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HISTORICAL LAND COVER IMPACTS ON WATER QUALITY IN THE PROVO RIVER WATERSHED, 1975-2002

by

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A thesis submitted to the faculty of
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GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Fredric J. Donaldson

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Fredric J. Donaldson in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

HISTORICAL LAND COVER IMPACTS ON WATER QUALITY IN THE PROVO RIVER WATERSHED, 1975-2002

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Master of Science

The Provo River watershed has experienced land cover change over the past several decades. Land cover influences water quality inasmuch as land cover determines the type and quantity of non-point source (NPS) pollutants that may enter the water. This study examines the historical impacts of land cover changes on water quality in the Provo River using remote sensing and statistical analysis. Statistical correlations and linear regressions were used to study the relationship between various land cover types and water quality variables for six years between 1975 and 2002. This thesis supports research finding myriad impacts of urban land cover on water quality. The study also revealed that increasing pH, alkalinity, and bicarbonate levels in the Provo River are likely related to increasing urbanization of the watershed.

Keywords: Provo River, Land Cover, Water Quality, Remote Sensing

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Chapter 1

Introduction

The water quality of the Provo River is affected by the land use and land cover within its drainage basin or watershed. The watershed, especially the lower section, has experienced urbanization over the past three decades as the cities of Provo, Orem, and Heber have grown and developed (see Table 3.1). Through remote sensing and statistical analysis, this thesis examines the historical impacts of land cover change in the Provo River watershed on the physical, chemical, and biological properties of the water in the Provo River from 1975 to 2002.

Provo River water quality is impacted by point sources (PS) and non-point sources (NPS) of pollution. Pollutants that enter surface waters from a pipe or other man-made conveyance are classified as PS pollutants (e.g. industrial or water treatment plant discharge). PS contaminants include dredged spoil, solid waste, incinerator residue, filter backwash, sewage, sewage sludge, garbage, munitions, chemical wastes, biological materials, some radioactive materials, heat, wrecked or discarded equipment, rock, sand, cellar dirt, and industrial, municipal, and agricultural waste (U.S. Geological Survey, 1999). In contrast, NPS pollution enters the water system through diffuse sources including percolation through land and soil cover and through storm runoff. NPS contaminants may include sediments, salts, nutrients, pesticides, bacteria, organics (such as oil and grease), and heavy metals. Common sources of NPS pollution include urban streets, parking lots, agricultural lands, and construction sites. NPS pollution presents great challenges because sources are ubiquitous yet highly variable (U.S. Geological Survey, 1999). The land covers in the

Provo River watershed affect both the type and quantity of NPS pollutants introduced in the river.

This study examines land cover within the watershed from 1975 to 2002 and identifies relationships between specific land covers and surface water quality variables; however, groundwater is also studied peripherally since it contributes to surface water. The terms *land cover* and *land use* are not synonymous. Land cover is anything covering the surface of the earth, while land use implies a human component. For example, the land cover in a particular area might be identified as urban or built-up, while the land use could be identified as residential and, specifically, used for multi-family units. In other words, the urban (built-up) land cover has a residential land use devoted to multi-family housing units (Anderson et al, 1976). This study focuses on general land cover as opposed to land use; however, a particular land cover may include multiple land uses.

In order to determine the impacts of land cover on water quality in the Provo River over time, this research combines remote sensing methods with quantitative analysis. Land cover was classified for six representative years of Landsat satellite imagery over a period of 27 years. The supervised classification was further refined using a slope layer derived from a digital elevation model (DEM). This land cover classification was found to be robust and accurate. After the land cover classification, percentages of land cover were calculated for each section of the river, upper and lower, and then these data were combined with Provo River water quality data for the corresponding years. Statistical analyses revealed differences and similarities between the upper and lower Provo River, identified potential relationships between specific land cover and water quality variables, and indicated the strength of relationships between each land cover type and each water quality variable.

This study is geographical in nature even though the topic is related to hydrology. The discipline of hydrology (the study of water) is a synthesis of the physical geography field of geomorphology and the technical field of engineering. Hydrologists have traditionally been concerned with water supply and quantity. However, hydrologists are currently beginning to recognize the importance of water quality since water quality and quantity are closely related. Water quantity, after all, directly impacts the dilution, diffusion, and dispersion of organic and inorganic water constituents. The relationship between humans and the environment is a major research theme in the discipline of geography. Land cover is often studied in this context.

The results of this study confirmed earlier studies that have identified a multiplicity of impacts on water quality from urbanization. The results of the study show that urban land cover affects the greatest number of water quality variables in the Provo River while forest and rangeland covers impact the fewest. Moreover this study shows that as urban land cover increased, the pH of the lower Provo watershed and alkalinity also increased. Alkaline waters can have adverse effects on aquatic organisms and human health.

This study offers supporting evidence for previous studies on land use and water quality and extends this research to a small urbanizing watershed in the semi-arid intermountain west. Furthermore, this study can serve as a reference to inform similar studies on water quality impacts of land covers in surrounding watersheds.

Chapter 2

Review of Literature

Surface water quality is affected by land use and land cover. Since this study is focused on in-stream water quality, a greater emphasis in this literature is given to studies on rivers and streams, not lakes or other holding structures such as reservoirs (though these structures are also affected by land use and land cover). This study does not examine the impacts of land use or land cover change on groundwater specifically; however, since groundwater contributes to surface water, it is studied peripherally.

Land use and land cover of a given region influence hydrological processes including water quality and quantity (Lahmer et al, 2001). Land use and land cover changes can affect the hydrological cycle and water quality in four ways: they can cause floods, droughts, and changes in river and groundwater regimes, and they can affect water quality; the first three impacts relate to water quantity, the last to water quality (Rogers, 1991). For a review of recent research examining the relationship between land use and water quality see Baker (2003). Griffith (2002) reviews current research that utilizes geographic techniques and remote sensing to examine landscape-water quality relationships and Gergel et al (2002) review the literature related to the use of landscape metrics to study human impacts on riverine systems. The impacts of land use and land cover change on hydrologic processes have been identified as a “major [research] focus for the future” (DeFries and Eshleman, 2004).

Point Source and Non-Point Source Pollution

Pollutants (chemical and mineral constituents) can enter surface water in two ways: through point sources, and through non-point sources. As the name indicates, in point-source (PS) pollution, a contaminant or nutrient enters the water at an identifiable point (often a pipe). This type of pollution usually emanates from a wastewater treatment plant (WWTP) or an industrial site. In contrast, non-point source (NPS) pollution enters the water in a distributed, cumulative way. For example, overland and subsurface flow carry pollutants from a variety of land cover types into nearby streams. Progress in controlling NPS pollution has yet to match progress in cleaning up PS pollution (U.S. Geological Survey, 1999). As of 1991, the United States had spent over $300 billion on controlling PS pollution since 1970 only to discover that many rivers and water bodies were still heavily polluted from NPS pollution. Agriculture and forestry are two major sources of NPS pollution, but urban storm runoff and sewer overflows also contribute significantly (Rogers, 1991).

Many early studies on NPS pollution focused on the effects from runoff over agricultural land. Studies noted increasing levels of nutrients in streams, specifically phosphorous and nitrogen (nitrate and nitrite), resulting from agricultural runoff (Omernik, 1976; Omernik, 1977; Omernik et al, 1981; Beaulac and Reckhow, 1982). As a result these nutrients became the focus of many later studies (Carpenter et al, 1998; Chang, 2004). Increased nutrient levels can have negative effects on downstream ecosystems (Peirels et al, 1991; Wernick et al, 1998). Some research advocated planning measures to ensure that agricultural watersheds were improved and sustained (Karr and

Schlosser, 1978) and the effectiveness of improved watershed management practices was later confirmed (Park et al, 1994).

After agriculture was identified as a major contributor to NPS pollution, it became a research focus for much of the early literature. In the late 1980s, Agricultural Non-Point Source Pollution Model (AGNPS), a mathematical model to analyze NPS pollution from agriculture, was developed (Young et al, 1989). This model was later linked to geographic information systems (GIS) and refined (He, 2003; Morse et al, 1994). Several studies in the early 1990s showed how GIS could be used to model water quality and NPS pollution (Vieux, 1991; Rifai et al, 1993; and Kim and Ventura, 1993). Another focused on a symposium on the minimization of NPS pollution (Sharpley and Meyer, 1994). Through the use of remote sensing, impervious surface was identified as a “key environmental indicator” in pollution mitigation (Arnold and Gibbons, 1996). Electrolytic conductivity was also proposed as a water quality indicator since, unlike most water quality variables, conductivity can be detected remotely as opposed to *in situ* (Wang and Yin, 1997).

There is currently a large research effort to determine the best methods in which GIS and remote sensing can be incorporated into studies of water resources and NPS pollution on local watershed scales (Basnyat et al, 2000; Bhaduri et al, 2001; Bhaduri et al, 2003; Sawaya et al, 2003). Remote sensing and GIS tools have been developed for assessing the hydrological impacts of various land covers (DelRegno and Atkinson, 1988; Choi et al, 2003, Pandey et al, 1999; Kim and Ventura, 1993; Grove et al, 2001; Ren et al, 2003; Tong and Chen, 2002). Recent studies have also examined NPS pollution from lawns and documented the development of GIS models of PS and NPS pollution for agricultural watersheds (Robbins and Birkenholtz, 2003; DiLuzio et al, 2004). Models have also been developed to predict the impacts of development scenarios on water quality and quantity (Butcher, 1999; Bhaduri et al, 2003; Mattikalli and Richards, 1996).

Land Cover and Land Use Impacts on Water Quality

The types of land cover utilized in this study are taken from the U.S. Geological Survey land cover and land use classification system for use with remotely sensed data (Anderson et al, 1976). Land covers used in this study include the following: urban land, agricultural land, rangeland, forest land, water, and barren land. Other covers in the scheme, including wetland, tundra, and perennial snow and ice, were not used in this study. There are known wetlands in the watershed located in the Heber Valley where the Provo River drains into Deer Creek Reservoir; however, these areas are not discernable in the 1975 and 1979 Landsat MSS imagery. Since the goal of study was to study land cover types from 1975 through 2002 and it was necessary to use these older images, wetlands were not included in the analysis.

Forest and rangeland are separate categories in the U.S. Geological Survey land cover classification system but are combined in the literature review due to their similar impacts on water quality. The literature review proceeds with a summary of the effects of specific land covers on surface water quality.

Forest and Rangeland

Forest and rangeland have minimal effects on water quality. In areas covered by forests and rangeland the terrestrial and aquatic environments are in dynamic equilibrium

(Karr and Schlosser, 1978; Rogers, 1991). Rainfall is absorbed by the land surface and vegetation and released over a long period of time. There is little surface runoff during periods of normal rainfall and few nutrients are carried away in drainage waters. The nutrients lost from the land are assimilated by the biotic communities in the watershed, and erosion in this state is minimal (ibid.). Flooding unbalances the equilibrium and leads to increased inputs of nutrients from the land to surface waters. Many studies have shown that water in forested areas has lower levels of nutrients than water closer to human activities (Omernik et al, 1981; Osborne and Wiley, 1988; Basnyat et al, 2000; Ngoye and Machiwa, 2004).

Agricultural Land

Agricultural land cover affects water quality. Agricultural land cover includes land used for production of food and fiber (e.g. cotton). This type of land cover includes cropland, pasture, orchards, groves, vineyards, nurseries, ornamental horticultural areas, confined feeding operations, and other agricultural lands (Anderson et al, 1976). Agricultural activities represent a human alteration of the natural environment. These alterations often lead to increasing erosion and water quality impacts (Karr and Schlosser, 1978; U.S. Geological Survey, 1999). As noted previously, much of the early literature examining NPS pollution, land use and land cover impacts on water quality was focused on agriculture.

Agricultural lands were found to contribute increased quantities of nitrogen to surface waters (Omernik, 1976; Omernik, 1977; Osborne and Wiley, 1988; U.S. Geological Survey, 1999; Fisher et al, 2000). Higher nitrogen levels detected in agricultural waters result from precipitation runoff and irrigation of agricultural lands where fertilizers, manure, and pesticides have been applied (Beaulac and Reckhow, 1982; U.S. Geological Survey, 1999; McFarland and Hauck, 1999).

In addition to nitrogen, agricultural land also contributes phosphorous to surface water through runoff, though a smaller amount of phosphorous is contributed in comparison to nitrogen (Soranno et al, 1996; U.S. Geological Survey, 1999; Fisher et al, 2000). Agricultural contributions of phosphorous often originate from livestock waste and fertilizers (McFarland and Hauck, 1999; Buck et al, 2003). Unlike nitrogen, phosphorous is not easily water-soluble and is carried into surface waters with suspended sediments. Phosphorous attaches itself to soil particles and moves with runoff to surface water sediments. Increased nitrogen and phosphorous can cause problems in fresh surface waters as they can lead to a condition called eutrophication. This causes excessive plant growth and algal blooms, which can choke out fish and other aquatic organisms by reducing the amount of dissolved oxygen in the water. Efforts to mitigate the effects of NPS pollution from agriculture have focused on identifying erosive areas and applying soil conservation practices (Schlosser and Karr, 1981).

Pesticides from agriculture (mainly herbicides such as atrazine, metolachor, alachlor, and cyanazine) can also find their way to surface waters. Other constituents related to agriculture found in streams include the insecticides DDT, dieldrin, and chlordane. All three of these substances are no longer used in the U.S., but remain in surface water sediment and fish (U.S. Geological Survey, 1999).

Urban (or Built-up) Land

Even though urban areas cover a relatively small proportion of the earth—just 5 percent in the United States (U.S. Geological Survey, 1999)—these areas contain much of the world's population and can have significant ecological impacts on water quantity and water quality. Urban land includes areas of intensive use where a significant percent of the land is covered by impervious materials (e.g. buildings, pavement, etc.). This type of land cover includes the following land uses: residential, commercial and services, industrial, transportation, communications and utilities, industrial and commercial complexes, mixed urban, and other urban. Urban land cover includes land covered by cities, towns, villages, strip developments, transportation components, power facilities, communications structures, malls, shopping centers, and industrial and commercial complexes (Anderson et al, 1976). The impacts of urban areas on hydrology (water quantity) (Douglas, 1976; Leopold, 1968; U.S. Soil Conservation Service, 1986; Environmental Protection Agency, 1997; Rose and Peters, 2001), geomorphology, temperature, and biology have been summarized elsewhere (Paul and Meyer, 2001).

Urban surface waters contain increased amounts of almost all constituents. Increases in oxygen demand, conductivity, suspended solids, ammonium, hydrocarbons and metals in urban streams have all been identified from both wastewater treatment plants and NPS pollution (Porcella and Sorenson, 1980; Lenat and Crawford, 1994; Latimer and Quinn, 1998; and U.S. Geological Survey, 1999; Ha and Bae, 2001). Storm runoff and combined sewer overflows are significant sources of NPS pollution in urban areas (Pierce, 1980). Water pollution problems in urban areas are also caused by urban runoff over areas affected by street sweeping, oil and gasoline leaks, salt application, and urban traffic. In fact, urban stormwater runoff is similar in chemical and biological contaminants to raw sewage from sewer overflows (Rogers, 1991).

Urban waters have also been found to contain elevated levels of insecticides, herbicides, and nutrients. Insecticides occurred at higher frequencies and in higher concentrations in urban streams than in agricultural streams; these constituents include the insecticides diazinon, carbaryl, chlorpyrifos, and malathion and the herbicides atrazine, simazine, and prometon (U.S. Geological Survey, 1999). These are commonly used around homes, gardens, and commercial and public areas. In addition, urban streams have been found to have higher frequencies of the relic pesticides DDT, chlordane, and dieldrin in fish and sediment and higher concentrations of chlordane and dieldrin in urban waters (U.S. Geological Survey, 1999). NPS pollutants from lawn maintenance chemicals— such as 2, 4, D, glyphosate, diazinon, and dicamba— also contribute to surface water quality problems in urban areas by attaching to sediments where they enter surface water through runoff (Robbins et al, 2001; Robbins and Birkenholtz, 2003). Most of these chemicals are toxic and may be especially detrimental to small biological organisms, but may impact human health as well (U.S. Geological Survey, 1999; Robbins, 2003).

Urban runoff also introduces nutrients and other ions. Concentrations of total phosphorous in urban area streams are also generally higher than in agricultural area streams (Brett et al, 2005; Omernik, 1976; U.S. Geological Survey, 1999; Winger and Duthie, 2000). These elevated levels of phosphorous are often due to PS pollution from wastewater treatment plants and NPS pollution from fertilizers (U.S. Geological Survey, 1999; Robbins et al, 2001; Robbins and Birkenholtz, 2003). Increased levels of nitrogen have also been observed in urban streams (Brett et al, 2005; Meybeck, 1998). Nitrogen concentrations downstream from wastewater treatment facilities have remained generally stable, suggesting that NPS pollution increases may have offset improvements in PS pollution discharge mitigation (U.S. Geological Survey, 1999). Increases in ammonium and nitrite have also been observed (Zampella, 1994; Wernick et al, 1998; U.S. Geological Survey, 1999). As noted, high levels of nutrients (phosphorous and nitrogen) in urban waters can lead to eutrophic conditions that adversely affect fish and other aquatic organisms.

Urban waters also have elevated levels of other ions including calcium, sodium, chloride, potassium, and magnesium (Zampella, 1994). The elevated levels of chloride often result from the application of deicing salt (sodium chloride) on urban roads. These inputs elevate electrolytic conductivity in urban surface waters.

Elevated levels of organic contaminants have also been detected in urban surface waters. Some of the more common contaminants are polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and petroleum-based aliphatic hydrocarbons (Whipple and Hunter, 1979; Moring and Rose, 1997; Frick et al, 1998). Carcinogenic PCBs were outlawed in industry, but they are still frequently detected because of their stability. PAHs include both natural and synthetic hydrocarbons found in organic solvents used in industry. These are probably from industrial effluents and spills. Petroleum-based aliphatic hydrocarbons from automobile oil are also found in urban waters (Klein, 1979). In addition, high concentrations of fecal-coliform, *E. coli*, and enterococci were also found in urban areas (Frenzel and Couvillion, 2002). These substances can adversely affect riparian organisms and human health.

Urban waters may contain pharmaceutical substances and other chemicals. Studies have identified levels of antibiotics, genotoxic chemotherapeutic drugs, analgesics, narcotics, and psychotherapeutic drugs in effluent and surface waters (Halling-Sorenson et al, 1998). The effects of these substances on biota are not yet fully understood.

Urban surface waters can have higher levels of metals in both the water and attached to sediments (Klein, 1979; Wilber and Hunter, 1977; Wilber and Hunter, 1979). Common metals found include cadmium, chromium, copper, lead, manganese, mercury, nickel, and zinc (Wilber and Hunter, 1979). Lead has declined in some urban surface waters since it was eliminated as a gasoline additive (Frick et al, 1998). Industrial discharges are common PS pollution sources of metals. NPS pollution sources of metals in urban environments include brake linings, tires, and engine parts, which can accumulate on roads and parking lots. Other metals, often from NPS pollution sources, that have been found in urban waters include antimony, arsenic, boron, cobalt, iron, lithium, molybdenum, rubidium, scandium, silver, strontium, and tin (Muschak, 1990; Mielke et al, 2000; Neal and Robson, 2000). The ecological impacts of increased metal concentrations include a decline in aquatic organism populations and alteration in community structures (Boyd, 2000).

Mixed-Use Land Cover

The complex and variable nature of mixed-use land cover leads to variability and complexity in water quality impacts. Mixed-use land cover is common even if it is not an identified class in the U.S. Geological Survey land cover classification system. Mixed-use land cover, including urbanizing land, has a combination of urban, agricultural, and natural land covers. A variety of pesticides have been found in basins that drain both agricultural and urban land (U.S. Geological Survey, 1999).

Urbanizing land is a type of mixed-use land cover. However, studies of "urbanization" or "urbanizing land" usually have a historical component since an area cannot be identified as urbanizing without showing that urban land cover has increased or is currently increasing over time. The effects of increasing urban land cover on water quality can be inferred from the discussion above and these effects generally depend on the type of land being overtaken by urban development. Studies on the hydrological effects of urbanization often refer to impervious surfaces and pervious surfaces. This is because increases in impervious surfaces lead to an increase in overland stream-flow and a decrease in percolation to groundwater (Rose and Peters, 2001). Location along the rural-urban gradient also influences land use impacts on water quality (Wear et al, 1998).

The Provo River watershed contains many of the land covers noted and can be thought of as an urbanizing watershed. In addition to studying the effects of general land cover change on Provo River water quality, this study also examines the specific effects of land covers in the watershed on water quality variables in the Provo River.

Chapter 3

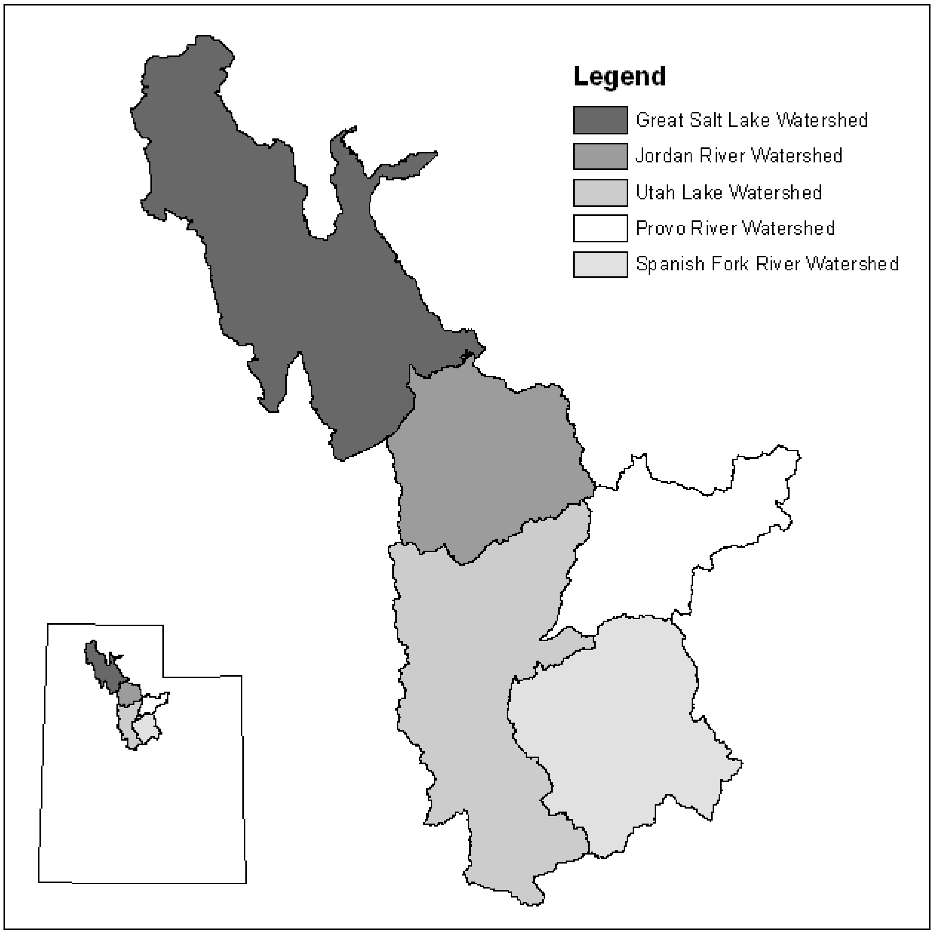
Description of the Watershed

The Provo River watershed (or sub-basin) is part of the larger Jordan River drainage basin, which flows into the Great Salt Lake in the state of Utah (see Figure 3.1). The Provo River watershed is the larger of the two main drainages that empty into Utah Lake (the other being the Spanish Fork River watershed). The Provo River traverses a distance of approximately 65 miles from its headwaters at Trial Lake in the Uinta Mountains in Summit County, passing through the Jordanelle and Deer Creek reservoirs in Wasatch County, before emptying into Utah Lake, the largest natural freshwater lake in the state. Utah Lake water then flows through the Jordan River to the Great Salt Lake, a terminal lake. The watershed topography is generally mountainous (see Figure 3.2), with flat areas found in the Heber and Kamas valleys and near Utah Lake. The maximum elevation in the Provo River watershed exceeds 10,000 feet above sea level. The lowest elevation in the watershed, where the Provo River enters Utah Lake, is close to 4,500 feet above sea level.

Physical Geography of the Provo River Watershed

The watershed is found in the desert-steppe climatic zone. Based on Western Regional Climate Center data for six stations within the watershed (Olmsted Powerhouse, Orem Treatment Plant, Heber, Kamas 3 NW, Snake Creek Powerhouse, and Deer Creek Dam), the average annual maximum temperature and minimum temperature in the watershed are 61.2° F and 32.3° F, respectively. The watershed as a whole receives 18.4 inches of precipitation per annum. Average annual snowfall equals 70.2 inches and average annual snow depth is 2.2 inches. The terrain in flat areas of the watershed consists of unconsolidated valley-fill and alluvial fan deposits ranging from less than 100 to more than 400 feet thick. These soils are generally fertile with adequate irrigation.

Figure 3.1: Map of area watersheds



History of Provo River Water Use

The Provo River has felt the imprint of humans for thousands of years. Nomadic Indians (Fremont, Paiute, Ute, Goshiute, and Shoshone) fished in the Provo River, especially during the spawning season (Jackson and Stevens, 1981). Explorers and trappers also fished in the Provo River watershed. In 1776, an exploration party led by the Spanish Friars Dominguez and Escalante also visited the region, recording the following description of the Provo River watershed: “[The Provo River] is more abundant than the two above mentioned [apparently the Spanish Fork River, and Spring and Hobble Creek]; [the Provo River] has large poplar groves and valleys of good soil with sufficient water to support two or even three large towns.” (Father Vélez de Escalante, September 1776). A prominent trapper named Etienne Provost worked in Utah Valley around 1820. Provo City and the Provo River were named after him. While leading a party of fur traders through the region, General William H. Ashley established a trading post near Utah Lake in 1825. Trapper John C. Fremont also visited the region around 1843. Early Indians, explorers, and trappers did not establish permanent settlements in the region. The first permanent settlements in the region were established by the Mormon pioneers who arrived in Utah in 1847 (Jackson and Stevens, 1981).

A settlement along the Provo River was established in 1849 and water from the river began to be diverted for agricultural irrigation. The first season, the settlers grew wheat, rye, and corn on 200 acres. Thereafter, more farms were established and the population began to grow. Soon water from the Provo River was diverted to other communities including Pleasant Grove, American Fork, and Lehi (Ibid.).

Settlers in the region fished in the Provo River. Early settlers caught spawning fish in the lower Provo River and ate them fresh, dry, or salted. After an 1855 dispute between settlers and Indians over spawning fish in the Provo River, the settlers even agreed to provide fish to the Indians, who were upset that the settlers were catching more fish using nets and seines than the Indians, who were using conventional methods. A small fisheries industry developed on the Provo River and at Utah Lake and its tributaries. The city of Provo began to regulate Provo River fishing in 1856. In the late

1860s and through the 1870s, commercial fishing waned as more water was diverted for agriculture and the amount of fish declined. Thereafter fishing continued in the Provo River with limitations (Jackson and Stevens, 1981). Today fishing on the Provo River is almost entirely recreational. Fish species currently found in the Provo River include Cutthroat Trout, Rainbow Trout, Brown Trout, Mountain Whitefish, Brook Trout and endangered June Sucker, among others (Thompson et al, 2003). Many of these species are non-native and have been introduced over time.

Population growth and economic development increased demand for water for agricultural irrigation, domestic use, and industrial use. The populations of the cities that use Provo River water exhibited slow growth followed by increased growth after the introduction of the railroad in 1873. The number of cities that use Provo River water has also grown. Local use of the Provo River water continues, but Salt Lake County and other northern communities now also use the water. As regional economies developed and changed, Provo River water was required for different uses. The construction of Geneva Steel in Orem and other manufacturing operations in the 1940s placed a greater demand on Provo River water for industrial use. Residential growth has also increased demand for water for domestic uses, including lawn and garden care.

Water from the Provo River is currently used for recreation, agricultural irrigation, culinary water, and power generation. The Provo River is a popular fishing stream. Floating the river is also a popular activity. Boating is popular in Jordanelle Reservoir and Deer Creek Reservoir. The city of Provo has built a trail that follows the Provo River through the lower part of Provo Canyon. This trail, named the Provo River Parkway, attracts joggers, cyclists, rollerbladers, and others. Water from the Provo continues to be used for agricultural irrigation, especially in the Wasatch Valley, but also in parts of the upper and lower sections of the watershed. The Provo River currently provides drinking water for 50 percent of the population of the state of Utah (BioWest, 2003). Deer Creek Power Plant generates upwards of 14,000,000 kilowatt-hours of power in 2004 for Deer Creek Dam and the surrounding area (U.S. Bureau of Reclamation, 2005a). The construction of a power plant at the Jordanelle Dam is currently underway.

History of Land Use in the Provo River Watershed

The land in the Provo River watershed was first used for hunting, fishing, and trapping. It is believed that the land in the watershed was first used by nomadic Indians who camped and hunted there, but did not establish permanent settlements. In the late 18th and early part of the 19th centuries, trappers and explorers visited the region. These visitors also camped, hunted, and fished, but they too did not establish any permanent settlements. Early camps were found near the Provo River channel and Utah Lake (Jackson and Stevens, 1981).

The land use in the area changed after the arrival of the Mormon pioneers in Utah in 1847. In 1849, Mormon settlers built homes and established farms in the land near the Provo River (Ibid.). Throughout the 19th century the land was used primarily for farming and for personal dwellings.

As the populations of the cities within the watershed have grown, land traditionally used for farming has been developed for housing. This trend is especially apparent in the lower section of the watershed, where most of the current land devoted to farming is now located right next to Utah Lake. Census population figures for the cities and towns located within the watershed are found in Table 3.1. The year of settlement is indicated at the top of each column with the settlement name. Population pressure is specifically evident in the figures for Provo, Orem, and Heber. Figure 3.2 is a map of the settlements within the Provo River watershed.

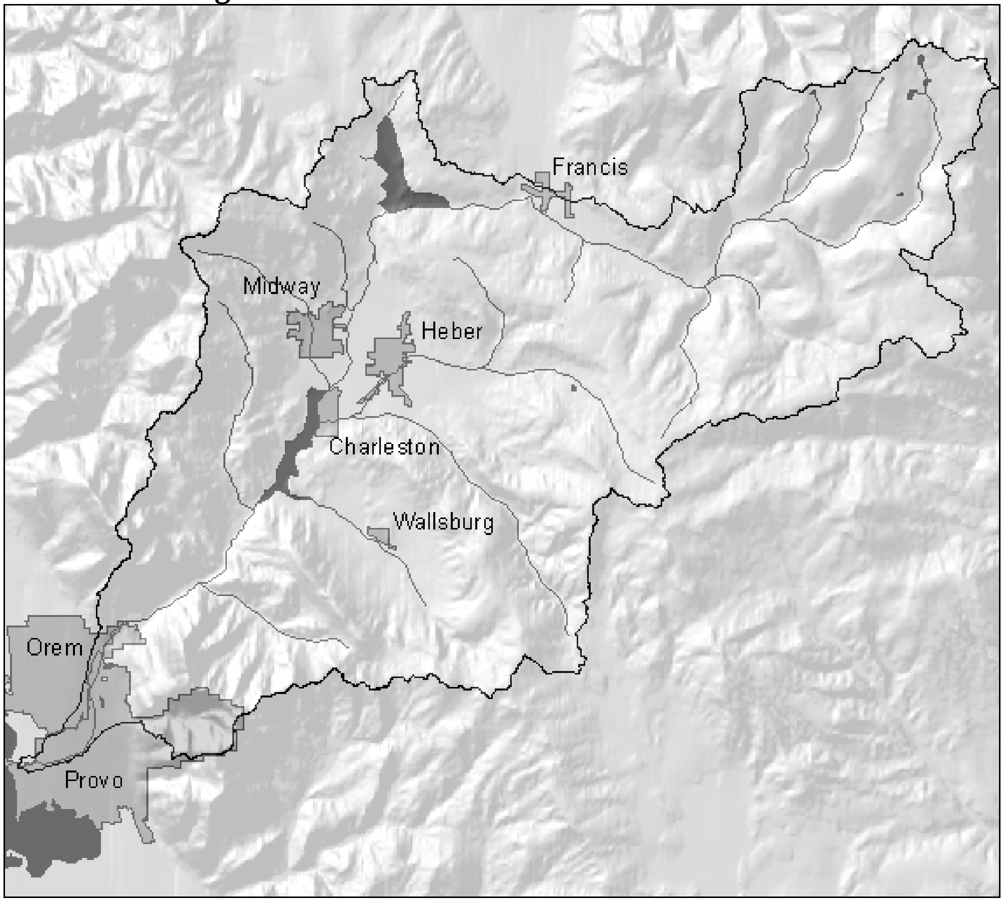
Table 3.1: Population of settlements in the Provo River watershed

	Provo, 1849	Orem, 1877	Wallsburg, 1861	Charleston, 1859	Heber, 1859	Midway, 1859	Francis, 1869
1860	2030				471		
1870	2384				658	378	
1880	3432		347	246	1291	718	
1890	5159	435	396	501	1538	769	
1900	6185	692	528	234	1534	719	
1910	8925	1064	493	283	2031	838	184
1920	10303	1664	300	361	1931	805	234
1930	14766	1915	240	343	2477	745	226
1940	18071	2914	233	323	2748	801	345
1950	28937	8351	207	201	2936	711	276
1960	36047	18394	180	223	2936	713	252
1970	53131	25729	211	196	3245	804	268
1980	74108	52399	239	320	4362	1194	371
1990	86835	67561	252	336	4782	1554	381
2000	105116	84324	274	378	7291	2121	698

Economic development has also been a driving factor for land use change. The early economy of the region was based on agriculture. The agricultural base has remained in many communities within the watershed, but it has been augmented by commercial and industrial enterprises. Currently, many businesses in the area are technology-oriented. Population growth has also fostered a burgeoning service industry.

Much of the land in the watershed is still rugged and undeveloped like it was when the first settlers arrived. There are still farms in the watershed, but the number of farms has declined. Communities in the watershed are still growing and developing. The construction of Jordanelle Dam coupled with the growth of Park City has led to several large developments near the Jordanelle Reservoir. Land in the watershed is now also used for commercial and industrial purposes. However, development in the Provo River watershed is generally concentrated in already-established cities and towns.

Figure 3.2: Provo River watershed settlements



Alterations to the Provo River

Due to water shortages and increased demand for water, alterations have been made in the structure of the Provo River. Diversions of Provo River water for irrigation began in 1849. Farmers began to construct small-scale water storage projects after 1902. Large-scale projects began to be constructed after 1921, following the formation of the Utah Water Storage Commission (UWSC).

The Provo River Project

The most significant alterations to the Provo River were part of the massive Provo River Project. In 1922, UWSC requested that the United States Bureau of Reclamation investigate a major reclamation plan on the Provo River. Planning continued for several years until a severe drought hit Utah between 1931 and 1935. During the drought, Utah Lake fell from 850,000 acre-feet to 20,000 acre-feet. The drought confirmed the necessity of the project. Congressional and Presidential approval was sought and obtained between 1933 and 1935. Construction of the components of the Provo River Project began in 1938. The project ended in 1958 and included the following components**:** Deer Creek Dam, Deer Creek Reservoir, Deer Creek Power Plant, Salt Lake Aqueduct & Terminal Reservoir, Duchesne Tunnel, Murdock Canal, Murdock Diversion Dam, Weber-Provo Diversion Dam and Canal, Alterations to the Provo River Channel, and Jordan Narrows Siphon and Pumping Plant (Bell, ca. 2005).

The largest storage component of the Provo River Project was Deer Creek Dam and reservoir. Construction of Deer Creek dam and reservoir began in 1938 and finished in 1941. The dam is 235 feet high and forms the 152,700 acre-feet Deer Creek Reservoir. The Deer Creek Power Plant was authorized in 1951, but construction was not initiated until 1955. The plant, completed in 1958, has two 2,474 Kilowatt generators (Ibid).

The Salt Lake Aqueduct carries water from the Provo River watershed to Salt Lake County for domestic use. Construction of the aqueduct also began in 1938. It was completed in 1950. The aqueduct begins at Deer Creek Dam and ends at a Terminal Reservoir in Sandy City, Utah. The pipeline follows the river through Provo Canyon through the Olmsted Tunnel and the Alpine-Draper tunnel. The aqueduct pipeline is 41.7 miles long and has a 69-inch diameter. The terminal reservoir was finished in 1951 (Ibid).

The Duchesne Tunnel carries water from the Duchesne River (a tributary of the Green River that flows into the Colorado River) to Deer Creek Reservoir in the Provo River watershed. The Duchesne Diversion Dam is located about 30 miles east of Heber City, Utah. Construction on the tunnel began in 1941, but was halted by war shortages in 1942. Construction did not resume until 1949. The tunnel was finally completed in 1951 (Ibid).

The Murdock Canal carries water from the Provo River through northeastern Utah County. The canal begins near the mouth of Provo Canyon at the Murdock Diversion Dam, and is 23 miles long. It runs northeast of Orem, Lindon, and Pleasant Grove, then it turns west between American Fork and Alpine and continues past Lehi before it flows into the Jordan Aqueduct. The canal was originally built by private interests. It was purchased by the government in 1940 and expanded thereafter until 1950. The Murdock Diversion Dam was built in 1950 (Ibid).

The Weber-Provo Diversion Dam and Canal diverts water from the Weber River to the Weber-Provo Canal. The diversion is located a mile east of Oakley, Utah above Deer Creek Reservoir. From the diversion, the 9-mile long canal carries water through the city of Kamas to the Provo River. Although construction on the canal began in 1941, it was delayed because of the war. Building resumed in 1944 and was finished in 1948 (Ibid).

The Provo River channel was altered between the Weber-Provo Diversion Dam and Deer Creek Reservoir beginning in 1944. The alterations were intended to provide additional carrying capacity and to prevent flooding in areas along the riverbanks. These alterations included the construction of dikes and the installation of timber sills in parts of the river channel. In addition, banks were reinforced at weak spots and rock jetties were placed in some areas to deflect currents away from where bank erosion was occurring. The alterations were completed in 1953. A project is underway at the present time to restore the Provo River channel. Further alterations to the Provo River channel were done between 1960 and 1965 (Ibid).

The Jordan Narrows Siphon and Pumping Plant take water from the Murdock Canal and Jordan River to land on the western side of Utah Lake and the Jordan River. The Jordan Narrows Siphon was constructed in 1947 and the Jordan Narrows Pumping Plant was completed in 1949 (Ibid).

The completion of the Deer Creek Power Plant in 1958 marked the completion of the Provo River Project. However, the components of the Provo River Project have required maintenance and improvement since then (Ibid).

Jordanelle Dam and Jordanelle Reservoir

The Jordanelle Dam on the upper Provo River was constructed in 1993. This dam is part of the Bonneville Unit of the Central Utah Project, the largest water development project ever undertaken in Utah. The project, which began in 1959, is designed to carry water from the Uinta Mountains to populated areas along the Wasatch Front including Salt Lake City. Construction of the Jordanelle Dam began in 1986 and continued until completion in 1993. The dam is located about six miles north of Heber City. Jordanelle Reservoir has a capacity of 320,300 acre-feet and a surface area of 3,068 acres. Municipal and industrial water is delivered to Salt Lake County from the Jordanelle

Reservoir through the Provo River and the Jordan Aqueduct and to northern Utah County via the Provo River and the Alpine Aqueduct (U.S. Bureau of Reclamation, 2005b; U.S. Bureau of Reclamation, 2005c). A power plant is currently under construction at Jordanelle Dam by Heber Light and Power and the Central Utah Water Conservancy District (CUWCD).

Olmsted Tunnel and Olmsted Diversion Dam and Screening Structure

A tunnel, diversion dam, and screening structure were constructed in the lower Provo River watershed to carry water to Orem for treatment. The Olmsted Tunnel, Diversion Dam, and Screening Structure were constructed in the 1990s with the tunnel being completed in 1991, and the diversion dam and screening structure being completed in 1996. These structures are maintained by the CUWCD (Central Utah Water Conservancy District, 2005a; Central Utah Water Conservancy District, 2005b).

Water Treatment Facility

A Provo River water treatment facility has been constructed in Orem. The Utah Valley Water Treatment Plant is located on the east Orem Bench and it treats water conveyed from the Provo River and Deer Creek Reservoir for the cities of Orem and Provo. The treated water is used for municipal and irrigation purposes. Water is conveyed to the plant from the Olmsted Diversion through the Olmsted Tunnel (Central Utah Water Conservancy District, 2005f.).

Upper Provo River Reservoir Dams

Small dams have been constructed on reservoirs in the upper Provo River watershed. Three dams, the Trial Lake Dam, the Washington Lake Dam, and the Lost Lake Dam were completed in 1991, 1996, and 1997, respectively (Central Utah Water Conservancy District, 2005c; Central Utah Water Conservancy District, 2005d; Central Utah Water Conservancy District, 2005e).

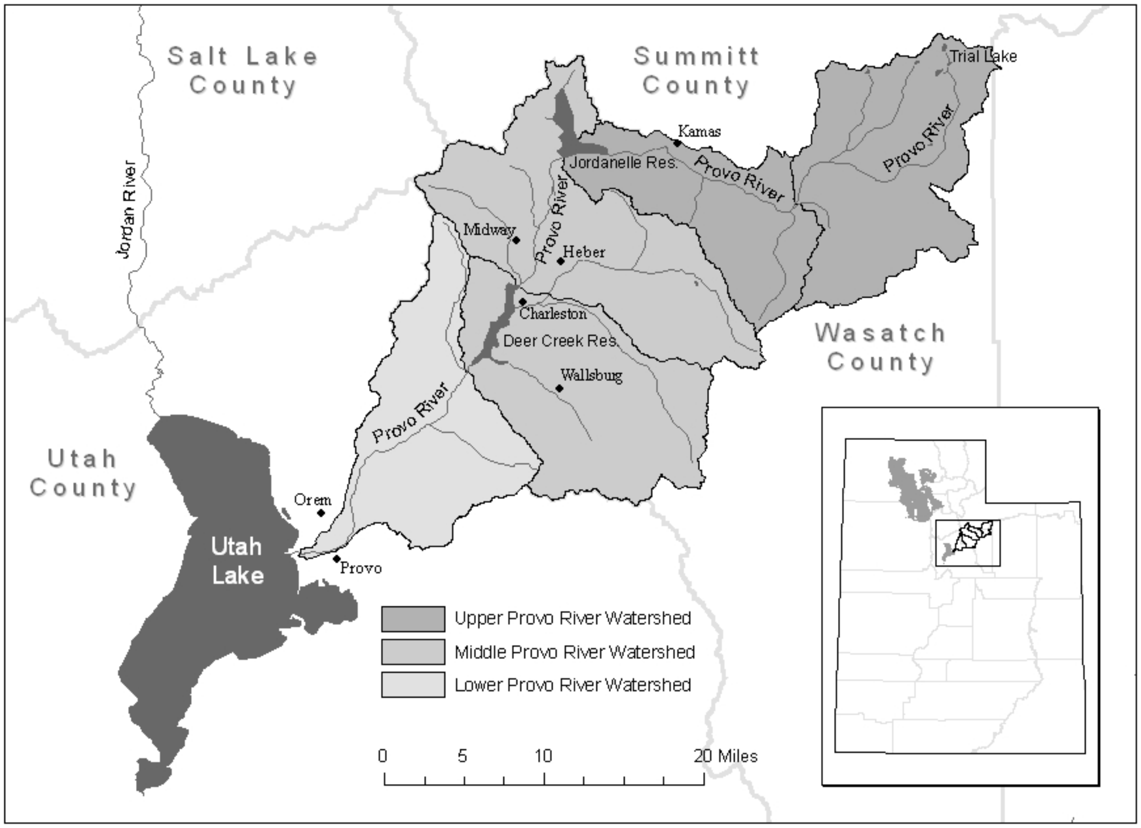
The Provo River Restoration Project

A project to restore the middle Provo River began in 1999. The project involves the restoration of meanders and wetland habitats, the reconnection of channels, and the creation of a flood plain to allow the river to pursue its own future course. The work on the middle Provo is scheduled to be completed in 2006 (Utah Reclamation Mitigation and Conservation Commission, 2001).

Alteration Results

The Provo River went from having a single section to having three distinct sections. The construction of Deer Creek Dam in 1941 created two sections of the river: the upper section which included the headwaters to Deer Creek Dam, and the lower section which included water from Deer Creek Dam to Utah Lake. After the construction of the Jordanelle Dam in 1993, three sections were created: the upper, middle, and lower section. The upper section included headwaters to Jordanelle Dam, the middle Provo includes the area between Jordanelle Dam and Deer Creek Dam, and the lower Provo River includes the water from Deer Creek Dam to Utah Lake (see Figure 3.3).

Figure 3.3: Sections of the Provo River watershed



Provo River Water Quantity

The quantity of water in the Provo River has increased over time mostly as a result of alterations and reclamation projects. Many alterations to the Provo River were intended to increase the quantity of the water in the river. For example, the Weber-Provo Diversion Dam and Tunnel and the Duchesne Tunnel bring water to the Provo from the Weber River and the Duchesne River.

Provo River Water Quality and Designated Uses

Official water quality standards are determined by government of the state of Utah with the approval of the Environmental Protection Agency. These water quality standards differ according to the so-called “designated use” of the water. Each water body is assigned a designated use and then evaluated as to whether the water quality is acceptable for that use. The Provo River has been assigned three designated uses. Some areas of the river are identified as having a Class 1C designated use. This means that the water is “protected for domestic purposes with prior treatment by treatment processes as required by the Utah Division of Drinking Water.” Parts of the river are also designated as Class 2B. This water is “protected for secondary contact recreation such as boating, wading, or similar uses.” Parts of the Provo River are designated as Class 3A, meaning the water is “protected for cold water species of game fish and other cold water aquatic life including the necessary aquatic organisms in their food chain.” Finally, parts of the Provo River drainage have been assigned a Class 4 designation: these waters are “protected for agricultural uses including irrigation of crops and stock watering.” Table 3.2 lists the designated uses for Provo River water (Utah Administrative Code, 2005).

Table 3.2: Provo River designated use classifications

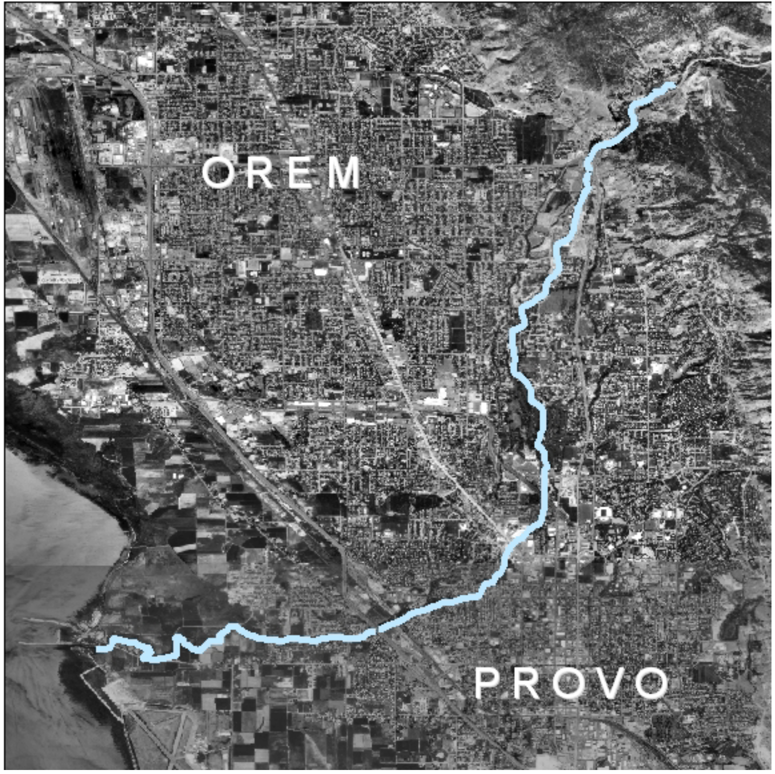
Segment	Designated Use Classes			
Provo River and tributaries, from Utah Lake to Murdock diversion		2B	3A	4
Provo River and tributaries, from Murdock Diversion to headwaters, except as listed below	1C	2B	3A	4
Upper Falls drainage above Provo City diversion	1C	2B	3A	
Bridal Veil Falls drainage above Provo City diversion	1C	2B	3A	
Lost Creek and tributaries above Provo City diversion	1C	2B	3A	

Some parts of the Provo River have been identified as meeting the state’s definition of Category 1 High-Quality Waters; these are the Upper Falls drainage above Provo City diversion, the Bridal Veil Falls drainage above the Provo City diversion, and Lost Creek and tributaries above Provo City diversion. This designation means that these waters have been determined by the state to be of exceptional recreational or ecological significance or have been determined to be a state or national resource requiring protection. This designation places restrictions on point source discharges and diffuse contamination, i.e. NPS pollution (Utah Administrative Code, 2005).

Water Quality Impairment

A 2002 assessment of the Provo River by the Environmental Protection Agency indicates a moderate water quality impairment with regard to pH in the lower Provo from the Murdock Diversion to Utah Lake, but lists the source of the impairment as unknown. The report notes that the impairment is likely related to algae growth in this segment of the river (Toole, 2002). Figure 3.4 shows the impaired section of the Provo River. In 1998, the Environmental Protection Agency listed Utah Lake as an impaired water body for phosphorous and dissolved solids.

Figure 3.4: Impaired segment of the Provo River



Chapter 4

Data and Methods

Two types of data were needed to complete this study: 1) water quality data and 2) land cover data for the study area. The following section contains a description of the temporal framework, the data, and the methodology used in the study.

Temporal Framework

This study examines the historical impact of land cover on surface water quality in the Provo River watershed from 1975 through 2003. This is accomplished by studying surface water quality variables and land cover for six years in a span of 27 years: 1975, 1979, 1985, 1990, 1995, and 2002.

Loading vs. Concentration

In water quality studies, it is important to differentiate between land use effects on in-stream concentrations of constituents and effects on loading. Loadings are usually calculated to measure the effects on downstream water receiving areas, such as lakes or reservoirs. This is the usual perspective of the engineer and those concerned with sedentary water management. A focus on in-stream concentrations is mainly used from a toxicological and biological perspective. It has been suggested that resources permitting, both loadings and concentrations can be determined (Schlosser and Karr, 1981). This study will follow the convention set by previous researchers who have only examined in-stream concentrations (Osborne and Wiley, 1988). The reasoning is that since a particular loading does not necessarily relate to the health of the stream itself, and the objective of this research is to study in-stream water quality rather than downstream lake or reservoir water quality, in-stream concentrations provide a more meaningful indication than loadings.

Water Quality Data

Water quality is a term that refers to the biological, chemical, and physical properties of water. There are hundreds of water quality variables. Governments have dictated different standards of water quality for particular uses; for example, acceptable water quality for drinking might differ from acceptable water quality for recreational use. Water quality data are often collected though direct measurement *in situ*. However, some variables cannot be measured in this way. In order to measure these variables, a sample must be taken and then analyzed in a laboratory. This study examines both water quality variables measured *in situ* and those measured in a laboratory.

Most of the information on water quality variables within the Provo River watershed was derived from Environmental Protection Agency STORET data. This data is collected by the Division of Water Quality under the auspices of the Utah Department of Environmental Quality and then deposited in a national repository for public dissemination. The U.S. Geological Survey collects temperature and flow data at several monitoring sites along the Provo River. These two sets of data, the STORET and U.S. Geological Survey data, will be examined together in this study.

Since this is a historical study, it will utilize data on variables that were measured consistently from 1975 through 2003. However, over time, data has been collected on different variables. Appendix A shows the variables that were measured in 1975 compared with the variables that were measured in 2003. Table 4.1 shows the variables used in the study.

Table 4.1: Water quality variables examined

Variable	**Units**
Alkalinity, Carbonate as CaCO3	mg/l
Bicarbonate	mg/l
Calcium	mg/l
Carbon dioxide	mg/l
Chloride	mg/l
Chromium	ug/l
Dissolved Solids	mg/l
Hardness, Ca + Mg	mg/l
Iron	mg/l
Magnesium	mg/l
Mercury	ug/l
Nickel	ug/l
Nitrogen, ammonia (NH3) as NH3	mg/l
Nitrogen, Nitrate (NO3) as NO3	mg/l
Nitrogen, Nitrite (NO2) as NO2	mg/l
Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N	mg/l
pH	
Phosphorus, orthophosphate as P	mg/l
Phosphorus as P	mg/l
Potassium	mg/l
Selenium	ug/l
Silver	ug/l
Sodium	mg/l
Specific conductance	umho/cm
Sulfur, sulfate (SO4) as SO4	mg/l
Turbidity	NTU
Zinc	ug/l

The number of stations has also changed over time. In 1975 there were only 13 water quality stations within the entire watershed. This number jumped to 80 in 1980 and then declined to 48 in 2002. Very few stations have been consistently monitored since 1975. The number of water quality stations used from each section of the watershed for each year of the study is found in Table 4.2. The total number of measurements of each water quality variable used in the study for each section for each year is found in Appendix B.

Table 4.2: Number of water quality stations used by year and river section

Year	Number of stations utilized	
	Lower	Upper
1975	3	10
1979	8	29
1985	8	72
1990	11	60
1995	9	44
2002	7	41

Prior to 1993, there were two sections of the Provo River: the Upper Provo and the Lower Provo. After 1993, the Middle Provo was added, but for the purposes of this study the Upper and Middle Provo are combined and the watershed is divided into just two sections, upper and lower. This was done to better facilitate historical comparison.

The STORET water quality data was aggregated temporally and geographically. First, all available data was organized by year. Then each station within the watershed was assigned to the lower or upper section of the watershed according to its location. Finally, an average yearly value was calculated for each water quality variable using measurement data from the assigned stations in each section of the river. These average values were used for the statistical analysis.

Other possible ways for using the data were explored. One possibility was to use the measurements from particular stations. But very few stations were consistently monitored throughout the study years. Another possibility would be to use the data from the lowest station within each section of the watershed. However, this could have led to the omission of data for some segments of the stream. The geospatial and temporal aggregation allowed all available data in the watershed for each study year to be analyzed.

Land Use and Land Cover Data

The land cover data were generated from Landsat multi-spectral imagery. The imagery used to create land cover data for 1975 and 1980 was obtained from the Landsat MSS sensor and has a spatial resolution of 80 meters. The imagery used for the remaining years was obtained from the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+) sensors at a spatial resolution of 30 meters. Ideally, the imagery would be from the same date a year apart; however, this is often not possible since the sensor only passes the same point every sixteen days. However, all of the imagery was collected in middle-to-late summer, between July and September, and the image dates are within 14 days (two weeks) of each other, except for the 2002 image. Table 4.3 contains the date that each image in the study was acquired from the Landsat sensor.

Table 4.3: Landsat image dates

Image Year	Image Date
1975	6 September
1979	3 September
1985	31 August
1990	29 August
1995	12 September
2002	21 July

For this study, the first level (Level I) of the United States Geological Survey land use and land cover classification scheme for remote sensing data was used (see Anderson et al, 1976). A list of the Level 1 classification schematic is found in Table 4.4.

Table 4.4: Level I of U.S. Geological Survey Classification (Anderson et al, 1976)

1. Urban Built-up Land
2. Agricultural
3. Rangeland
4. Forest Land
5. Water
6. Wetland
7. Barren Land
8. Tundra
9. Perennial Snow or Ice

Land Cover Descriptions

Urban or built-up land

Urban (built-up) land includes areas that have developed intensely. These areas include cities, towns, villages, residential areas, strip developments, transportation developments, power and communications facilities, mills, shopping centers, industrial and commercial complexes and other built structures. Land that is less intensely developed but located within densely developed urban areas, such as residential lawn or garden, is also included in this category. This land cover also includes mixed urban land cover i.e. areas that are dominated by urban development though not entirely developed. This land cover includes other urban land including zoos, urban parks, cemeteries and other developed or semi-developed areas (Anderson et al, 1976).

Agricultural land

Agricultural land is land devoted to the production of food and/or fiber. This includes cropland, pasture, orchards, groves, vineyards, nurseries, ornamental horticulture areas, confined feeding operations and other agricultural land such as agricultural areas near wetlands (Anderson et al, 1976).

Rangeland

Rangeland comprises areas where the potential natural vegetation is predominantly grasses, grasslike plants, or shrubs. These areas are generally unaltered, but may be seeded to encourage plant species growth. These areas include herbaceous rangeland where natural grasses dominate, shrub and brush rangeland where xerophytic or chaparral vegetation have developed, and mixed rangeland where rangeland dominates, but intermixed land use occurs (Anderson et al, 1976). In the Provo River watershed this land cover includes deciduous shrubs, evergreen sub-desert shrubs, and perennial forbs (U.S. Geological Survey, 1995).

Forest land

According to the U.S. Geological Survey system, forest land has tree crown areal density of 10 percent or more. In a broader sense, forest lands are areas where trees capable of producing timber or wood products dominate. There are several types of forest within this land cover group including deciduous forest dominated by trees that lose leaves seasonally, evergreen forest dominated by needle-leaf or other evergreen trees, and mixed forest with a mixture of deciduous and evergreen trees (Anderson et al, 1976).

Deciduous and evergreen coniferous forests are found in the Provo River watershed (U.S. Geological Survey, 1995).

Barren land

Barren land is characterized by a limited ability to support life. Other land covers including vegetation do not cover more than a third of the barren area. Barren lands are usually areas with thin soil, rocks, and sparse widely-spaced vegetation. This land cover includes dry salt flats on the floors of interior desert basins. It also includes beaches and other sandy areas. Barren land cover includes exposed rock (e.g. bedrock, desert pavement, talus slides, volcanic material, cliff faces, other rock exposures and accumulations), strip mines, quarries, and gravel pits. This category also includes transitional areas, or areas that are in transition from one land use to another and mixed barren land (Anderson et al, 1976).

Water

Areas covered by water are not difficult to identify from imagery. These areas include streams, canals, lakes, reservoirs, ponds, bays, and estuaries (Anderson et al, 1976).

Land Cover Classification

Because of the existence of supporting ancillary data including personal experience, maps, and aerial photography of the study area the imagery was classified using a supervised classification algorithm. The supervised classification involved the selection of a number of training sites for each class throughout each image (at least ten training sites were identified for each class, usually more). Once the training sites were identified Maximum Likelihood supervised classification was completed in ERDAS Imagine image analysis software.

The Maximum Likelihood classification is based on statistics and involves the calculation of Bayesian probabilities in order to classify each pixel into the class to which it most probably belongs. Minimum Distance is another common classification method. It sets up the classes in multidimensional space and then assigns each pixel to the nearest class based on the shortest vector distance (Jensen, 1996). Both classifications were tried, but Maximum Likelihood classification appeared to have higher accuracy and was thus used in this study.

Since each year of imagery was classified independently and no direct pixel comparisons were done, it was not necessary to normalize or resample the imagery. Imagery normalization would have been necessary if a single set of training sites was to be used to classify each year of imagery. Although imagery with differing spatial resolutions were used in the study, no resampling was performed on the images since the study did not involve pixel-to-pixel comparison and statistics were calculated individually for each year.

In order to increase classification accuracy, an algorithm was developed to refine the classifications using a slope layer derived from a 30-meter resolution digital elevation model. The slope refinement was applied to each image after the supervised classification was completed. This refinement algorithm was based on the assumptions that agriculture activities generally occur on gentle slopes, urban development is generally not found in areas with extreme slopes, and water surfaces are generally flat. The refinement allowed misclassified water, urban, and agricultural pixels to be reclassified. For example, a pixel that classified as agricultural land located on a 19° slope would be reclassified as rangeland and a pixel classified as urban land on a 30° slope would be reclassified as barren (cliff face). The refinement was done in ERDAS Imagine modeler. The algorithm stated in plain English reads: If the slope is greater than 5º and the pixel is marked as water reclassify the pixel as rangeland (shadow), and if the slope is greater than 5º and the pixel is marked as agriculture reclassify the pixel as rangeland, and if the slope is greater than 5º and the pixel is marked as urban reclassify the pixel as barren, otherwise leave the pixel classification alone. The ERDAS model is included in Appendix C.

Land Cover Classification Accuracy Assessment

Accuracy assessment was performed on the resulting classified imagery. This process involves generating a set of points in the classified imagery and comparing them with actual points on the ground either through field work or through ancillary data. In this study the accuracy assessment was accomplished by using high-resolution digital orthophoto quadrangles (DOQs) where available. For older years and where gaps existed, existing land cover maps and other analog aerial photography of the study were used. Table 4.5 contains a listing of sources used for the accuracy assessment.

Table 4.5: Accuracy assessment sources and potential sources

Year	Sources and Potential Sources
2002	2003 NAIP digital aerial photography, 2003 SWGAP Land Cover Data
1995	1997 Digital Orthophoto Quadrangles, 1995 GAP Land Cover Data
1990	1993 Digital Orthophoto Quadrangles, 1992 NLCD Land Cover Data
1985	1985 Aerial Photographs
1979	1980 Aerial Photographs
1975	1974 Aerial Photographs

Because digital aerial photography is available for the most recent years, the accuracy assessment was performed from the latest years to the earliest. For the earliest years, digitized aerial photography data either does not exist or was prohibitively expensive. The study utilized as much of the data as possible within the fiscal and temporal constraints placed on the research.

In order to complete the accuracy assessment, for each year of classified imagery a set of 300 stratified random points was generated—50 for each land cover class. The land cover classification assigned to each pixel was then compared with the same location on the reference sources to see if the classification result was accurate. The digital aerial photography was used for reference first, followed by analog photography and then, if necessary, other land cover classification results (e.g. Southwest Regional Gap Analysis, U.S. Geological Survey GIRAS land cover data).

The overall land cover classification accuracy levels were believed to be robust. Although no real standard for accuracy has been established by the remote sensing community 85% accuracy is considered acceptable (Congalton and Green, 1999). Generally and intuitively, higher accuracy percentages are better than lower ones. Table 4.6 shows the overall percentage results of the accuracy assessment for the three latest years of the study. Systematic accuracy assessment for the earliest years (1975, 1979, and 1985) was not completed because of the lack of available higher-resolution data sources. However, visual appraisal suggests that the 1985 classification was probably as accurate as the other classifications. The 1975 and 1979 classifications are believed to be not as accurate as the later years because lower-resolution (79 meter) imagery was used resulting in larger mixed-pixels, where heterogeneous areas are forced into a particular classification.

Table 4.6: Overall land cover classification accuracy

Year	Estimated Percentage Accuracy
2002	72%
1995	77%
1990	85%

Studying the error matrices for the years assessed reveals more about the land cover classification errors. These matrices show the results of the accuracy assessment for a set of random pixels. Fifty random pixels were identified from each class of the land cover classification. Each classified pixel was then compared with higher-resolution ancillary data to ascertain the pixel's classification accuracy. A perfect classification for a land cover would result if all 50 sample pixels assigned to a particular land cover were found to actually have the land cover they were assigned. This only occurred once, for water in 1990. The number of sample pixels misclassified is displayed in each matrix along with the number of accurately classified sample pixels for each year of classified imagery that was systematically studied. In the error matrices, each number off the diagonal represents some error either inclusion error, where a pixel was included in the wrong class, or exclusion error, where a pixel was excluded from its proper class.

The error matrices reveal that barren land was the land cover with the lowest classification accuracy, while forest and water had the highest classification accuracy. In fact for two of the years (2002 and 1995), barren land was misclassified more than it was classified properly. Barren land is difficult to classify because it can share similar spectral characteristics to other land covers. It is especially similar to sparsely vegetated rangeland, however it is also similar to built land and it can even share similar characteristics as fallow agricultural land. Forest and water classification was accurate for the three years tested. These classes both have unique spectral characteristics.

The error matrix for 2002 is presented in Table 4.7. This matrix reveals that forest was most often accurately classified in that year of imagery followed by water, then agricultural land, rangeland, urban land, and barren land. Some areas covered by agricultural, forest, and barren land were sometimes mistaken for rangeland in 2002. The confusion between forest and agricultural land and rangeland is understandable since these land covers share similar spectral characteristics. Urban land was sometimes mistaken for agricultural land. This may have resulted due to the proximity of built spaces to cultivated areas.

Table 3.7: 2002 Classification error matrix

		Reference						
		Agriculture	Barren	Forest	Range	Urban	Water	Total
Classification	Agriculture	41	0	0	6	2	1	50
	Barren	0	17	9	22	2	0	50
	Forest	0	0	44	6	0	0	50
	Range	1	0	10	37	2	0	50
	Urban	7	3	3	1	34	2	50
	Water	0	4	2	2	0	42	50

The 1995 classification error matrix shown in Table 4.8 reveals that water was accurately classified most often, followed by forest, rangeland, agricultural land, urban land, and barren land. In the 1995 classification, barren land was commonly mistaken for rangeland. Also in the 1995 classification, urban land was often confused with rangeland. The presence of residential lawns in the urban areas may have contributed to the classification confusion.

Table 4.8: 1995 Classification error matrix

		Reference						
		Agriculture	Barren	Forest	Range	Urban	Water	Total
Classification	Agriculture	38	0	1	8	1	2	50
	Barren	0	25	5	17	2	1	50
	Forest	0	0	45	5	0	0	50
	Range	2	1	8	39	0	0	50
	Urban	2	2	4	6	36	0	50
	Water	0	0	1	0	0	49	50

The 1990 classification error matrix is displayed in Table 4.9. The accuracy assessment indicated that water was most accurately classified. The classification of forest and rangeland was also fairly accurate. Agricultural land, barren land, and urban land was sometimes confused with rangeland. In addition, urban land was sometimes mistaken for barren land.

Table 4.9: 1990 Classification error matrix

		Reference						
		Agriculture	Barren	Forest	Range	Urban	Water	Total
Classification	Agriculture	40	0	2	7	1	0	50
	Barren	0	36	2	7	5	0	50
	Forest	0	0	46	4	0	0	50
	Range	2	0	2	46	0	0	50
	Urban	1	4	1	6	38	0	50
	Water	0	0	0	0	0	50	50

Resulting Data

The data preparation culminated in two usable data sets. Mean values for water quality variables were calculated for each year for each river segment (upper and lower) of the stream using the observations from the stations found within the appropriate segment. From the classified land cover images, percentage land covers were calculated for each section of the watershed for each year.

Statistical Methods

A number of statistical tests were then performed with the land cover and water quality data. These included paired sample t-tests to find significant differences between the upper and lower Provo River watershed sections, correlations to find relationships between variables, and linear regression to examine the relationship between land covers and water quality variables. All of the statistical tests were performed in SPSS 9.0 for Windows.

In order to test the differences between the upper and lower sections of the Provo River watershed, paired sample t-tests on land cover percentages and water quality parameters were performed. These t-tests were used to identify significant differences in mean values for land cover percentages and water quality variable measurements.

Spearman’s non-parametric correlations were used to find relationships between variables since the assumptions for parametric correlations (Pearson’s) were not met because of the small sample sizes in this study (N=6).

Finally, linear regression was used to examine the relationship between the different land cover types and particular water quality variables. Regression analysis is used to study the causal relationship between a dependent variable and a set of independent, explanatory, variables. Linear regression assumes that a linear relationship exists between the dependent and independent variables. It fits a straight line to the set of observed data. In this case the dependent variable is the water quality parameter value and the independent variable was percentage land cover. Linear regression was used because there was only one set of independent variables used: percentage land cover.

Stream flow was also input into the regression as an independent variable against the dependent water quality variables to see if any strong relationships could be identified.

Chapter 5

Results and Discussion

The statistical tests revealed differences with regard to both land cover and water quality among the upper and lower regions of the Provo River watershed, identified relationships between specific land cover types and water quality variables, and showed the strength of the relationships between land covers and specific water quality parameters. The results of the statistical analyses are reported hereafter.

Differences Between the Upper and Lower Provo River Watershed

Paired sample t-tests showed that the two regions of the Provo River watershed, lower and upper, differed significantly in three land covers: agriculture, barren land, and water (see Table 5.1). The upper Provo River watershed has significantly more agricultural land, while more barren land was found in the lower Provo River watershed. The upper Provo watershed also had more identifiable water; Deer Creek Reservoir and Jordanelle Reservoir are both found in the upper Provo watershed. Streamflow was also significantly higher in the upper Provo. The higher elevations in the upper region of the watershed receive more precipitation than the areas in the lower watershed. Moreover, streamflow in the lower Provo is highly regulated by the dams at Deer Creek and those dams farther upstream while the streamflow upper Provo is less regulated. Interestingly, the upper and lower Provo river regions did not differ significantly in terms of percentage of urban, forest, and range land covers.

The lower Provo was found to contain a significantly higher proportion of barren land than the upper region. Also, the lower Provo region contains significantly less agricultural land. The lower region also has a higher percentage of urban (built-up land), though the difference was not found to be statistically significant at the .05 level. The cumulative average amount of land covered by urban land in the upper Provo was ~4% (~14746 acres) compared with ~6% (~4880 acres) in the lower Provo. Figure 5.1 and Figure 5.2 illustrate the land covers in the upper and lower sections of the Provo River watershed. The total average area of the lower Provo River watershed section is ~80237 acres, and the total average area of the upper Provo River watershed is ~341,724 acres.

Figure 5.1: Lower Provo River watershed average land cover, 1975-2002

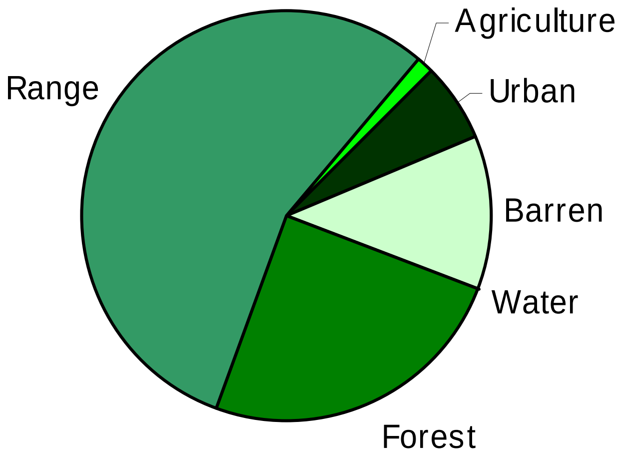
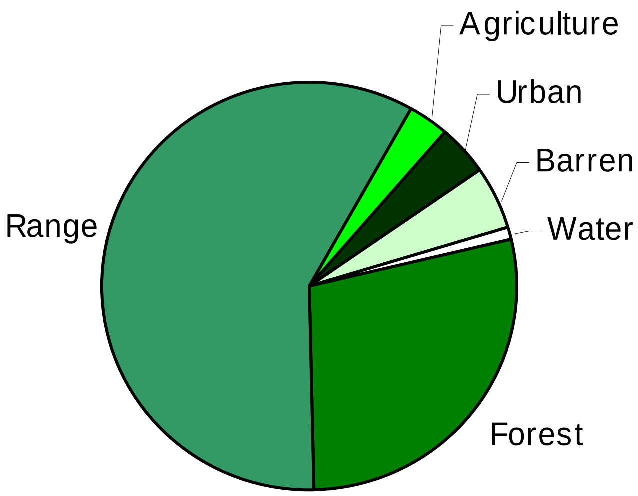


Figure 5.2: Upper Provo River watershed average land cover, 1975-2002



The upper and lower Provo watersheds also differed significantly in alkalinity, bicarbonate, and pH levels (see Table 5.1). These three variables are related to each other. The pH of water refers to its acidic or basic properties. Waters with higher pH are basic or alkaline while waters with lower pH are said to be acidic. Alkalinity is therefore a measure of the concentration of bases in water. The primary bases in water are carbonate and bicarbonate (Boyd, 2000). The lower Provo had significantly higher measurements of these three variables. This confirms earlier findings that indicated that the lower Provo is in violation of the government pH standard. Statistically significant (.05) differences between the lower and upper Provo River watershed are shown in the Table 5.1.

Table 5.1: Significant differences in the upper and lower Provo River watershed

Variable	t	Sig. (2-tailed)	N	Std. Deviation
Agriculture	-7.994	.000	6	.4602%
Barren	7.517	.001	6	2.3775%
Water	-6.022	.002	6	.3367%
Streamflow	-3.328	.021	6	62.216 cfs
Alkalinity	2.767	.040	6	38.374 mg/l
Bicarbonate	2.873	.035	6	46.249 mg/l
pH	3.591	.016	6	.189

Similarities in Variables of the Upper and Lower Provo River Watershed

Correlations between variables in the upper and lower segments of the watershed showed that some variables were highly correlated with each other. Table 5.2 shows the significant correlation results. The correlations for carbon dioxide, mercury, and pH are based on all of the study years, while the correlation for zinc is based on five study years (in 1975 zinc was only measured once in the lower Provo), the correlation of nickel is based on four study years (1975, 1979, 1990, 2002), and the correlation for total nitrogen is based on three study years (1979, 1995, and 2002).

Carbon dioxide in the lower Provo was highly correlated with carbon dioxide in the upper Provo. Other strong correlations between the two regions of the watershed were found in the following variables: mercury, nickel, total nitrogen (nitrate + nitrite), pH, and zinc. This shows similarity in the fluctuation of these variables (covariance). Table 5.2 shows significant correlations among the same variable for the lower and upper regions of the watershed and indicates the number of study years upon which the correlation is based.

Table 5.2: Significant correlations in the upper and lower Provo River watershed

Variable	Correlation Coefficient	Sig. (2-tailed)	N
CO2	1.000	.000	6
Mercury	.884	.019	6
Nickel	.987	.013	4
Total Nitrogen	1.000	.016	3
pH	.970	.001	6
Zinc	.927	.024	5

Covariance between the same variables in the upper and lower segments of the river is understandable since the river flows over similar terrain. Moreover, the lower segment of the river contains cumulative solutes from the upper segment. Therefore, high levels in the upper region should correspond with high levels in the lower region. Perhaps more illustrative is the fact that many variables were not strongly correlated. Differences may result from differing point and non-point sources of pollution in the two sections of the watershed. The various land covers in the two regions may also introduce differing amounts of constituents into the water.

Statistical Correlations in the Lower Provo River Watershed

Nonparametric correlations identified possible relationships between percentage land covers and water quality variables in the lower Provo. Negative relationships were found between the percentage of agricultural land cover and chromium and selenium. The percentage of urban land cover was correlated with carbon dioxide, chloride, dissolved solids, mercury, ammonia, pH, potassium, and specific conductance. Table 5.3 shows the results of the nonparametric correlations for the lower region of the Provo river watershed.

Table 5.3: Statistical correlations in the lower Provo River watershed

Land Cover	Water Quality Variable	Correlation Coefficient	Sig. (2-tailed)	N
Agriculture	Chromium	-.820	.046	6
	Selenium	-.880	.021	6
Urban	Carbon Dioxide	-1.000	.000	6
	Chloride	-1.000	.000	6
	Dissolved Solids	-.829	.042	6
	Mercury	-.941	.005	6
	Ammonia	-.943	.005	6
	pH	.829	.042	6
	Potassium	-.943	.005	6
	Specific Conductance	-.886	.019	6

While these correlations show potential relationships they do not indicate causal relationships. Aside from the existence of a legitimate relationship between the land cover types and the variables indicated, alternative reasons for the correlations identified might include coincidence, error, or the presence of an unseen variable or variables.

The only positive correlation found in the lower Provo was found between the percentage of urban land cover and pH. This means that according to the analysis as the percent of urban land cover increased, pH also increased. This finding suggests that the pH violation in the lower Provo River might be caused by some factor or combination of factors related to the increase in urban land cover.

Agricultural activities are negatively correlated with chromium and selenium. Chromium and selenium occur naturally in the earth’s crust. Agricultural areas are often covered by vegetation which stabilizes underlying sediments. Thus, land that is uncultivated or barren allows more of the crust to be exposed which can lead to increased erosion resulting in higher levels of chromium and selenium. This may account for the increase in chromium and selenium with decreasing agriculture land cover. In any case, the presence of these constituents was not significant; for three of the six study years, the amount of chromium and selenium had an average close to zero.

Urban land cover exhibits negative relationships with carbon dioxide, chloride, dissolved solids, mercury, ammonia, potassium, and specific conductance. The negative relationships were not expected since the previous research has noted increases in most constituents from increasing urban land cover. However, declines in carbon dioxide, dissolved solids, and specific conductance may result with a decrease in erosive sediments from barren and agricultural covers. The other declines may be in part to increased flow velocity over urban surfaces. After a storm event, solutes and other particles on urban surfaces are quickly transported to the nearest stream, and as the stream velocity increases, the stream load is quickly transported to receiving waters. In this case, overland flow takes the solutes to the Provo River which quickly carries these waters to Utah Lake. Therefore unless a measurement was taken after a storm event it would be difficult to capture the actual amount of constituents in the water at peak flow. The water quality response of the Provo River to urban stormflow has been examined elsewhere (Gray, 2004).

Statistical Correlations in the Upper Provo River Watershed

In the Upper Provo other relationships were found using nonparametric correlations. Agriculture was found to be related to both iron and zinc. Urban land cover was related to alkalinity, bicarbonate, and nitrogen. Barren land cover related to chloride, nickel, and nitrite. The results of the nonparametric correlations in the upper region of the watershed are found in Table 5.4.

Table 5.4: Statistical correlations in the upper Provo River watershed

Land Cover	Water Quality Variable	Correlation Coefficient	Sig. (2-tailed)	N
Agriculture	Iron	-.886	.019	6
	Zinc	.829	.042	6
Urban	Alkalinity	.943	.005	6
	Bicarbonate	.943	.005	6
	Total Nitrogen	1.00	.000	4
Barren	Chloride	-.886	.019	6
	Nickel	1.00	.000	5
	Nitrite	-1.00	.000	4

The findings indicate a negative relationship between agricultural cover and iron, and a positive relationship between agricultural cover and zinc in the upper Provo River watershed. Agricultural practices are not known to utilize iron nor are they thought to introduce iron into the ground or water. The increase in iron could be attributed to the development of agricultural land into urban land. The positive relationship of agricultural cover and zinc is interesting because zinc is commonly used in fertilizers as zinc sulfate, and this compound is highly soluble in water. Therefore, increases in zinc are likely due to the application of zinc sulfate to crops.

As in the lower Provo section, urban land cover in the upper region was found to be positively correlated to alkalinity and bicarbonate. As urban land cover increases, alkalinity and bicarbonate levels also increase. The results indicate a strong possibility that a factor related to urban land cover is leading to increases in pH and related constituents (bicarbonate and carbonate).

Urban land cover is also positively correlated with total nitrogen (nitrate + nitrite). This confirms earlier research that identified minimal increases in nitrogen concomitant with urban land cover (Brett et al, 2005; Meybeck, 1998). However, the correlation is based on only 4 years of sampling data (1979, 1985, 1995, and 2002).

Barren land cover is negatively correlated with chloride and nitrite, and positively correlated with nickel. These variables are probably related to the other land covers as well, but only shown to be significantly related to barren land. Decreases in barren land would necessarily correspond with increases in other land covers (probably urban land or agricultural land) and increases in these other land covers could be the cause of increases in chloride and nitrite.

Regression Results

The primary motivation for this study was to determine the impacts of specific land covers on water quality. The regression results show the *strength* of the relationship between particular land covers and water quality variables. Table 5.5 and Table 5.6 indicate the variables and land covers examined and show the results of the regression analysis.

The Lower Provo River Watershed

Neither barren nor forest land covers were found to be strongly related to any particular water quality parameter. It was found that a cumulative average of ~25% of land cover within the lower Provo was forested and ~12% was barren. The barren land found in this region of the watershed mostly represents exposed rocks and cliff faces.

A relationship was identified between rangeland and iron and rangeland and potassium in the lower Provo region of the watershed. Iron exhibited a weak negative correlation (-.314), while potassium had a stronger positive correlation to rangeland (.714). The amount of rangeland did not change significantly through the years in this region of the watershed. Minor fluctuations in the proportion of rangeland classified are more likely caused by classification error due to spectral confusion than to any real change in the amount of rangeland itself; rangeland exhibits similar spectral characteristics to both forest and agricultural land cover. Rangeland was found to cover ~55% of the land surface on average through the study years.

In the lower Provo River region, a strong relationship was found between agricultural land cover and total nitrogen (nitrate + nitrite); even though it was determined that agricultural land cover in the lower Provo was consistently near or below 2% from 1975 to 2002. Non-parametric correlations indicated a moderately strong positive relationship (correlation coefficient = .5) between agricultural land cover and total nitrogen and a strong negative relationship between agricultural land cover and nitrite (correlation coefficient = -.949). The positive relationship confirms earlier research (Omernik, 1976; Omernik, 1977; Beaulac and Reckhow, 1982; Osborne, 1988; U.S. Geological Survey, 1999; McFarland and Hauck, 1999) that found increases in nitrogen from agricultural activities, while the negative relationship is harder to explain. It should be noted that these relationships were computed from extremely small samples (n = 4 for nitrite, and n = 3 for total nitrogen). Small sample sizes are not as representative of reality. Furthermore, for two years of measurements the average yearly level of nitrite was zero (0). This shows that nitrite does not seem to be very significant in terms of impacts on water quality. However small amounts of nitrogen and nitrite can accumulate in receiving waters and increase phytoplankton productivity and lead to harmful algae blooms.

Strong relationships, negative except for pH, were discovered between urban land and the following variables (relationship indicated in parentheses): chloride (-), dissolved solids (-), total nitrogen (-), pH (+), potassium (-), specific conductance (-), and zinc (-).

Urban land steadily increased in the lower Provo and had the least amount of yearly fluctuation which could be a result of the relative ease of the classifier to identify urban land. In the lower Provo watershed in 1975 urban land was found to cover ~4% of the land while in the 2002 it was found to cover ~8% percent of the land in the watershed. This represents a doubling of the amount of land devoted to urban land uses within a span of 27 years. Urban land cover included all of the land uses under the Level I U.S. Geological Survey classification level which includes residential, commercial, industrial, and mixed urban land uses (Anderson et al, 1976).

The strongest negative correlations for urban land were displayed in chloride (-1), potassium (-.943), specific conductance (-.886), and dissolved solids (-.829). The regression results with regard to zinc and nitrogen may not be faithful in spite of the correlations found even though total nitrogen had the highest r-square value (.973). Errors may have resulted from the small sample sizes and the existence of confounding outliers. Only three samples were used for total nitrogen and one of these was an extreme outlier. The relationship with zinc was based on five samples including an outlier.

The other negative relationships found between urban land cover and the listed water quality variables (chloride, potassium, dissolved solids, and specific conductance) seem to contradict earlier studies that found positive relationships. It may be that improved point-source discharge controls have resulted in the decline since 1975 in average chloride levels. The dissolved solids variable is an indicator variable showing the total amount of mineral constituents in a stream. Both chloride and potassium contribute to dissolved solids, thus it follows that decreases in these constituents would also lead to decreases in total dissolved solids. Specific conductance is also related to the presence of dissolved solids since dissolved solids greatly influence electric conductance; pure water is a poor conductor of electricity. Decreases in dissolved solids would also generally lead to decreased specific conductance.

The moderately strong positive relationship between pH and urban land cover ($r^2 = .672$, correlation coefficient = .829) indicates a probable link between this land cover and the pH violation in the lower reach of the river. According to the water quality standards of the state of Utah, waters with pH outside of the range of 6.5 to 9 are in violation of the pH standard (Utah Administrative Code, 2005). This relationship is discussed in greater detail later in this thesis.

Streamflow was found to be strongly related to nickel and nitrogen in the lower Provo region of the watershed. There was a moderately strong positive correlation for each of these variables, meaning that they changed in the same direction as flow. However, the nitrogen relationship was based on measurements from just three of the six study years. In addition, of the five years of nickel measurements used, only the first year of the study, 1975, showed more than a trace concentration of the metal.

Table 5.5: Regression results in the lower Provo River watershed

	Agriculture	Urban	Barren	Forest	Range	Flow
	R square					
Alkalinity, Carbonate as CaCO3	0.178	0.493	0.453	0.005	0.262	0.065
Bicarbonate	0.094	0.400	0.506	0.021	0.193	0.059
Calcium	0.426	0.640	0.316	0.000	0.303	0.003
Carbon dioxide	0.188	0.508	0.060	0.124	0.308	0.409
Chloride	0.007	**0.902**	0.039	0.094	0.316	0.213
Chromium, hexavalent	0.496	0.065	0.405	0.548	0.379	0.139
Dissolved Solids	0.156	**0.865**	0.026	0.092	0.289	0.140
Hardness, Ca + Mg	0.343	0.554	0.328	0.011	0.411	0.007
Iron, acid soluble	0.096	0.129	0.007	0.595	**0.779**	0.000
Magnesium	0.176	0.334	0.308	0.053	0.525	0.008
Mercury	0.207	0.483	0.062	0.124	0.300	0.412
Nickel	0.216	0.473	0.051	0.113	0.292	**0.811**
Nitrogen, ammonia (NH3) as NH3	0.202	0.491	0.061	0.123	0.301	0.420
Nitrogen, Nitrate (NO3) as NO3	0.320	0.050	0.277	0.007	0.191	0.017
Nitrogen, Nitrite (NO2) as NO2	**0.903**	0.367	0.318	0.655	0.518	**0.672**
Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N	**0.988**	**0.973**	0.033	0.011	0.179	0.016
pH	0.080	**0.672**	0.026	0.085	0.312	0.550
Phosphorus, orthophosphate as P	0.037	0.488	0.663	0.347	0.006	0.015
Phosphorus as P	0.166	0.342	0.001	0.002	0.028	0.563
Potassium	0.092	**0.754**	0.003	0.334	**0.776**	0.099
Selenium	0.258	0.424	0.082	0.122	0.265	0.397
Silver	0.213	0.480	0.059	0.121	0.299	0.468
Sodium	0.550	0.476	0.108	0.087	0.454	0.049
Specific conductance	0.090	**0.799**	0.024	0.084	0.483	0.319
Sulfur, sulfate (SO4) as SO4	0.262	0.003	0.035	0.314	0.449	0.239
Turbidity	0.007	0.030	0.003	0.026	0.075	0.479
Zinc	0.470	**0.733**	0.003	0.005	0.006	0.154
Flow	0.161	0.220	0.032	0.000	0.010	

The Upper Provo River Watershed

Neither forest cover nor range cover was found to be strongly related to any specific water quality variable. As in the lower Provo watershed, forest and rangeland cover a great proportion of the land in the upper Provo watershed. Forest covers ~28% and range covers ~59% for a combined cumulative average total of ~87% coverage.

Barren land cover was strongly related to ammonia, nitrite, and nitrogen. Barren land accounted for ~5% of the land in the upper Provo region of the watershed. Based on four years of measured nitrite values in the upper Provo, the relationship of barren land to nitrite was apparent but not significant; average nitrite values were consistently negligible (averaging between 0 and .02 mg/l). Average nickel concentration values declined from a high of 8.75 mg/l in 1975 to a low of 0.00 mg/l in 2002 with an overall average for the study period of just 2.44 mg/l. Ammonia level variance correlated with variation in barren land, but ammonia levels too exhibited their highest values in 1975 at 5.22 mg/l and quickly fell to .07 mg/l in 1979, falling even further thereafter to 0.00 mg/l in 2002.

In the upper Provo, agricultural land cover was not found to be strongly related to any specific water quality variable. Through the study years, agricultural land cover remained relatively stable hovering between 2% and 4%. The minor yearly fluctuations in the proportion of agriculture were probably due to temporal resolution differences of the imagery. In other words, agricultural land cover in the imagery would vary according to the month it was acquired. It is likely that a greater amount of land would be agriculturally active during the month of July than during the month of September and crops would be in different stages of growth.

Strong positive relationships were found between urban land cover and alkalinity, bicarbonate, and total nitrogen. Urban land cover averages just over 4% of the land cover in the upper region of the Provo River watershed. Akin to land cover changes in the lower Provo region, the amount of urban land appears to be growing in the upper Provo watershed as well. It appears that urban land cover was overestimated in the earliest years of the study. This may be a result of misclassification of fallow agricultural land and barren land as urban surfaces. However since 1985, when higher resolution imagery was utilized for the classifications, urban land cover figures appear to be more consistent with existing land cover maps and primary knowledge. Urban land cover steadily increases from 1985 to 2002. The relationship between urban land cover and alkalinity and bicarbonate in the upper Provo confirms findings related to the lower Provo region. Apparently, something associated with urban land cover is contributing to increasing levels of bicarbonate and increasing water alkalinity. Urban land cover's relationship with total nitrogen was based on measurements from four study years because total nitrogen was only collected for those four years. The correlation was strongly positive. As urban land cover increased total nitrogen levels also increased. This confirms earlier research that identified modest increases in nitrogen with urban development (Brett et al, 2005) and is likely due water draining over excess residential lawn and garden fertilizers.

Based on five sample years, stream flow was found to be related only to nickel in the upper Provo region of the watershed. Yearly average nickel levels in the upper Provo were consistently higher than nickel levels in the lower region, however, all measurements were low and the difference in mean levels was not statistically significant.

Table 5.6: Regression results in the upper Provo River watershed

	Agriculture	Urban	Barren	Forest	Range	Flow
	R square					
Alkalinity, Carbonate as CaCO3	0.179	**0.688**	0.469	0.000	0.165	0.347
Bicarbonate	0.231	**0.708**	0.437	0.001	0.172	0.344
Calcium	0.082	0.056	0.000	0.001	0.009	0.010
Carbon dioxide	0.196	0.582	0.484	0.016	0.071	0.434
Chloride	0.012	0.148	0.154	0.000	0.055	0.185
Chromium, hexavalent	0.186	0.420	0.299	0.030	0.023	0.251
Dissolved Solids	0.214	0.122	0.029	0.041	0.087	0.195
Hardness, Ca + Mg	0.036	0.118	0.116	0.028	0.000	0.055
Iron, acid soluble	0.270	0.000	0.444	0.034	0.118	0.291
Magnesium	0.190	0.000	0.439	0.101	0.197	0.441
Mercury	0.429	0.558	0.140	0.064	0.005	0.137
Nickel	0.151	0.551	**0.650**	0.000	0.178	**0.884**
Nitrogen, ammonia (NH3) as NH3	0.011	0.583	**0.688**	0.015	0.253	0.167
Nitrogen, Nitrate (NO3) as NO3	0.006	0.172	0.499	0.045	0.032	0.373
Nitrogen, Nitrite (NO2) as NO2	0.028	0.418	**0.760**	0.000	0.164	0.476
Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N	0.054	**0.693**	0.566	0.263	0.496	0.064
pH	0.139	0.589	0.501	0.022	0.065	0.334
Phosphorus, orthophosphate as P	0.020	0.159	0.475	0.018	0.052	0.266
Phosphorus as P	0.093	0.038	0.003	0.005	0.000	0.092
Potassium	0.036	0.019	0.001	0.001	0.005	0.010
Selenium	0.189	0.049	0.102	0.236	0.045	0.065
Silver	0.051	0.360	0.446	0.166	0.448	0.000
Sodium	0.025	0.127	0.122	0.001	0.054	0.199
Specific conductance	0.060	0.009	0.145	0.036	0.001	0.032
Sulfur, sulfate (SO4) as SO4	0.277	0.222	0.033	0.098	0.167	0.101
Turbidity	0.327	0.002	0.305	0.078	0.135	0.099
Zinc	0.465	0.001	0.123	0.094	0.140	0.067
Flow	0.043	0.137	0.478	0.025	0.159	

Summary and Discussion of Significant Results

This study revealed two important insights. First, the statistical analysis showed that urban land cover affected the greatest number of water quality variables while forest and rangeland covers impacted the fewest; nine water quality variables were shown to be influenced by urban land cover while no water quality variables were found to be significantly influenced by forest cover and only two variables were shown to be affected by rangeland. However, as has been discussed above, these relationships are based on probabilities and are affected by various factors. Nevertheless, the number of variables affected supports the conclusion.

Second, the source of pH impairment in the lower Provo River is probably related to urban land cover in the lower section of the watershed. The pH of water is a measure of the concentration of hydrogen ions in it. pH is measured on a scale of 0.0 to 14.0 with 7.0 being neutral. Waters with pH values lower than 7.0 are increasingly acidic, while waters with pH values higher than 7.0 are more alkaline (or basic). The pH of water influences many chemical reactions in water. The pH of water also affects aquatic life. Alkaline waters can damage fish eyes and gills. High pH can also slow growth of aquatic organisms and affect reproduction adversely. Organisms will die in waters with pH levels greater than ~11 (Boyd, 2000). In addition, acidic and basic solutions can also be harmful to humans. The pH in most rivers and lakes ranges between 6 and 8.5. The pH of a stream is determined by the type and amount of dissolved minerals, gases, and organisms in the water such as phytoplankton.

The pH of the lower Provo is higher than the acceptable range meaning the water is more alkaline than normal. The cumulative average pH value was 7.93 in the lower Provo from 1975 to 2002 compared with 7.65 in the upper section. The pH value rose in both sections of the river over time as illustrated in Figures 5.3 and 5.4 (the upper and lower 5% ranges are indicated). The earliest pH was somewhat acidic—around 6.5 in both sections of the river—however the pH quickly rose. Even though the average pH value in the lower Provo in 2002 was measured at less than 9, impairment was still indicated presumably since pH values, which fluctuate diurnally, could climb into dangerous levels during the course of a day.

Daily and seasonal fluctuations in stream pH are caused by daily and seasonal variation in photosynthesis done by aquatic plants including phytoplankton. By using up hydrogen molecules, photosynthesis causes the concentration of hydrogen ions to decrease and pH to increase. Conversely, respiration and decomposition lower pH. Stream pH is therefore higher when photosynthesis is at its peak during daylight hours and during the growing season, and stream pH is lower during the nighttime hours and the non-growing season (winter and fall). The magnitude in pH fluctuation increases as phytoplankton abundance increases. The daily fluctuation varies between one and two points on the pH scale depending on the trophic nature of the stream (Boyd, 2000).

Figure 5.3: Average Lower Provo River pH, 1975-2002

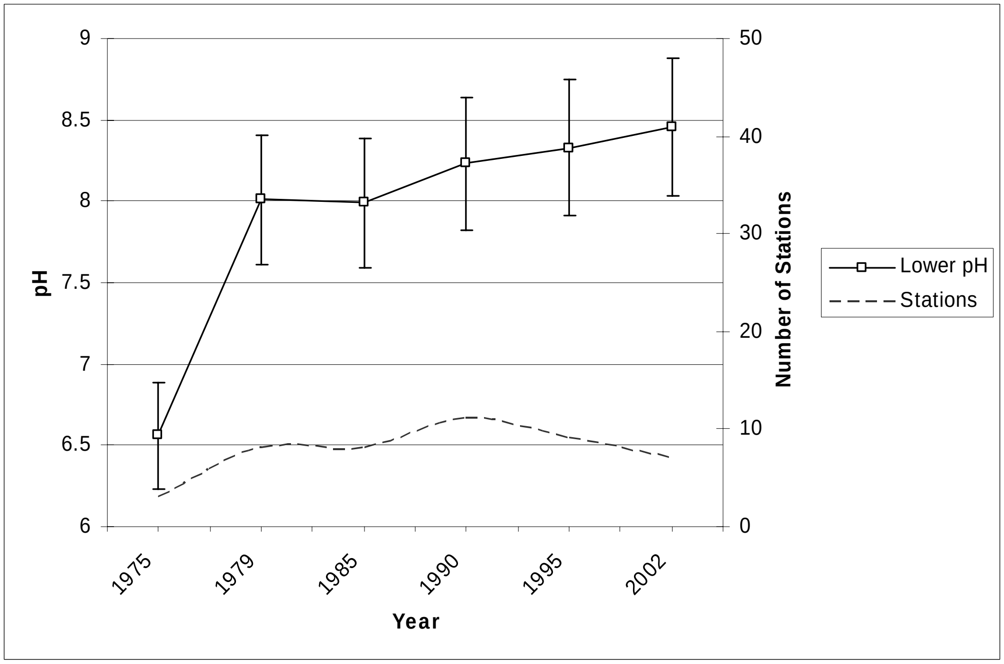
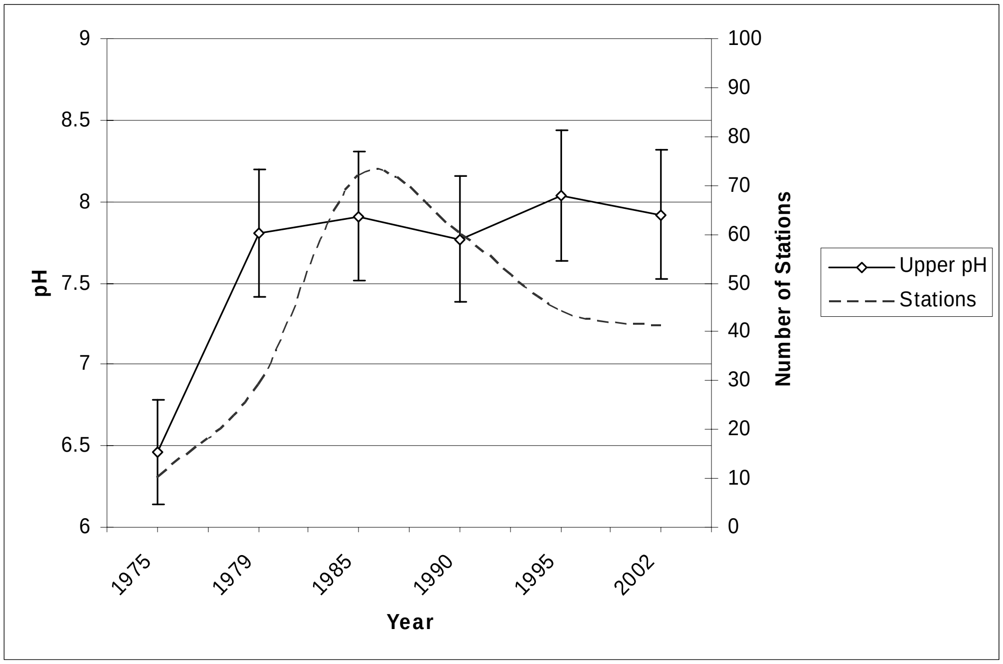


Figure 5.4: Average Upper Provo River pH, 1975-2002



Water alkalinity results mainly from carbonate and bicarbonate ions. Alkalinity is a measure of the concentration of bases in water and is expressed in milligrams per liter of calcium carbonate ($CaCO_3$). The primary bases in natural waters are carbonates and bicarbonates, and these comprise most of the alkalinity in natural waters. Limestone dissolution is the primary source of alkalinity. However, bicarbonate may also be introduced by reactions between the hydrogen ion of water and basic ions including calcium, magnesium, sodium, or potassium. Research has shown that areas with arid and semi-arid climates have moderate to high natural alkalinity. The pH is usually between 7 and 8.5 in moderate and high alkalinity waters (Livingstone, 1963).

The lower Provo had higher alkalinity and bicarbonate levels each year of the study leading to higher overall cumulative averages. The cumulative average alkalinity, as represented by milligrams per liter of calcium carbonate, was 175.92 in the lower

Provo and 133.57 in the upper Provo. Bicarbonate values in the study years averaged 214.80 in the lower Provo and 160.58 in the upper Provo.

The validity of the preceding analysis is based almost entirely on the validity of the data. Errors in the data could be introduced in several ways. This study relied on secondary water quality data collected and provided by the state of Utah. Possible errors in this data include measurement or recording error. However, it is believed that the data contain few errors since it was required to be in compliance with Environmental Protection Agency water quality measurement standards. The study was based on a sampling of six years to study a period of 27 years. It is believed that the addition of a greater number of study years would result in a more exhaustive study with similar results, but it would also require additional resources for data processing and analysis.

The primary source of potential errors and problems in this study was the small sample size used. Six years of data were used within a period of 27 years. All existing water quality data for the watershed were aggregated for each of the six years. In addition, Landsat imagery was classified for each of these years. The reason that more years were not included in this study are first, land cover classification and accuracy assessment are very time-consuming and could have been allowed to extend this research beyond an acceptable timeframe; second, some of the imagery has errors, for example the 2000 image could not have been used because it contained a large area of missing data; third, it was deemed unnecessary to used many more years since measures were taken to mitigate the effects of having a small sample size such as using statistical tools including linear regression and non-parametric correlation that do not required large sample sizes.

Error may also result from the land cover classification. Land cover classification errors are unavoidable but can be diminished through careful measures. Paramount to an understanding of land cover classification results is the so-called mixed pixel problem. Here is the problem: each pixel of a Landsat image represents an area on the ground, 30 meters by 30 meters in later years, 79 meters by 79 meters in earlier years. Within this amount of area there is bound to be variation in land covers. However, only one brightness value can be assigned to each pixel. This means that if a 30 meter area had urban land covering 80% of the area and agricultural land covering only 20% of the area only one value could be assigned and the classifier would likely group the pixel with urban land even though part of the land area contains agricultural land.

Spectral confusion is another way that error can be introduced in a land cover classification. This results when two or more land covers share a similar spectral signature. For example, barren land and urban land can have similar pixel brightness values. In order to mitigate this problem it is important to use rigorous classification methods including choosing representative pixels throughout an image. It is also helpful, as in this study, to use ancillary sources of data to inform and refine the land cover classification.

Further historical studies on water quality and land use in the Provo River are merited. Future studies examining the water quality at a finer temporal scale, monthly or seasonally, would be particularly useful. Studies that focus on a particular variable or particular variable in greater depth might also be insightful. Furthermore, these studies could be improved through the use of more years of land cover data accompanied by efforts to achieve increased classification accuracies. Finally, the use of a greater volume of high (spatial) resolution ancillary data would allow for additional accuracy assessments and greater research validity.

Conclusion

This study has examined the historical impacts of land cover change on water quality in the Provo River watershed. It has shown that among land covers, urban land cover impacts the greatest number of water quality variables followed by agricultural land cover. It has also shown that urban land cover may have contributed to the increasing alkalinity of the water in the upper and lower Provo. These results indicate that more research should be done on point and non-point sources of alkaline pollutants from urban land cover. The findings also support the conclusion that small changes in the areal extent of urban and agricultural can have significant impacts on water quality.

In addition to supporting earlier research, this study reveals geographically specific insights about land cover impacts on water quality on semi-arid urbanizing watersheds in western United States. This study is intended to be used to inform future research on watersheds with similar geographic characteristics.

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APPENDIX A: Comparison of water quality variables measured in 1975 and 2003

1975	2003
Alkalinity, Carbonate as CaCO3	Alkalinity, Carbonate as CaCO3
Arsenic	Aluminum
Bicarbonate	Antimony
Boron	Arsenic
Cadmium	Barium
Calcium	Bicarbonate
Carbon dioxide	BOD, Biochemical oxygen demand
Chloride	BOD, carbonaceous
Chromium	Cadmium
Chromium, hexavalent	Calcium
Dissolved Solids	Carbon dioxide
Fluorides	Carbonate ion (CO3-2)
Gross alpha radioactivity, (Thorium-230 ref std)	Chloride
Gross beta radioactivity, (Cesium-137 ref std)	Chlorine
Hardness, Ca + Mg	Chlorophyll a, uncorrected for pheophytin
Iron	Chromium
Lead	Copper
Magnesium	Cyanide
Mercury	Depth, data-logger (ported)
Nickel	Dissolved oxygen (DO)
Nitrogen, ammonia (NH3) as NH3	Dissolved oxygen saturation
Nitrogen, Kjeldahl	Dissolved Solids
Nitrogen, Nitrate (NO3) as NO3	Fecal Coliform
Nitrogen, Nitrite (NO2) as NO2	Fixed Solids
pH	Flow
Phosphorus, orthophosphate as P	Hardness, Ca + Mg
Potassium	Hydroxide
Selenium	Iron
Silica	Lead
Silver	Magnesium
Sodium	Manganese
Specific conductance	Mercury
Sulfur, sulfate (SO4) as SO4	Molybdenum
Tritium	Nickel
Turbidity	Nitrogen, ammonia (NH3) as NH3
Zinc	Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N
	pH
	Phosphorus as P
	Potassium
	Salinity
	Secchi disk depth
	Selenium
	Silver
	Sodium
	Specific conductance
	Sulfur, sulfate (SO4) as SO4
	Temperature, water
	Thallium
	Total Coliform
	Total Organic Carbon (TOC)
	Total Suspended Solids (TSS)
	Turbidity
	Volatile Solids
	Zinc

APPENDIX B: Number of data measurements used by year

Lower Provo River watershed

	1975	1979	1985	1990	1995	2002
Alkalinity, Carbonate as CaCO3	15	9	40	32	66	48
Bicarbonate	15	9	37	32	55	48
Calcium	10	9	31	47	67	52
Carbon dioxide	30	9	37	32	55	48
Chloride	10	9	31	23	51	12
Chromium	6	9	31	34	23	17
Dissolved Solids	10	21	30	57	51	48
Hardness, Ca + Mg	15	9	31	45	67	52
Iron	10	9	34	35	19	15
Magnesium	10	9	31	47	67	52
Mercury	3	9	31	34	23	17
Nickel	1	9	0	9	4	2
Nitrogen, ammonia (NH3) as NH3	5	20	40	65	79	53
Nitrogen, Nitrate (NO3) as NO3	10	9	31	46	0	0
Nitrogen, Nitrite (NO2) as NO2	2	9	32	46	0	0
Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N	0	20	0	0	67	48
pH	14	34	57	99	130	105
Phosphorus, orthophosphate as P	10	9	30	45	0	0
Phosphorus as P	0	20	39	69	131	90
Potassium	10	9	31	47	51	20
Selenium	1	9	31	34	23	17
Silver	1	9	31	34	23	17
Sodium	10	9	31	47	51	20
Specific conductance	14	20	73	90	131	69
Sulfur, sulfate (SO4) as SO4	10	9	31	47	51	12
Turbidity	14	9	31	23	51	12
Zinc	1	9	31	35	19	15

Upper Provo River watershed

	1975	1979	1985	1990	1995	2002
Alkalinity, Carbonate as CaCO3	69	53	440	14	195	345
Bicarbonate	70	53	401	14	161	345
Calcium	21	53	375	154	183	321
Carbon dioxide	138	50	106	14	161	345
Chloride	21	53	379	33	147	71
Chromium	6	53	108	70	69	86
Dissolved Solids	20	67	761	350	150	343
Hardness, Ca + Mg	69	53	375	135	183	321
Iron	26	70	271	87	69	86
Magnesium	21	53	372	154	183	321
Mercury	1	54	212	70	71	86
Nickel	4	54	2	52	0	1
Nitrogen, ammonia (NH3) as NH3	1	74	846	499	319	321
Nitrogen, Nitrate (NO3) as NO3	19	53	631	388	0	0
Nitrogen, Nitrite (NO2) as NO2	0	53	595	371	0	0
Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N	0	76	283	0	351	362
pH	69	102	1072	511	523	1577
Phosphorus, orthophosphate as P	21	53	858	454	0	0
Phosphorus as P	0	76	857	540	690	652
Potassium	19	53	372	153	147	110
Selenium	0	54	107	70	71	86
Silver	4	54	107	70	69	86
Sodium	21	53	374	154	179	110
Specific conductance	68	98	1038	377	500	1299
Sulfur, sulfate (SO4) as SO4	21	53	378	153	179	98
Turbidity	69	53	91	6	147	96
Zinc	3	54	274	91	69	86

APPENDIX C: Land cover classification refinement model

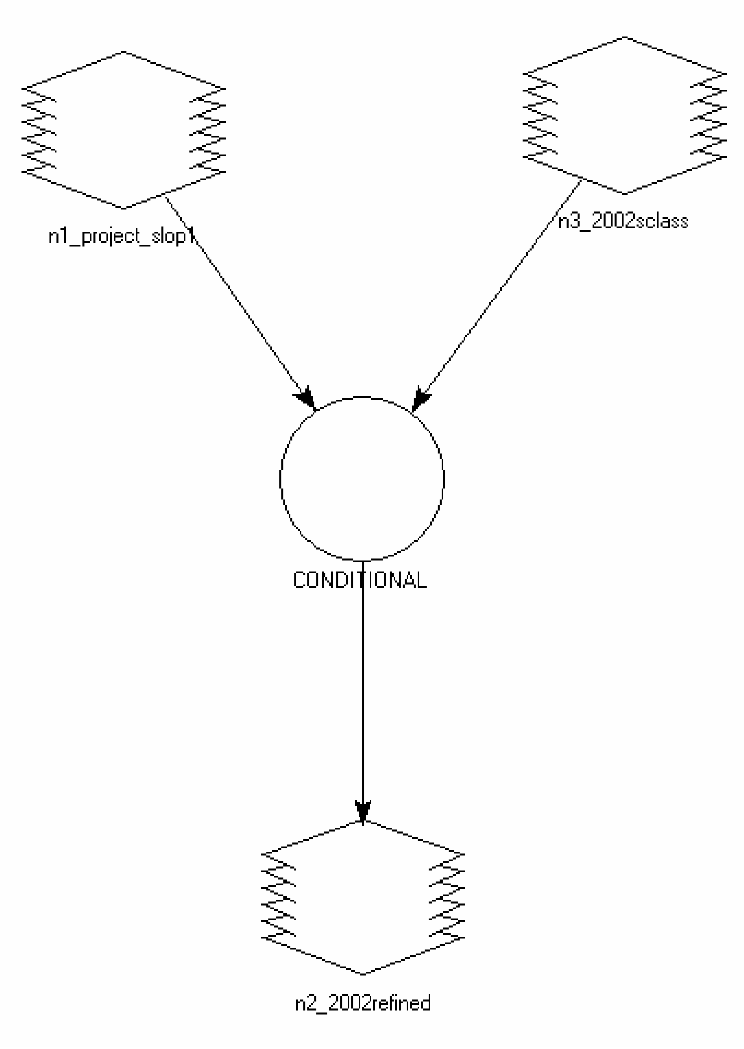
“n1_project_slop1” = the slope layer

“n3_2002sclass” = the classified image

“CONDITIONAL” = the conditional statement

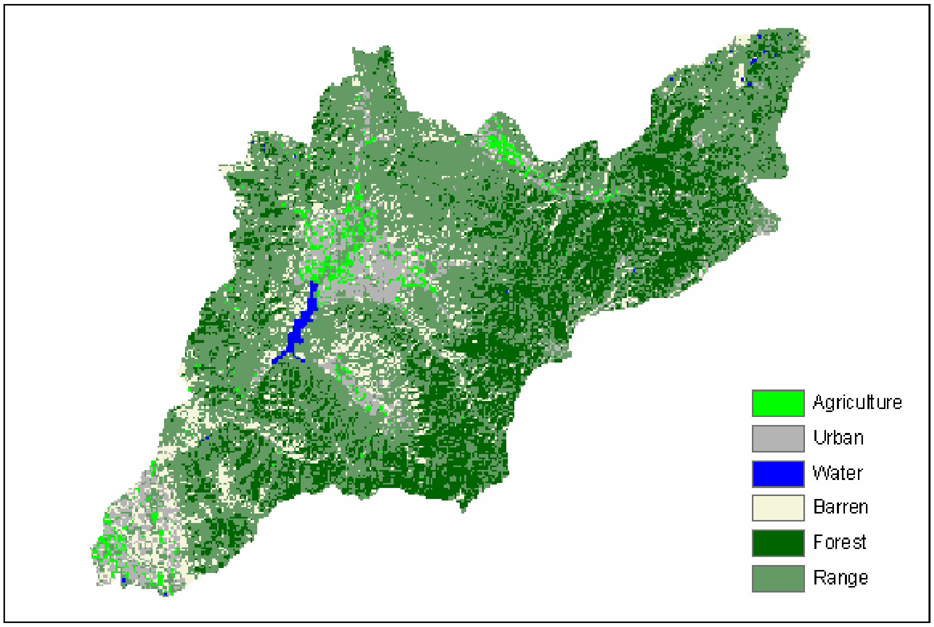
CONDITIONAL {
($n1_project_slop1 > 5 &&
$n3_2002sclass == 2) 6,
($n1_project_slop1 > 5 &&
$n3_2002sclass == 5) 11,
($n1_project_slop1 > 5 &&
$n3_2002sclass == 1) 11,
($n3_2002sclass)
$n3_2002sclass}

“n2_2002refined” = the refined classification image

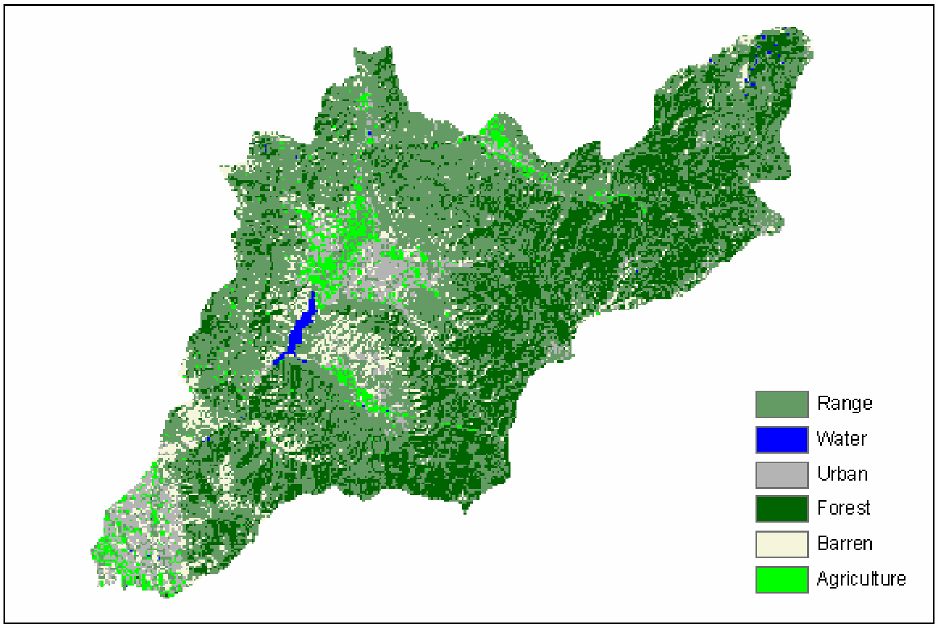


APPENDIX D: Land cover maps of the Provo River watershed, 1975 – 2002

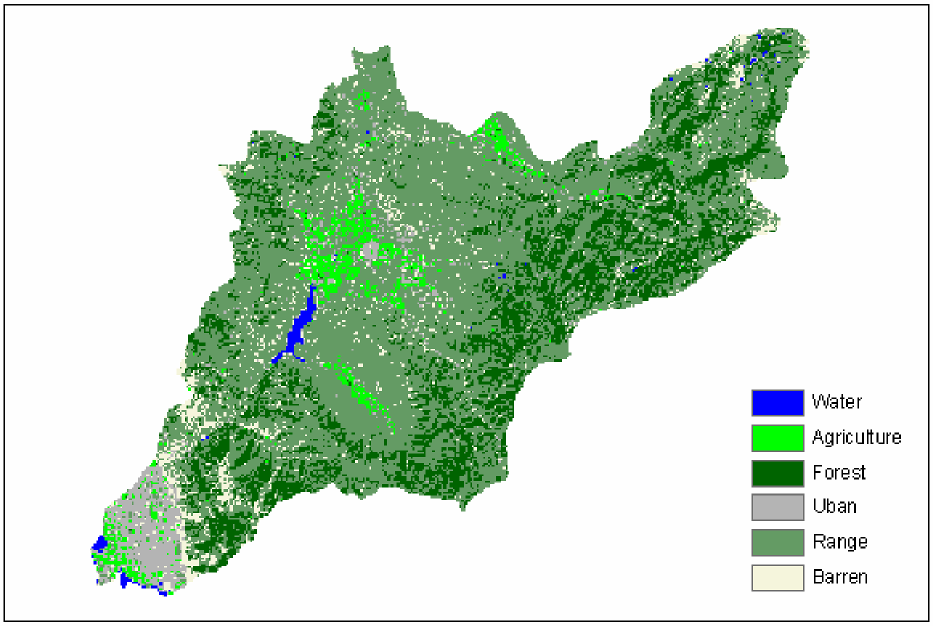
1975



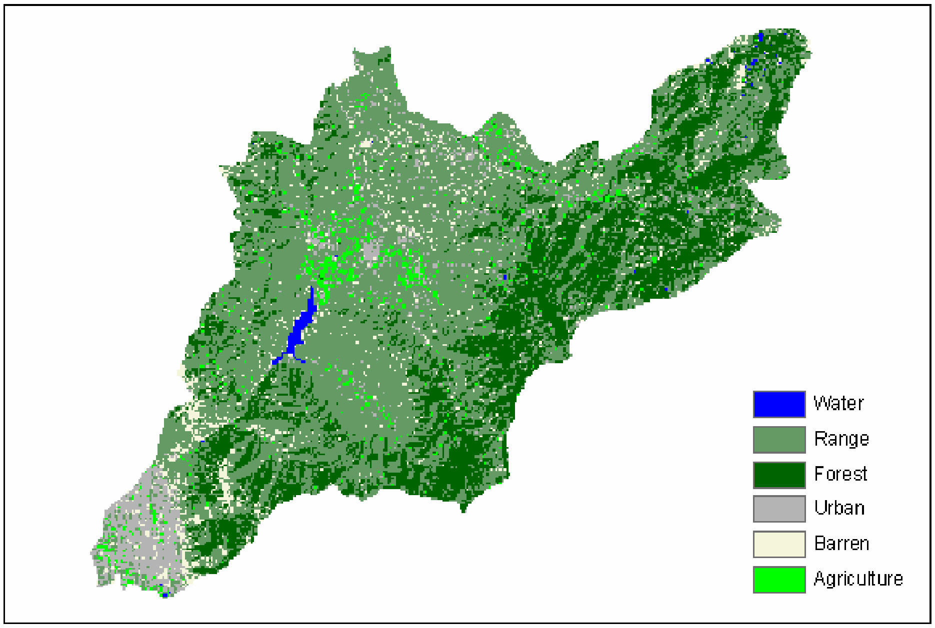
1979



1985


Water
Agriculture
Forest
Uban
Range
Barren

1990


Water
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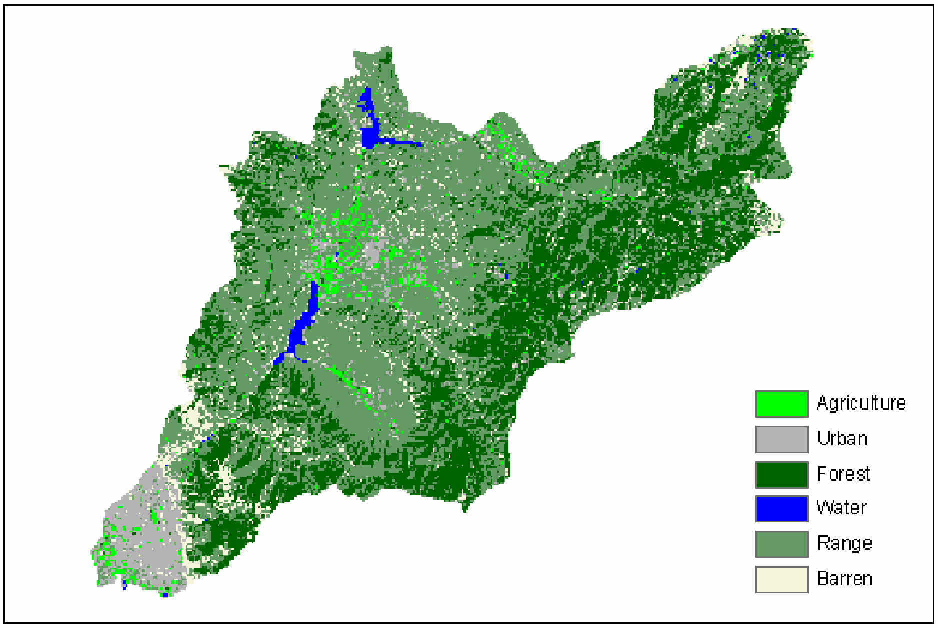
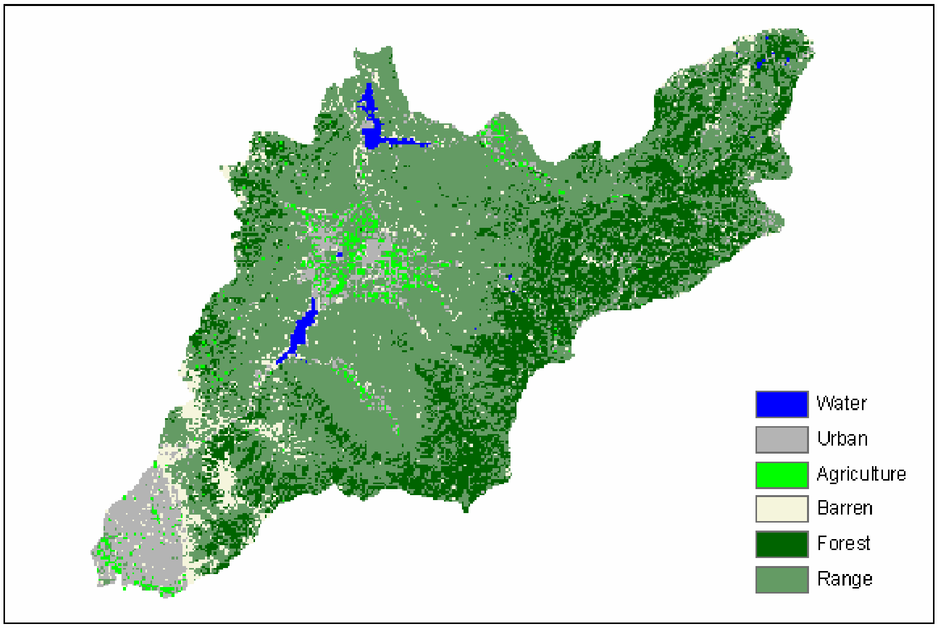
Forest
Urban
Barren
Agriculture

1995


Agriculture
Urban
Forest
Water
Range
Barren

2002


Water
Urban
Agriculture
Barren
Forest
Range