WETLANDS IN NORTHERN SALT LAKE VALLEY, SALT LAKE COUNTY, UTAH—AN EVALUATION OF THREATS POSED BY GROUND-WATER DEVELOPMENT AND DROUGHT

by Sandow M. Yidana, Mike Lowe, and Richard L. Emerson

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Cover Photo: *View looking to the northeast of southern Great Salt Lake wetlands in Salt Lake County, Utah.*

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ABSTRACT

Salt Lake Valley is a largely urban area with a growing population. Most of the development in Salt Lake Valley uses municipal water sources, principally wells completed in the basin-fill aquifer system. The population growth and concomitant increase in municipal ground-water pumping could significantly decrease the amount of ground water discharged from the principal aquifer system (where most wells are completed) to the shallow unconfined aquifer system.

The shallow unconfined aquifer overlies confining beds above the principal aquifer system in the central and northern parts of the valley, and provides water to springs and approximately 58,000 acres (23,500 hm^2) of wetlands in ground-water discharge areas. Decreased recharge to the shallow unconfined aquifer from the principal aquifer due to increased ground-water pumping could reduce water supply to these springs and wetlands. Also, water supply to the springs and wetlands is affected by climatic conditions and Great Salt Lake level. Drought conditions during 1999–2004 reduced the amount of recharge to ground-water aquifers across the state, including the Great Salt Lake area, negatively impacting the Salt Lake Valley wetlands. In 2005 and 2008, the elevation of Great Salt Lake declined to near its historic lowstand reached in 1963, allowing some parts of the Salt Lake Valley wetlands to dewater.

To evaluate the potential impacts of drought and increased development on the Salt Lake Valley wetlands, we used existing data to estimate a water budget and develop regional, three-dimensional, steady-state and transient MODFLOW models to evaluate water-budget changes for the wetland areas; these efforts focused on wetlands around the margins of Great Salt Lake, although the results may apply to all of the wetlands in Salt Lake Valley. The modeling suggests that subsurface inflow into the wetland areas would be most affected by decreased subsurface inflow due to long-term (20-year) drought conditions, which would also cause changes in Great Salt Lake levels, but subsurface inflow would also decrease due to increased municipal and industrial well withdrawals over the same time period. Therefore, the worst-case scenario for the wetlands would be a combination of both conditions. If the U.S. Environmental Protection Agency's goal on no net loss of wetlands is to be met, the Salt Lake Valley wetland areas should be managed to maintain their current budget of water (estimated at about 52,420 acre-feet per year [65 hm^3/yr] of recharge).

We also installed shallow monitoring wells in the Salt Lake Valley wetland areas to determine hydraulic gradient and ground-water quality in the shallow unconfined aquifer. The magnitude and direction of the hydraulic gradient are similar to those documented previously, where ground water in the wetland areas flows north toward Great Salt Lake. Total-dissolved-solids concentrations for water samples collected from two shallow monitoring wells are 6786 and 21,324 mg/L.

This model-dependent study indicates that wetlands in Salt Lake Valley may be stressed in the future. Drought and increased development due to population growth could dramatically reduce the amount of water the wetlands receive. Measures to reduce the potential for degradation of the Salt Lake Valley wetlands include development restrictions, re-use of wastewater upgradient of the wetlands, and implementation of water conservation practices.

INTRODUCTION

Background

Salt Lake Valley (figures 1 and 2), in Salt Lake County, Utah, is a largely urban area along the southern margin of Great Salt Lake that continues to undergo population growth. Most of the development in Salt Lake Valley uses municipal water sources, principally wells completed in the basin-fill aquifer system. The population growth and concomitant increase in ground-water usage for municipal supply (figure 3) could significantly decrease the amount of ground water discharged from the principal aquifer system (where most wells are completed) to the shallow unconfined aquifer system. The shallow unconfined aquifer overlies confining beds above the principal aquifer system in the central and northern parts of the valley, and provides water to springs and approximately 58,000 acres (23,500 hm^2) of wetlands in ground-water discharge areas, which accounts for 98% of Salt Lake County wetlands.

Salt Lake Valley has been closed to new water rights appropriations since 2002, and between 1991 and 2002 only fixed-time water appropriations were available to residents with special circumstances (Utah Division of Water Rights, 2008a,

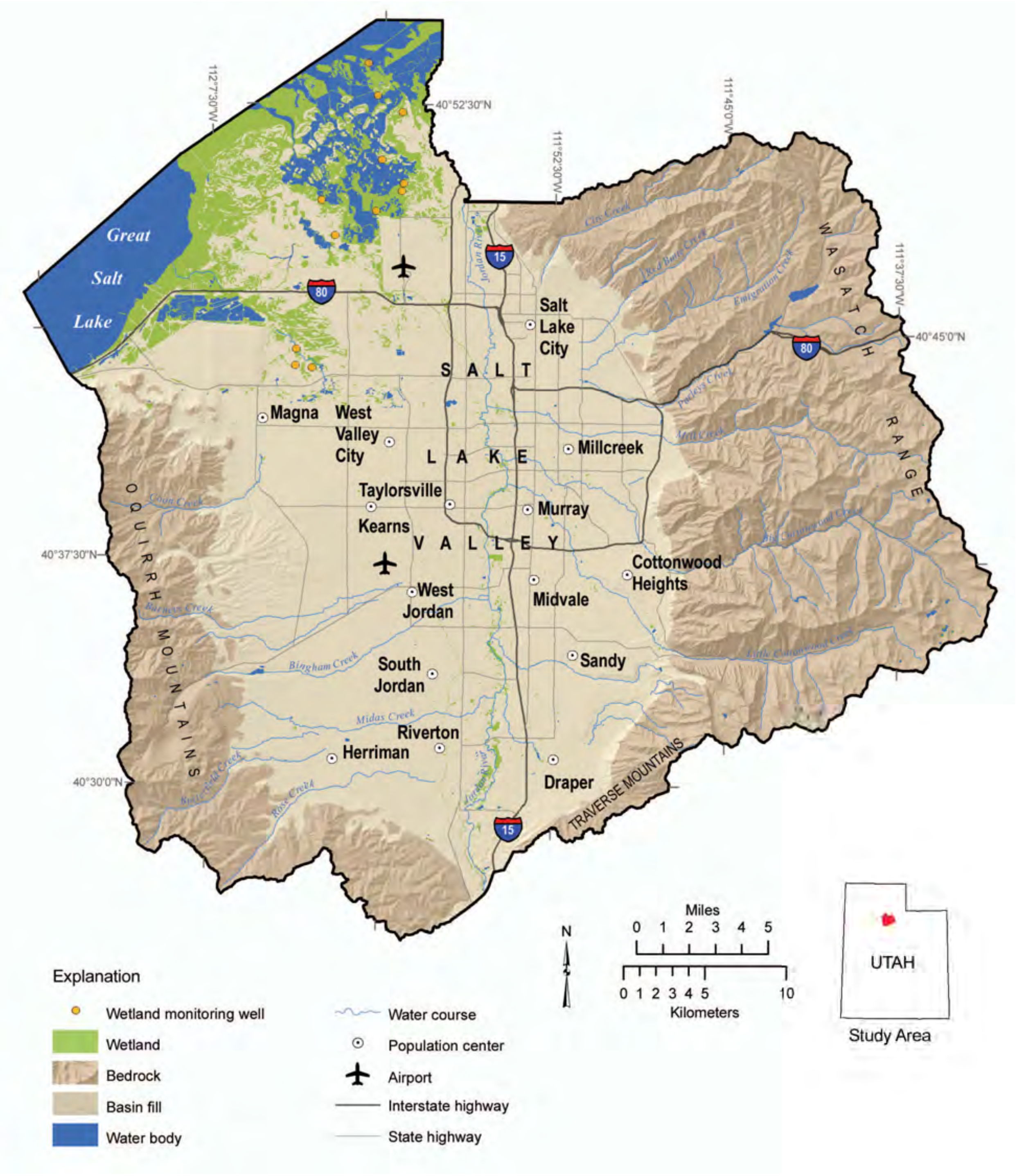

Figure 1. *Wetlands and wetland monitoring wells, Salt Lake County, Utah.*

2008b). Thus, water rights for development in the incorporated areas are primarily obtained through purchase/exchange of existing water rights, mainly those formerly used for agriculture.

This change from agricultural to municipal water use could have a significant effect on the amount of ground water discharged from the confined aquifer system (where most wells are completed) to the shallow unconfined aquifer system, which provides water to springs and wetlands in ground-water discharge areas. Ground-water discharge areas are predominantly located in the central and northern parts of Salt Lake Valley (Anderson and others, 1994). The amount of ground water discharged from the confined aquifer system to the shallow unconfined aquifer system could decrease, even if no new water rights are issued, because seepage of unconsumed irrigation/lawn water contributes nearly 18% of the total recharge to aquifers in Salt Lake Valley (Lambert, 1995a); this component of recharge to the aquifer system would likely decrease as a result of changing from agricultural to domestic water usage.

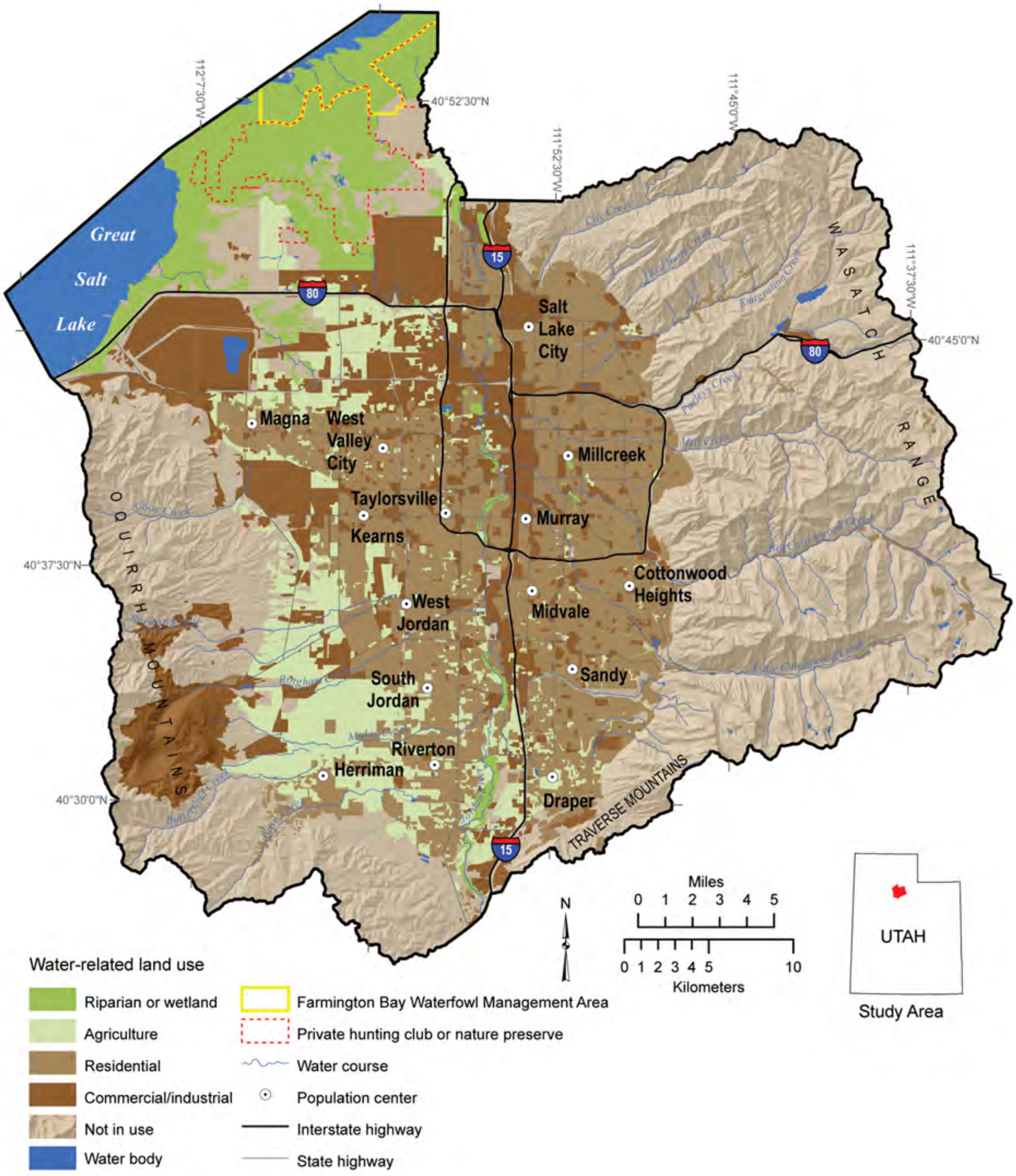

Figure 2. *Water-related land use in 2006, Salt Lake County (data from the Utah Division of Water Resources).*

Significant portions of Utah's wetlands are located in areas surrounding Great Salt Lake, including the Salt Lake Valley wetlands. Preliminary estimates from existing National Wetlands Inventory (NWI) coverage (U.S. Fish and Wildlife Service, 2010) indicate that wetlands in Salt Lake Valley occupy about 58,400 acres (23,600 hm^2; about 22% of the valley-floor area). An estimated 49,300 acres (20,000 hm^2), or 84% of Salt Lake Valley's wetland area, is within 3 miles (5 km) of Great Salt Lake. Wetlands are important to diverse plant and animal species (about 45% of the species listed as threatened or endangered under the Endangered Species Act use wetland habitat), clean and abundant water supplies, and flood and erosion control (National Wildlife Federation, 1989). The Utah State Water Plan recognizes the potential impact of increased ground-water development on these critical natural resources and proclaims " . . . studies need to be undertaken to ensure that groundwater withdrawals are not adversely affecting spring flows nor impairing water rights associated with existing wetlands" (Utah Division of Water Resources, 2001).

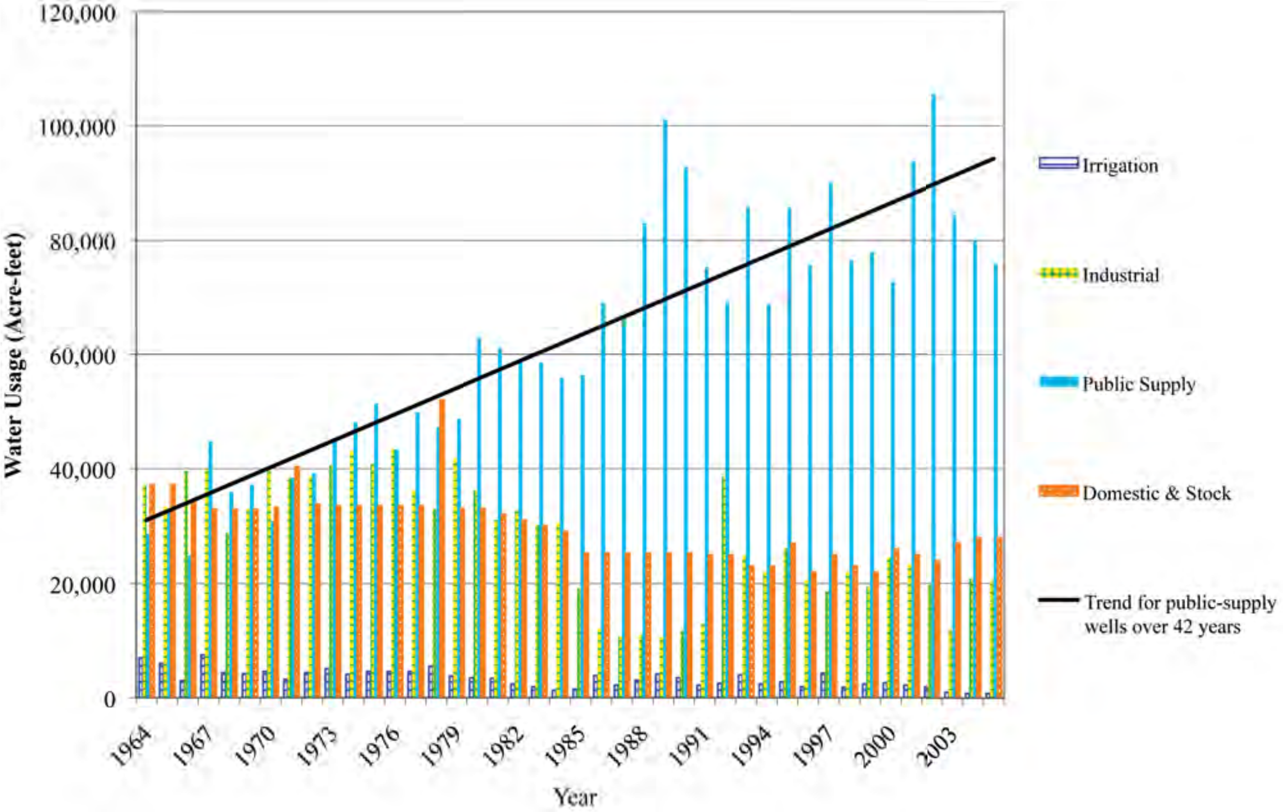

Figure 3. *Annual water usages by category for Salt Lake Valley (based on data from Utah Division of Water Rights).*

Purpose and Scope

The purpose of this study is to use existing data to estimate a water budget for the wetland areas, and to use existing steady-state and transient ground-water flow models developed by the U.S. Geological Survey (USGS) (Lambert, 1995a) to simulate the hydrologic effects on wetlands from various recharge rates and projected ground-water withdrawals at various projected Great Salt Lake levels; the estimated water budget and model simulations focus on wetlands around the margins of Great Salt Lake, although the study results may apply to all of the wetlands in Salt Lake Valley. These simulations can be used to assess potential threats to wetlands from increased ground-water withdrawals and drought, and provide a basis for (1) implementing restrictions on domestic withdrawals, (2) assessing water needs for wetland preservation, and (3) encouraging the development of water conservation programs.

Our study combines empirical and modeling analyses to understand the effects of changes in land use and climate. We used an estimated water budget to compare and interpret numerical ground-water flow models, which simulate fluxes into and out of the Salt Lake Valley wetland areas. Numerical ground-water flow models have been used to understand the interaction between wetlands and ground water in other studies (Burk and others, 2005; Bishop and others, 2009). The accuracy of the solutions obtained by numerical methods is generally sufficient; however, the accuracy depends on several factors, including our understanding of the complexity of the system, boundary and initial conditions, and numerical methods used.

A second objective is to document the hydraulic gradient and current quality of ground water in the wetland areas near Great Salt Lake. We used water levels in shallow wells to document the hydraulic gradient in the shallow unconfined aquifer, and data from water samples from two of the wells to provide insight into the current quality of ground water flowing into the wetland areas. Data from two wells are not sufficient to accurately characterize the quality of ground water entering the wetland areas, but information from these two wells in addition to data from previous work provide a sense of the quality of ground water recharging the wetland areas.

This report provides the necessary integration of geologic and hydrologic wetland studies to more fully understand the hydrologic system of the Salt Lake Valley wetlands area in relation to wetland functionality, with emphasis on the wetlands near Great Salt Lake. The scope of this study includes a thorough literature search; a compilation of published and unpublished geologic, hydrologic, and wetland information; and field sampling and analysis of water data from shallow wells. Detailed USGS ground-water models, which are described in this report, were used by the USGS and other agencies to identify historical changes in the ground-water flow system in Salt Lake Valley.

Methods

We installed 12 shallow monitoring wells in three wetland areas near Great Salt Lake (figure 1 and appendix C). Two wells were sampled for water quality, and ground-water depth was measured in nine of the wells (three wells did not yield water). The wells were manually installed using a hand auger to bore a hole into the ground to a depth of 3 to 7 feet (1–2 m), and then inserting one-inch-diameter slotted PVC and backfilling the void between the borehole and PVC with the hand-auger cuttings. We mapped the well locations using a Trimble Total Station GPS system having sub-centimeter vertical and horizontal accuracy. Water levels in the wells were measured manually during the spring and summer of 2008. The two water-quality monitoring wells were sampled in May 2008, and the samples were analyzed at the Utah Division of Epidemiology and Laboratory Services for general chemistry, dissolved metals, nutrients, and total organic carbon. Computer modeling was conducted during 2007 and 2008.

Previous Studies

Richardson (1906) conducted the first investigation of ground-water conditions in Salt Lake Valley (previously known as Jordan Valley); that study, which included Utah Valley, produced maps showing depth to ground water and areas of flowing wells. Taylor and Leggette (1949) conducted a more thorough investigation that included many well records, and discussions of ground-water occurrence, recharge and discharge, and chemical quality. Lofgren (1952) discussed the status of ground-water development in Salt Lake Valley as of 1951. Marsell (1964) discussed water-supply issues as part of a comprehensive review of the geology of Salt Lake County. Marine and Price (1964) updated previous studies and subdivided the valley into ground-water districts for water-resource management purposes. Hely and others (1967, 1968, 1969) compiled hydrologic and climatalogic data that were used to produce a summary of ground-water hydrology in Salt Lake Valley (Mower, 1969a) and water resources in Salt Lake County (Hely and others, 1971). Arnow and Mattick (1968) evaluated the thickness of basin-fill deposits. Mower (1968) discussed ground-water discharge toward Great Salt Lake in basin-fill deposits. Mower (1969b) discussed ground-water inflow through channel fill in seven Wasatch Range canyons in Salt Lake County. Arnow and others (1970) used water-well logs to delineate the pre-Quaternary surface in Salt Lake Valley to be used as a general guide for water-well drilling. Mower (1970) discussed ground-water recharge to Salt Lake Valley from Utah Valley. Seiler and Waddell (1984) conducted an assessment of the shallow unconfined aquifer in Salt Lake Valley. Herbert and others (1985) conducted a seepage study of six canals in Salt Lake County. Waddell and others (1987b) evaluated the chemical quality of ground water in the basin-fill aquifer for the 1969–85 time period. Waddell and others (1987a) evaluated ground-water conditions in Salt Lake Valley with emphasis on predicted effects of increased withdrawals from wells. Thiros (1992) compiled selected hydrologic data for Salt Lake Valley with emphasis on data from the shallow unconfined aquifer and confining layers. Anderson and others (1994; see also Anderson and Susong, 1995) mapped ground-water recharge and discharge areas for the principal aquifers along the Wasatch Front, including the principal aquifer in Salt Lake Valley. Thiros (1995) investigated the chemical composition and movement of ground water, and the hydrologic properties of basin-fill material, to better understand the flow system in Salt Lake Valley. Lambert (1995a) produced a three-dimensional, finite-difference, numerical ground-water flow model for the basin-fill aquifer, which he (Lambert, 1995b) subsequently used to produce capture zones for selected public supply wells and simulate (Lambert, 1996) the movement of sulfate in ground water. Waddell and others (2004) assessed water quality in the Great Salt Lake basins, including Salt Lake Valley. Burden and others (2005) described changes in ground-water conditions in Utah, including Salt Lake Valley, from 1975 to 2005. Lowe and others (2005) and Lowe and Wallace (2006) mapped ground-water sensitivity and vulnerability to pesticides for the Salt Lake Valley basin-fill aquifer. Wallace and Lowe (2009) mapped ground-water quality classes for the Salt Lake Valley basin-fill aquifer.

SETTING

Physiography

Salt Lake Valley is a north-south-trending valley located in north-central Utah southeast of Great Salt Lake. Salt Lake Valley is in the Salt Lake Valley segment of the Wasatch Front Valleys section of the Great Basin physiographic province (Stokes, 1977). The valley is bounded on the east and northeast by the central portion of the Wasatch Range, on the northwest by Great Salt Lake, on the west by the Oquirrh Mountains, and on the south by the Traverse Mountains. Elevations range from about 4200 feet (1280 m) in the lowest part of the valley near Great Salt Lake to more than 7000 feet (2130 m) in the Traverse Mountains, 9000 feet (2740 m) in the Oquirrh Mountains, and 11,000 feet (3350 m) in the Wasatch Range.

Salt Lake Valley has also been referred to as Jordan Valley because of the Jordan River, which flows northward into the valley through the Jordan Narrows, a water gap in the Traverse Mountains, and ultimately into Great Salt Lake. Six other major streams flow into the valley from the Wasatch Range to the east and into the Jordan River; these streams are mainly fed by snowmelt during the spring and early summer. Minor amounts of water enter the valley from the Oquirrh Mountains.

The mountains that surround Salt Lake Valley are composed of rocks that range in age from Precambrian to Tertiary. The Wasatch Range consists of Precambrian, Paleozoic, Mesozoic, and Cenozoic sedimentary and metasedimentary rocks that have been intruded by Tertiary granitic and dioritic stocks.

The Oquirrh Mountains consist of Paleozoic sedimentary rocks, predominantly the Oquirrh Formation, and intrusive and extrusive Cenozoic rocks. The Traverse Mountains are composed of Paleozoic sedimentary rocks and Cenozoic volcanics.

Salt Lake Valley occupies a graben that is bounded by faults on its east, west, and south sides. Sediments have been filling this graben since Tertiary time. The Tertiary and Quaternary basin fill is up to 4000 feet (1220 m) thick in some areas of the valley (Mattick, 1970), and consists of unconsolidated to semiconsolidated clay, silt, sand, gravel, and tuff. Quaternary sediments in the upper part of the basin fill range from 0 to 2000 feet (0–610 m) thick (Arnow and others, 1970). The depositional sequence in the basin fill is complex (Marine and Price, 1964) due to alternating periods of lacustrine and interlacustrine conditions during the late Tertiary and Quaternary. During the lacustrine periods, or deep-lake cycles (figure 4), much of Salt Lake Valley was covered with water and offshore silt and clay were deposited in the central parts of the valley while deltaic (at the mouths of canyons) and nearshore sand and gravel were deposited along valley margins. During interlacustrine periods, sediments were deposited primarily as alluvial fans at canyon mouths and as fluvial-channel and floodplain sediments in the central parts of the valley. As a general rule, coarser grained sediments exist near valley margins and finer grained sediments exist in the middle and north end of the valley.

Climate

The climate in Salt Lake Valley can be described as semiarid with hot summers and moderately cold winters. Due to the local topography and the great relief between the mountains and valley, the weather can be quite variable and is very much related to orographic effects and local weather patterns (Murphy, 1981). The mountains surrounding the valley typically receive substantially more precipitation and have cooler temperatures than the valley, and the southeast part of Salt Lake County receives the most precipitation.

In Salt Lake County, 24 weather stations are or have been operated by the Utah Climate Center, and Moller and Gillies (2008) provide information for nine of these stations. Based on data collected from those weather stations, Salt Lake Valley receives between 13.74 and 25.79 inches (34.9 and 65.5 cm) of precipitation annually, at the Draper Point of the Mountain and Cottonwood Weir stations, respectively. The mountains receive much more precipitation; the Alta station (elevation 8730 feet [2661 m]) receives 58.28 inches (148.03 cm) of precipitation annually.

Temperatures in Salt Lake County are also quite variable, and like precipitation, are related to elevation; the mountains are 10 to 15˚F (5 to 8˚C) cooler than the valley. To illustrate these extremes, the Salt Lake City International Airport station has an elevation of 4225 feet (1288 m) and a normal maximum temperature, normal minimum temperature, normal mean temperature, and record high temperature of 64.0, 41.2, 52.6, and 107.0˚F (17.8, 5.1, 11.4, and 41.7˚C), respectively. In contrast, the Alta station has an elevation of 8730 feet (2661 m) and a normal maximum temperature, normal minimum temperature, normal mean temperature, and record high temperature of 47.8, 28.7, 38.2, and 94.0˚F (8.8, -1.8, 3.4, and 34.4˚C), respectively (Moller and Gillies, 2008).

Evapotranspiration is dependent upon solar radiation, temperature, wind, and humidity, but does not directly correlate with elevation like temperature and precipitation, at least in Salt Lake County. The Draper Point of the Mountain station

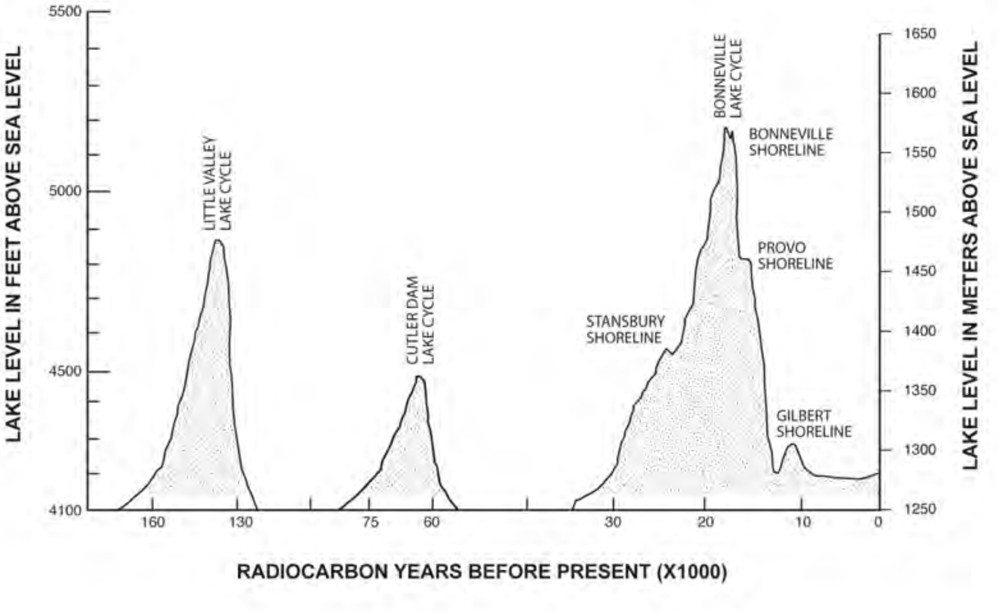

Figure 4. *Schematic diagram of probable lake levels in the Bonneville basin during the past 170,000 years. Modified from Machette and others (1992); note breaks in temporal scale.*

recorded the greatest evapotranspiration value of 47.64 inches (121.01 cm) and the Alta station recorded the lowest value of 28.87 inches (73.33 cm) (Moller and Gillies, 2008). However, most weather stations have evapotranspiration values between 42 and 48 inches (107 and 122 cm), including the Mountain Dell station (44.88 inches [113.0 cm]), which has an elevation of 5420 feet (1652 m) and is located in Parleys Canyon (Moller and Gillies, 2008).

Population and Land Use

Salt Lake County has the largest county population in Utah, estimated at 1,009,518 in 2007 (Demographic and Economic Analysis Section, 2008). Based on this estimate, Salt Lake County residents make up 42% of Utah's total population of 2,385,358 (Demographic and Economic Analysis Section, 2008). The population of Salt Lake County is expected to increase to 1,663,994 in 2050 (Demographic and Economic Analysis Section, 2005). The increase in population in Salt Lake County between 2000 and 2007 averaged 1.7% per year (Demographic and Economic Analysis Section, 2008).

Salt Lake Valley was permanently settled in 1847 by Mormon pioneers. Agriculture, the dominant land use then, is now practiced by relatively few in the valley (although many residents have gardens). Salt Lake City, Utah's capital, is now a major metropolitan area with numerous types of businesses and industries. Most Salt Lake County residents (94%) live and work within the county (Demographic and Economic Analysis Section, 2003). Salt Lake County's largest employer is the University of Utah, followed by the State of Utah and the Granite and Jordan School Districts, so local government agencies provide a substantial number of jobs (Salt Lake County Economic Development Department, undated). Residential and commercial developments are major industries in the valley, so most existing open space is either being developed or is planned for development, including some wetland areas.

GROUND-WATER CONDITIONS

Basin-Fill Aquifers

Basin-fill aquifers in Salt Lake Valley include (1) a confined aquifer in the central and northern parts of the valley, (2) a deep unconfined aquifer between the confined aquifer and the mountains, (3) a shallow unconfined aquifer overlying the artesian aquifer, and, locally, (4) unconfined perched aquifers (Hely and others, 1971). Together, the confined aquifer and the deep unconfined aquifer form the "principal aquifer"—most of the ground water discharged from wells in Salt Lake Valley is from the principal aquifer.

The confined aquifer consists primarily of Quaternary clay, silt, sand, and gravel that are hydraulically interconnected (Hely and others, 1971). The Quaternary deposits range in thickness from 0 to over 2000 feet (0–600+ m) (Arnow and others, 1970); underlying these sediments are relatively impermeable consolidated and semiconsolidated Tertiary and pre-Tertiary deposits. A few areas exist where the Tertiary deposits consist of permeable sand and gravel that yield water to wells, and these areas are considered part of the principal aquifer (Hely and others, 1971).

Overlying the confined aquifer is an upper confining layer composed of Quaternary deposits of clay, silt, and fine sand that collectively create a single impermeable layer. The confining layer is between 40 and 100 feet (12 and 30 m) thick, and the top of the layer is between 50 and 150 feet (15 and 46 m) below the land surface.

The shallow unconfined aquifer overlies the confining layer and is composed primarily of fine-grained sediments (Hely and others, 1971). It is only slightly more permeable than the confining layer, and in some areas it is difficult to differentiate between the two (Hely and others, 1971). The shallow unconfined aquifer has a maximum thickness of about 50 feet (15 m) and yields little water (the water is generally of low quality), so it is rarely used for water supply (Seiler and Waddell, 1984).

The deep unconfined aquifer lies between the confined aquifer and the mountains. It is part of the principal aquifer, where the water table lies below the confining layer or the confining layer is absent (Hely and others, 1971). Perched aquifers exist above the deep unconfined aquifer where there is an unsaturated zone between the water table in the deep unconfined aquifer and the bottom of the upper confining layer. The principal areas with perched aquifers are east of Midvale and between Riverton and Herriman (Hely and others, 1971), but less extensive perched aquifers are scattered around the margins of Salt Lake Valley.

Recharge to the ground-water flow system in the basin-fill aquifer is primarily from inflow from consolidated rock along the valley margins; seepage from rivers, streams, and canals that have a water-level elevation higher than the water table; infiltration of precipitation on the valley floor; and infiltration from unconsumed irrigation water (Hely and others, 1971). Ground water flows from the primary recharge areas in the mountains and near the valley margins to the deep unconfined aquifer, then toward the central and northern parts of the valley, where the principal aquifer is confined (figures 5 and 6). This creates an upward gradient, and ground water in the confined aquifer flows upward into the confining layer and then into the shallow unconfined aquifer, where it discharges into the Jordan River, springs, drains, canals, and Great Salt Lake, or is lost through evapotranspiration. Ground water in the principal aquifer is either discharged into the shallow unconfined aquifer or is withdrawn by wells (Hely and others, 1971).

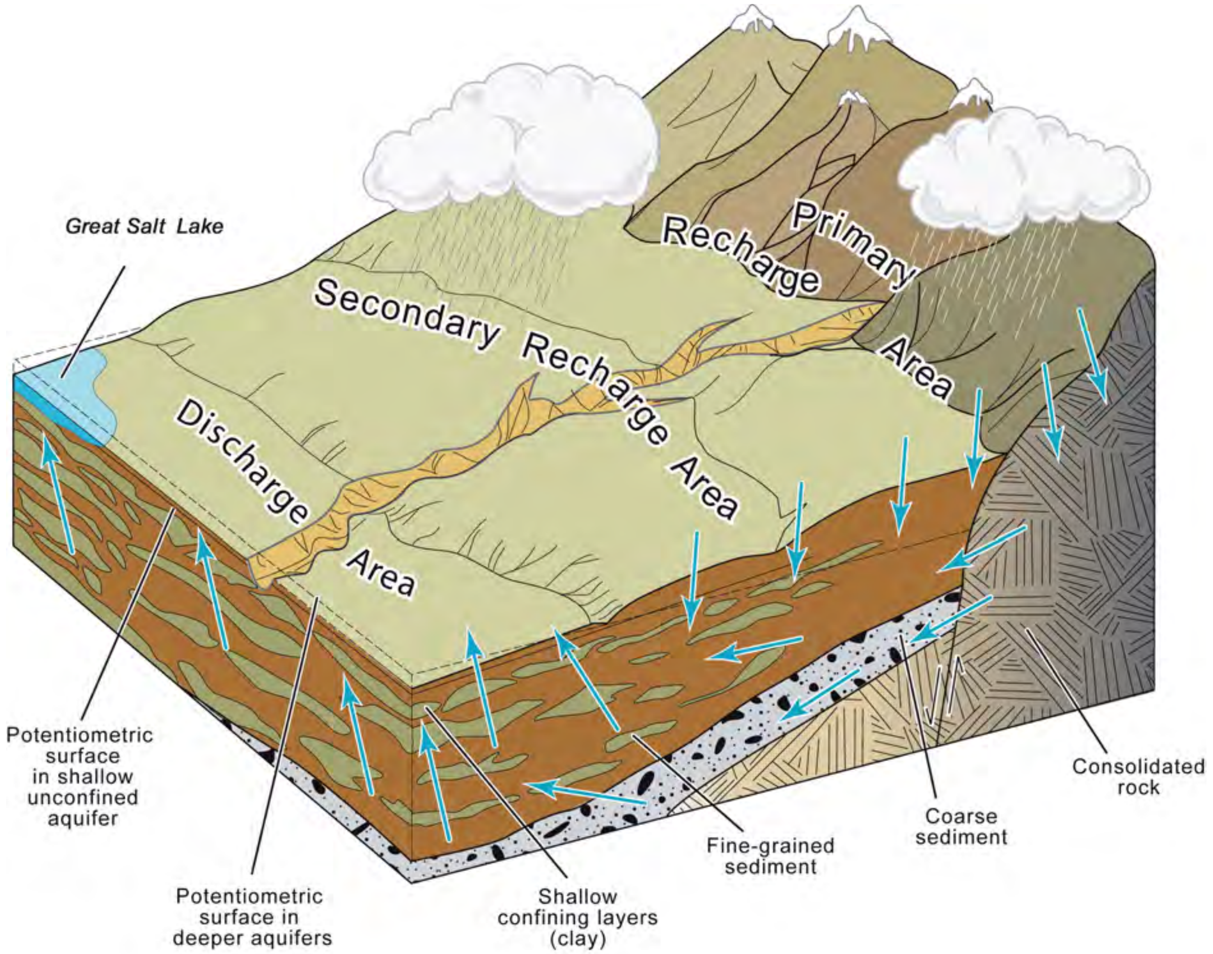

Figure 5. Generalized block diagram showing water-bearing formations, probable directions of ground-water movement (arrows), and areas of recharge and discharge, Salt Lake Valley, Salt Lake County, Utah (modified from Hely and others, 1971; Thiros and Manning, 2004).

Transmissivity and storage coefficients range from 1000 to 50,000 feet squared per day (90–5000 m^2/d) and 0.15 to less than 0.0001 for the unconfined and confined parts of the principal aquifer, respectively (Hely and others, 1971). The transmissivity of the shallow unconfined aquifer ranges from 50 to 4000 feet squared per day (5–400 m^2/d) (Waddell and others, 1987a), and the storage coefficient is estimated to average 0.15 (Hely and others, 1971). The vertical hydraulic conductivity of the confining bed between the shallow unconfined and principal aquifer is estimated to average 0.025 feet per day (0.008 m/d) (Hely and others, 1971).

Water levels in wells completed in the principal aquifer generally declined in most parts of Salt Lake Valley between 1975 and 2005 (Burden and others, 2005), with the greatest declines in the central-eastern and southern parts of the valley (figure 7). Water levels rose in wells in the northwestern and northeastern parts of the valley during the same time period.

Ground-Water Quality

The chemical composition of ground water in Salt Lake Valley varies with location and depth, primarily due to quality of recharge sources and water-rock interactions as it moves through the aquifer. Most of the recharge occurs on the east side of the valley, and ground water in the principal aquifer typically has lower total-dissolved-solids (TDS) concentrations near the mouths of the larger streams (Big Cottonwood Creek, Little Cottonwood Creek) in southeastern Salt Lake Valley (Hely and others, 1971); calcium-magnesium-bicarbonate type ground water is generally found in this part of the valley (Thiros, 1995). Both bicarbonate type ground water and sodium-chloride type ground water exist in the northwestern part of Salt Lake Valley (Thiros, 1995). Ground water in the principal aquifer with the highest TDS concentrations is generally found in the vicinity of Great Salt Lake in the northwestern part of the valley (Hely and others, 1971). Based on wells completed in the principal aquifer from 1988 to 1992, the TDS concentrations ranged from 110 mg/L on the southeast side of the valley to 48,100 mg/L on the northwest side (Thiros, 1995). Ground-water quality classification of the principal basin-fill aquifer is based on the Utah Water Quality Board's system, which is based primarily on TDS concentration (table 1). According to this system, 19% of the basin-fill area is classified as Pristine ground water, 62% is classified as Drinking Water Quality ground water, 7% is classified as Lim-

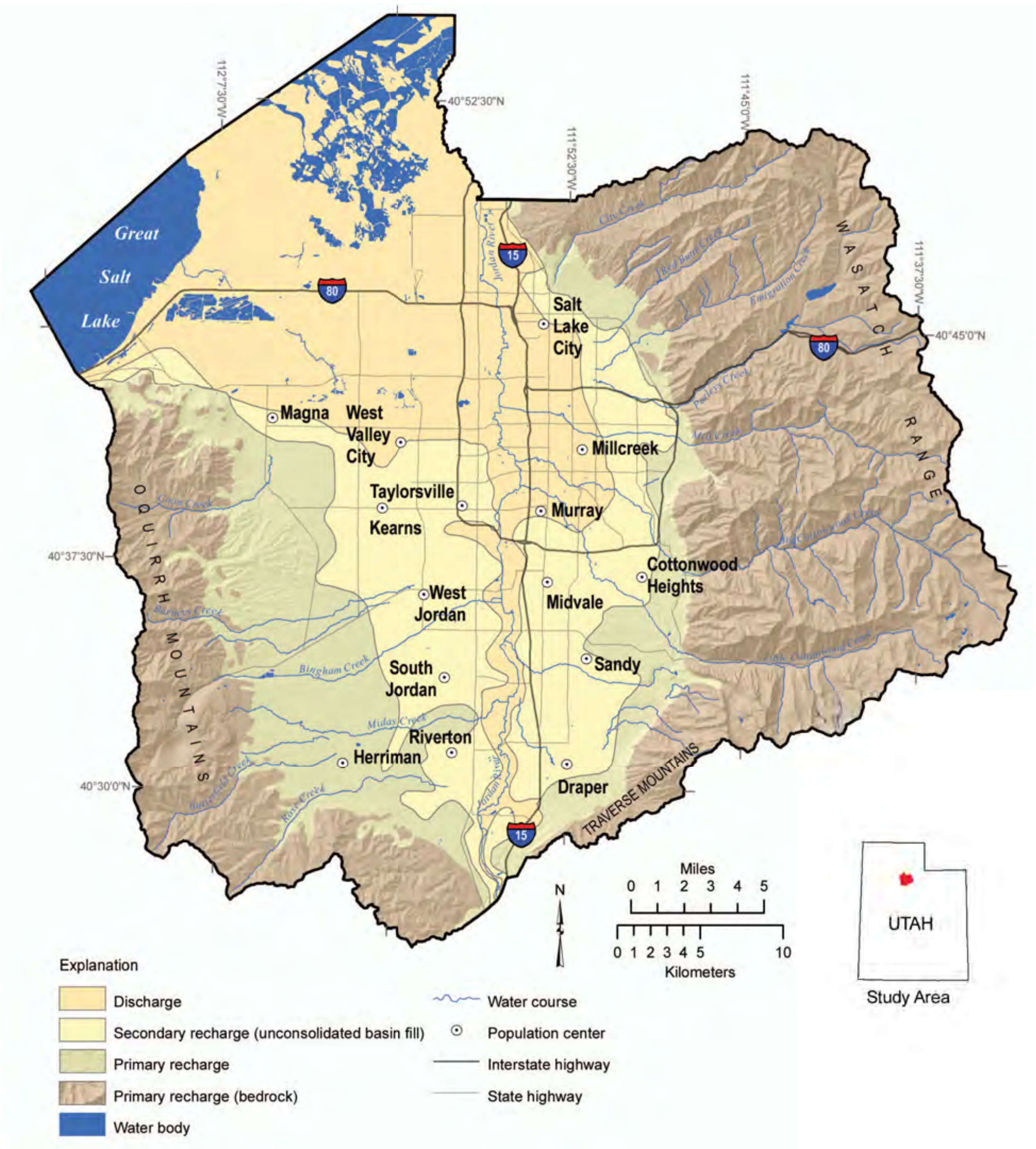

Figure 6. *Recharge and discharge areas, Salt Lake Valley (modified from Anderson and others, 1994).*

ited Use ground water, and 12% is classified as Saline ground water (Wallace and Lowe, 2009) (figure 8). Ground water in the principal aquifer generally has lower TDS concentrations than water in the shallow unconfined aquifer (Hely and others, 1971).

Total-dissolved-solids concentrations for ground water in the shallow unconfined aquifer range from 331 mg/L in the eastern portion to 20,900 mg/L for the western portion of the valley (Thiros, 1995). The proximity to land surface, evapotranspiration, dissolution of minerals, and recharge from water diverted from the Jordan River create more localized variations and higher dissolved-solids concentrations in water from the shallow unconfined aquifer (Hely and others, 1971; Thiros, 1995). Chloride concentrations have steadily increased in the principal aquifer, probably from salt used for de-icing roads (Thiros, 1995).

Ground water between the mouth of Bingham Canyon and the Jordan River has been contaminated by seepage from evaporation ponds associated with mining activities (Hely and others, 1971). The contaminated ground water is acidic

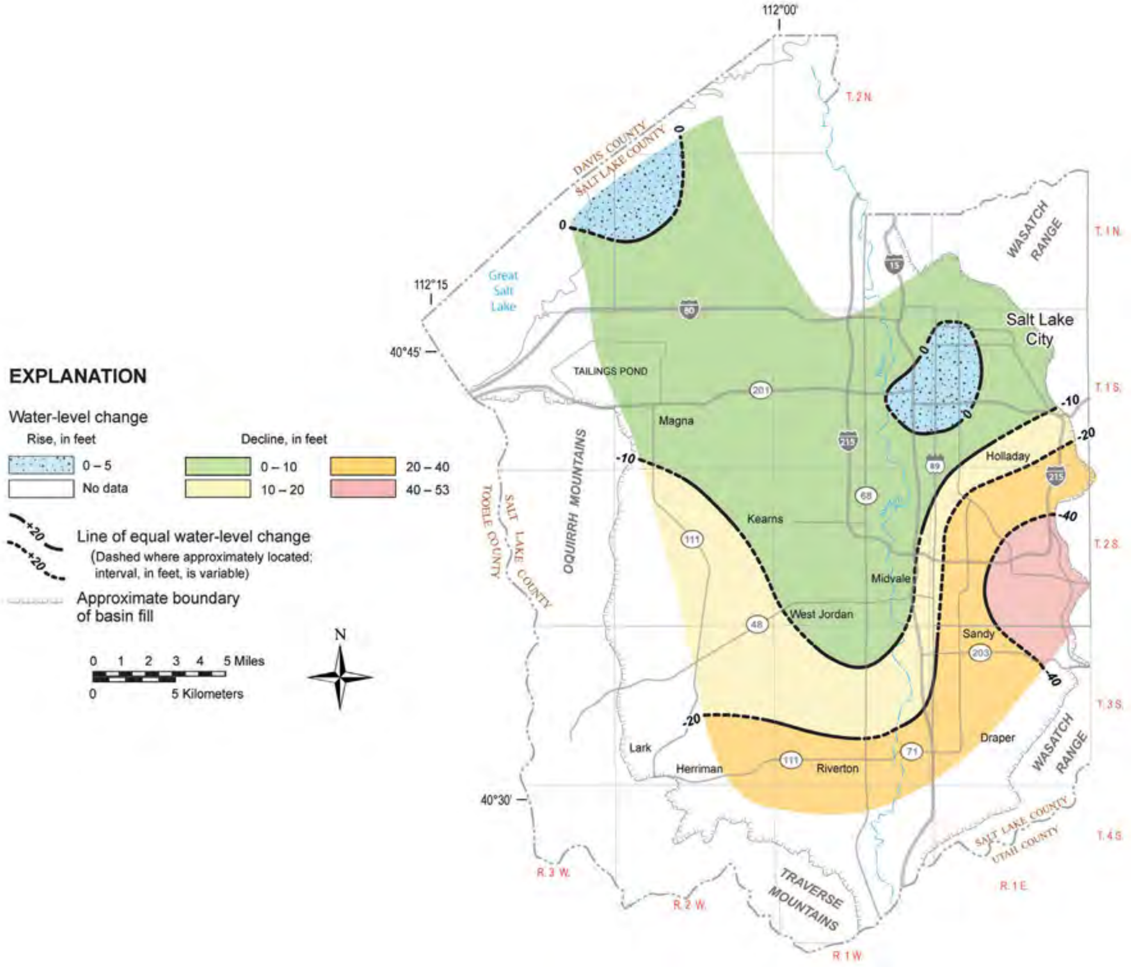

Figure 7. Change in water level in Salt Lake Valley from spring 1975 to spring 2005 (modified from Burden and others, 2005).

Table 1. *Ground-water quality classes under the Utah Water Quality Board's total-dissolved-solids- (TDS) based classification system (modified from Utah Division of Water Quality, 1998).*

Ground-Water Quality Class	TDS Concentration	Beneficial Use
Class IA[1] /IB[1] /IC[2]	less than 500 mg/L[3]	Pristine/Irreplaceable/ Ecologically Important
Class II	500 to less than 3000 mg/L	Drinking Water[4]
Class III	3000 to less than 10,000 mg/L	Limited Use[5]
Class IV	10,000 mg/L and greater	Saline[6]

[1] Irreplaceable ground water (Class IB) is a source of water for a community public drinking-water system for which no other reliable supply of comparable quality and quantity is available due to economic or institutional constraints; it is a ground-water quality class that is not based on TDS. In addition to TDS, Class IA must not exceed any ground-water quality standards.

[2] Ecologically Important ground water (Class IC) is a source of ground-water discharge important to the continued existence of wildlife habitat; it is a ground-water quality class that is not based on TDS.

[3] For concentrations less than 7000 mg/L, mg/L is about equal to parts per million (ppm).

[4] Water having TDS concentrations in the upper range of this class must generally undergo some treatment before being used as drinking water.

[5] Generally used for industrial purposes.

[6] May have economic value as brine.

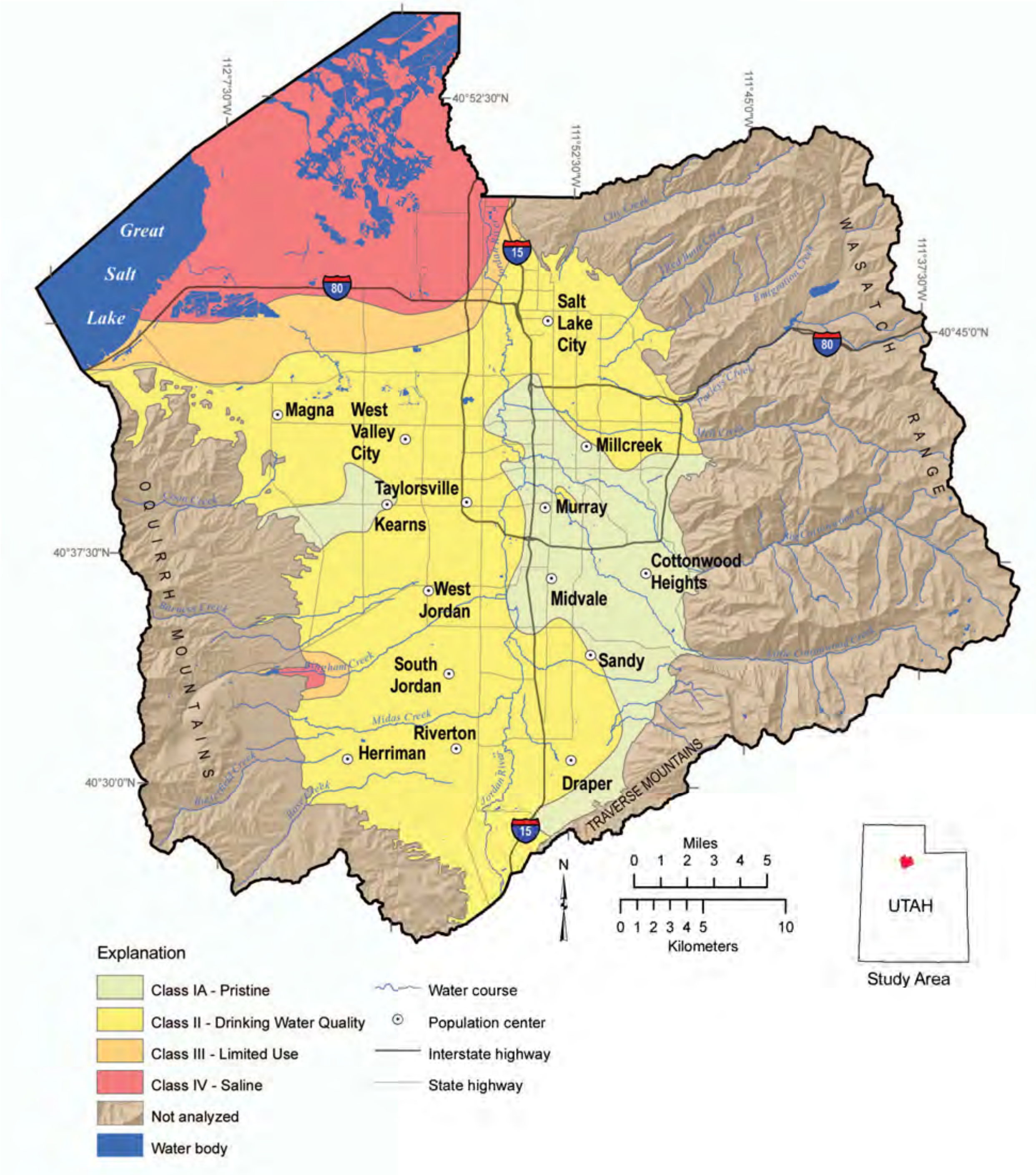

Figure 8. *Ground-water quality classes for the principal basin-fill aquifer, Salt lake Valley (from Wallace and Lowe, 2009).*

and has TDS concentrations as high as 75,000 mg/L (Waddell and others, 1987b). Ground water in the shallow unconfined and principal aquifer in the vicinity of South Salt Lake near the Jordan River has also been contaminated by leachate from uranium-mill tailings; ground water from this area has TDS concentrations as high as 21,000 mg/L, and is contaminated with chloride, sulfate, iron, and uranium (Waddell and others, 1987b). Volatile organic compounds and pesticides (primarily atrazine) are commonly found in monitoring wells completed in the shallow unconfined aquifers; most of the volatile organic compounds and all of the pesticides from shallow wells sampled in 1999 were below drinking water standards (Waddell and others, 2004).

WETLANDS

Introduction

Wetlands are one of the most important ecosystems on Earth. They perform numerous biological and hydrological functions and are a valuable resource to communities. Wetland functions include wastewater treatment or water filtration, biogeochemical cycling, floodwater control and storage, wildlife habitat, biologic productivity, and food-chain support; additionally, they have economic and cultural value (Lock, 1994) such as increased residential property values.

Wetlands are facing long-term impacts from both human-related and natural causes. Human impacts are due to agricultural, industrial, and urban development and the resulting pollution. Natural impacts are generally due to climatological changes. In the United States, an estimated 53% of wetlands in the lower 48 states have been destroyed since the 1700s due to human activities (Mitsch and Gosselink, 2000). Agricultural fields, commercial developments, and residential developments have typically replaced wetlands. Prior to the mid-1970s, U.S. domestic policies encouraged the drainage of wetlands so that the land could be developed for economic benefits. Now that the value and importance of wetlands have been recognized, conservation efforts have followed. The current goal of the U.S. government is to prevent net loss of wetlands, so when development of wetlands occurs, the amount of wetland area lost must be restored, created, or enhanced through the wetland mitigation process (U.S. Fish and Wildlife Service, 1994). For additional information about wetlands background, definitions, and functions, refer to appendix A.

Salt Lake County Wetlands

Current National Wetland Inventory data (U.S. Fish and Wildlife Service, 2010) show that 77% of wetlands in Utah are located within 3 miles (5 km) of Great Salt Lake, which corresponds to an estimated 1.1 million acres (4450 km^2) of wetlands. The Salt Lake County wetlands are mostly concentrated in the northern portion of the county along the shore of Great Salt Lake corresponding to 49,300 acres (20,000 hm^2), or 84% within 3 miles (5 km) of Great Salt Lake.

Lock (1994) estimated that 30% of Utah's wetlands has been lost, mostly due to land-development practices. Salt Lake County wetlands have been impacted by agricultural activities (including grazing), industrial and urban development, and water diversions with ditches and dikes.

Ninety-one percent of the wetlands are located in the principal aquifer ground-water discharge areas as determined by Anderson and others (1994; figure 6), where there are one or more confined aquifers with an upward vertical flow gradient at depth and an overlying shallow unconfined aquifer near the land surface. Much of the water supply for the wetlands is from the shallow unconfined aquifer. Thus, the elevation of the water table in the shallow unconfined aquifer partly determines the areal extent of the wetlands. The shallow water-table elevation can also be controlled by surface water supply to the wetlands, which varies with changes in recharge due to climatic conditions and/or ground-water withdrawals from wells and fluctuating Great Salt Lake levels.

Wetland Types

The Emergency Wetland Resources Act of 1986 directs the U.S. Fish and Wildlife Service to map the wetlands of the United States; this mapping effort is referred to as the National Wetlands Inventory (NWI). Wetlands are typically mapped using aerial photographs and are classified using the Cowardin system. The Cowardin system of wetland classification (Cowardin and others, 1979) separates wetlands into five basic categories or systems: (1) lacustrine, or lake-like, (2) riverine, or river, (3) palustrine, or pond-like, (4) estuarine, or estuary, and (5) marine, or oceanic. Once the wetlands have been mapped and classified, any changes in their status or trends can be monitored. NWI mapping for Salt Lake County shows that the wetlands are dominantly lacustrine and palustrine with some riverine wetlands (figure 9, appendix B). Lacustrine wetlands are associated with the shoreline of Great Salt Lake as well as canals, ditches, and impoundments. The palustrine wetlands are associated with springs that discharge ground water.

Salt Lake Valley wetlands occupy various types of habitats or environments. Except during periods of extreme drought, the area is largely permanently or periodically flooded lacustrine wetland or open water (20,143 acres [8152 hm^2]) of Great Salt Lake.

From 2003 to 2008 much of this area was exposed as Great Salt Lake levels remained near historic lows (figure 10). Other open-water environments are associated with sewage-treatment ponds and spring-fed ponds. The northwestern area consists of vegetated and non-vegetated mineral and wet mud flats, transitioning to wet-meadow and emergent marsh environments to the northeastern border of the study area where impoundments have been built in the Farmington Bay Waterfowl Management Area (FBWMA), private reserves, and hunting clubs.

Originally built in 1935 and occupying 3800 acres (1500 hm^2), the FBWMA has been expanded to over 12,000 acres (4900 hm^2) in Davis and Salt Lake Counties and is managed by the Utah Division of Wildlife Resources (UDWR). As many as 200 avian species have been documented using the wetlands associated with the FBWMA. The FBWMA wetlands provide critical year-round habitat for up to 57 species of waterfowl and shorebirds, as many as 200,000 individuals, nesting and foraging in the spring and summer, and are also an important stopover for millions of migrating waterfowl seasonally. The wetlands north of Interstate 80 are sourced by the Jordan River, Salt Lake City Sewer Canal, Rudy Drain, and Goggin Drain through a complex network of impoundments, canals, dikes, and various water-control structures (figure 11).

Approximately 17,000 acres (6900 hm^2) of wetlands are diked or impounded and are very precisely managed with water depths ranging from 0 to 14 inches (0–36 cm) to maximize waterfowl habitat (Utah Division of Wildlife Resources, 2006).

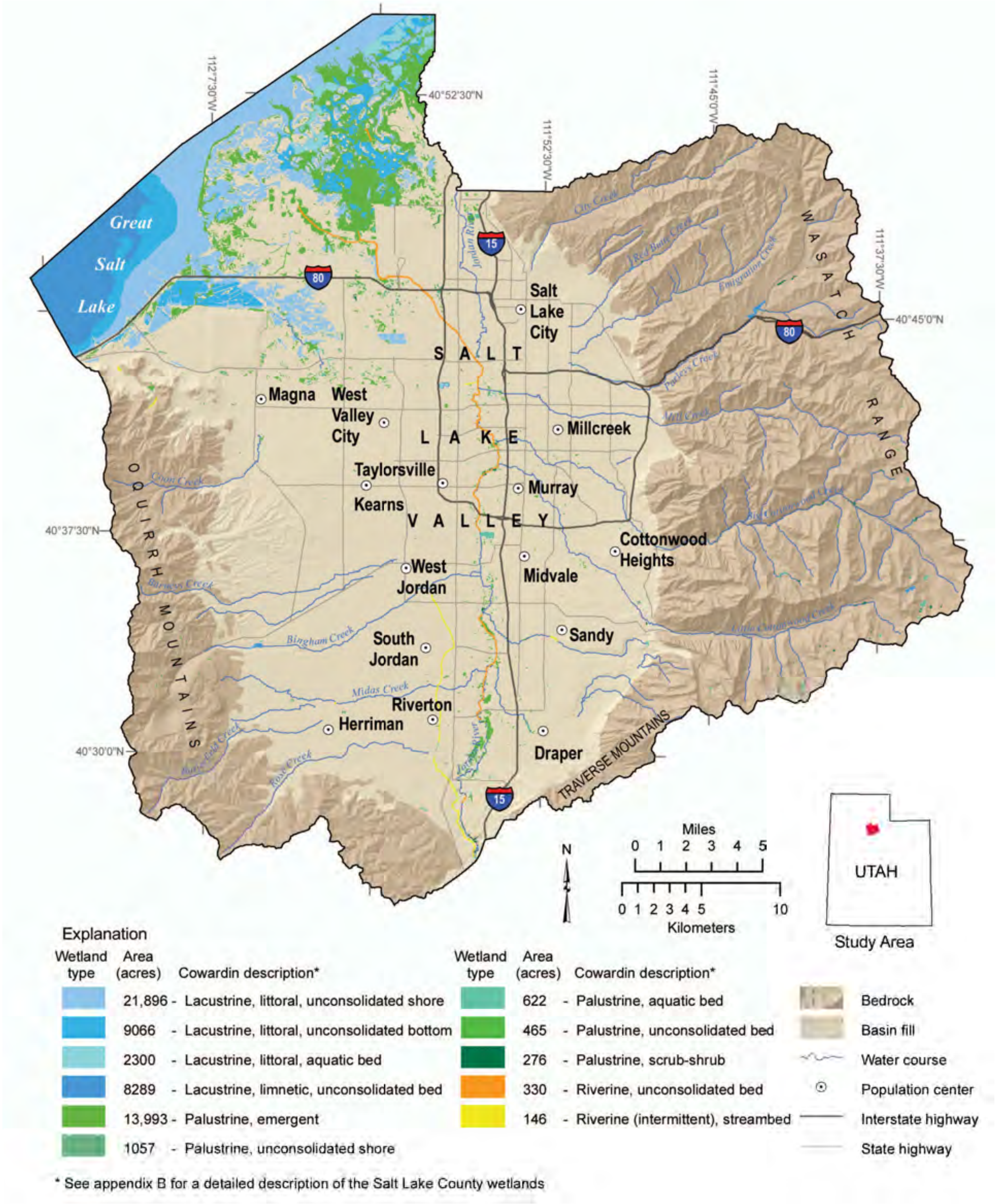

Figure 9. *National Wetlands Inventory simplified Cowardin classification in Salt Lake Valley (U.S. Fish and Wildlife Service, 2001).*

Because of this management, shallow ground-water levels in the wetlands can be difficult to monitor and often are a function of surface-water control in the FBWMA. Large areas can be filled seasonally for flood control and water storage, or drained periodically to eradicate noxious and non-native vegetation (Rich Hansen, FBWMA manager, verbal communication, 2007). Shallow ground-water levels normally would be at their highest during spring runoff from May to July. The runoff reaching Great Salt Lake in 2008 was exceptionally low due to upstream reservoirs capturing more runoff than normal, as well as below-average soil moisture which contributed to the fall of Great Salt Lake to 4294.1 feet (1308.8 m) in October 2008, just above the historical low of 4291.4 feet (1308.0 m) set in October 1963 (U.S. Geological Survey, 2009).

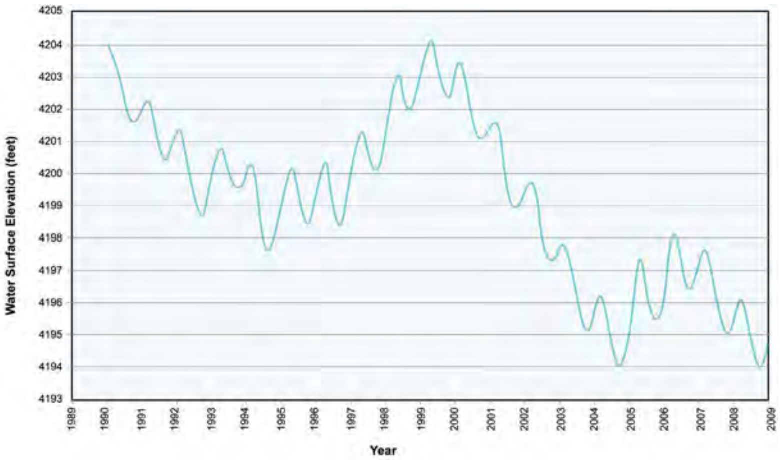

Figure 10. *Great Salt Lake monthly mean elevation, January 1990 to December 2008. Water surface elevation from U.S. Geological Survey Saltair Boat Harbor station 1001000 (U.S. Geological Survey, 2009).*

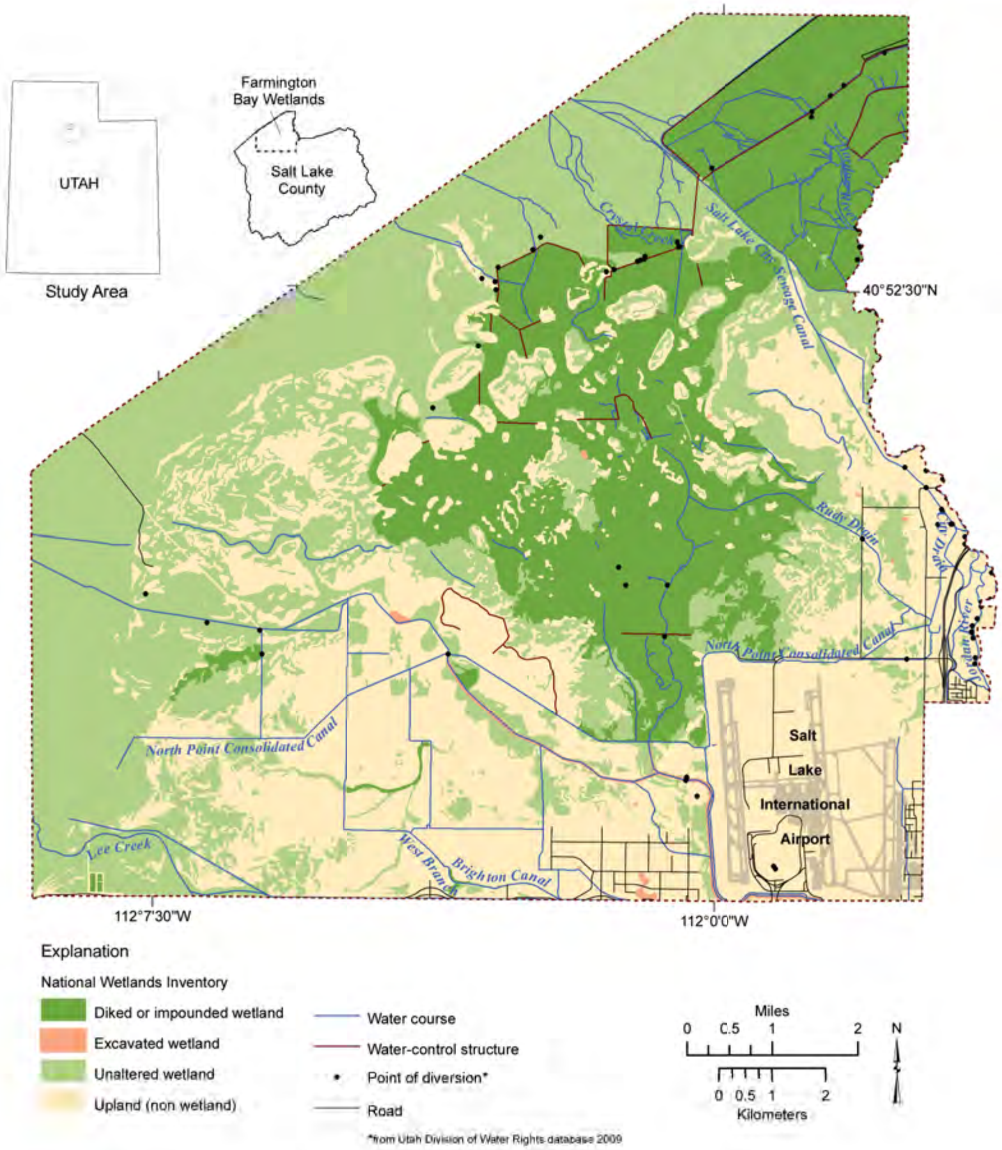

Figure 11. *Water-control and wetland classification (NWI) in Farmington Bay, northern Salt Lake Valley.*

Hydraulic Gradient and Water Quality

Based on water-level data from the 12 shallow piezometers we installed (appendix C), we found that the magnitude and direction of the hydraulic gradient were similar to those documented previously (low gradients toward Great Salt Lake), whereby ground water in the wetland areas flows north toward Great Salt Lake (appendix C, figure C1). We sampled water from two wells in the northeastern part of the study area. The shallow ground-water chemistry from wetlands in the southern Farmington Bay area is variable. At well 2 (appendix C, figure C1), the more upgradient well, water has a TDS concentration of 21,324 mg/L (Class IV). At well 8 (appendix C, figure C1), the downgradient well, water has a TDS concentration of 6786 mg/L (Class III). The classes are based on the Utah Water Quality Board's TDS-based classification system (table 1). Well 8 is likely influenced by nearby surface-water sources. However, in most cases the ground-water quality in this area likely declines northward due to the increased salt content in the soil and proximity to Great Salt Lake, where the only outlet for water is through evapotranspiration.

Most of the wetlands in Salt Lake Valley are in the area mapped by Anderson and others (1994) as a ground-water discharge area, where an upward hydraulic gradient exists between the underlying principal aquifer and the overlying shallow unconfined aquifer. Average annual evapotranspiration at the Antelope Island weather station is 49.13 inches (124.79 cm) (Ashcroft and others, 1992). Evapotranspiration of water from the shallow unconfined aquifer and the upward hydraulic gradient create a system where solutes concentrate in the shallow unconfined aquifer, increasing TDS concentration in the ground water. If solute concentrations reach high enough levels, precipitation reactions may occur.

GROUND-WATER FLOW/WETLANDS DEGRADATION ANALYSIS

Introduction

The wetlands in Salt Lake Valley are mainly concentrated along the margins of Great Salt Lake, which have been mapped as a ground-water discharge area by Anderson and others (1994). In this area, ground water discharges from the shallow unconfined aquifer by natural means, mainly as springs or seeps. The source of most of the discharging ground water is the confined principal aquifer below the wetlands. The palustrine wetlands are dependent upon springs and seeps as their source of water; any decrease in discharge from these springs and seeps would alter and possibly adversely degrade the wetlands. Additionally, the population of Salt Lake Valley is growing rapidly, and land use is becoming more residential and industrial and less agricultural. This change in land use will decrease the amount of recharge from seepage of unconsumed irrigation water (partly because many acres of permeable soil will be covered by impermeable asphalt and concrete), which is an additional contributor to the total recharge to aquifers in the Salt Lake Valley area (Hely and others, 1971; Waddell and others, 1987a; Lambert, 1995a). Public water suppliers in Salt Lake Valley rely primarily on ground water from the principal aquifer. Most of the wells in the area are upgradient of the wetland areas (figures 1 and 2); if more wells are drilled or more water is withdrawn from the principal aquifer to support the growing population, less ground water would be discharged from springs and seeps that provide water to the wetlands.

Not only are wetlands in Salt Lake Valley threatened by development, but fluctuating climatic conditions are also impacting the wetlands. Utah experienced drought during 1999–2004 (Utah Division of Water Resources, 2007), which reduced recharge to aquifers throughout the state and lowered the level of Great Salt Lake, the ultimate barometer for water abundance in northern Utah. If drought conditions persist, the level of Great Salt Lake may drop even more. Great Salt Lake is the farthest downgradient component of the hydrologic system in Salt Lake Valley. The wetlands surrounding Great Salt Lake are just upgradient of the lake, so climate-related water-level changes in Great Salt Lake also affect the wetlands.

To evaluate the hydrology of the wetlands in Salt Lake Valley, we used steady-state and transient ground-water flow models developed by Lambert (1995a). We investigated the current (steady state) and historical water use of the wetlands and developed a water budget for Salt Lake Valley. We then altered the models to investigate possible scenarios that could affect the wetlands, including (1) continued drought conditions with accompanying decreased recharge to the aquifer and lower Great Salt Lake level, (2) wet conditions resulting in increased recharge to the aquifer, and (3) increased development and ground-water withdrawals from the principal aquifer; these scenarios focused on wetlands in the vicinity of Great Salt Lake, but scenario implications likely extend to all wetlands in the valley because they are also supplied with ground water in the basin-fill aquifer system. These ground-water models are the best available tools to understand how the wetlands in Salt Lake Valley could be affected by further development and/or drought.

Overview of Models

Lambert (1995a) developed modular, three-dimensional ground-water flow models (McDonald and Harbaugh, 1988) to simulate the regional flow system in the basin-fill material in Salt Lake Valley, and calibrated the models for both steady-state and transient-state conditions. Steady-state conditions require the volume of water flowing into the system to be simulated to equal the volume of water leaving the system. The steady-state simulation was therefore developed using available data that were assumed to represent near steady-state or equilibrium conditions during which storage to the aquifer does not appreciably change. Because of relatively constant pumping and small changes in storage during the 1964–68 period (Waddell and others, 1987a), recharge was assumed to be about the same as discharge during 1968 and representative of near steady-state conditions. During 1968, withdrawals from wells were about 105,000 acre-feet (130 hm^3), 2000 acre-feet (2.5 hm^3) less than the average for the 1964–68 period (Waddell and others, 1987a). Changes in storage were less than 2000 acre-feet (2.5 hm^3) in 1968 and averaged about 3000 acre-feet (4 hm^3) during 1964–68 (Waddell and others, 1987a); both quantities represent less than 1% of the total budget for that period (Waddell and others, 1987a). Calibration of the steady-state model involved comparing the computed water levels in the model to measured water levels, and computed ground-water flow to measured ground-water flow. The simulated ground-water budget was compared with estimates of ground-water budgets for the same period to evaluate the fit of the model to measured conditions.

Lambert (1995a) developed the transient simulation using data that represent the hydrologic conditions for the 1969–91 period. Lambert (1995a) used the results of the steady-state simulation as the initial condition for the transient simulation. The transient simulation involves simulation of annual variations in recharge from surface and subsurface sources and discharge from pumping with time. During calibration, Lambert (1995a) compared model-computed water-level changes with measured water-level changes over this period.

Areally, Lambert (1995a) divided the model domain into 94 rows and 62 columns, with each model cell 0.35 mile (0.56 km) on a side. Vertically, Lambert (1995a) divided the aquifer system into seven layers. The shallow unconfined aquifer and the underlying confining layer were represented by one model layer each (model layers 1 and 2, respectively). The thicknesses of model layers 1 and 2 were variable and roughly imitated the estimated depth and thickness of the shallow unconfined aquifer and the underlying confining layer. Lambert (1995a) divided the principal aquifer into five layers (model layers 3 to 7) to represent the types of sediments in the basin fill. Model layers 3 to 5 were each 150 feet (46 m) thick; simulated saturated thickness of model layer 3 may vary during problem solution. Model layer 6 was 200 feet (60 m) thick, and model layer 7 ranged in thickness between 200 feet (60 m) and 1500 feet (460 m).

Lambert (1995a) divided the transient simulation from January 1969 to December 1991 into 23 stress periods of one year in length. During each stress period, external stresses on the simulated system, representing recharge or discharge for a given year, were held constant. Each stress period was divided into three time steps.

Model Boundary Conditions

Since a ground-water flow model requires certain mathematical and physical boundaries of a ground-water system to be specified in order to simulate flow at surface boundaries and internal sources and sinks, Lambert (1995a) described boundary conditions as follows:

1. A no-flow boundary was fixed for the contact between the consolidated rock of pre-Tertiary age and basin-fill material, or a depth within the basin-fill material below which sediments were assumed not to contribute substantially to the basin-fill ground-water flow system.
2. On the west and east sides of the modeled area, no-flow boundaries were fixed to correspond to the contact between the consolidated rock of the mountains and the basin-fill.
3. The northern border of the modeled area also approximates a flow line and was accordingly treated as a no-flow boundary.
4. The shore of Great Salt Lake in the northwestern part of the modeled area was treated as a constant-head boundary, representing the altitude of the lake surface.

Lambert (1995a) used specified-flux boundaries to simulate recharge entering the ground-water flow system as:

1. inflow from consolidated rock in areas at the margins of the valley,
2. seepage from streams and major canals,
3. infiltration of precipitation on the valley floor,
4. infiltration of unconsumed irrigation water from fields, lawns, and gardens,
5. seepage from reservoirs at the mouth of Bingham Canyon and evaporation ponds in the southwestern part of the valley, and
6. underflow at the Jordan Narrows.

Specified-flux boundaries were also used to simulate discharge from the ground-water flow system to wells, canals, and springs. The specified-flux boundary condition allows the flow rate across a given boundary to be specified as a function of location and time. Flow rates across these boundaries were specified in advance in the steady-state simulation and for each stress period of the transient simulation (Lambert, 1995a).

Head-dependent flux boundaries were used to simulate:

1. ground-water flow to and seepage from the Jordan River and the lower reaches of its principal tributaries,
2. inflow from consolidated rock at the northern end of the Oquirrh Mountains,
3. discharge from the shallow unconfined aquifer to drains, and
4. discharge by evapotranspiration.

A head-dependent flux boundary allows the flow rate across a boundary surface to change in response to changes in water levels in the aquifer adjacent to the boundary (Lambert, 1995a). The flow rate is therefore a function of the water level in the adjacent aquifer and may vary during problem solution, and from one time step to the next in the transient simulation.

A head-dependent river boundary (McDonald and Harbaugh, 1988) was used by Lambert (1995a) in the model to represent the Jordan River and the lower reaches of its major tributaries, and simulates ground-water flow to or seepage from the river depending on the simulated water-level gradient between the river and the adjacent aquifer.

Lambert (1995a) used a head-dependent drain boundary to simulate the influence of surface and buried drains on the ground-water flow system. The head-dependent drain boundary is similar to the river boundary but does not simulate flow from the drain to the aquifer. When the model-computed head in a given drain cell is lower than the bottom elevation of the drain in that cell, no flow to or from the drain occurs.

A general head boundary (McDonald and Harbaugh, 1988) was used by Lambert (1995a) to simulate inflow from consolidated rock at the northern end of the Oquirrh Mountains. The general head boundary is similar to the drain and river boundaries because flow into or out of a given boundary cell from an external source is a function of the difference between the model-computed water level in the cell and the specified water level of the external source, and the conductance between the external source and the cell. Details of the boundary conditions, initial conditions, and hydraulic properties of the different model layers can be found in Lambert (1995a).

To simulate the effects of different pumping scenarios and protracted drought on the water budgets at the Salt Lake Valley wetland areas, we modified the Lambert (1995a) model, which had been converted by the Utah Division of Water Rights to a MODFLOW 2000 format from the original MODFLOW 1988 format, to suit the purpose of this exercise. We consider the domain of the study as consisting of the seven layers as described by Lambert (1995a). We consider the top layer (layer 1; figure 12) as representing the Salt Lake Valley wetlands to evaluate the effects of the pumping scenarios and protracted drought on the wetlands. Although the top layer does not exactly match the size of the wetlands, we consider flow conditions in the top layer to represent flow conditions in the wetlands, and modeling results in the top layer the best way to determine effects of changes in recharge and pumping on the conditions of the wetlands. We selected cells in the top layer where the wetlands are located to determine the approximate water budgets of the wetlands under the various water-budget scenarios. As discussed earlier, the main source of recharge into the basin-fill aquifers is subsurface flow from the principal aquifer. Discharge from the top layer is in the form of drains and springs, canals, evapotranspiration, and drainage to Great Salt Lake.

Modeling Results

Water budget components for ground-water flow simulations for Lambert's (1995a) layer 1 under steady-state and transient conditions are summarized in table 2. The transient model simulates historical changes in the water budget's model layer 1 from 1969 to 1991. Ground-water budgets for model layer 1 in 1969 in the transient simulation are similar to those simulated by the steady-state model (table 2). Note that recharge is close to discharge under both conditions at the end of the simulations.

Because layer 1 (top layer) in the model is larger than the wetland areas, cells representing the wetland areas (figure 12) were selected to evaluate the conditions of the wetlands under the historical steady-state and transient-state conditions. Table 3 summarizes the water-budget components of the wetland areas. Under the historical steady-state conditions, the ground-water inflow to the wetlands is almost balanced by the outflow. Recharge from subsurface flow to the wetlands increased from about 26,400 acre-feet per year (33 hm^3/yr) under the steady-state conditions to about 27,800 acre-feet per year (34 hm^3/yr) after the last stress period of the historical transient simulation. Generally, under the historical transient conditions, there appears to be a surplus of about 0.6% in the ground-water budget for the Salt Lake Valley wetland areas.

Budget Scenarios

The water budget in layer 1 was evaluated under four scenarios: (1) reduced recharge due to sustained drought conditions, (2) increased discharge from wells completed in the principal aquifer, (3) increased pumping with decreasing recharge, and (4) increased recharge with the same pumping as in the last stress period of the transient model. Ten additional stress periods were added to the transient model to simulate these scenarios. For each scenario, we first discuss the results for the entire layer 1 followed by the results for the wetland areas.

Scenario 1 – Reduced Recharge

Table 4 summarizes the results of the first scenario, which can be compared to table 2. This scenario simulates a 10-year sustained drought period, during which recharge from precipitation is reduced by 10%. The results indicate that recharge from precipitation would decrease from 83,000 acre-feet per year (100 hm^3/yr) at the end of the last transient stress period to about 75,000 acre-feet per year (90 hm^3/yr) at the end of the scenario period. Recharge from irrigation fields would decrease by 10% from 23,500 acre-feet per year (30 hm^3/yr) to 21,200 acre-feet per year (26 hm^3/yr). Discharge to the Jordan River would increase slightly, and subsurface inflow, subsurface outflow, and evapotranspiration would remain about the same. A ground-water deficit will develop by about 9000 acre-feet per year (11 hm^3/yr) in model layer 1 under this scenario. The water table will fall considerably, which will put a significant strain on the wetlands.

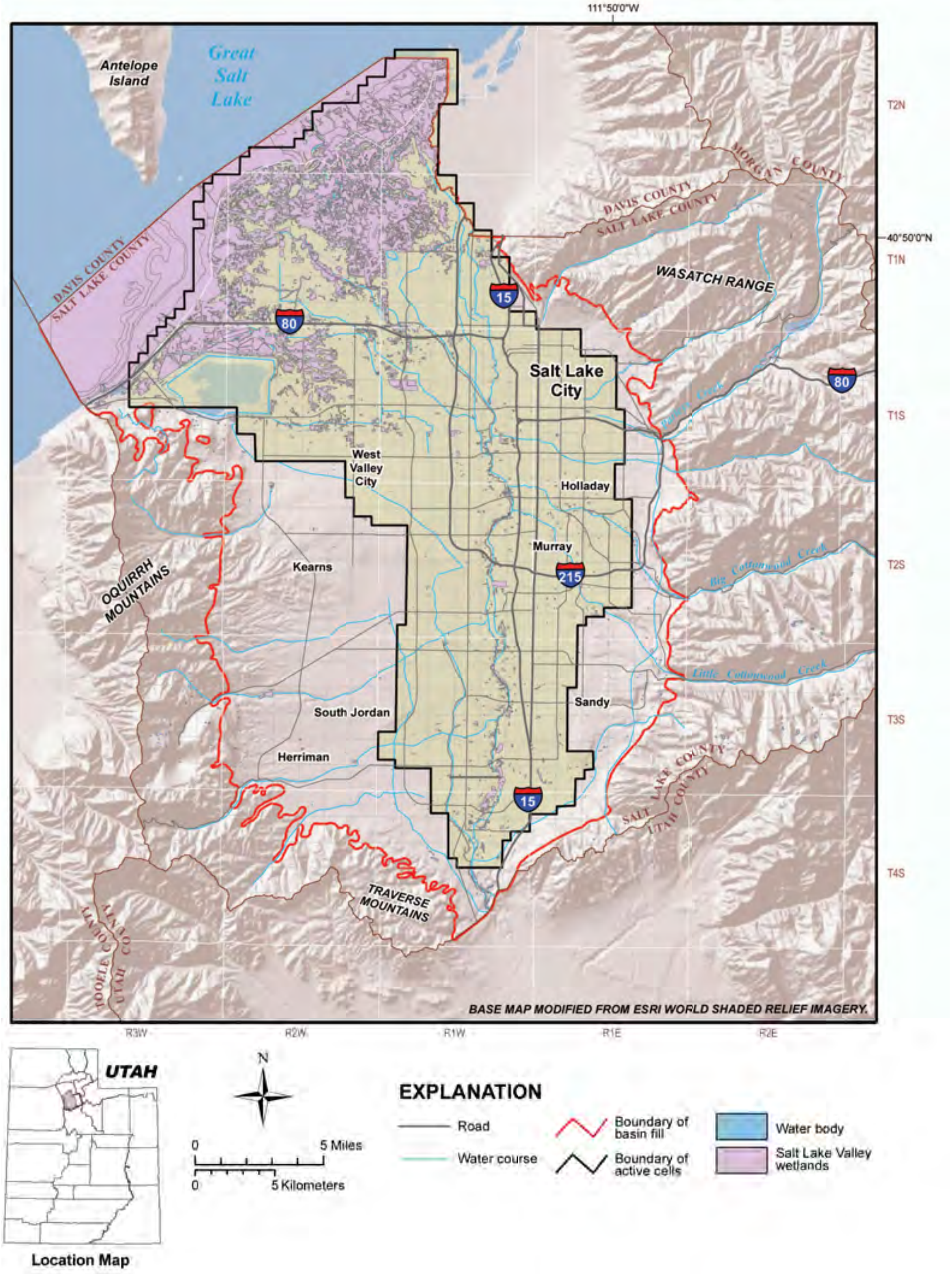

Figure 12. *Areal extent of model layer 1 in Salt Lake Valley (from Lambert, 1995a).*

With respect to the specific wetlands areas under this scenario (table 4), recharge from precipitation would decrease from 24,300 acre-feet per year (30 hm^3/yr) during the last stress period of the historical transient simulation (table 3) to 24,100 acre-feet per year (29.7 hm^3/yr). Subsurface inflow to the wetland regions would similarly decrease from 27,800 acre-feet per year (34 hm^3/yr) to 14,500 acre-feet per year (18 hm^3/yr). Total ground-water discharge from the wetlands will be higher at 39,610 acre-feet per year (49 hm^3/yr) than total ground-water inflow of 38,910 acre-feet per year (48 hm^3/yr), resulting in a deficit of 1.8% in the ground-water budget.

Scenario 2 – Increased Pumping

If recharge remains the same as the level of the last stress period of the transient model (table 2) while pumping rate is increased by 10%, a surplus of about 1600 acre-feet per year (2 hm^3/yr) will develop in model layer 1. Other budget components are as shown in table 5. Our results show that the hydrologic conditions of the wetlands will improve under a 10% increase in pumping while maintaining historical recharge levels compared to a reduction in recharge by the same margin.

Table 2. *Average annual simulated ground-water recharge and discharge for model layer 1.*

	Water-budget component	Steady-state simulations	Transient-state simulations	Change from steady state to transient
		Estimated quantity (acre-feet per year)	Estimated quantity (acre-feet per year)	%
Recharge				
	Jordan River	1300	1900	+46
	Precipitation	88,000	83,000	-6
	Subsurface inflow (from principal aquifer)	114,000	93,000	-19
	Irrigation fields	23,500	23,500	0
	Storage	-	700	-
	TOTAL	**226,800**	**202,100**	**-11**
Discharge				
	Great Salt Lake	1200	1200	0
	Springs and drains	9600	7200	-25
	Evapotranspiration	36,400	32,000	-12
	Jordan River	140,000	116,000	-17
	Subsurface outflow	36,600	37,000	+1
	Canals	6300	6300	0
	TOTAL	**230,100**	**199,700**	**-13**

Table 3. *Ground-water budget for the wetland areas under steady-state and historical transient conditions.*

	Water-budget component	Steady-state simulations	Transient-state simulations
		Estimated quantity (Acre-feet per year)	Estimated quantity (Acre-feet per year)
Recharge			
	Storage	-	290
	Jordan River	40	30
	Precipitation	23,700	24,300
	Subsurface inflow (from principal aquifer)	26,400	27,800
	TOTAL	**50,140**	**52,420**
Discharge			
	Great Salt Lake	1200	1200
	Springs and drains	3500	3800
	Evapotranspiration	27,000	27,900
	Jordan River	18,500	19,100
	Subsurface outflow	10	80
	TOTAL	**50,210**	**52,080**

Table 4. *Ground-water budget for model layer 1and wetland areas after a 10% drop in recharge for 10 stress periods.*

	Water-budget component	**Model layer 1 (Acre-feet per year)**	**Wetland areas (Acre-feet per year)**
Recharge			
	Precipitation	75,000	24,100
	Subsurface inflow (from principal aquifer)	93,000	14,500
	Irrigation fields	21,200	-
	Jordan River	1900	30
	Storage	77,700	280
	TOTAL	**268,800**	**38,910**
Discharge			
	Evapotranspiration	32,400	24,940
	Jordan River	116,200	10,150
	Springs and drains	7200	2420
	Great Salt Lake	1200	1180
	Canals	6400	-
	Subsurface outflow	36,600	650
	Out storage	77,800	270
	TOTAL	**277,800**	**39,610**

The wetland areas (table 5) would receive a total of 42,410 acre-feet per year (50 hm^3/yr) in recharge, and discharge a total of 42,420 acre-feet per year (50 hm^3/yr). A 10% increase in pumping at historical recharge rates will reduce evapotranspiration.

Scenario 3 – Increased Pumping and Decreased Recharge

A decrease in recharge by 10% with an increase in pumpage from the principal aquifer by 10% would result in a deficit of about 19,000 acre-feet per year (23 hm^3/yr) in the ground-water budget for model layer 1. Both recharge and discharge are lower than the scenario under which there is a 10% decrease in recharge but pumping remains the same (table 4), and the deficit in the ground-water budget is about doubled. The ground-water budget components under this scenario are summarized in table 6.

For the wetlands areas under this scenario (table 6), the ground-water budget is expected to be in deficit by about 1.5%. Evapotranspiration would decrease from its historical transient level of 27,900 acre-feet per year (34 hm^3/yr) to about 17,000 acre-feet per year (21 hm^3/yr). About 3500 acre-feet per year (4 hm^3/yr) of ground water would be discharged through springs and drains. This figure is lower compared to the 3800 acre-feet per year (5 hm^3/yr) discharged through springs and drains during the last stress period of the historical transient simulation. Ground-water outflow to Great Salt Lake would remain the same at 1200 acre-feet per year (1.5 hm^3/yr), while subsurface outflow would drastically fall from 80 acre-feet per year (0.1 hm^3/yr) at the end the historical transient simulation to about 10 acre-feet per year (0.01 hm^3/yr). The combined effect of increased pumping and reduced recharge would thus pose the most damaging effect on the conditions of the wetlands in the area.

Scenario 4 – Increased Recharge with Increasing Pumpage

With both pumpage and recharge increased by 10%, the ground-water budget for model layer 1 indicates a surplus of about 11,000 acre-feet per year (14 hm^3/yr) (table 7). In terms of wetlands hydrology, this is the best (most beneficial to wetlands health) of the scenarios we chose to model as part of this study. Recharge from precipitation and subsurface recharge both increase with respect to the historical and steady-state values. Model layer 1 has no pumping wells completed within it, and the principal sources of discharge are evapotranspiration, subsurface discharge, discharge through drains and

Table 5. *Ground-water budget for model layer 1 and wetland areas after a 10% increase in pumping from the principal aquifer for 10 stress periods, while maintaining historical recharge levels.*

	Water-budget component	Model layer 1 (Acre-feet per year)	Wetland areas (Acre-feet per year)
Recharge			
	Precipitation	83,000	24,290
	Subsurface inflow (from principal aquifer)	87,600	17,800
	Irrigation fields	23,500	-
	Jordan River	2000	30
	Storage	640	290
	TOTAL	**196,940**	**42,410**
Discharge			
	Evapotranspiration	31,700	17,910
	Jordan River	109,900	19,110
	Springs and drains	7000	3820
	Great Salt Lake	1100	1190
	Canals	7000	-
	Subsurface outflow	38,000	80
	Out storage	630	310
	TOTAL	**195,330**	**42,420**

Table 6. *Ground-water budget for model layer 1 and wetland areas after a 10% decrease in recharge and a 10% increase in pumping.*

	Water-budget component	Model layer 1 (Acre-feet per year)	Wetland areas (Acre-feet per year)
Recharge			
	Precipitation	75,000	24,100
	Subsurface inflow (from principal aquifer)	83,000	14,500
	Irrigation fields	21,200	-
	Jordan River	1900	30
	Storage	640	280
	TOTAL	**181,740**	**38,910**
Discharge			
	Evapotranspiration	32,000	17,000
	Jordan River	116,000	17,500
	Springs and drains	7200	3500
	Great Salt Lake	1100	1200
	Canals	7000	-
	Subsurface outflow	36,600	10
	Out storage	630	300
	TOTAL	**200,530**	**39,510**

Table 7. Ground-water budget for model layer 1 and wetland areas after a 10% increase in recharge and pumping.

	Water-budget component	Model layer 1 (Acre-feet per year)	Wetland areas (Acre-feet per year)
Recharge			
	Precipitation	91,000	27,000
	Subsurface inflow (from principal aquifer)	93,000	6200
	Irrigation fields	26,000	-
	Jordan River	1900	30
	Storage	600	280
	TOTAL	**212,500**	**33,500**
Discharge			
	Evapotranspiration	32,000	24,000
	Jordan River	116,000	630
	Springs and drains	7200	2400
	Great Salt Lake	1200	1200
	Canals	7000	-
	Subsurface outflow	37,000	460
	Out storage	700	250
	TOTAL	**201,100**	**28,940**

springs, discharge to Great Salt Lake, and discharge through canals.

If recharge increases by 10% while pumpage increases by the same margin, the wetland areas (table 7) would receive about 4,560 acre-feet per year (6 hm^3/yr) more recharge than discharge. Obviously, this would be beneficial for maintaining Salt Lake Valley wetlands.

Conclusions from Water-Budget Modeling

The wetlands in Salt Lake Valley are downgradient of most of the water users in the basin, so wetland health and functionality depend on upgradient activity.

Determining the worst-case scenario for wetland degradation is difficult due to ground-water-model limitations (such as simplified ground-water recharge mechanisms) and the complexity of the ground-water flow system in Salt Lake Valley. As with all models, the ground-water flow models of Salt Lake Valley are based on a conceptual model of the basin that in turn depends on (1) how well we understand the processes operating in the aquifer, (2) how well we know and represent the geometry of the system, and (3) how accurate our underlying assumptions are in relation to development of the model. We believe Lambert (1995a) had a good understanding of aquifer processes and system geometry and made relatively accurate assumptions in relation to the development of his models, but recognize the limitations of ground-water modeling. Models can predict an outcome that may not actually occur within the real-world ground-water system. However, the models offer the best tools we have for evaluating the complexity of ground-water flow. The modeled results are meant to generate possible outcomes for the proposed scenarios, which, most importantly, will help guide land-use planning and development decisions.

Maintaining hydrologic conditions at their historical levels is extremely important for the maintenance of the Salt Lake Valley wetlands. The water-budget analysis we conducted quantifies the amount of water flowing into and out of the Salt Lake Valley wetlands area, at least according to the ground-water flow models. Our modeling results suggest that recharge as subsurface inflow to wetland areas would decrease more by continuing drought than by increased pumping (at least at the decreased recharge and increased pumping levels used in our scenarios), especially in light of the lowering Great Salt Lake levels that could occur during such a drought. The model suggests that a change to wetter-than-normal conditions would increase recharge as subsurface inflow to the wetland areas, causing an increase in spring and seep discharge and evapotranspiration; this represents the most beneficial scenario for the wetlands. Increased water withdrawals from wells in Salt Lake Valley causes a reduction in recharge to the wetland areas, but most of the change is accounted for by reduced subsurface outflow from the wetlands area. Development in Salt Lake Valley does have some effect on recharge to the wetland areas, as shown by the reduced recharge from steady-state conditions at the end of the transient simulation. The worst-case scenario for the wetlands would be a combination of long-term drought and increased ground-water pumpage. Considering the pressure for more development and the likelihood of periodic drought, this combined scenario seems plausible. If this combined scenario occurs, the loss of recharge to the Salt Lake Valley wetland areas would most likely result in a decrease in wetland functionality; some parts of the wetlands would dry up and upland plants would replace wetland plants, or the land would become so dry and saline that only halophilic plants would be able to survive. The other possibility under the combined increased pumpage and drought scenario would be that the wetlands function for only a short time during the spring when water is abundant enough to produce ponds and marshes; later in the year the wetlands would dry up, leaving little to no water for plants or animals in the wetland community.

CONCLUSIONS AND RECOMMENDATIONS

The federal government has a "no net loss" policy for wetlands, but the local community is responsible for identifying the threats posed to local wetlands, and developing a plan for preserving and managing the wetlands. To meet this federal policy, the Salt Lake Valley wetlands area should be managed to maintain the current water budget, estimated to include 52,420 acre-feet per year (65 hm^3/yr) of recharge from all sources, of which 27,800 acre-feet per year (34 hm^3/yr) is subsurface inflow. To reduce the potential for degradation to the Salt Lake Valley wetlands, restrictions could be placed on the areas of potential development, such as allowing development only in upland environments or placing a non-development buffer zone around the wetland areas. Overall, agricultural land use is more beneficial to wetland health and functionality than industrial and urban land use, because of the prospect of recharge from irrigation and other agricultural return flow. If local governments intend to allow continued development in these areas, allowing land uses that have minimal impacts to wetlands, such as rotational grazing on irrigated pastures, low-density rural developments, and single-family residential developments with a half acre of native vegetation between houses, would be the best approach for preserving the Salt Lake Valley wetlands. Treated wastewater from municipal sewers, where possible, could be reused or discharged to the environment upgradient of the wetlands, preserving this water for wetland use. Implementation of water-conservation practices would also be beneficial for wetland environments. This would help ensure that the wetlands receive the water they need to maintain their functionality.

Our study indicates the wetlands in Salt Lake Valley may be stressed in the future. The potential causes of this stress are drought and increased development due to population growth, which could dramatically reduce the amount of water the wetlands receive. We cannot predict changes in climate with certainty, but we can plan appropriately for future development.

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APPENDICES

APPENDIX A

WETLANDS BACKGROUND, DEFINITIONS, AND FUNCTIONS

WETLANDS BACKGROUND, DEFINITIONS, AND FUNCTIONS

The material in this appendix is from Burk and others (2005). Wetland scientists have had a tremendous amount of difficulty defining a wetland because wetlands can be very different from place to place. Due to this variability, scientists have made numerous attempts at deriving an all-encompassing definition of a wetland. Wetlands are generally defined as transitional lands between terrestrial and aquatic ecosystems. Three criteria are used to define a wetland: hydrology, soil, and vegetation. To be classified as a wetland, an area must have specific characteristics related to one or more of these criteria.

The two interest groups that require a definition for wetlands are wetland scientists and wetland managers and regulators. Wetland scientists are interested in a definition that facilitates classification, inventory, and research of wetlands, whereas wetland managers are interested in the laws and regulations surrounding wetlands. The most widely accepted scientific definition, developed by the U.S. Fish and Wildlife Service as part of the National Wetlands Inventory, states: "Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water… Wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year" (Cowardin and others, 1979).

The two entities that deal with the laws and regulations on wetlands are the U.S. Environmental Protection Agency (EPA) and the U.S. Army Corps of Engineers, which define wetlands as "those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas" (U.S. Army Corps of Engineers, 1987, p. 9). The U.S. Army Corps of Engineers oversees the regulatory aspect of wetlands, specifically in relation to the Clean Water Act, so they are the agency in charge of enforcing the "no net loss" policy of the federal government.

The presence of water at or near the surface in a wetland is obvious, but water need not be there all the time in a wetland. Many wetlands are "wet" only during certain periods of the year. The presence of water is nonetheless a critical part of a wetland, and influences the soil and vegetation in a wetland. The type of soil in a wetland is termed hydric. "A hydric soil is a soil that is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions that favor the growth and regeneration of hydrophytic vegetation" (Mitsch and Gosselink, 2000, p. 756). The term hydrophytic vegetation or hydrophyte refers to "water loving" plants, which are able to survive with little or no oxygen, and can withstand fluctuating water levels. Two types of hydrophytes exist: aquatic and emergent. Aquatic plants, such as the water lily, actually live in the water. Emergent plants have roots that grow in soil that is saturated with water, while the rest of the plant may be exposed to the atmosphere. Emergent plants include cattails, reeds, and sedges. The soil and vegetation in a wetland are very dependent upon water for their development and growth, illustrating that water is the master variable when it comes to wetlands.

One of the most important functions of wetlands is their ability to improve water quality. This occurs by filtration of water as it flows through a wetland. Water that enters a wetland may be laden with pollutants, which can settle out of the water column during transport. Toxic substances can be buried and trapped in bottom sediments. Plants and microorganisms can absorb and consume the toxic substances and return them to the environment in benign forms. Many wastewater treatment plants use constructed or modified wetlands to treat water before returning it to the environment.

Another benefit of wetlands is their ability to control flooding and act as storage reservoirs. When floodwater encounters a wetland, the force and velocity of the water is dissipated, so downstream damage is typically reduced. Additionally, as wetlands capture floodwater, the water is stored in the wetlands and released slowly during the following months. This stored water can recharge ground-water aquifers, which is very important for drought-stricken areas.

Wetlands are also important habitat areas. They have high biodiversity and productivity that is comparable to rain forests and coral reefs (U.S. EPA, 2003). Wetlands are important to many plant and animal species; about 45 percent of the species listed as threatened or endangered under the Endangered Species Act use wetland habitat (National Wildlife Federation, 1989). Wetlands offer habitat for plants, insects, fish, amphibians, reptiles, mammals, and birds, creating a self-sustaining food web. Animals use wetlands as a source for food, as nesting grounds, and as nurseries.

APPENDIX B

COWARDIN WETLANDS CLASSIFICATION

Table B1. *Cowardin classification scheme for Salt Lake County wetlands.*

For a complete description of the Cowardin wetland classification system see the USGS wetland website http://wetlandsfws.er.usgs.gov/NWI/webatx/atx.html

	Area			
Code	**Acres**	**Hectares**		**Cowardin description**
L2USA	13944.4	5643.1	23.9%	Lacustrine, Littoral - Unconsolidated shore - Temporarily flooded
L1UBH	8130.4	3290.3	13.9%	Lacustrine, Limnetic - Unconsolidated bed - Permanently flooded
L2USC	5692.5	2303.7	9.7%	Lacustrine, Littoral - Unconsolidated shore - Seasonally flooded
PEM/USA	5413.8	2190.9	9.3%	Palustrine - Emergent/Unconsolidated shore - Temporarily flooded
PEMFH	4727.7	1913.2	8.1%	Palustrine - Emergent - Semi-permanently flooded/Permanently flooded
L2UBFH	2420.7	979.6	4.1%	Lacustrine, Littoral - Unconsolidated bed - Semi-permanently flooded/Permanently flooded
L2UBGH	2420.4	979.5	4.1%	Lacustrine, Littoral - Unconsolidated bed - Intermittently exposed/Permanently flooded
L2UBG	2055.7	831.9	3.5%	Lacustrine, Littoral - Unconsolidated bed - Intermittently exposed
L2USAH	1806.4	731.0	3.1%	Lacustrine, Littoral - Unconsolidated shore - Temporarily flooded/Permanently flooded
L2ABGH	1559.6	631.2	2.7%	Lacustrine, Littoral - Aquatic bed - Intermittently exposed/Permanently flooded
PEMC	1411.1	571.0	2.4%	Palustrine - Emergent - Seasonally flooded
L2UBH	1318.3	533.5	2.3%	Lacustrine, Littoral - Unconsolidated bed - Permanently flooded
PEMF	1176.3	476.0	2.0%	Palustrine - Emergent - Semi-permanently flooded
L2AB/UBGH	688.3	278.5	1.2%	Lacustrine, Littoral - Aquatic bed/Unconsolidated bottom - Intermittently exposed/Permanently flooded
PUSA	606.5	245.5	1.0%	Palustrine - Unconsolidated shore - Temporarily flooded
L2UBF	554.2	224.3	0.95%	Lacustrine, Littoral - Unconsolidated bed - Semi-permanently flooded
PEMA	371.4	150.3	0.64%	Palustrine - Emergent - Temporarily flooded
PEM/USAH	350.1	141.7	0.60%	Palustrine - Emergent/Unconsolidated shore - Temporarily flooded/Permanently flooded
L2USCH	219.5	88.8	0.38%	Lacustrine, Littoral - Unconsolidated shore - Seasonally flooded/Permanently flooded
L2UB/ABGH	211.7	85.7	0.36%	Lacustrine, Littoral - Unconsolidated bed/Aquatic bed - Intermittently exposed/Permanently flooded
L2USAh	208.7	84.5	0.36%	Lacustrine, Littoral - Unconsolidated shore - Temporarily flooded - Diked or impounded
R2UBH	183.6	74.3	0.31%	Riverine - Unconsolidated bed - Permanently flooded
PUSAH	182.5	73.9	0.31%	Palustrine - Unconsolidated shore - Temporarily flooded/Permanently flooded
PEM/UBFH	180.4	73.0	0.31%	Palustrine - Emergent/Unconsolidated bottom - Semi-permanently flooded/Permanently flooded
PABFx	155.3	62.8	0.27%	Palustrine - Aquatic bed - Semi-permanently flooded - Excavated
PUBFx	138.8	56.2	0.24%	Palustrine - Unconsolidated bed - Semi-permanently flooded - Excavated
PSS/EMC	138.8	56.2	0.24%	Palustrine - Scrub-shrub/Emergent - Seasonally flooded
R2UBHx	134.6	54.5	0.23%	Riverine - Unconsolidated bed - Permanently flooded - Excavated
L1UBGh	128.7	52.1	0.22%	Lacustrine, Limnetic - Unconsolidated bed - Intermittently exposed - Diked or impounded
R4SBFx	128.3	51.9	0.22%	Riverine - Streambed - Semi-permanently flooded - Excavated
PUBFH	124.3	50.3	0.21%	Palustrine - Unconsolidated bed - Semi-permanently flooded/Permanently flooded
PABGx	120.7	48.8	0.21%	Palustrine - Aquatic bed - Intermittently exposed - Excavated
PEMAH	119.2	48.2	0.20%	Palustrine - Emergent - Temporarily flooded/Permanently flooded
PEMCH	104.9	42.5	0.18%	Palustrine - Emergent - Seasonally flooded/Permanently flooded
PABGh	92.1	37.3	0.16%	Palustrine - Aquatic bed - Intermittently exposed - Diked or impounded
PABG	88.5	35.8	0.15%	Palustrine - Aquatic bed - Intermittently exposed
L2UBFx	85.1	34.4	0.15%	Lacustrine, Littoral - Unconsolidated bed - Semi-permanently flooded - Excavated
PUBGH	84.6	34.2	0.14%	Palustrine - Unconsolidated bed - Intermittently exposed/Permanently flooded
PSSC	81.3	32.9	0.14%	Palustrine - Scrub-shrub - Seasonally flooded
PUB/EMFH	68.3	27.7	0.12%	Palustrine - Unconsolidated bed/Emergent - Semi-permanently flooded/Permanently flooded
PUS/EMA	65.0	26.3	0.11%	Palustrine - Unconsolidated shore/Emergent - Temporarily flooded
PUSCx	56.1	22.7	<0.10%	Palustrine - Unconsolidated shore - Seasonally flooded - Excavated
PABFh	49.6	20.1	<0.10%	Palustrine - Aquatic bed - Semi-permanently flooded - Diked or impounded
PUSCH	45.4	18.4	<0.10%	Palustrine - Unconsolidated shore - Seasonally flooded/Permanently flooded
L2ABGh	33.0	13.4	<0.10%	Lacustrine, Littoral - Aquatic bed - Intermittently exposed - Diked or impounded
PUSCh	32.5	13.2	<0.10%	Palustrine - Unconsolidated shore - Seasonally flooded - Diked or impounded
PUSAx	30.0	12.2	<0.10%	Palustrine - Unconsolidated shore - Temporarily flooded - Excavated
L1ABGh	30.0	12.2	<0.10%	Lacustrine, Limnetic - Aquatic bed - Intermittently exposed - Diked or impounded
PAB/UBGH	24.5	9.9	<0.10%	Palustrine - Aquatic bed/Unconsolidated bottom - Intermittently exposed/Permanently flooded
PABGH	23.9	9.7	<0.10%	Palustrine - Aquatic bed - Intermittently exposed/Permanently flooded
PEM/UBFx	23.9	9.7	<0.10%	Palustrine - Emergent/Unconsolidated bottom - Semi-permanently flooded - Excavated
PUBGx	22.6	9.1	<0.10%	Palustrine - Unconsolidated bed - Intermittently exposed - Excavated
PEMCx	21.7	8.8	<0.10%	Palustrine - Emergent - Seasonally flooded - Excavated
PUBF	19.7	8.0	<0.10%	Palustrine - Unconsolidated bed - Semi-permanently flooded
L2ABFh	18.7	7.6	<0.10%	Lacustrine, Littoral - Aquatic bed - Semi-permanently flooded - Diked or impounded
PUSAh	18.7	7.6	<0.10%	Palustrine - Unconsolidated shore - Temporarily flooded - Diked or impounded
PEMCh	18.6	7.5	<0.10%	Palustrine - Emergent - Seasonally flooded - Diked or impounded
PSS/FOC	17.9	7.2	<0.10%	Palustrine - Scrub-shrub/Forest - Seasonally flooded
R4SBC	17.1	6.9	<0.10%	Riverine - Streambed - Seasonally flooded
PAB/EMFh	15.9	6.4	<0.10%	Palustrine - Aquatic bed/Emergent - Semi-permanently flooded - Diked/impounded
PEM/UBF	14.1	5.7	<0.10%	Palustrine - Emergent/Unconsolidated bottom - Semi-permanently flooded
PABF	13.9	5.6	<0.10%	Palustrine - Aquatic bed - Semi-permanently flooded
L2USCh	12.9	5.2	<0.10%	Lacustrine, Littoral - Unconsolidated shore - Seasonally flooded - Diked or impounded
PEMB	12.2	5.0	<0.10%	Palustrine - Emergent - Saturated
PFOA	11.8	4.8	<0.10%	Palustrine - Forest - Temporarily flooded
PAB/EMF	11.7	4.7	<0.10%	Palustrine - Aquatic bed/Emergent - Semi-permanently flooded
L2USAx	11.3	4.6	<0.10%	Lacustrine, Littoral - Unconsolidated shore - Temporarily flooded - Excavated
PSS/EMA	11.2	4.5	<0.10%	Palustrine - Scrub-shrub/Emergent - Temporarily flooded
PUSC	11.2	4.5	<0.10%	Palustrine - Unconsolidated shore - Seasonally flooded
PEM/SSA	10.4	4.2	<0.10%	Palustrine - Emergent/Scrub-shrub - Temporarily flooded
PEM/SSC	9.9	4.0	<0.10%	Palustrine - Emergent/Scrub-shrub - Seasonally flooded

Table B1. *continued*

	Area			
Code	**Acres**	**Hectares**		**Cowardin description**
PFO1A	9.9	4.0	<0.10%	Palustrine - Forest - Broad-leaved deciduous - Temporarily flooded
PSS1/EMA	9.6	3.9	<0.10%	Palustrine - Scrub-shrub, broad-leaved deciduous/Emergent - Temporarily flooded
PEMFx	8.8	3.6	<0.10%	Palustrine - Emergent - Semi-permanently flooded - Excavated
PUS/EMC	8.6	3.5	<0.10%	Palustrine - Unconsolidated shore/Emergent - Seasonally flooded
PSSA	8.0	3.2	<0.10%	Palustrine - Scrub-shrub - Temporarily flooded
R2UBG	7.5	3.0	<0.10%	Riverine - Unconsolidated bed - Intermittently exposed
PAB/EMFx	6.6	2.7	<0.10%	Palustrine - Aquatic bed/Emergent - Semi-permanently flooded - Excavated
PFO/SSA	6.6	2.7	<0.10%	Palustrine - Forest/Scrub-shrub - Temporarily flooded
PUBG	6.1	2.5	<0.10%	Palustrine - Unconsolidated bed - Intermittently exposed
PSS/EMCh	4.7	1.9	<0.10%	Palustrine - Scrub-shrub/Emergent - Seasonally flooded - Diked/impounded
PEMAX	4.2	1.7	<0.10%	Palustrine - Emergent - Temporarily flooded
PEMFh	3.7	1.5	<0.10%	Palustrine - Emergent - Semi-permanently flooded - Diked or impounded
PEM/USC	3.6	1.4	<0.10%	Palustrine - Emergent/Unconsolidated shore - Seasonally flooded
R2UBh	3.3	1.4	<0.10%	Riverine - Unconsolidated bed - Diked or impounded
PSS/USC	2.7	1.1	<0.10%	Palustrine - Scrub-shrub/Unconsolidated shore - Seasonally flooded
PSSCx	2.1	0.9	<0.10%	Palustrine - Scrub-shrub - Seasonally flooded - Excavated
PEM/USAh	1.5	0.6	<0.10%	Palustrine - Emergent/Unconsolidated shore - Temporarily flooded - Diked/impounded
PEMAh	1.4	0.6	<0.10%	Palustrine - Emergent - Temporarily flooded - Diked or impounded
PEM/SSCh	1.4	0.5	<0.10%	Palustrine - Emergent/Scrub-shrub - Seasonally flooded - Diked/impounded
PEM/SSCx	1.2	0.5	<0.10%	Palustrine - Emergent/Scrub-shrub - Seasonally flooded - Excavated
R4SBA	1.1	0.4	<0.10%	Riverine - Streambed - Temporarily flooded
PEM/SSF	1.0	0.4	<0.10%	Palustrine - Emergent/Scrub-shrub - Semi-permanently flooded
PABHx	0.8	0.3	<0.10%	Palustrine - Aquatic bed - Permanently flooded - Excavated
PEM/ABFx	0.6	0.3	<0.10%	Palustrine - Emergent/Aquatic bed - Semi-permanently flooded - Excavated
PUBFh	0.6	0.2	<0.10%	Palustrine - Unconsolidated bed - Semi-permanently flooded - Diked or impounded
R2USA	0.5	0.2	<0.10%	Riverine - Unconsolidated shore - Temporarily flooded
RUSCx	0.4	0.2	<0.10%	Riverine - Unconsolidated shore - Seasonally flooded - Excavated
total	58449	23654		

APPENDIX C
WATER-QUALITY DATA

Table C1. *Water-quality data.*

Site ID*	Location	Well Depth (feet)	Ground-water Elevation (ft above sea level)	Sample Date	Nitrogen NO2 + NO3 dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Field Temperature, (°C)	Field, Specific Conductance (µS/cm)	Lab, Specific Conductance (µmhos)	pH, lab	pH, field	Aluminum, dissolved (µg/L)
1	Rudy Gun Club	4	4210.7	5/20/2008	-	-	-	-	-	-	-	-
2	Salt Lake International Airport	5	4213.8	5/20/2008	<0.1	21,324	20.4	32.5	>12,000	8.66	9.27	296.0
3	Salt Lake International Airport	6	4214.7	5/20/2008	-	-	-	-	-	-	-	-
4	Rudy Gun Club	6	4212.0	5/20/2008	-	-	-	-	-	-	-	-
5	Rudy Gun Club	6	4212.2	5/20/2008	-	-	-	-	-	-	-	-
6	Salt Lake International Airport	7	4218.1	5/20/2008	-	-	-	-	-	-	-	-
7	Farmington Bay WMA[+]	7	4209.4	5/20/2008	-	-	-	-	-	-	-	-
8	Farmington Bay WMA[+]	4	4207.4	5/20/2008	<0.1	6786	14.2	11.5	11,180	8.75	9.06	784.0
9	Farmington Bay WMA[+]	5	4203.1	5/20/2008	-	-	-	-	-	-	-	-
10	Lee Kay Center	6	4222.3	5/20/2008	-	-	-	-	-	-	-	-
11	Lee Kay Center	7	4220.6	5/20/2008	-	-	-	-	-	-	-	-
12	Lee Kay Center	5	4216.1	5/20/2008	-	-	-	-	-	-	-	-

Site ID*	Location	Carbonate (CO3) Solids (mg/L)	Copper, dissolved (µg/L)	Hydroxide (mg/L)	Iron, dissolved (µg/L)	Lead, dissolved (µg/L)	Magnesium, dissolved (mg/L)	Manganese, dissolved (µg/L)	Mercury, dissolved (µg/L)	Nickel (µg/L)	Potassium, dissolved (mg/L)
1	Rudy Gun Club	-	-	-	-	-	-	-	-	-	-
2	Salt Lake International Airport	199	25.6	0.0	1350.0	4.14	562	515.0	<0.2	<50.0	252
3	Salt Lake International Airport	-	-	-	-	-	-	-	-	-	-
4	Rudy Gun Club	-	-	-	-	-	-	-	-	-	-
5	Rudy Gun Club	-	-	-	-	-	-	-	-	-	-
6	Salt Lake International Airport	-	-	-	-	-	-	-	-	-	-
7	Farmington Bay WMA[+]	-	-	-	-	-	-	-	-	-	-
8	Farmington Bay WMA[+]	507	10.1	0.0	1220.0	5.49	388	71.2	<0.2	<50.0	109
9	Farmington Bay WMA[+]	-	-	-	-	-	-	-	-	-	-
10	Lee Kay Center	-	-	-	-	-	-	-	-	-	-
11	Lee Kay Center	-	-	-	-	-	-	-	-	-	-
12	Lee Kay Center	-	-	-	-	-	-	-	-	-	-

\- no data

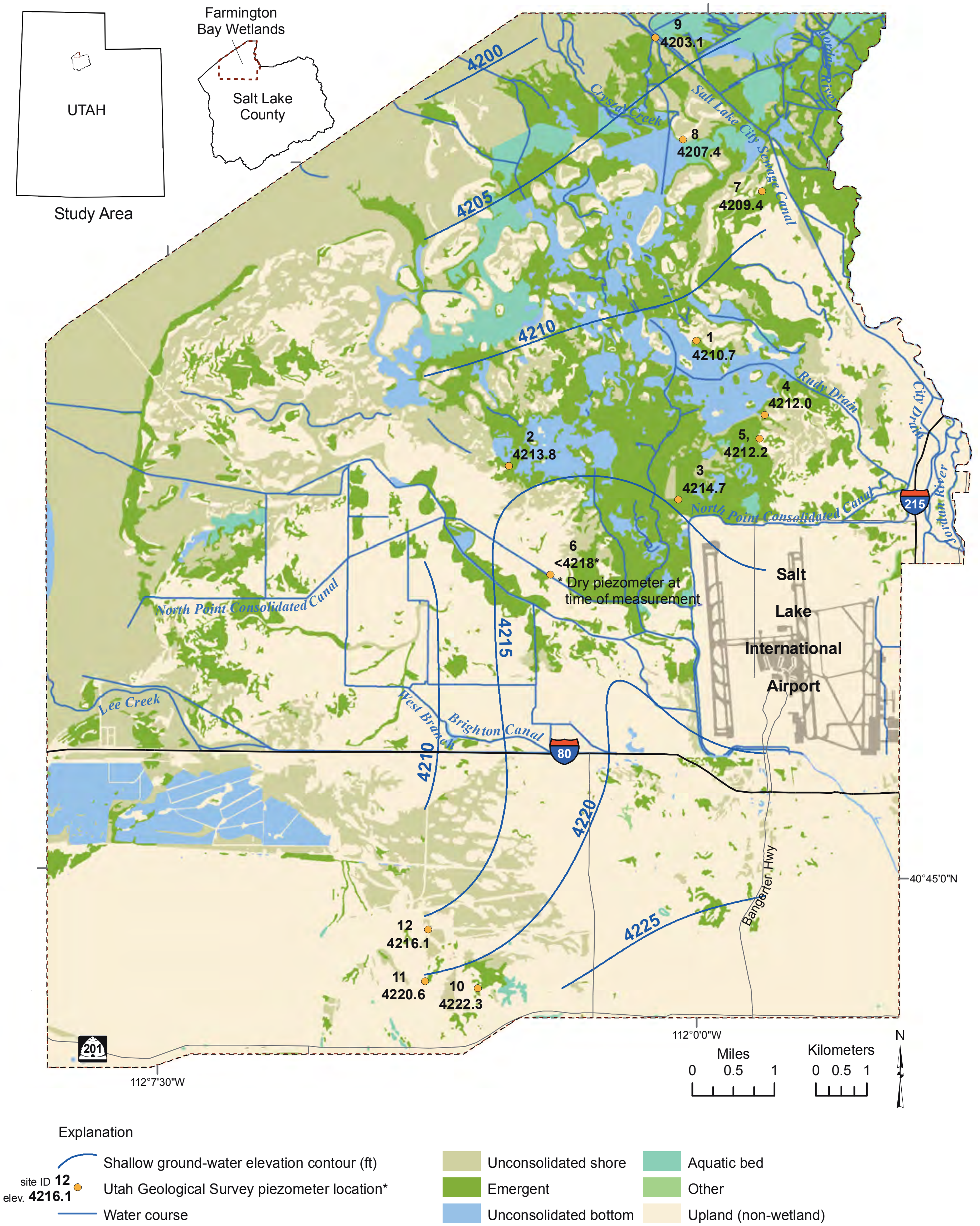
*see figure C1 for site ID location

[+] WMA - Waterfowl Management Area

Table C1. *continued*

Arsenic, dissolved (µg/L)	Barium, dissolved (µg/L)	Bicarbonate (mg/L)	Boron (µg/L)	Cadmium, dissolved (µg/L)	Calcium, dissolved (mg/L)	Carbon dioxide (mg/L)	Carbonate (mg/L)	Chloride (mg/L)	Chromium, dissolved (µg/L)
-	-	-	-	-	-	-	-	-	-
66.4	<100.0	174	4890.0	<1.0	116	1	113.0	7590.0	<20.0
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
35.7	152.0	895	1330.0	<1.0	165	3	66.0	3030.0	<20.0
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-

Selenium, dissolved (µg/L)	Silver, dissolved (µg/L)	Sodium, dissolved (mg/L)	Sulfate (mg/L)	Total Alkalinity (mg/L)	Total Hardness (mg/L)	Total Organic Carbon	Total Suspended Solids (mg/L)	Turbidity, (NTU)	Zinc, dissolved (µg/L)
-	-	-	-	-	-	-	-	-	-
16.2	<5.0	7350.0	2780.0	331.0	2601.8	42.7	860.0	790.0	<100.0
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
<10.0	<5.0	1790.0	757.0	845.0	2008.1	12.7	1682.0	1535.0	<100.0
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-



* See appendix C for piezometer data by location ID number (1-12)
Elevation in feet above sea level

Figure C1. *Piezometer locations showing shallow ground-water elevation and wetland type, north Salt Lake Valley (U.S. Fish and Wildlife Service, 2001).*