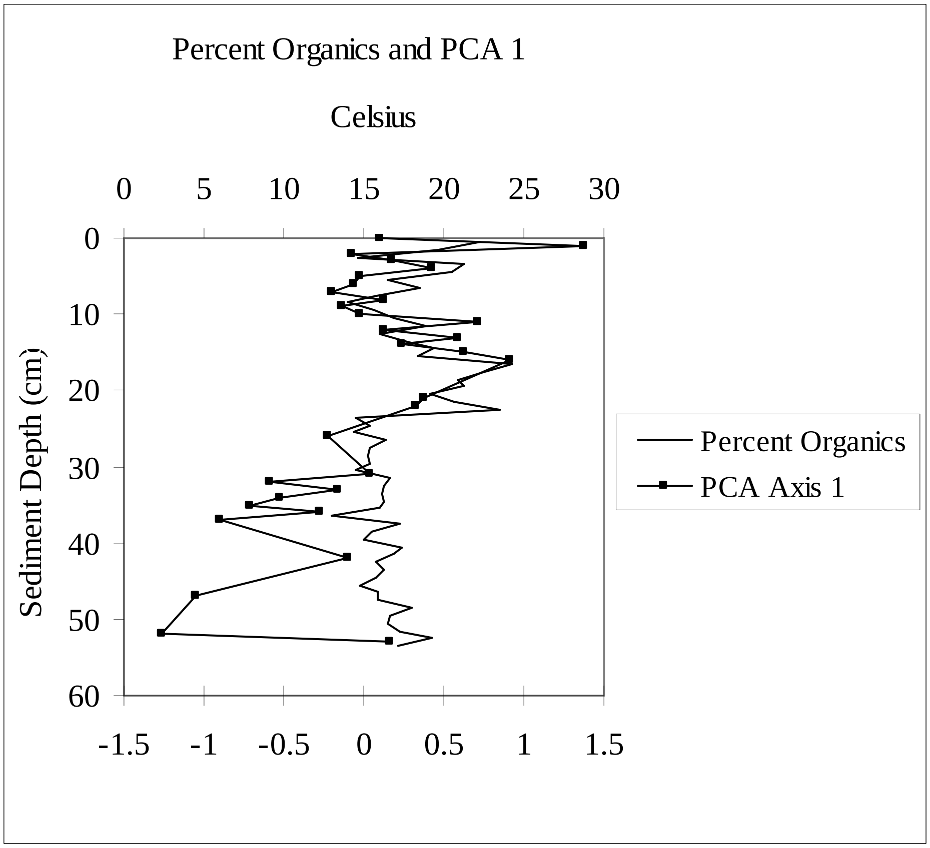
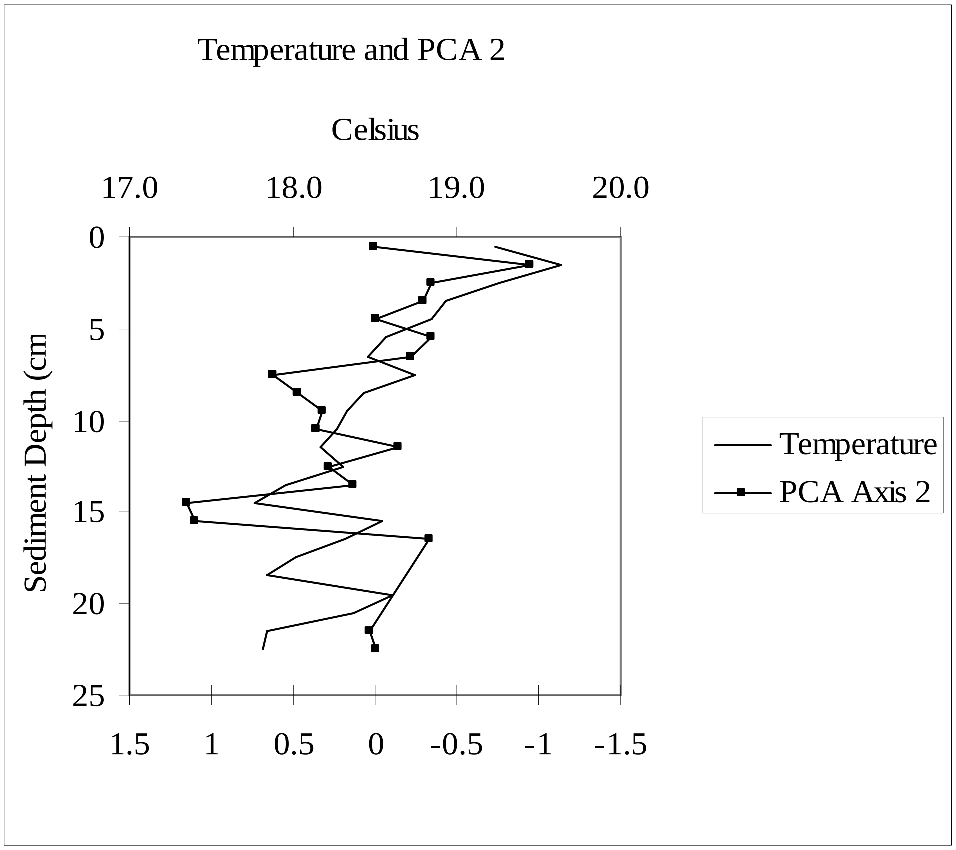


Figure 22 cont.



Subzone 3b is marked by the first appearance of *Cyclotella* and *Diatoma ssp.* It has been suggested that *Cyclotella ssp*. are increasing worldwide and that this is related to warming temperatures (Ruhland, Patterson, & Smol, 2008). This research has found a trend between warming temperatures and *Cyclotella-Aulacoseira-Fragalaria* diatom assemblages. When *Cyclotella sp.* increase, *Aulacoseira-Fragalaria* (small species) decrease due to warmer temperatures (Figure 14). The link between changes in diatom community composition and temperature at East Canyon Reservoir is supported by the strong relationship between diatom PCA axis 2 sample scores and temperature (Figure 22). Recent research has also suggested that warmer temperatures give blue-green algae a competitive advantage over diatoms (Paerl & Huisman, 2008).

My research, therefore, may indicate that recent warming temperatures are having the greatest impact among all factors, although further investigation would be needed to test this idea.

CHAPTER 6

CONCLUSION

This research tested the hypothesis that increased populations and urbanization in the East Canyon Reservoir catchment have caused increased erosion and nutrient inputs into the reservoir. MS and percent organics are tied closely to dam construction and only show a weak relationship to increased populations and urbanization, as evidenced by increased road networks. Additionally, our results indicate that East Canyon Reservoir has always been eutrophic but that P has increased, although only slightly, resulting in a decrease in nutrient ratios, N:P and Si:P as a result of increased nutrient inputs related to land clearance and trophic upsurge following dam construction and enlargement .

The recent shift in the diatom assemblage indicates a decrease in P and suggests that the reservoir should be improving, which is in direct conflict with observations of increased algal blooms. I speculate that the increase in *Cyclotella* and consistent appearance of cyanobacteria is the result of warming temperatures.

This research shows how multiple stressors have impacted East Canyon Reservoir and enables a better understanding of the history of East Canyon Reservoir and its natural variations. I hope that my research will allow water managers to make improved decisions. Because this reservoir historically has been eutrophic, it is even more important that anthropological reduction of nutrient inputs be controlled.

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