





WETLANDS IN THE FARMINGTON BAY AREA, DAVIS COUNTY, UTAH—AN EVALUATION OF THREATS POSED BY GROUND-WATER DEVELOPMENT AND DROUGHT

by Charles E. Bishop, Mike Lowe, Janae Wallace, Richard L. Emerson, and J. Scott Horn

UTAH DNR GEOLOGICAL SURVEY

REPORT OF INVESTIGATION 264
UTAH GEOLOGICAL SURVEY
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Cover:
Main photo is a view looking east from Farmington Bay Wetlands area.
Inset bottom-right photo is part of the Farmington Bay Water Fowl Management Area.
Left inset photos are various views of the wetlands.

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THE UTAH GEOLOGICAL SURVEY
contact
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ABSTRACT

The east shore area of Great Salt Lake in Davis County, which contains the Farmington Bay wetlands, is in a formerly rural area along the southeastern margin of Great Salt Lake that is now largely urban and continues to undergo population growth. Most of the development in the Farmington Bay area uses municipal water sources, principally wells completed in the east shore aquifer system, and some agricultural wells continue to be used for irrigation and stock watering. This population growth and concomitant increases 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 western part of the east shore area, and provides water to springs and approximately 18,630 acres (7540 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 levels. Drought conditions during 1999-2004 reduced the amount of recharge to ground-water aquifers across the state, negatively impacting the Farmington Bay area wetlands. In 2005, the elevation of Great Salt Lake declined to near its historic lowstand reached in 1963, allowing some parts of the Farmington Bay wetlands to dewater.

To evaluate the potential impacts of drought and increased development on the Farmington Bay area wetlands, we used existing data to estimate a water budget for the wetlands area. To determine the potential impacts posed by increased ground-water development and further drought, we used two regional, three-dimensional, steady-state and transient MODFLOW models for the east shore area of Great Salt Lake to evaluate water-budget changes for the wetland areas. 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, 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. As a conservative goal, the Farmington Bay wetlands area should be managed to maintain its current budget of water, which is estimated to include at least 16,000 acre-feet per year (20 hm^3/yr) of recharge as subsurface inflow.

This study indicates that wetlands in the Farmington Bay area are endangered. The threats posed are from drought and increased development due to population growth, which could dramatically affect the amount of water the wetland area receives. To reduce the potential for degradation of the Farmington Bay wetlands, restrictions could be placed on the areas of development, such as allowing development only in upland environments or placing a non-development buffer around the wetland areas. Wastewater from sewers could, where possible, be reused or discharged to the environment upgradient of the wetlands. Enactment of water conservation practices would also be beneficial for the wetland environments.

INTRODUCTION

Background

The Farmington Bay area (figure 1), Davis County, is in a formerly rural area along the southeastern margin of Great Salt Lake that is now largely urban (figure 2) and continues to undergo population growth. Most of the development in the Farmington Bay area uses municipal water sources, principally wells completed in the east shore aquifer system, and some agricultural wells continue to be used for irrigation and stock watering. This population growth and concomitant increase in muncipal pumping (figure 3) could significantly decrease the amount of ground water discharged from the principal aquifer system (where most wells are completed) to the shallow aquifer system.

The Farmington Bay area has been closed to new water rights appropriations since 1997 (DWR, 2006a, 2006b), so water rights for development in the unincorporated areas are primarily obtained through purchase/exchange of existing rights, mainly those formerly used for agriculture. The combination of population growth and change from agricultural to municipal water use could significantly decrease the amount of ground water discharged from the principal, confined 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 western part of the east shore area, and

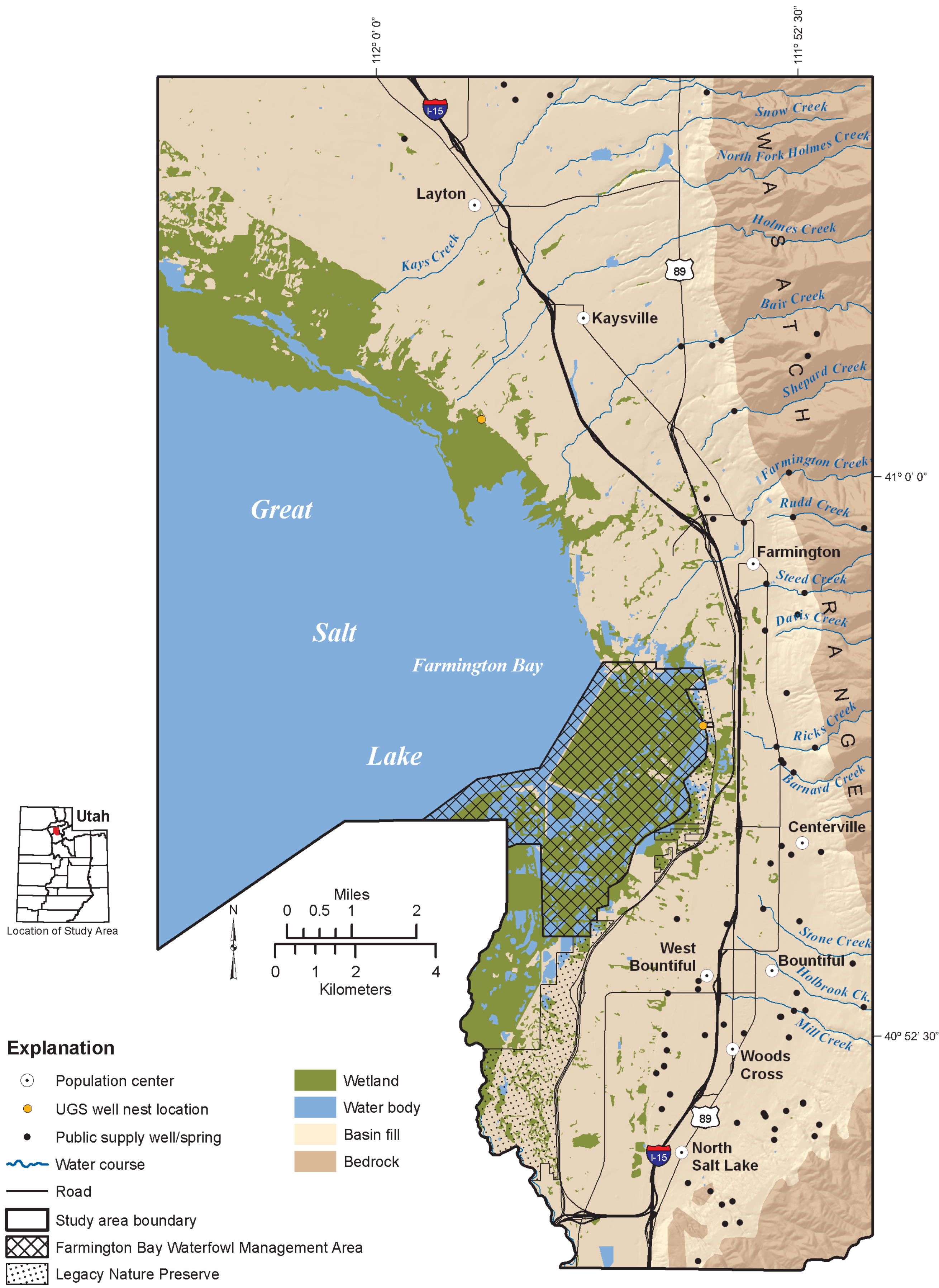


***Figure 1.** Farmington Bay area, Davis County, Utah.*

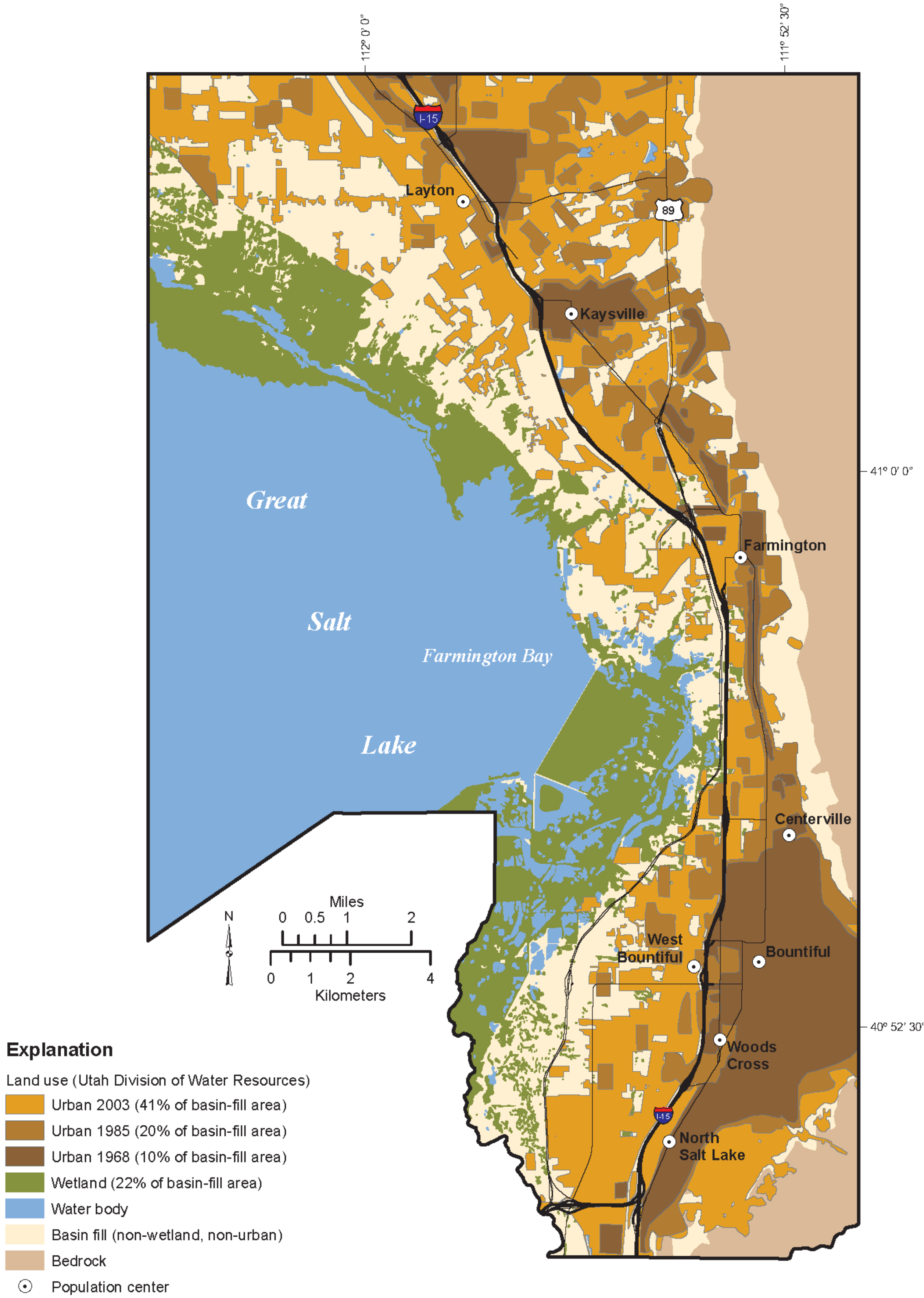


Figure 2. *Urbanization from 1968 to 2003, Farmington Bay area.*

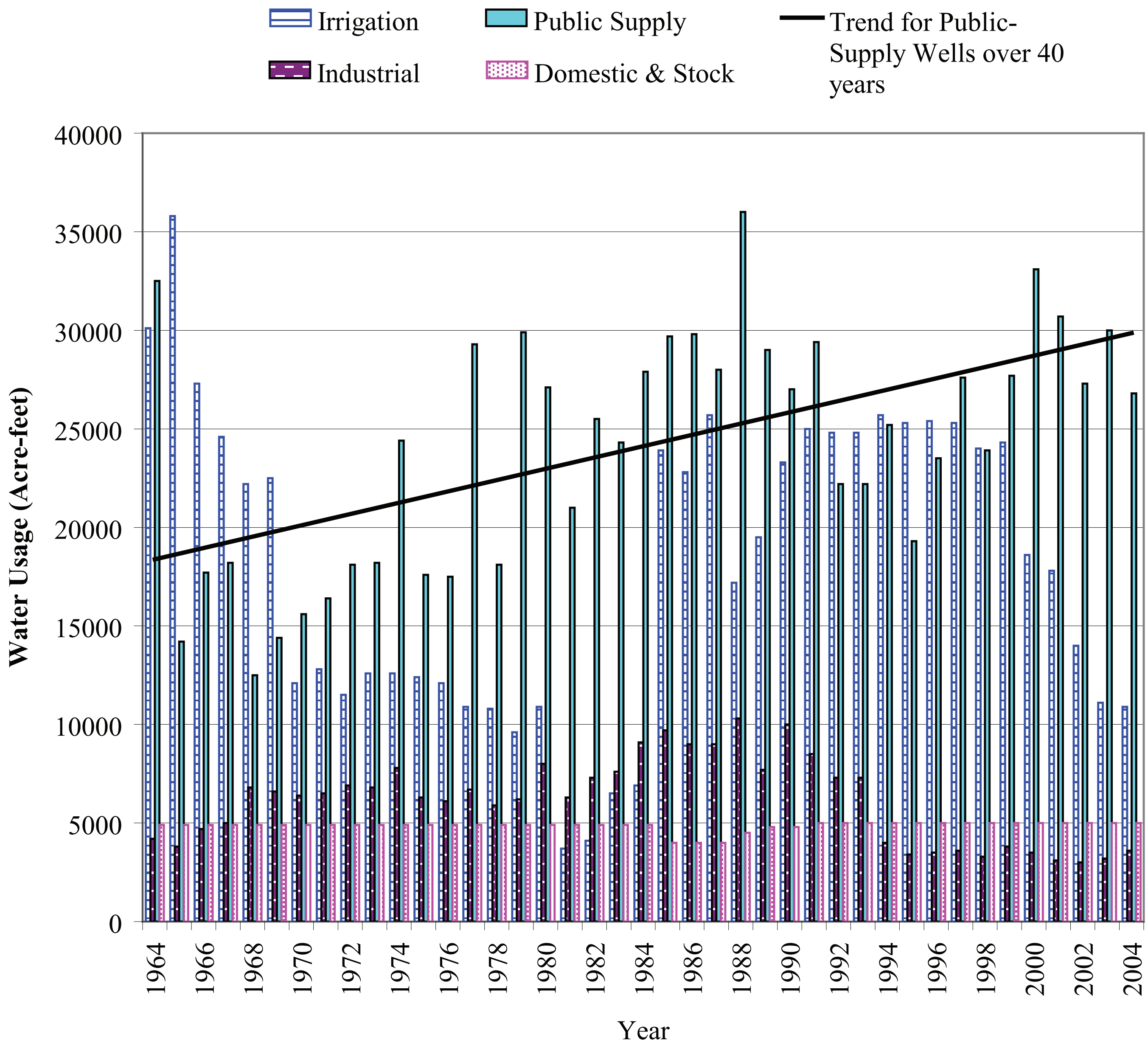


Figure 3. *Annual water usage by category for the east shore area of Great Salt Lake.*

provides water to springs and approximately 18,630 acres (7540 hm^2) of wetlands in ground-water discharge areas.

Ground-water discharge areas are predominantly located in southern Davis County (Anderson and others, 1994). The amount of ground water discharged from the confined aquifer system could decrease even if no new water rights are issued, because seepage of unconsumed irrigation/lawn water contributes nearly 11 to 19 percent of the total recharge to aquifers in the Farmington Bay area (Clark and others, 1990; Clark, 1991); this component of recharge to the aquifer system would likely decrease as a result of changing from agricultural to domestic water usage.

Significant portions of Utah's wetlands are located in areas surrounding Great Salt Lake, including the Farmington Bay area. Preliminary estimates from existing Geographic Information System (GIS) wetlands coverage indicate that wetlands in the Farmington Bay area occupy about 27 percent of the valley-floor area. Wetlands are important to diverse plant and animal species (about 45 percent 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).

Purpose and Scope

The purpose of this study is to use existing data to estimate a water budget for the wetlands area, and to use two existing steady-state and transient ground-water-flow models developed by the U.S. Geological Survey (USGS) (Clark and others, 1990; Clark, 1991) to simulate the hydrologic effects on wetlands from various recharge rates and projected ground-water withdrawals at various projected Great Salt Lake levels. 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.

A second objective is to document the current water quality of the wetlands area. We used data from water sampled from shallow wells to document the current quality of ground water flowing into the wetlands area, and to document any downgradient changes in ground-water chemistry.

This report provides the necessary integration of geologic and hydrologic wetland studies to more fully understand the hydrologic system of the Farmington Bay area in relation to wetland functionality. The scope of this report 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. The detailed USGS models, which are documented in this report, were originally used to identify historical changes in the ground-water flow system in the east shore area of Great Salt Lake.

Methods

Our study combines empirical and modeling analyses to understand the effects of changes in land use and climate. We use an estimated water budget to compare and interpret numerical ground-water flow models, which simulate fluxes into and out of the Farmington Bay wetlands area. Numerical ground-water flow models have been used in other studies to understand the interaction between wetlands and ground water, and have produced reliable results (for example, Burk and others, 2005). 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.

We installed five shallow monitoring wells in two wetland areas for water-quality sampling during October 2006. The wells were manually installed using a hand auger to bore a hole into the ground to a depth of about 5 feet (1.5 m), and then inserting one-inch-diameter (2.5 cm) slotted PVC pipe and backfilling the void between the borehole and pipe with the hand-auger cuttings. We mapped the well locations by using a hand-held Global Positioning System (GPS) device and cross-referencing the location and elevation with the most up-to-date 1:24,000-scale USGS topographic map. The monitoring wells were sampled during November 2006 and analyzed at the Utah Division of Epidemiology and Laboratory Services for general chemistry, dissolved metals, nutrients, and total organic carbon.

Previous Studies

The study area is in the southern part of the east shore area of Great Salt Lake in southern Davis County and north-central Salt Lake County. Dennis and McDonald (1944) conducted an early study of ground-water conditions in the east shore area. Thomas and Nelson (1948) studied the geology and ground-water conditions in the Bountiful sub-area of the east shore area. Dennis (1952) evaluated ground-water recharge in the east shore area. Smith (1961) provided basic data on water levels and ground-water quality for the east shore area, and Smith and Gates (1963) evaluated changes in ground-water quality and water levels based on that data for the 1953-61 time period. Feth and others (1966) conducted a comprehensive study of basin-fill deposits and hydrogeologic conditions in the Weber Delta sub-area of the east shore area. Bolke and Waddell (1972) mapped ground-water quality and evaluated changes in water levels and ground-water quality in the east shore area for the 1960-69 time period. Clark and others (1990) re-evaluated ground-water conditions and constructed a computer model for the Weber Delta sub-area of the east shore aquifer, including the northern part of Farmington Bay. Clark (1991) re-evaluated ground-water conditions and constructed a computer model for the Bountiful sub-area of the east shore aquifer, including the southern part of Farmington Bay. 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 aquifers in the east shore area of Great Salt Lake. Gates (1995) provided a description and quantification of ground-water basins along the Wasatch Front, including a discussion of how water budgets changed from one ground-water study to the next. Lowe and others (2004) evaluated ground-water sensitivity and vulnerability to pesticides for the principal aquifers in the east shore area of Great Salt Lake. Burden and others (2005) described changes in ground-water conditions in Utah, including the east shore area, from 1975 to 2005.

Erickson and others (1968) mapped soils (scale 1:15,840) for parts of Davis and Weber Counties, including the Farmington Bay area. Regional geologic maps for the study area include a surficial geologic map along part of the Wasatch Front by Miller (1980, scale 1:100,000) and a surficial geologic map along the Wasatch fault zone by Nelson and Personius (1993, scale 1:50,000). Lowe and others (2008) mapped the geology of the Farmington 7.5-minute quadrangle, which includes most of Farmington Bay.

SETTING

Physiography

The Farmington Bay area (figure 1) is in the Ogden Valley segment of the Wasatch Front Valleys section of the Great Basin physiographic province (Stokes, 1977). The Farmington Bay area is part of a basin lowland that extends westward from the Wasatch Range. Elevation ranges from over 9000 feet (2700 m) for some peaks in the Wasatch Range to about 4200 feet (1280 m) at the shore of Great Salt Lake. Streams in Davis County are not tributaries to major river systems, but flow directly to Great Salt Lake. The major streams flowing into Farmington Bay include Farmington, Ricks, Parrish, Centerville, Stone, and Mill Creeks (Clark and others, 1990, table 3). Other smaller perennial, intermittent, and ephemeral streams flow westward from the Wasatch Range into the Farmington Bay area (Clark and others, 1990, table 4).

Rocks in the Wasatch Range east of Farmington Bay consist primarily of Precambrian to Tertiary-age metamorphic and sedimentary rocks that are variably deformed and fractured, due to late Mesozoic to early Cenozoic thrust faulting (Bryant, 1984). The most extensive rock unit is the Farmington Canyon Complex, a complex mixture of high-grade metamorphic and igneous rocks (Eardley, 1944; Bryant, 1984; Yonkee and others, 2000); these rocks include meta-ultramafic and mafic rocks, quartz-rich gneiss, biotite-rich schist, migmatitic gneiss, granitic gneiss, and pegmatite (Bryant, 1984; Yonkee and Lowe, 2004). Tertiary conglomerate crops out on the Salt Lake salient (Van Horn, 1981).

The east shore area of Great Salt Lake, including the Farmington Bay area, is part of a north-south-trending graben where great thicknesses of sediment have accumulated since its inception in early Tertiary time (Eardly, 1955). The active Wasatch normal fault at the base of the Wasatch Range forms the eastern margin of this depositional basin. Gravity, seismic, and drill-hole data indicate that the sediments filling this graben are locally as much as 10,000 feet (3000 m) thick in some areas (Feth and others, 1966; Cook and others, 1967; Glenn and others, 1980; Zoback, 1983; McNeil and Smith, 1992). The basin fill likely includes an older sequence of tilted Eocene to Oligocene strata consisting of a mixture of conglomerate, sandstone, reworked tuff, and minor lacustrine limestone similar to rocks preserved beneath parts of eastern Great Salt Lake (Constenius, 1996) and locally exposed on Antelope Island (Willis and Jensen, 2000). These older basin-fill deposits are overlain by Miocene to Pliocene rocks that are generally assigned to the Salt Lake Formation and consist of heterogeneous mixtures of poorly consolidated sedimentary rocks and reworked tuff (Miller, 1991). This Miocene to Pliocene basin fill is, in turn, overlain by less consolidated Quaternary basin-fill and surficial deposits of predominantly fluvial, lacustrine, and deltaic origin (Feth and others, 1966). The poorly consolidated to unconsolidated Quaternary basin-fill sediments are the primary focus of this report because they comprise the principal ground-water aquifers that underlie the Farmington Bay wetlands.

The study area is within the hydrologically closed Bonneville basin, and water flowing into this basin generally leaves it only by evapotranspiration. The Bonneville basin has been an area of internal drainage for much of the past 15 million years, and lakes of various sizes have existed in the area during most of that time (Currey and others, 1984). Due to this history of deep-lake cycles interspersed with periods when lakes stood at low levels or were not present, the Quaternary basin-fill deposits consist of complexly interfingering, overall westward-fining bodies of gravel, sand, silt, and clay deposited in lacustrine and fluvial environments (Feth and others, 1966; Sprinkel, 1993).

Climate

Three weather stations in the study area provide climatic data for different time periods (Farmington USU Field Station, elevation 4340 feet [1323 m], 1948-92; Farmington, elevation 4267 feet [1301 m], 1948-65; and Bountiful-Val Verda, elevation 4540 feet [1384 m], 1981-92). However, because precipitation varies significantly with elevation, we herein use climatic data from the Antelope Island weather station (elevation 4225 feet [1288 m], period of record 1952-72) (Ashcroft and others, 1992) for the Farmington Bay wetlands that range in elevation from about 4200 to 4350 feet (1280-1326 m). Temperatures reach an average minimum of 18.6˚F (-7.4˚C) in January and an average maximum of 95.6˚F (35.3˚C) in July. The average mean annual temperature is 51.8˚F (11.0˚C). Average annual precipitation is 15.46 inches (30.3 cm) (table 1), and average annual evapotranspiration is 49.13 inches (124.8 cm). The average number of frost-free days is 152.

Population and Land Use

From 1990 to 2000, population in Davis County increased by 27 percent (51,053 individuals) (Demographic and Economic Analysis Section, 2001). The 2005 population of Davis County was estimated at 276,374, and the county's population is projected to grow to 424,177 by 2050 (Demographic and Economic Analysis Section, 2005). The cities of Farmington, Centerville, Bountiful, West Bountiful, Woods Cross, and North Salt Lake are in the Farmington Bay area (figure 1) and have estimated 2005 populations of 18,436, 15,133, 41,821, 4675, 8676, and 10,376, respectively (Demographic and Economic Analysis Section, 2005). Most cities and rural development in Davis County are on basin-fill deposits of the east shore area of Great Salt Lake.

Table 1. *Summary statistics for Antelope Island precipitation, 1952-72 (from Ashcroft and others, 1992). Data are in inches.*

Month	Maximum precipitation	Minimum precipitation	Mean
January	3.15	0.0	1.16
February	3.86	0.29	1.32
March	3.30	0.00	1.39
April	4.83	0.78	2.41
May	4.86	0.00	1.66
June	3.54	0.00	1.44
July	0.77	0.00	0.23
August	4.04	0.00	0.92
September	3.33	0.00	1.00
October	3.16	0.00	1.16
November	2.71	0.27	1.37
December	3.92	0.20	1.40
Total average annual precipitation			15.46

Residential development has become the main land use in Davis County, but agriculture is still a major land use (Barry Burton, Davis County Community and Economic Development Department, verbal communication, 2003). Trade, non-farm proprietors, government, and services are the largest sources of employment in Davis County, and are approximately equal in terms of the number of people employed (18,000-22,000 in 2000) (Utah Division of Water Resources, 1997).

GROUND-WATER CONDITIONS

Basin-Fill Aquifers

Basin-fill aquifers in Davis and Weber Counties west of the Wasatch Range are part of the east shore aquifer system. In the past, some authors (Thomas and Nelson, 1948; Feth and others, 1966; Clark and others, 1990; Clark 1991) have divided the east shore area into sub-areas. The Bountiful sub-area covers about 40 square miles (100 km^2) extending from northern Centerville to the Salt Lake County line (figure 4). The Weber Delta sub-area is about 40 miles long (60 km) and 3 to 20 miles (5-30 km) wide, and extends from the Wasatch Range westward to Great Salt Lake, and from Willard in Box Elder County southward to Centerville (figure 4) (Feth and others, 1966; Clark and others, 1990; Gates, 1995). The boundary between the two sub-areas is the line between T. 2 N. and T. 3 N., Salt Lake Base Line and Meridian. The Farmington Bay area includes the Bountiful sub-area and the southern part of the Weber delta sub-area (figure 4).

Important ground-water resources in the Farmington Bay area exist in unconsolidated to semiconsolidated Quaternary basin-fill deposits (Thomas and Nelson, 1948; Feth and others, 1966; Clark and others, 1990) (figure 5). These deposits include relatively coarse-grained alluvial sediments near the mountain front, and finer grained lacustrine and alluvial sediments westward away from the mountains (Feth and others, 1966; Bolke and Waddell, 1972; Clark and others, 1990). In some areas near the mountain front, poorly sorted silt- to boulder-sized sediments deposited as debris flows and floods make up a significant portion of the basin fill (Thomas and Nelson, 1948).

Deeper ground water in the east shore aquifer system is predominantly confined, but unconfined conditions exist locally in recharge areas along a narrow band at the base of the Wasatch mountain front (figure 6) (Anderson and others, 1994). Two principal aquifers, the Sunset and Delta, have been delineated in the central part of the Weber Delta sub-area (Feth and others, 1966). The Delta aquifer is the primary source of ground water for the Ogden area and is composed mostly of coarse-grained, pre-Bonneville fluvial and deltaic sediments (Clark and others, 1990). The top of the Delta aquifer is 500 to 700 feet (150-200 m) below ground surface in the Ogden area, and the aquifer is about 50 to 200 feet (15-60 m) thick (Feth and others, 1966). The shallower Sunset aquifer has a lower permeability and is used to a lesser extent as a source of ground water. The top of this aquifer is 200 to 400 feet (60-120 m) below ground surface in the Ogden area, and it is also is about 50 to 200 feet (15-60 m) thick (Feth and others, 1966). Fine-grained confining intervals overlie both aquifers away from the mountain front. A shallow unconfined aquifer is commonly found above the upper confining beds within Quaternary surficial deposits (Clark and others, 1990) (figure 5). Tertiary basin fill deeper than about 1500 feet (450 m) is commonly more lithified and less permeable, contains poorer quality water, and is not considered an important ground-water source (Clark and others, 1990). Thomas and Nelson (1948) delineated three confined aquifers–the shallow, intermediate, and deep “artesian” aquifers–in the Bountiful sub-area based on slight head differences in wells; depths to the tops of these aquifers range from 60 to 250, 250 to 500, and greater than 500 feet (20-80, 80-150, and greater than 150 m), respectively. Because these head differences were not apparent in 1983-85 and because

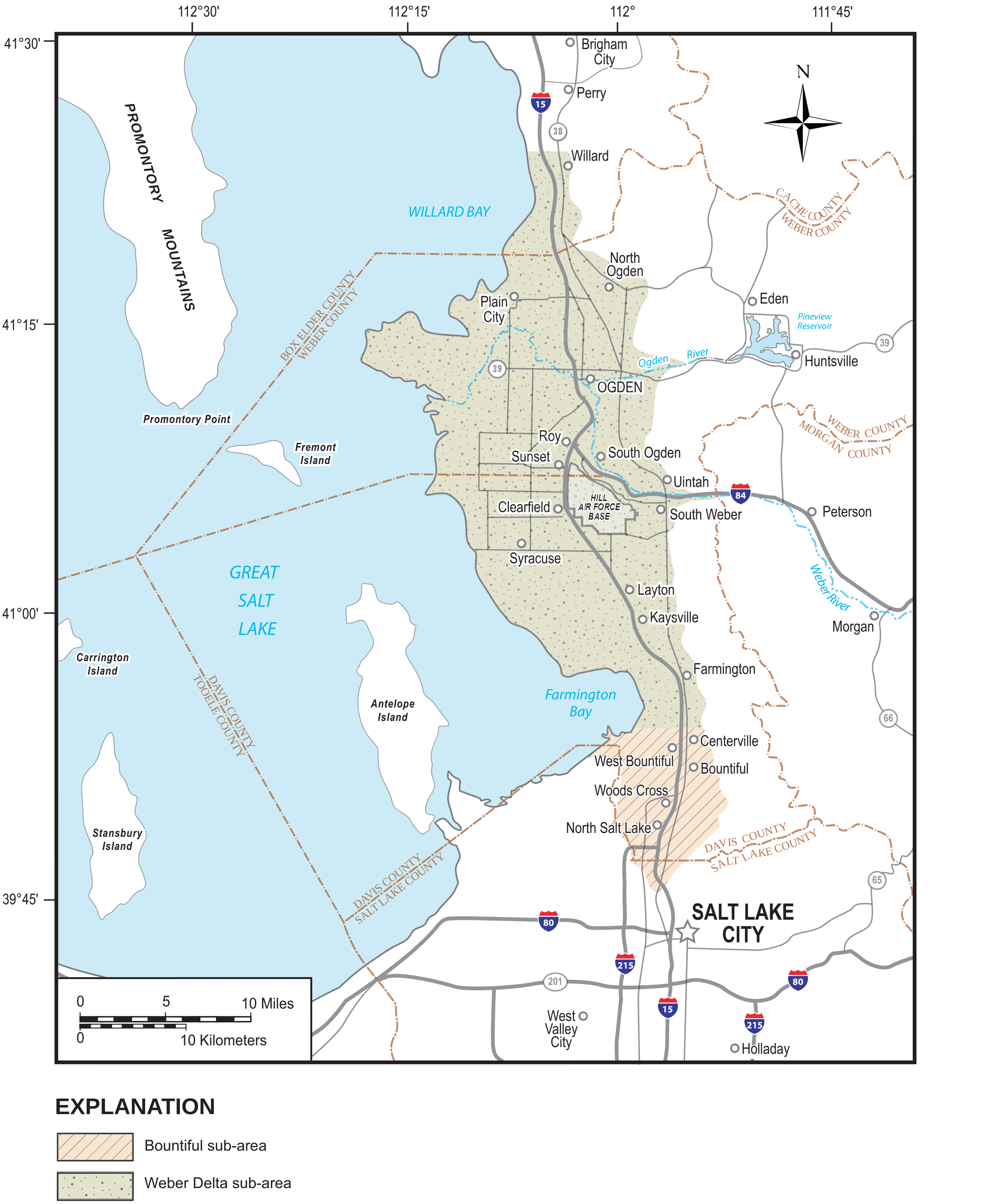


Figure 4. *Location of the Weber Delta and Bountiful sub-areas of the east shore aquifer system, Box Elder, Davis, and Weber Counties, Utah (modified from Clark and others, 1990).*

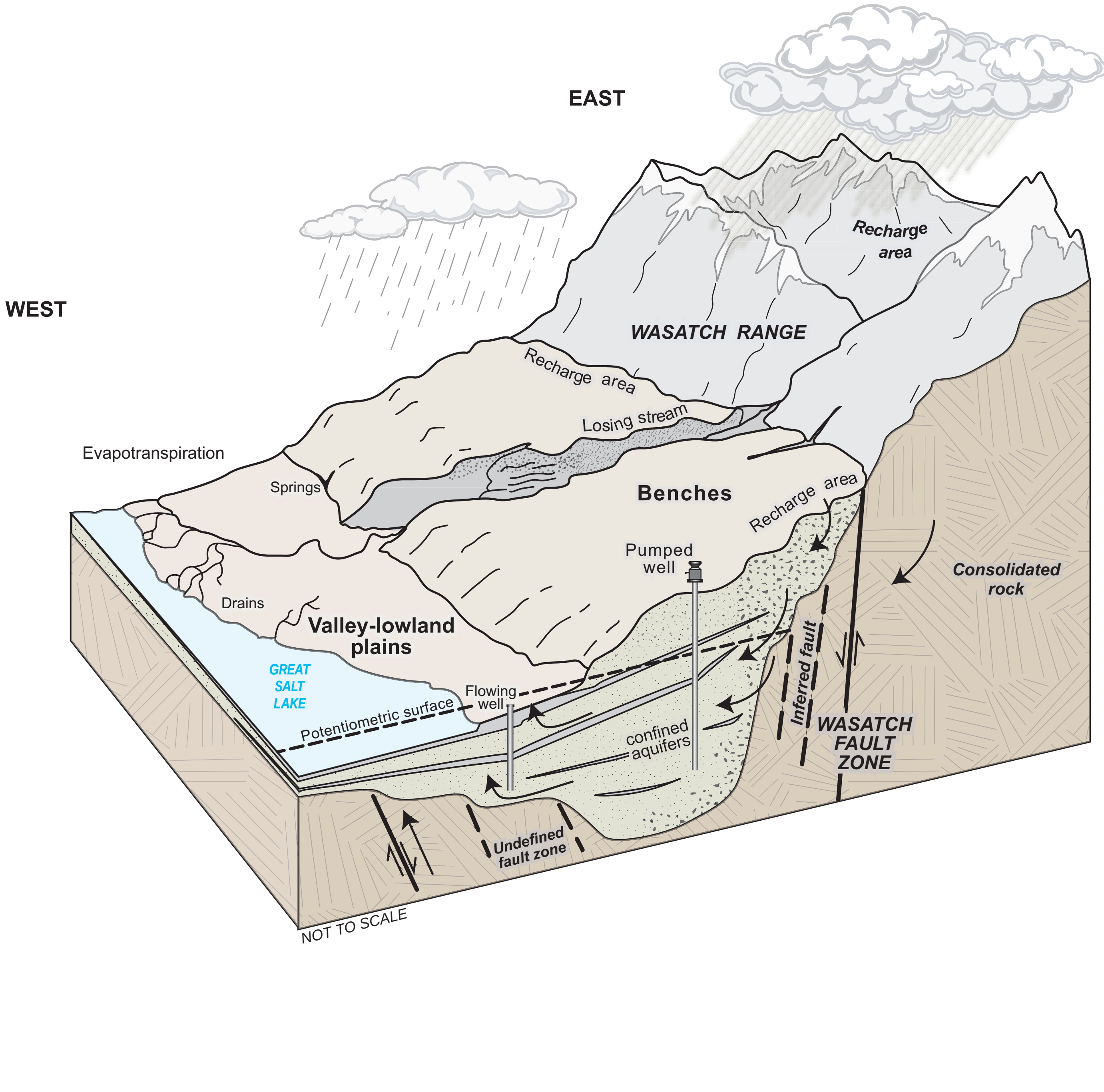


***Figure 5.** Generalized block diagram showing water-bearing formations, probable directions of ground-water movement, and areas of recharge and discharge, east shore area of Great Salt Lake (from Clark and others, 1990).*

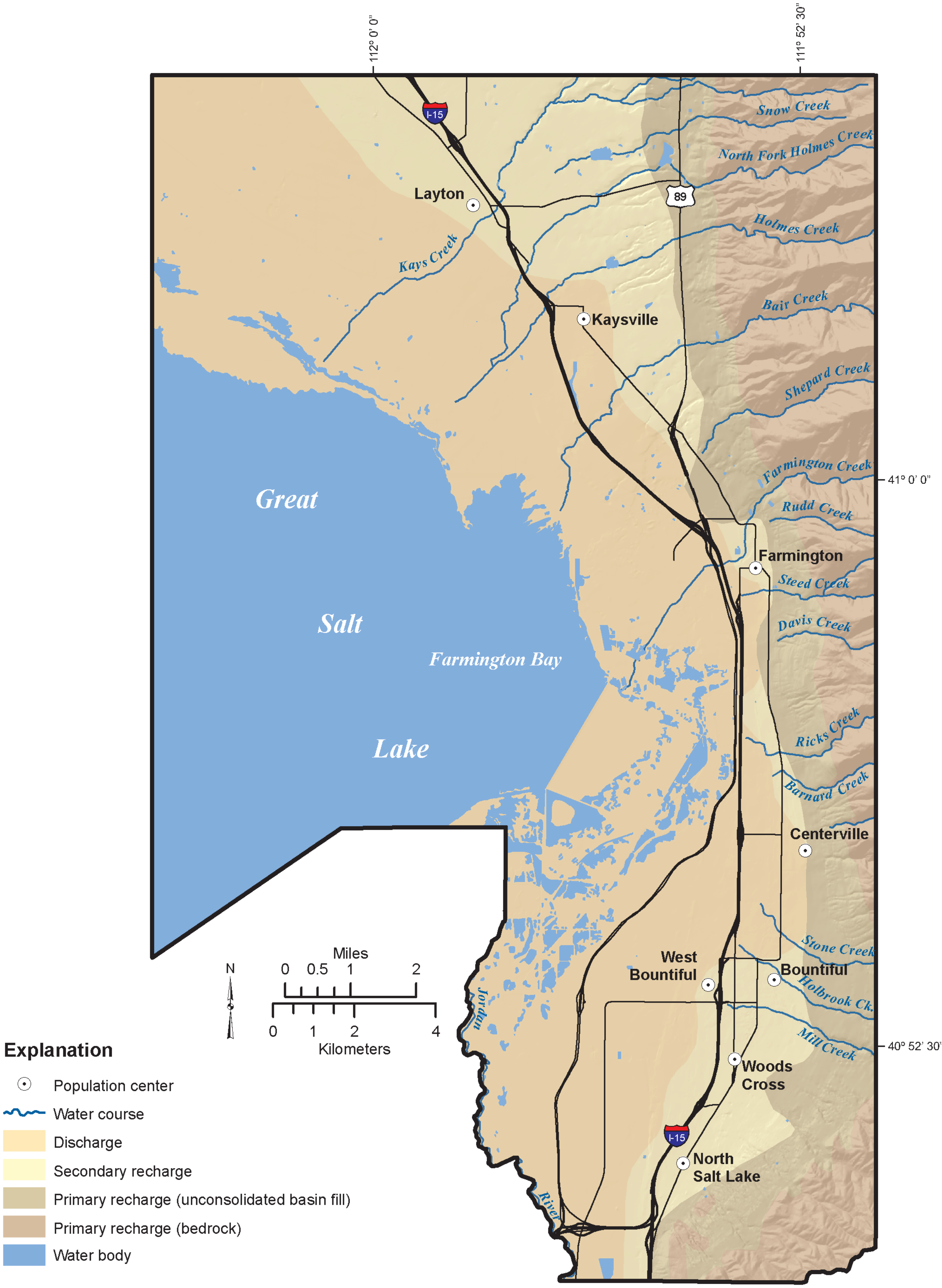


Figure 6. Recharge and discharge areas, east shore area, Davis County, Utah (from Anderson and others, 1994).

of the lack of substantial lithologic differences between Thomas and Nelson's (1948) aquifers, Clark (1991) considered all water-bearing units below 100 feet (30 m) to be part of a single aquifer system.

The ultimate source of ground water recharging the east shore aquifer system is precipitation in the drainage basin (Clark and others, 1990), but after 1960 recharge in the Farmington Bay area includes an average of 17,000 acre-feet per year (21 hm^3/yr) of Weber River water brought into the area via the Gateway Tunnel and the Davis Aqueduct (Clark, 1991). Recharge enters the east shore aquifer system through channel seepage along losing stretches of streams and canals; seepage from irrigated fields, lawns, and gardens; direct infiltration of precipitation; and subsurface inflow from bedrock of the Wasatch Range (Thomas and Nelson, 1948; Clark and others, 1990). Most recharge takes place in the primary recharge area along the mountain front (figure 6), especially near the mouth of Weber Canyon (Anderson and others, 1994). Subsurface inflow from bedrock along the mountain front and seepage from perennial streams are probably the dominant recharge sources (Thomas and Nelson, 1948; Feth and others, 1966).

Discharge from the east shore aquifer system includes (1) flow into gaining stretches of streams, drains, and ditches and to small springs and seeps, (2) water-well withdrawal, (3) evapotranspiration of shallow ground water, and (4) diffuse ground-water seepage to Great Salt Lake (Thomas and Nelson, 1948; Feth and others, 1966; Clark, 1991). Water-well withdrawal and flow to gaining streams, springs, and seeps are the main discharge components (Clark and others, 1990).

Ground-water flow in the east shore aquifer system is generally westward from recharge areas near the Wasatch Range toward Great Salt Lake (Thomas and Nelson, 1948; Feth and others, 1966). For the Farmington Bay area, the horizontal hydraulic gradient ranges from about 250 to 450 feet per mile (47-85 m/km) for the water table east of the upper Bonneville canal to less than 5 feet per mile (1 m/km) for the shallower wells completed in confined aquifers in the Woods Cross area (Clark, 1991). The vertical hydraulic gradient in the east shore aquifer system is generally downward in recharge areas near the mountain front, and generally upward where confined conditions exist west of the mountain front, but vertical flow is probably relatively slow through low-permeability confining layers (Clark and others, 1990).

Transmissivity values for confined parts of the aquifer system in the Farmington Bay area range from 200 to 30,000 feet squared per day (20-2800 m^2/d), based on 11 aquifer tests conducted between 1936 and 1981 (Clark, 1991, table 4). Storage coefficients for the Weber Delta sub-area of the east shore aquifer system range from about 0.002 to 0.00007, based on tests conducted between 1944 and 1956 (Feth and others, 1966, table 8). Specific yields, related to dewatering of pore space, are likely in the range of 0.25 to 0.07 for the Weber Delta sub-area, based on observed porosities and limited recharge tests (Feth and others, 1966). The Bountiful sub-area aquifers likely exhibit similar values for storage coefficients and specific yields.

Seasonal ground-water levels in the east shore aquifer system generally rise in the spring during net recharge and decline in the summer; greatest declines occur near the mountain front (Thomas and Nelson, 1948; Clark and others, 1990). According to Clark (1991), long-term water levels in the Farmington Bay area:

(1) generally followed the predominantly falling trend of cumulative departure from normal precipitation from 1935 to 1962,

(2) rose substantially from 1962 to 1965 due to decreased ground-water withdrawals from wells partly in response to importation of Weber River water via the Davis Aqueduct,

(3) declined slightly from 1965 to 1968 in response to increased withdrawals from wells,

(4) remained stable from 1970 to 1975 as increased recharge from precipitation balanced increasing well withdrawals,

(5) declined substantially from 1975 to 1978 due to increased well pumping, and

(6) rose substantially from 1978 to 1984 in response to increased precipitation despite a slight increase in ground-water withdrawals.

Burden and others (2005) documented an overall trend in water-level declines in the Farmington Bay area from 1975 to 2005 (figure 7), probably due to continued large ground-water withdrawals for public supply and decreased recharge due to less-than-average precipitation.

Ground-Water Quality

Ground-water quality in the east shore aquifer system is generally good (figure 8); with total-dissolved-solids (TDS) concentrations range from 92 mg/L in the Weber Canyon area to 9800 mg/L in the southwest North Ogden area, based on ground-water-quality data from Smith (1961, table 3), Smith and Gates (1963, table 4), Feth and others (1966, table 9), Bolke and Waddell (1972, table 2), Plantz and others (1986, table 5), Clark and others (1990, table 13), and Anderson and others (1994, table 2). Geochemically, ground-water quality types in the east shore aquifer system are calcium-magnesium-bicarbonate, calcium-bicarbonate, sodium-bicarbonate, sodium-chloride, and no predominant type ground water (figure 8) (Smith and Gates, 1963; Feth and others, 1966; Bolke and Waddell, 1972; Clark and others, 1990). The calcium-magnesium-bicarbonate ground water is the predominant ground-water type in the east shore area of Great Salt Lake, and generally contains less than 300 mg/L TDS (Feth and others, 1966, figure 14). The sodium-bicarbonate type ground water exists along the eastern margin of Great Salt Lake in the northern and southern parts of the study area, and generally contains less than 400 mg/L TDS (Smith and Gates, 1963). The sodium-chloride type ground water exists mostly north in the southwest North Ogden/northeast Plain City area and in a few areas along the shore of Great Salt Lake, and contains from 500 mg/L TDS at the mouth of Ogden Canyon to more than 9000 mg/L TDS in the southwest North Ogden area (Smith and Gates, 1963, figure 8; Feth and others, 1966, figure 14). Mixed-type ground water exists in an area extending westward from Ogden

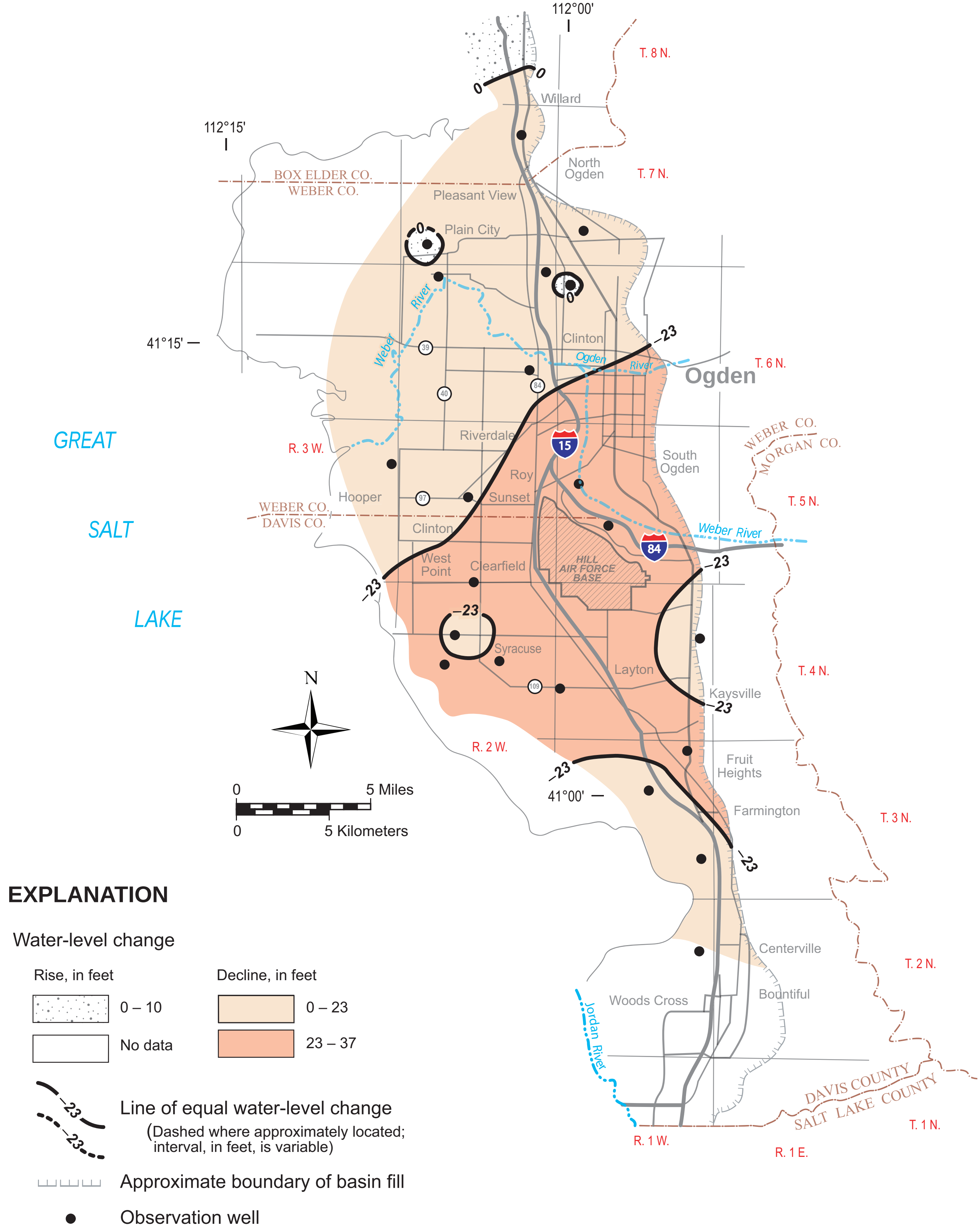


Figure 7. *Change of water level from March 1975 to March 2005, east shore area (from Burden and others, 2005).*

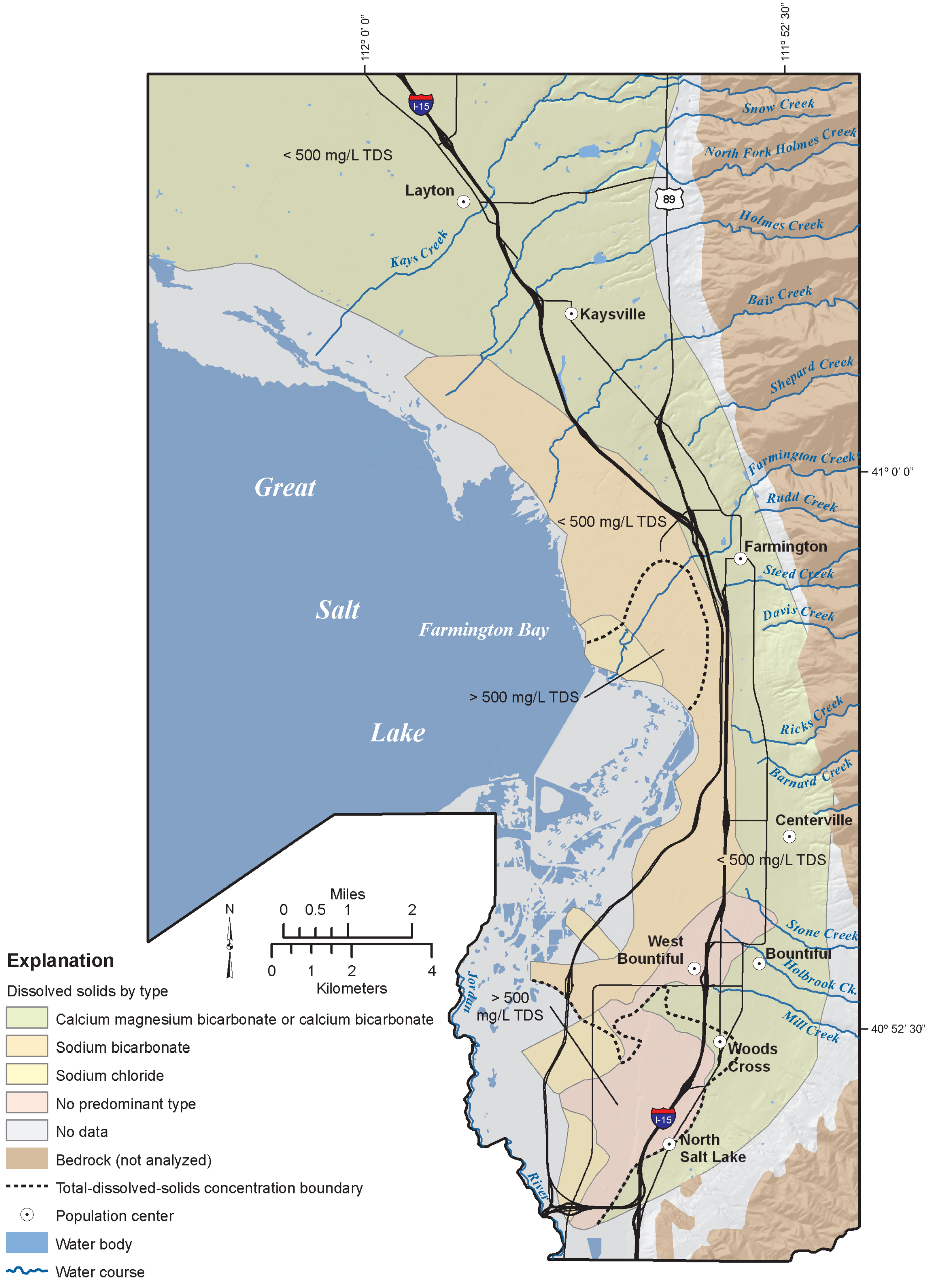


Figure 8. *Ground-water quality types and areas with greater than or less than 500 mg/L total-dissolved-solids (TDS) concentrations, east shore area, Davis County, Utah (modified from Bolke and Waddell, 1972).*

Canyon and in the Bountiful/North Salt Lake area (figure 8), and contains from 500 to 1,000 mg/L TDS (Smith and Gates, 1963, figure 8; Feth and others, 1966, figure 14).

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, flood-water 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 and natural causes. Human impacts are due to agricultural, industrial, and urban development and the resulting pollution. Natural causes are generally due to climatological changes. In the United States, an estimated 53 percent 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. It is the current goal of the U.S. government 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.

Farmington Bay Wetlands

The wetlands in the Farmington bay area are located along a portion of the east shore of Great Salt Lake. Approximately 80 percent of the wetlands in Utah surround Great Salt Lake, which corresponds to an estimated 400,000 acres (1600 km^2) of wetlands (Lock, 1994). Lock (1994) estimates that 30 percent of Utah's wetlands has been lost, mostly due to land-development practices.

Most of the Farmington Bay wetlands are located on the western edge of the Davis County urban corridor adjacent to the east shore of Great Salt Lake where the land surface has low relief (figure 1). The Farmington Bay wetlands have been impacted by agricultural activities (including grazing), industrial and urban development, and water diversions including ditches and dikes. The wetlands are primarily located in ground-water discharge areas for the principal aquifers (Anderson and others, 1994; figure 6), where there is 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 Farmington Bay wetlands. The water-table elevation is controlled by water supply to the wetlands, which varies with changes in recharge due to climatic conditions and/or ground-water withdrawals from wells, and with changing 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. An NWI map for the Farmington Bay area (figure 9) shows that the wetlands are in the lacustrine and palustrine systems. Lacustrine wetlands are associated with the shoreline of Great Salt Lake, and the palustrine wetlands are associated with the springs that discharge ground water and form ponds. Within the broad wetland systems are subdivisions called classes and subclasses. Wetlands are further classified by addition of a modifier that describes the amount of time a wetland is inundated by floodwater. The classes located within the Farmington Bay study area, and the total area of each class, are provided in appendix B.

Within the east shore area are various types of habitats or environments. The eastern part of the study area is highly urbanized. Open-water environments are associated with Great Salt Lake, sewage-treatment ponds, and spring-fed ponds. The western part of the area consists of vegetated and non-vegetated mineral and wet mud flats. Wet-meadow and emergent marsh environments are near the southwestern border of the study area where ponds have been built in the Farmington Bay Waterfowl Management Area (FBWMA).

Originally built in 1935 and occupying 3800 acres (1500 hm^2), today 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 Department of Wildlife Resources (UDWR). As many as 200 avian species have been documented using the wetlands associated with the FBWMA. The FBWMA provides critical habitat for up to 57 species of waterfowl and shorebirds (as many as 200,000 individuals) that use the wetlands for nesting and foraging in the spring and summer, and is also an important stopover for millions of migrating waterfowl seasonally. The wetlands here are primarily sourced by the Jordan River through a complex network of impoundments, canals, 22 miles (35 km) of dikes, and 126 water-control structures. Water depths in these wetlands are very precisely managed and range from 0 to 14 inches (0-36 cm) to maximize waterfowl habitat (Utah Division of Wildlife Resources, 2006). Because of this management, shallow ground-water levels can reflect surface-water control in the FBWMA. Large areas can be filled seasonally for flood control or water storage, or drained periodically to eradicate noxious and non-native vegetation (Rich Hansen, FBWMA manager, verbal communication, 2007).

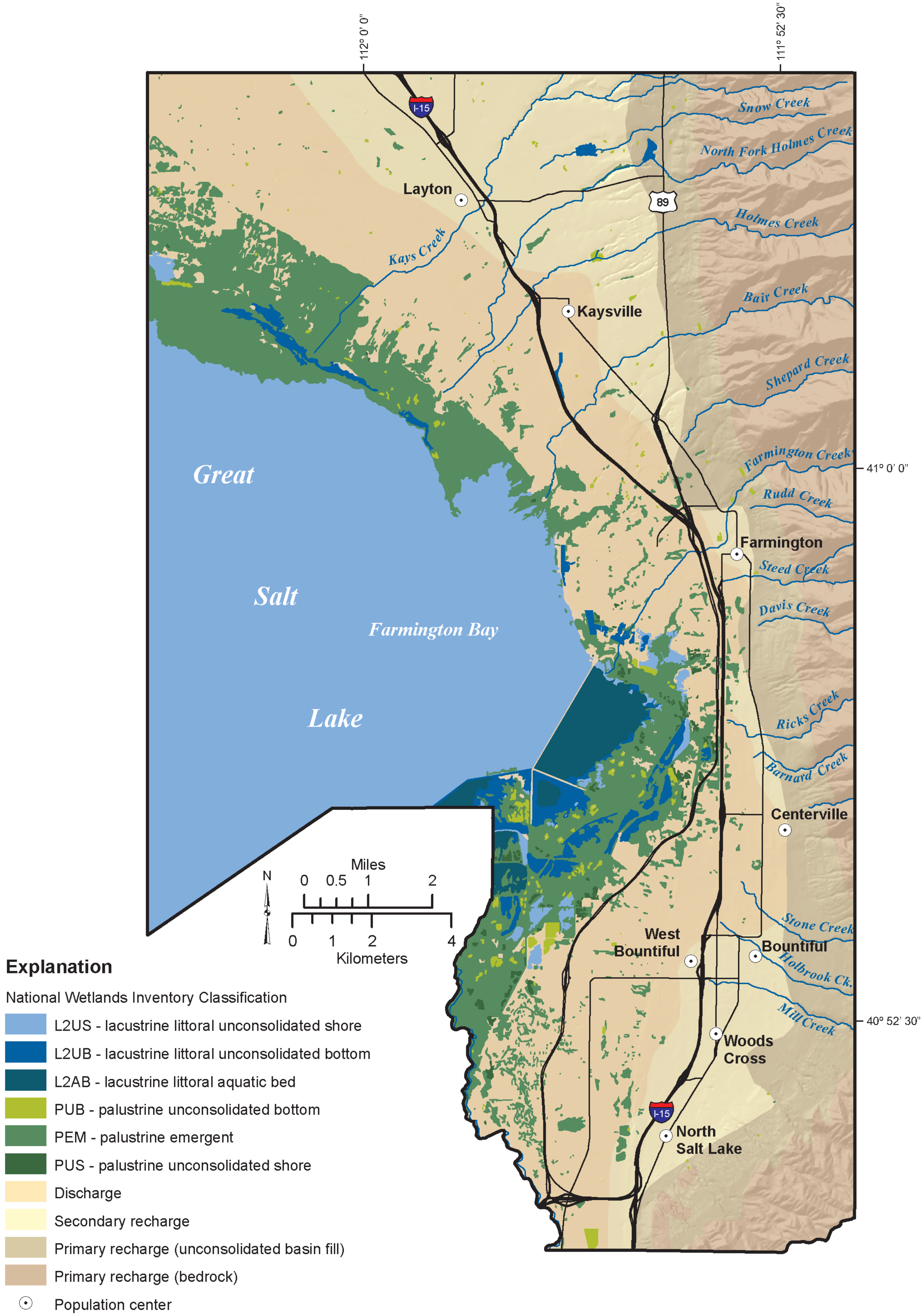


Figure 9. *National Wetlands Inventory, Farmington Bay area.*

A recent addition to the wetland conservation effort of Farmington Bay is the Legacy Nature Preserve (LNP) (figure 1). This 2225-acre (900 hm^2) area was reserved as mitigation for the Legacy Parkway to prevent future residential and industrial encroachment west of the parkway (Utah Department of Transportation, 2007). To maintain the LNP, water will be acquired from multiple sources including the Jordan River, North Canyon Creek, storm runoff from local municipalities, and ground water from the deep confined aquifer. Five wells drilled near the LNP will supplement the wetlands in times of need with up to 70 acre-feet (0.09 hm^3) of water available year-round.

Wetland Evaluation

Based on the wetland classification system developed by Cowardin and others (1979), all of the wetlands for this study are either lacustrine or palustrine wetlands (figure 9, appendix B). 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 2007 much of this area was exposed as Great Salt Lake levels fell to 4194 feet (1278 m) in October 2004, only 3 feet (1 m) above the record low of 4191 feet (1277 m) in 1963 (figure 10).

Because of the fluctuating lake level, wetlands and associated vegetation can vary year to year. In October and November 2006, the wetlands near wells 1, 2, and 3 (northern location, figure 1; appendix C) were all palustrine emergent transitioning from seasonally flooded (PEMC well 1), to semi-permanently flooded (PEMF, well 3). The vegetation here varied from grasses (well 1) to salt grasses (well 2) to cattail (*Typha* spp.) at well 3 where the water table was just beneath the surface. Wells 4 and 5 (southern location, figure 1; appendix C) were located within the FBWMA and classified as a palustrine emergent mosaic of semi-permanently (PEMF) to permanently flooded wetland (PEMH). The vegetation here included cattail (*Typha* spp.), hardstem bulrush (*Schoenoplectus acutus*), softstem bulrush (*Schoenoplectus tabernaemontani*), and phragmites (*Phragmites australis*).

Water Quality

We sampled water from two different areas in the Farmington Bay area–three wells in the north, near Kaysville, and two wells in the south, near Centerville (figure 1). The well locations and water chemistry for the samples collected from each well are presented in appendix C. The shallow ground water chemistry from wetlands in the northern Farmington Bay area near Kaysville (wells 1, 2, and 3) is variable. Well 1, the most upgradient well, has a TDS concentration of 1328 mg/L (Class II); well 2, the intermediate location-well, has a TDS concentration of 30,644 mg/L (Class IV); and well 3, nearest Great Salt Lake, has a TDS concentration of 5550 mg/L (Class III). The classes are based on the Utah Water Quality Board's TDS-based classification system (table 2). Dominant ion chemistry classification is sodium-chloride-type ground water for wells 2 and 3, and magnesium-bicar-

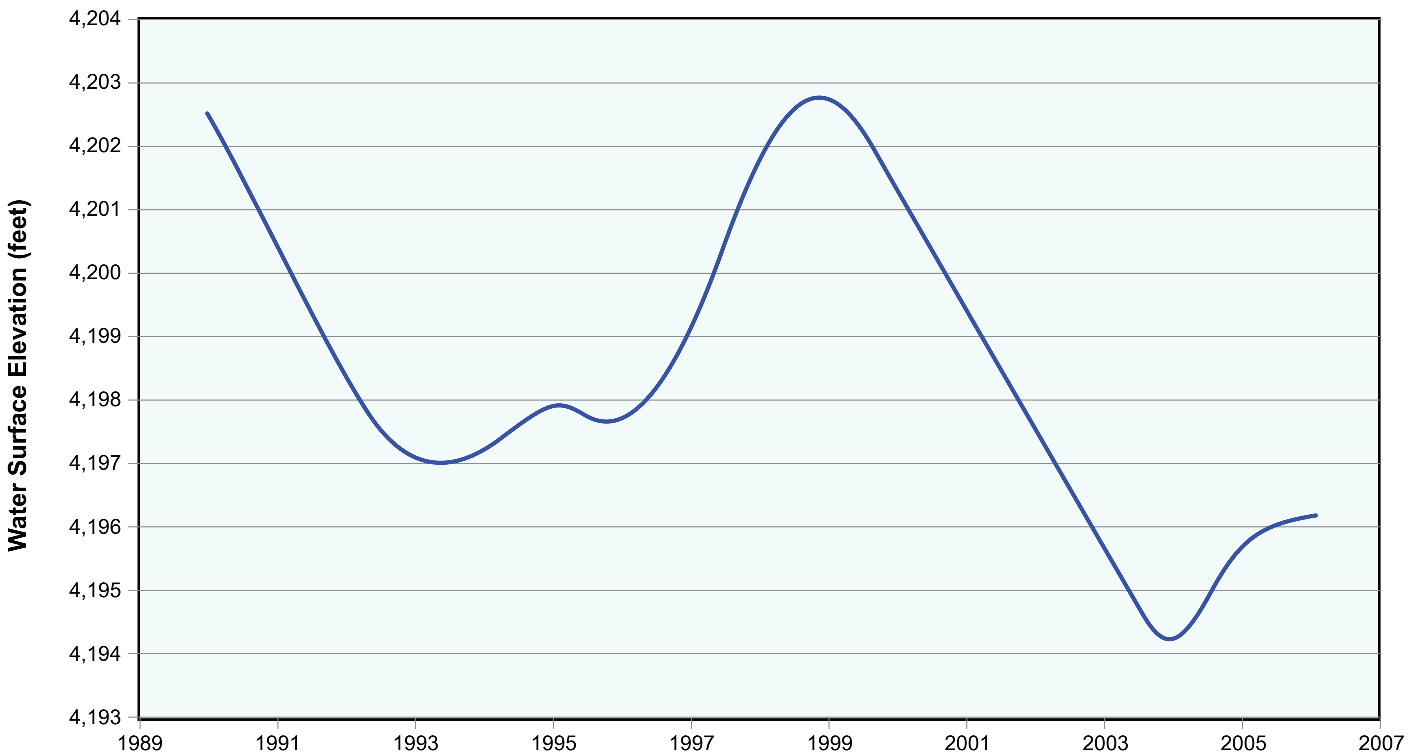


Figure 10. *Great Salt Lake monthly mean elevation from January 1990 to October 2006. Water surface elevation from USGS Saltair Boat Harbor gage (USGS station 1001000).*

bonate-type ground water for well 1 (figure 11). Arsenic is reported in all of the wells in the northern Farmington Bay area ranging from 114 to 617 μg/L, which exceeds the current ground-water quality (health) standard of 10 μg/L (U.S. EPA, 2008). A selenium concentration of 1582 μg/L in well 2 exceeds the EPA ground-water quality standard of 50 μg/L. Selenium can be associated with agricultural runoff and is a trace element found in many soils (Seiler and others, 2003); grazing in this area is common and the selenium may be associated with cattle grazing. Water from well 2 also contains iron having a concentration of 5270 μg/L that exceeds the EPA secondary water-quality standard of 300 μg/L. The arsenic, selenium, and iron data may be used to suggest that the ground water in the area has been influenced by nearby refining activities; further studies would be needed to confirm this suggestion.

Shallow ground water collected from wells in the southern Farmington Bay area wetlands near Centerville (wells 4 and 5, appendix C) varies in quality. Well 4, the most upgradient well, has a TDS concentration of 47,490 mg/L (Class IV), and well 5, nearest Great Salt Lake, has a TDS concentration of 5992 mg/L (Class III) (table 2). Dominant ion chemistry classification for wells 4 and 5 is sodium-chloride-type ground water (figure 11). Arsenic is reported in well 5 having a concentration of 66.5 μg/L, which exceeds the current ground-water quality (health) standard of 10 μg/L (U.S. EPA, 2008).

Most of the wetlands in the Farmington Bay area are in the area classified 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 (124.8 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 the Farmington Bay area are located along the margins of Great Salt Lake, which has been classified as a ground-water discharge area by Anderson and others (1994). In this area, ground water discharges to 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 change in discharge from these springs and seeps would alter and possibly degrade the wetlands. Additionally, the population in the Farmington Bay area is growing rapidly, and land use is becoming more residential and less agricultural. This change would likely decrease the amount of recharge from seepage of unconsumed irrigation water, which is an additional contributor to the total recharge to aquifers in the Farmington Bay area (Thomas and Nelson, 1948; Feth and others, 1966; Clark and others, 1990; Clark 1991). Public water suppliers in the Farmington Bay area rely primarily on ground water from the principal aquifer. As figure 1 shows, most of the wells in the area are upgradient of the wetland areas; 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.

Table 2. *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.

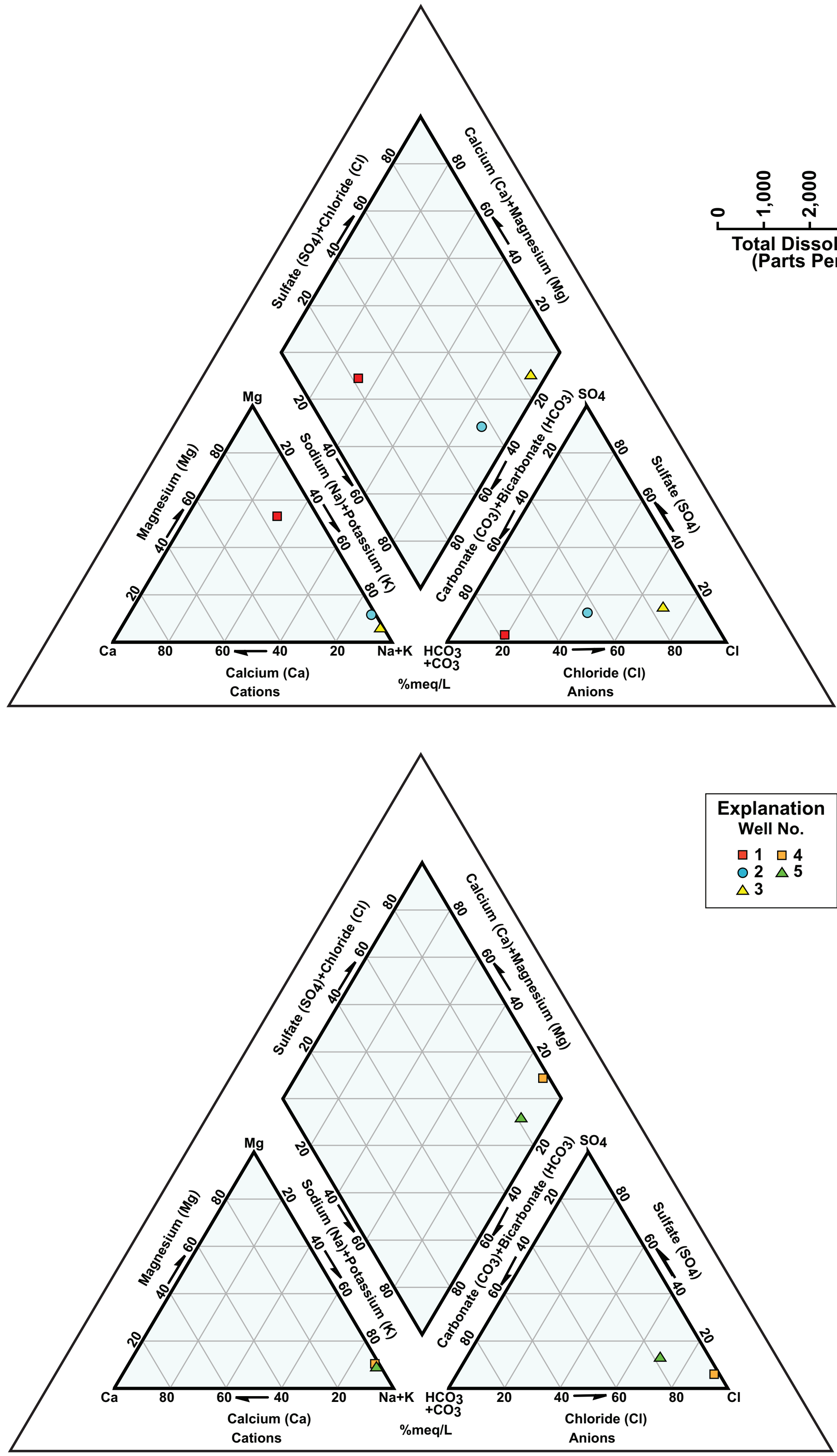


Figure 11. Piper diagram showing dominant ion chemistry classification for wells in the Farmington Wetlands (see appendix C for well number location).

Not only are wetlands in the Farmington Bay area 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 over an even longer time period, the level of Great Salt Lake may drop even further. Great Salt Lake is the farthest downgradient component of the hydrologic system in the Farmington Bay area and the surrounding drainage basins. The wetlands surrounding Great Salt Lake are immediately upgradient of the lake, so water-level changes in Great Salt Lake also affect the wetlands.

To evaluate the hydrology of the wetlands in the Farmington Bay area, we used steady-state and transient ground-water flow models developed by Clark and others (1990) and Clark (1991). We investigated the current (steady state) and historical water use of the wetlands and developed a water budget for the Farmington Bay area; 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. This ground-water model is the best available tool to understand how the wetlands in the Farmington Bay area could be affected by further development and/or drought.

Hydrologic Setting and Water Budget

Overview

To understand the hydrological complexity of the Farmington Bay wetland system we determined a water budget and used the regional, three-dimensional, steady-state and transient MODFLOW models of Clark and others (1990) and Clark (1991). The hydrology of the Farmington Bay wetlands is dominated by Great Salt Lake influences. Because the waters of Great Salt Lake are too saline for most wetland plant and wildlife species, preservation of much of the Farmington Bay wetlands is dependent on freshwater inflows (Christianson and Low, 1970). Freshwater inflows can vary seasonally, and are high in March through June because of snow melt and spring runoff, and low from September through January because of low precipitation and irrigation use. Freshwater flows into the wetlands are primarily in the form of ground water throughout much of the year. Low-lying areas of the wetlands may be periodically inundated by Great Salt Lake, resulting in saline surface water mixing with the fresh water that supplies the wetlands. Inflows of fresh water can also vary annually due to climatic conditions.

Great Salt Lake influences the hydrological regime of the wetlands by controlling water-table elevation and periodic flooding of wetland areas. The Farmington Bay wetlands are subject to the natural cycles of rising and falling lake levels. Historically, Great Salt Lake has fluctuated more than 20 feet (6 m); seasonally the lake fluctuates within a range of several feet. With variations in lake levels, large areas of mud flats are alternately submerged and exposed. During lake-level rises, or expansions, the lake margin in the Farmington Bay area moves eastward and additional areas are submerged and converted to open water. Wetlands along the fringe of the lake are regularly influenced by the lake's saline water. The spatial patterns of vegetation are an indication of this strong lake influence: sparse vegetation is mainly associated with areas most affected by lake-level variability, while uniform vegetation is typical of areas not flooded. At high lake levels, for example, 4212 feet (1284 m), 64 percent or more of the wetlands would be converted to open water.

The ground-water system in the east shore area is recharged through precipitation and applied water that infiltrates into the sediments in recharge areas. Clark and others (1990) estimated that 2 to 4 inches (5-10 cm) of annual average precipitation, 7 to 14 inches (18-36 cm) of irrigation water on cropland, and 2 to 4 inches (5-10 cm) of applied lawn and garden water infiltrates into the aquifer system in recharge areas; remaining water either becomes surface runoff or evaporates. Fresh water discharges from the east shore area by several mechanisms: (1) evapotranspiration, (2) well withdrawals, (3) direct flow to springs and seeps, (4) diffuse seepage along the shores of Great Salt Lake, and (5) probably some direct seepage into the lake.

The general ground-water system in the Farmington Bay wetlands area is shown on figure 5. The aquifer system in this area is unconfined along the mountain front, and unconfined and semi-confined away from the mountain front (Feth and others, 1966; Clark and others, 1990; Clark, 1991). Aquifers are recharged along the mountain front where vertical gradients exist; ground water then flows vertically and then laterally into the unconfined and semi-confined aquifers toward discharge areas in the lakeward-sloping east shore areas, such as springs, wetlands, marshes, and Great Salt Lake. Some of the water that moves laterally encounters the upper semi-confining unit, where some of the flow moves into the upper unconfined aquifer. The predominant movement of ground water is in a horizontal direction through aquifers and in a vertical direction through semi-confining units. Where the ground water encounters the saline ground water of Great Salt Lake, the less dense fresh water is forced upward. The upward-moving fresh ground water is again inhibited by semi-confining units, but eventually discharges into the wetlands.

Because surface-water stages and ground-water levels in the wetlands are lower than the surface-water stages and ground-water levels in topographically higher areas, ground water and surface water flows into the wetlands. The rate of water exchange between the Farmington Bay wetlands and the upgradient aquifers is proportional to the hydraulic gradients, transmitting character, and cross-sectional areas through which flow occurs. Water levels in the wetlands fluctuate throughout the year in response to the amount of recharge and discharge from the system. Water-level declines in the spring and summer indicate the effects of increased evapotranspiration. Upward seepage of ground water into the wetlands has been established from water-level data and regional ground-water flow modeling (Clark and others, 1990; Clark, 1991).

The Farmington Bay wetlands depend on a supply of fresh water that varies considerably, primarily due to variation in precipitation that falls in the form of rain or snow on the slopes of the Wasatch Range. Difficulties in measuring water inflows, outflows, and changes in storage complicate our understanding of the Farmington Bay wetland hydrology. We developed a simple hydrologic budget to quantify the volume and rate of water flowing into and out of the aquifer system in the vicinity of the Farmington Bay wetlands. The evaluation identifies key components of the hydrologic system, describes their interaction, and quantifies their spatial and temporal variations. The hydrologic budget of a wetland area is an expression of the conservation of water mass by an accounting of inflow to and outflow from the system during a given time period. We used the budget to investigate components of the hydrology system and provide the framework for understanding and interpreting other wetland functions.

To describe a generalized hydrologic budget for the wet-[1]lands area along Great Salt Lake in the vicinity of Farmington Bay, inflow must equal the outflow plus or minus the change in storage:

$$Inflow = Outflow \pm \Delta storage$$

[2]

The inflows and outflows themselves consist of several components. For a given time period, a component water budget for the Farmington Bay wetlands area in equation form is:

$$R + S_i + G_i = ET + S_o + G_o + \pm \Delta storage$$

where R is infiltration and recharge from precipitation, irrigation field runoff, and seepage from associated canals; S_i is surface inflow; G_i is ground-water inflow; ET is evapotranspiration; S_o is surface outflow, or diversions leaving the wetlands to Great Salt Lake; G_o is ground-water outflow; and Δstorage is change in storage (including surface water, soil moisture and ground water). However, we are evaluating the wetlands area at steady-state conditions, so there is no change in storage. Terms in a wetlands-area hydrologic budget vary in significance depending on the wetlands. In the Farmington Bay wetlands area, surface-water and ground-water inflow, and subsurface ground-water outflow and evapotranspiration, are significant components of the hydrologic budget.

Recharge

Recharge in the Farmington Bay wetlands area is dependent on time, quantity of water available, and uses by vegetation. In some areas, such as mud flats or other areas that are almost devoid of vegetation, net infiltration may occur during unusually wet periods when rainfall or local runoff exceeds evapotranspiration. Infiltration to the water table in the wetlands area where the water table is near the land surface may also occur during some months (October and April) when precipitation exceeds evapotranspiration. Irrigated fields that are in or directly upgradient of the wetlands area also contribute water to the ground-water system. Clark and others (1990) estimated that about 4 feet (1.2 m) of water per year is used to irrigate agricultural fields in the east shore area; however, the irrigation water is not evenly distributed throughout the area, and many areas are not irrigated.

We estimate, based on precipitation amounts and the areas of irrigated fields, that an average of 1.8 inches (4.5 cm) per year of water recharges the shallow aquifer in the wetlands area. The surface area of the Farmington Bay wetlands area multiplied by this depth indicates that about 6000 acre-feet (7.4 hm^3) of precipitation and irrigation water recharges the wetlands area annually. Uncertainties in the estimated amount of precipitation from rain and snow can result from measurement errors and from methods of data manipulation. Winter (1981) suggested that precipitation measurement error, assuming a worst possible estimate of precipitation, results in an overall uncertainty of about 30 percent. Irrigation runoff is subject to similar uncertainties in measurement error.

We used Darcy's law to estimate subsurface inflow into the wetlands area from topographically upgradient sources.[3] By estimating hydraulic conductivity, hydraulic gradient, and cross-sectional area (table 3), an estimate of the subsurface inflow per day per length at the edge of the wetlands can be obtained using the following equation:

$$G_i = KiA$$

where G_i is discharge (l/t), K is the saturated hydraulic conductivity (l/t), i is the hydraulic gradient (l/l), and A is the cross-sectional area. Area is calculated as an assumed saturated depth of sediments multiplied by a length of the perimeter around the wetlands. The hydraulic conductivities and hydraulic gradients used in calculating subsurface inflow are from Clark and others (1990). Using these estimates, about 16,000 acre-feet per year (20 hm^3/yr) of ground water enters the subsurface below the wetlands area. Uncertainties in estimating subsurface inflow are dependent on errors of the various components of Darcy's equation; hydraulic conductivity has the largest uncertainty. Uncertainties associated with subsurface inflow estimates can be plus or minus about two orders of magnitude (Hunt and others, 1996).

The flow of surface water into the Farmington Bay wetlands varies from year to year depending on mountain precipitation. Numerous perennial streams begin on the western slopes of the Wasatch Range, but become ephemeral and intermittent in the valley and flow only during spring runoff. However, during periods of high water flow, water reaches the lower valley floor. Stream discharge above the Farmington Bay wetlands is not gaged routinely; six of the largest streams above the Farmington Bay wetlands were gaged between 1969 and 1984 at the mountain front (Clark and others, 1990), and the data collected demonstrate that fluctuations in annual flow can be significant. Additional surface-water inflow to the wetlands was estimated by correlation of short-term records with longer term stream-flow records. Surface-water flow that reaches the Farmington Bay wetlands area probably averages about 16,000 acre-feet per year (20 hm^3/yr). This value is subject to error as a result of the use of different data sources (gaged and ungaged streams, etc.), and uncertainties may be as high as 70 percent (Winter, 1981).

The Jordan River is the largest source of surface water into Farmington Bay, and supplies water to the FBWMA through the Jordan Canal. However, the Jordan River is the western (downgradient) boundary of the Farmington Bay wetlands area, and is considered to have little or no influence on the overall wetlands area hydrology. Because the Jordan River does not contribute subsurface flow to the wetlands ground-water system, it was not considered in the budget.

Table 3. *Estimated subsurface inflow into the Farmington Bay wetlands.*

*Hydraulic Conductivity (ft/day)	*Average Hydraulic Gradient (dimensionless)	Length of section line (ft)		**Calculated ground-water inflow	
				ft^3/day	Acre-feet/year
18	0.00089	19,050		-305,000	-2500
12	0.0032	17,500		-672,000	-5500
17	0.0016	35,400		-963,000	-8000
			total	-1,940,000	-16,000

Negative numbers indicate ground-water flow into the wetlands
*from Clark and others (1990)
**based on an assumed saturated thickness of 1000 feet

Discharge

The largest water-budget component in the Farmington Bay wetlands is evapotranspiration. The Farmington Bay wetlands monthly evapotranspiration was determined by adjusting values from class A evaporation pans in areas along Great Salt Lake (Christiansen and Low, 1970). In the Bear River Migratory Bird Refuge, north of the Farmington Bay wetlands area, pan evaporation is highest in April through September and lowest in November through January (Christiansen and Low, 1970). This pattern of high summer and low winter pan evaporation is also expected in the Farmington Bay wetlands area. The average annual evapotranspiration rate in the Farmington Bay wetlands area is estimated to be about 60 inches (150 cm) per year based on the adjusted class A pan evaporation data and on data in Clark and others (1990). We estimated evapotranspiration in the Farmington Bay Wetlands by adding together monthly approximations of evapotranspiration for areas, as defined in Clark and others (1991) and Clark (1991), where evapotranspiration are believed to be significant. The uncertainties in evapotranspiration values calculated from pan evaporation data may be as high as 20 percent (Winter, 1981).

Surface-water outflow from the wetlands area into Great Salt Lake is complicated by the FBWMA's dikes and changing shoreline. There are no estimates of water release from the ponds via the dike-outlet channel. All stream flow gages are located upstream of the wetlands, leaving the wetlands area ungaged. Waddell and Fields (1977) estimated surface outflow to be about 15,000 acre-feet per year (18 hm^3/yr) from the wetlands area to Great Salt Lake for the 1931 to 1973 time period by correlating short-term records for sites near the lake with longer term records for upstream sites. We assume this is an averaged number and apply it here. Surface-water discharge estimates from short-term records correlated with gaged upstream sites may have uncertainties as high as 70 percent (Winter, 1981).

Subsurface outflow from the Farmington Bay wetlands area to Great Salt Lake is likely small, and is difficult to distinguish from other sources of inflow to Great Salt Lake. The subsurface seepage from the wetlands to Great Salt Lake is small because of the high density contrast between the fresh ground water and the saline water of Great Salt Lake, which limits mixing of the two. As fresh ground water moves toward the lake, flow paths are sharply deflected upward by density gradients. Consequently, ground water discharges from the unconfined aquifer adjacent to, but landward of, the saline-freshwater interface. Mixing of fresh ground water and interstitial saline water results in the higher dissolved-solids concentrations found in the area. Clark and others (1990) estimated that about 20,000 acre-feet per year (25 hm^3/yr) of subsurface ground water flows out of the wetland areas along Great Salt Lake. As reported by Clark and others (1990), this discharge is probably overestimated because they used a freshwater model of the area. Waddell and Fields (1977) estimated subsurface outflow from the Farmington Bay wetlands area to Great Salt Lake to be about 2000 acre-feet per year (2.5 hm^3/yr), which is the value we use for this study.

Well discharge in the east shore area includes discharge from both pumping and flowing wells. The total quantity of ground-water pumpage varies each year depending on the need. Not all the ground water pumped from wells is consumed; some water returns to the aquifer, particularly in the low valley areas where depth to water is only a few feet below land surface. Net well discharge from the Farmington Bay wetlands area was considered insignificant by Clark and others (1990).

Resulting Budget

The estimated hydrologic budget for the Farmington Bay wetlands is summarized in table 4. This is an overall water budget, summarizing sources of inflow to and outflow from the wetlands. Development of this hydrologic budget involved using data from a number of sources covering different time periods, but represents averaged conditions for the hydrologic system. We believe these averaged conditions are representative of steady-state conditions for the hydrologic system in the Farmington Bay wetlands area.

Review of Models

We used the models of Clark and others (1990) and Clark (1991) to simulate the freshwater hydrologic system for the Farmington Bay wetlands area. We conceptualize the hydrologic system represented by these models as having five parts: (1) an unsaturated zone affected by precipitation and evapotranspiration (not included in the models), (2) a

Table 4. Estimated hydrologic budget for the Farmington Bay wetlands.

Water-budget component		(acre-feet per year)
Recharge		
Infiltration from precipitation, and irrigation runoff		6000
Surface inflow		16,000
Ground-water inflow		16,000
	Total	38,000
Discharge		
Evapotranspiration		21,000
Surface outflow		15,000
Ground-water outflow		2000
	Total	38,000

shallow unconfined aquifer system that interacts with the unsaturated zone (not modeled explicitly), (3) a principal aquifer that is both confined and unconfined, (4) a surface-water system that supplies water to the basin-fill aquifer, and (5) a surface-water system consisting of Great Salt Lake, but modeled as fresh water. Modeled recharge to the basin-fill ground-water flow system is from subsurface inflow from consolidated rock in the surrounding mountains, seepage from stream-channel deposits where streams enter the valley, and infiltration of irrigation and precipitation on the upper bench of the valley. Modeled discharge from the basin-fill aquifer is primarily from springs and drains, evapotranspiration, and subsurface discharge to Great Salt Lake.

Clark and others (1990) and Clark (1991) used the "quasi" three-dimensional ground-water flow code MODFLOW, developed by McDonald and Harbaugh (1988), which uses standard finite-difference techniques to approximate the partial differential equations describing saturated anisotropic, heterogeneous, and layered ground-water flow. These ground-water flow models, referred to as the Weber Delta and Bountiful steady-state and transient models, were calibrated and verified by Clark and others (1990) and Clark (1991) for 1955 (steady-state) and 1956 to 1985 (transient-state) conditions for the Weber Delta area, and 1946 (steady-state) and 1947 to 1986 (transient-state) conditions for the Bountiful area. We converted the Weber Delta models (Clark and others, 1990), which were created with MODFLOW 1988, to MODFLOW 2000 (Harbaugh and others, 2000). The Bountiful area models (Clark, 1991) had already been converted to MODFLOW 2000 by the Utah Division of Water Rights.

Clark and others (1990) and Clark (1991) used a technique referred to as a distributed-parameter approach to simulate observed spatial and temporal variations in the models. Even when using a distributed-parameter approach, not all characteristics of the actual aquifer system were included in the ground-water flow models. Simplifying assumptions are required to make the modeling effort manageable (Anderson and Woessner, 1992). Many of the assumptions used in developing the Weber Delta and Bountiful ground-water flow models are characteristic of numerical ground-water flow models (Wang and Anderson, 1982; Anderson and Woessner, 1992; Harbaugh and others, 2000). Additional assumptions made in the application of the MODFLOW computer program to the Weber Delta and Bountiful aquifer systems are discussed in Clark and others (1990) and Clark (1991).

Clark and others (1990) used a finite-difference grid of 32 rows, 28 columns, and 3 layers in the Weber Delta area, and Clark (1991) used a finite-difference grid of 67 rows, 36 columns, and 2 layers in the Bountiful area. The models were oriented so that their grid's long axis parallels the Wasatch Front. Each grid cell was assigned values that represent the average aquifer characteristics and hydrologic stresses for that area. The area of active cells in the models corresponds approximately with basin-fill materials of Quaternary age, and represents the shallow aquifer, shallow confining layer, and principal aquifer of the Weber Delta and Bountiful areas.

Cells representing consolidated rock were, for the most part, considered to have a lower permeability than the basin fill, and for the purposes of the models were designated inactive. However, some cells representing consolidated rock along the mountain front were designated as a specified-flux boundary, used to simulate recharge from bedrock, and were active. Head-dependent relations were used to simulate springs and evapotranspiration interaction with the aquifer system. Constant-head cells were used along the western side of the models to simulate the interaction between ground water and Great Salt Lake, and between ground water and the Jordan River. Specified flux terms were used to approximate discharge from wells and recharge from precipitation, streams, canals, and ditches. The upper aquifer was designated as unconfined to represent the water table, and some of these cells were assigned a specified flux to represent recharge. The bottoms of the models are either rock, the top of a partly consolidated unit, or an arbitrary depth based on the depth of production wells, and is modeled as a no-flow boundary.

Boundary conditions are designed to approximate the physical system of the Weber Delta and Bountiful areas. The shallow unconfined aquifer is represented by layer 1 of the models and is simulated as it relates to underlying layers; this means that layer 1 was used to simulate discharge from the underlying aquifer system and not discharge or recharge from the wetlands explicitly. Recharge to layer 1 is from subsurface flow only. The unconfined aquifer is represented as a variable-head boundary overlying the confined-aquifer system.

Division of the aquifer system into hydrogeologic units and model layers was more arbitrary than the selection of boundary conditions. Layer 1 in the models represents a source for discharge from lower layers. In the topographically lower areas along Great Salt Lake, the shallow water-table aquifer was not considered part of the principal aquifer by Clark and others (1990) and Clark (1991). The areal extent of layer 1 is limited to the western and lower parts of the models. Layer 2 in the Bountiful area, and layers 2 and 3 in the Weber Delta area, represent the principal aquifer. In layers 1 and 2, where layer 2 is unconfined in the eastern part of the models, transmissivity is allowed to vary spatially as a function of saturated thickness of the layer. In parts of layer 2 in the Weber Delta and Bountiful areas, and in layer 3 in the Weber Delta area, transmissivity was specified for each cell in the simulations, and the saturated thickness of the layers is assumed to remain constant. In the Weber Delta area, layers 2 and 3 are each 150 feet (46 m) thick, but where unconfined layer 2 may vary from 50 to 400 feet (15-120 m) thick. Flow between the layers was approximated by a relation that uses calculated heads in vertically adjacent cells and an estimate of vertical conductance between cells. Vertical conductance is calculated from vertical hydraulic conductivity, thickness between layers, and horizontal area of the cell.

Clark and others (1990) and Clark (1991) concluded that the results of available field tests did not accurately represent the transmissivity of the principal aquifer, and used known values to estimate probable ranges of hydraulic conductivity to derive the transmissivities that were actually used in the models. The hydraulic properties of the aquifers and confining units are not uniform throughout the model area. Hydraulic properties for layer 1 in the models are based on the hydraulic properties of the principal aquifer. Calibration of the ground-water flow models involved a trial-and-error adjustment of model parameters representing aquifer characteristics and certain recharge and discharge components to obtain an acceptable match between measured ground-water levels and computed heads. Hydraulic characteristics that vary spatially in these analyses are transmissivity, storage coefficient, and vertical leakance. Values for these parameters were estimated from available measurements of physical and hydrologic properties.

Modeling Results

We used the steady-state and transient ground-water flow models, which used historical data, to represent the amount of water received by the Farmington Bay wetlands during a typical steady-state year, and how changing recharge and discharge in the east shore area affects the amount of water entering the study area. The model simulations provide ground-water-flow data in relation to approximate aquifer characteristics, water in storage, and rates of inflow and outflow for the principal aquifer in the wetlands area.

We evaluated the amount of water received under steady-state conditions by combining the 1955 calibrated steady-state model of the Weber Delta area by Clark and others (1990), and the 1946 calibrated steady-state model of the Bountiful area by Clark (1991). Clark and others (1990) and Clark (1991) assumed hydrologic conditions in 1955 and 1946 were near steady-state conditions for each area. Water levels fluctuated both seasonally and annually in each area prior to 1955 and 1946, respectively, but the changes were small (Clark and others, 1990; Clark, 1991). We therefore assume that the 1955 calibrated model was also at steady-state condition in 1946 and combined the two. We used the simulated results from the upper model layer to represent the Farmington Bay wetlands because it is the part of the model related to the wetland area. Even though the models did not explicitly represent the wetlands area, we assume recharge to layer 1 is related to the actual aquifer recharge because the models were calibrated to water levels that included wells in the lower elevations of the basin.

Based on the results of the steady-state simulations, the Weber Delta area receives about 100,000 acre-feet per year (120 hm^3/yr) and the Bountiful area about 25,000 acre-feet per year (30 hm^3/yr) of recharge to the basin-fill aquifer. Of this recharge, about 45,000 acre-feet per year (55 hm^3/yr) in the Weber Delta area and 13,000 acre-feet per year (16 hm^3/yr) in the Bountiful area occurs along the mountain front. This mountain-front recharge is from either stream flow entering the model areas or a constant recharge that correlates to inflow from bedrock. In the models, all stream flows in the Weber Delta and Bountiful areas recharge the basin-fill aquifer along the mountain front. Recharge from precipitation and unconsumed irrigation water on the benches is about 11,000 acre-feet per year (14 hm^3/yr) in the Weber Delta area, and 3000 acre-feet per year (4 hm^3/yr) in the Bountiful area. For the Weber Delta and Bountiful areas combined, discharge of ground water from springs and drains is about 45,000 acre-feet per year (55 hm^3/yr), evapotranspiration from the valley floor is 5000 acre-feet per year (6 hm^3/yr), subsurface flow to Great Salt Lake is 32,000 acre-feet per year (39 hm^3/yr), and well discharge is 35,000 acre-feet per year (43 hm^3/yr). The steady-state simulations indicate water levels in model layer 2 have a similar pattern, but are generally higher than water levels in layer 1 in the lower valley areas. This trend indicates upward flow from layer 2 to layer 1.

To evaluate ground-water changes in the Farmington Bay wetlands area, we needed to evaluate ground-water conditions after steady-state conditions no longer exist in areas surrounding the wetlands. To evaluate these conditions, we used the transient models of Clark and others (1990) and Clark (1991), which simulated the periods 1956-85 and 1947-86, respectively; these models used historical ground-water withdrawals and natural variations in recharge for the simulation periods. The transient simulations were during a period when recharge was variable, and pumpage for public water supplies was increasing. Recharge in both models varied from periods of less-than-normal to greater-than-normal precipitation, and additional water was imported into the area from the Weber River after 1960.

Based on the results of the transient-state simulations, about 115,000 acre-feet per year (142 hm^3/yr) of water recharges the basin-fill aquifer in the Weber Delta area and about 28,000 acre-feet per year (34 hm^3/yr) recharges the basin-fill aquifer in the Bountiful area at the end of both transient simulations. This is about an 18 percent increase over the steady-state simulation. Discharge from pumping and flowing wells increased to about 66,700 acre-feet per year (82 hm^3/yr) (48,300 acre-feet [60 hm^3] in the Weber Delta and 18,400 acre-feet [22 hm^3] in the Bountiful area) at the end of the transient simulations. This is about a 50 percent increase over steady-state conditions. Spring and drain discharge remained about the same as in the steady-state simulations, about 45,500 acre-feet per year (56 hm^3/yr) (36,000 acre-feet [44 hm^3] in the Weber Delta and 9500 acre-feet [12 hm^3] in the Bountiful area). Evapotranspiration increased to 6800 acre-feet per year (8 hm^3/yr) (5000 acre-feet [6 hm^3] in the Weber Delta and 1800 acre-feet [2 hm^3] in the Bountiful area) at the end of the transient simulations. The results of the transient simulations show water-level declines in the shallow unconfined aquifer (layer 1 of the models) that are generally less than 5 feet (1.5 m) in areas near the Farmington Bay wetlands area, but water-level declines are more than 10 feet (3 m) in some areas upgradient of the study area. Increased recharge in the transient simulations is probably due to the extremely wet years that occurred in the later part of the modeled period. Although the transient models simu-

Table 5. Average annual simulated ground-water recharge and discharge for the basin-fill aquifer in the Weber Delta and Bountiful areas, Davis and Salt Lake Counties, Utah.

	Water-budget component	Steady-state simulations Estimated quantity (acre-feet per year)	Transient-state simulations Estimated quantity (acre-feet per year)
Recharge			
	Subsurface inflow	125,000	143,000
Discharge			
	Great Salt Lake	32,000	25,000
	Springs and drains	45,000	45,500
	Evapotranspiration	5000	6800
	Pumping and flowing wells	35,000	66,700

late more recharge than the steady-state models, they also simulate more discharge. The additional discharge is taken out of aquifer storage.

Table 5 shows the average annual ground-water recharge and discharge for the steady-state and transient-state simulations. In the transient simulation, recharge during the late 1950s and early 1960s was less than normal, and water levels in many areas declined due to decreased recharge and increased well discharge. In the normal to wet conditions in the late 1960s through 1984, many areas of the valley had a rise in simulated water levels, but the simulated water levels declined elsewhere in the valley. Large withdrawals have caused the water levels in some areas to decline below the land surface, thereby causing some wells to cease flowing in the lower valley. This duality of response is typical of the complexity observed in the hydrologic system. The overall difference between the two budgets (steady state and transient state) is due to variation in recharge, with recharge being higher during the later part of the transient-state modeled periods. The differences between recharge and discharge in the budget are due to the combining of the two models and how the models treat each component. Discharge from the basin-fill aquifer in the east shore area increased at the end of the transient simulations by about 50 percent, but natural discharge (outflow to Great Salt Lake, springs and drains, and evapotranspiration) decreased by only about 6 percent.

Water-Budget Scenarios

The valley-wide ground-water flow models were used to evaluate selected hypothetical alternative water-budget scenarios for the Farmington Bay wetlands area. The specific hypothetical alternatives were chosen based on evaluations of the Tooele Valley wetlands (Burk and others, 2005). The scenarios are (1) the steady-state budget, (2) the transient water budget under historical conditions, (3) the transient water budget under increased well discharge, (4) the transient water budget under drought conditions, (5) the transient water budget under drought conditions and lower Great Salt Lake levels, and (6) the transient water budget under wetter-than-normal conditions.

Scenario 1 – steady-state conditions: In the first scenario, we evaluated the average conditions (steady state) of the aquifer system, and how much water the wetlands area receives under these average conditions. The Farmington Bay wetlands area is represented by part of layer 1 in both models. In this simulation, the wetlands area receives about 23,300 acre-feet per year (28 hm^3/yr) of ground-water recharge as subsurface inflow. The wetlands area aquifer discharges about 2500 acre-feet per year (3 hm^3/yr) by evapotranspiration, 16,400 acre-feet per year (20 hm^3/yr) by springs and drains, and 4400 acre-feet per year (5 hm^3/yr) by subsurface ground-water outflow. As shown in table 6, recharge is equal to discharge under steady-state conditions in the wetlands area.

Scenario 2 – transient-state, historical conditions: To evaluate the effects of historical conditions compared to steady-state conditions in the Farmington Bay wetlands area, we used the transient models. The Weber Delta and Bountiful models use historical ground-water withdrawals and variations in recharge for 25- and 30-year periods, respectively. The results of this scenario show water-level change in the shallow unconfined aquifer in the area of the wetlands was generally less than 5 feet (1.5 m). The aquifer in the Farmington Bay wetlands area, under transient-state conditions, receives about 21,400 acre-feet per year (26 hm^3/yr) of ground-water recharge as subsurface inflow. The aquifer in the wetlands area discharges about 1500 acre-feet per year (2 hm^3/yr) by evapotranspiration, 14,100 acre-feet per year (17 hm^3/yr) by springs and drains, and 7400 acre-feet per year (9 hm^3/yr) by subsurface ground-water outflow. Under these conditions, recharge from subsurface inflow to the Farmington Bay wetlands area is reduced by 8 percent compared to steady-state conditions, while discharge from the Farmington Bay wetlands area is reduced by only 1 percent (table 7).

Scenarios 3 through 6 – transient-state, future conditions: To evaluate future conditions, we used a 20-year additional time period applied to each transient ground-water flow model (Weber Delta area [Clark and others, 1990] and Bountiful area [Clark, 1991]) for the east shore area to simulate additional stress on the wetlands area aquifer. We used these projected transient ground-water flow models to evaluate the final four hypothetical scenarios for the Farmington Bay wetlands area. However, because ground-water flow in the east

Table 6. *Steady-state budget for the Farmington Bay wetlands area.*

Water-budget component		(acre-feet per year)
Recharge		
Subsurface inflow		23,300
	Total	23,300
Discharge		
Evapotranspiration		2500
Springs and drains		16,400
Ground-water outflow		4400
	Total	23,300

Table 7. *Transient-state budget under historical conditions for the Farmington Bay wetlands area.*

Water-budget component		(acre-feet per year)
Recharge		
Subsurface inflow		21,400
	Total	21,400
Discharge		
Evapotranspiration		1500
Springs and drains		14,100
Ground-water outflow		7400
	Total	23,000

shore area is complex, the hypothetical scenarios simulated valley-wide conditions.

The third scenario evaluated what would happen to the Farmington Bay wetlands area aquifer if pumping of public and industrial wells continued to increase to meet population-growth demands in the east shore area. Projective simulations were conducted by increasing municipal and industrial well pumpage over the additional 20-year period. An average annual increase in historical pumpage rate for municipal and industrial wells for the time period between 1980-85 (about 32,800 acre-feet per year [40 hm^3/yr]; 23,400 acre-feet [29 hm^3] per year in the Weber Delta area and 9400 acre-feet [11 hm^3] per year in the Bountiful area) was used as the annual rate of increase in municipal and industrial well discharge in the models. This discharge about doubled the withdrawals from municipal and industrial wells at the end of this simulation. We simulated normal recharge by using an average annual recharge rate of 108,000 acre-feet per year (133 hm^3/yr) in the Weber Delta area and 24,000 acre-feet per year (30 hm^3/yr) in the Bountiful area. Under this scenario, the Farmington Bay wetlands area receives about 18,700 acre-feet per year (23 hm^3/yr) of recharge as subsurface inflow (table 8). Wetlands-area discharge is about 14,100 acre-feet per year (17 hm^3/yr) from springs and drains, 1450 acre-feet per year (2 hm^3/yr) from evapotranspiration, and 3500 acre feet per year (4 hm^3/yr) from subsurface outflow (table 8).

Under this ground-water development scenario, recharge as subsurface inflow to the wetlands area decreases by an additional 13 percent compared to the transient simulations using historical conditions, because of increased well withdrawals under average annual recharge. Compared to the transient simulations under historical conditions, discharge from the wetlands area by springs and drains remains the same, discharge by evapotranspiration decreases by about 3 percent, and subsurface flow out of the wetlands is reduced by 53 percent.

In the fourth scenario, we simulated drought conditions using the projected transient models by reducing all basin-fill recharge by an arbitrary 20 percent. This results in a recharge as subsurface inflow to the Farmington Bay wetlands area of 18,000 acre-feet per year (22 hm^3/yr), a decrease of 16 percent compared to the transient simulations under historical conditions (table 8). Under this scenario, discharge from springs and drains is about 14,000 acre-feet per year (17 hm^3/yr), a 1 percent decrease compared to the transient simulations under historical conditions; evapotranspiration is about 1400 acre-feet per year (2 hm^3/yr), a 7 percent decrease; and about 6300 acre-feet per year (8 hm^3/yr) leaves the area through subsurface outflow, a decrease of about 15 percent (table 8). Water levels declined throughout

Table 8. *Average annual ground-water recharge and discharge for the Farmington Bay wetlands area for scenarios 2 through 6.*

	Recharge (acre-feet per year)	Discharge (acre-feet per year)		
	Subsurface inflow	**Springs and drains**	**Evapotranspiration**	**Subsurface outflow**
Scenario 2 (historical conditions)	21,400	14,100	1500	7400
Scenario 3 (increased well discharge)	18,700	14,100	1450	3500
Scenario 4 (drought conditions)	18,000	14,000	1400	6300
Scenario 5 (drought & lower GSL level)	17,800	200	0	17,000
Scenario 6 (wetter-than-normal conditions)	22,400	15,500	1800	4700

the simulated areas, but declines were less than 5 feet (1.5 m) in the wetlands area. The reduced recharge in this scenario results in reduced spring discharge and evapotranspiration.

We further simulated drought conditions in the fifth scenario by using the projected transient model and reducing all basin-fill recharge by 20 percent and lowering Great Salt Lake water levels 10 feet (3 m). Great Salt Lake was lowered from the 4200-foot (1280 m) level used at the end of the transient simulation based on historical data, to 4190 feet (1277 m) at the end of this projected transient simulation. This was accomplished by lowering the general head boundaries, which represent lake levels in the models; this did not change the locations of the boundaries in the models. Analysis of a greater change in average recharge and lake level would require reinterpretation of the models. The effects of this scenario on recharge and discharge in layer 1 in the Farmington Bay wetlands area are presented in table 8. In this simulation, the Farmington Bay wetlands area receives 17,800 acre-feet per year (22 hm^3/yr) of recharge as subsurface inflow, about 17 percent less than in the transient simulation using historical data. Discharge from springs and drains is reduced to 200 acre-feet per year (0.2 hm^3/yr), a decrease of 99 percent compared to the transient simulations under historical conditions; evapotranspiration drops to zero; and subsurface outflow from the wetlands area increases to 17,000 acre-feet per year (21 hm^3/yr), an increase of 130 percent. For this simulation, water levels in the wetlands area drop more than 10 feet (3 m), which would result in springs drying up and ground-water levels below the reach of phreatophyte roots. Because fresh water in the shallow unconfined aquifer becomes lower in elevation than Great Salt Lake, salt water intrusion may also occur in the aquifer.

Finally, in the sixth scenario we simulated what would happen if average recharge is increased using the projected transient model. Here we used the projected transient simulation with 20 percent increased recharge. The effect on recharge and discharge in layer 1 in the Farmington Bay wetlands area is presented in table 8. In this simulation, the wetlands area receives about 22,400 acre-feet per year (27 hm^3/yr) as subsurface inflow, a 5 percent increase in recharge compared to the transient simulations under historical conditions. Discharge from the wetlands area by springs and drains is about 15,500 acre-feet per year (19 hm^3/yr), an increase of 10 percent compared to the transient simulations under historical conditions; evapotranspiration increases to 1800 acre-feet per year (2 hm^3/yr), a 20 percent increase; and subsurface outflow decreases to 4700 acre-feet per year (6 hm^3/yr) (due to the increased evapotranspiration and discharge to springs in the wetlands area), a decrease of 36 percent reflecting the rise of the water table in the wetlands area, causing surface inflow to Great Salt Lake.

Conclusions from Water-Budget Modeling

Three-dimensional steady-state and transient-state ground-water flow models were used to simulate six scenarios for estimating present and future impacts of urban development and climate change on ground-water conditions in the Farmington Bay wetlands area. The wetlands in the Farmington Bay area 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 the east shore area of Great Salt Lake. As with all models, the ground-water flow models of the east shore area 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. The fact that the models predict or suggest a situation does not necessarily mean that situation will occur. However, the models offer the best tool that we have for evaluating something as complex as 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.

Hydrologic conditions are extremely important for the maintenance of the Farmington Bay wetlands. The water-budget analysis we conducted quantifies the amount of water flowing into and out of the Farmington Bay wetlands area, at least according to the ground-water flow models. The models assume that recharge to the wetlands area occurs only in the subsurface, which causes an underestimation of recharge and discharge in the ground-water flow models.

Our modeling results suggest that recharge as subsurface inflow to the wetlands area 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 when considering the drop in Great Salt Lake level that would occur during such a drought. The model suggests that a change to wetter-than-normal conditions would increase recharge as subsurface inflow to the wetlands area, 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 the east shore area causes a reduction in recharge to the wetlands area, but most of the change is accounted for by reduced subsurface outflow from the wetlands area. Development in the east shore area has some effect on recharge to the wetlands area, as shown by the reduced recharge from the steady-state condition 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 pressures for more development and the likelihood of periodic drought, this combined scenario seems likely. If this combined scenario occurs, the loss of recharge to the Farmington Bay wetlands area would most likely result in a decrease of the functionality of the wetlands; 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 it is up to the local community to identify the threats posed to local wetlands, and to develop a plan for preserving and managing the wetlands. To meet this federal policy, the Farmington Bay wetlands area should be managed to maintain its current water budget, estimated to include 38,000 acre-feet per year (47 hm^3/yr) of recharge from all sources, of which 16,000 acre-feet per year (20 hm^3/yr) is subsurface inflow (table 4). To reduce the potential for degradation of the Farmington Bay wetlands, restrictions could be placed on the areas of development, such as allowing development only in upland environments or placing a non-development buffer around the wetland areas. Another option could be to restrict development to only the more beneficial land uses. Overall, agricultural land use is more beneficial to wetland health and functionality than industrial and urban land use. If local governments intend to allow continued development in these areas, allowing only 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 Farmington Bay area wetlands. Wastewater from municipal sewers, where possible, could be reused or discharged to the environment upgradient of the wetlands, preserving this water for wetland use. Enactment 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 studies indicate the wetlands in the Farmington Bay area are endangered. The threats posed are drought and increased development due to population growth, which could dramatically affect the amount of water that the wetlands receive. We cannot predict changes in climate with certainty, but we can plan appropriately for future development.

ACKNOWLEDGMENTS

We thank the U.S. Environmental Protection Agency for providing partial funding for this project. We give special thanks to Nancy Keate, former Wetlands Coordinator for the State of Utah, for the help and guidance she provided for this project. We thank the Utah Division of Forestry, Fire & State Lands for allowing us access to their land for installing the monitoring wells, and Kim Nay, Utah Geological Survey, for preparing many of the figures for this publication. Sandow Yidana and Mike Hylland, Utah Geological Survey, provided critical reviews and comments for this report.

REFERENCES

Anderson, M.P., and Woessner, W.W., 1992, Applied groundwater modeling - Simulation of flow and advective transport: San Diego, Academic Press, Inc., 381 p.

Anderson, P.B., and Susong, D.D., 1995, Hydrogeology of recharge areas of the principal aquifers along the Wasatch Front and adjacent areas, Utah, *in* Lund, W.R., editor, Environmental and engineering geology of the Wasatch Front region: Utah Geological Association Publication 24, p. 249-268.

Anderson, P.B., Susong, D.D., Wold, S.R., Heilweil, V.M., and Baskin, R.L., 1994, Hydrogeology of recharge areas and water quality of the principal aquifers along the Wasatch Front and adjacent areas, Utah: U.S. Geological Survey Water Resources Investigations Report 93 4221, 74 p.

Ashcroft, G.L, Jensen, D.T., and Brown, J.L., 1992, Utah climate: Logan, Utah Climate Center, Utah State University, 125 p.

Bolke, E.L., and Waddell, K.M., 1972, Ground-water conditions in the East Shore area, Box Elder, Davis, and Weber Counties, Utah, 1960-69: Utah Department of Natural Resources Technical Publication No. 35, 59 p.

Bryant, B., 1984, Reconnaissance geologic map of the Precambrian Farmington Canyon Complex and surrounding rocks between Ogden and Bountiful, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1447, scale 1:50,000.

Burden, C.B., and others, 2005, Ground-water conditions in Utah, spring of 2005: Utah Division of Water Resources, Utah Division of Water Rights, and U.S. Geological Survey Cooperative Investigations Report No. 46, 138 p.

Burk, N., Bishop, C., and Lowe, M., 2005, Wetlands in Tooele Valley, Utah–an evaluation of threats posed by groundwater development and drought: Utah Geological Survey Special Study 117, 37 p., scale 1:40,000.

Christiansen, J.E., and Low, J.B., 1970, Water requirements of waterfowl marshlands in northern Utah: Utah Division of Fish and Game, Publication No. 69-12, 108 p.

Clark, D.W., 1991, Ground-water resources and simulated effects of withdrawals in the Bountiful area, Utah: Utah Department of Natural Resources Technical Publication No. 95, 58 p.

Clark, D.W., Appel, C.L., Lambert, P.M., and Puryear, R.L., 1990, Ground-water resources and simulated effects of withdrawals in the East Shore area of Great Salt Lake, Utah: Utah Department of Natural Resources Technical Publication No. 93, 150 p.

Constenius, K., 1996, Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt: Geological Society of America Bulletin, v. 108, p. 20-39.

Cook, K.L., Berg, J.W., Jr., and Lum, D., 1967, Seismic and gravity profile across the northern Wasatch trench, *in* Musgrave, A.W., editor, Seismic refraction prospecting: Tulsa, Oklahoma, Society of Exploration Geophysicists, p. 539-549.

Cowardin, L.M., Carter, V., Golet, F.C., and LaRoe, E.T., 1979, Classification of wetlands and deepwater habitats of the United States: Washington, D.C., U.S. Fish and Wildlife Service, 103 p.

Currey, D.R., Atwood, G., and Mabey, D.R., 1984, Major levels of Great Salt Lake and Lake Bonneville: Utah Geological and Mineral Survey Map 73, scale 1:750,000.

Demographic and Economic Analysis Section, 2001, Utah data guide, spring 2001: Salt Lake City, Utah Governor's Office of Planning and Budget, 16 p.

Demographic and Economic Analysis Section, 2005, Utah data guide, spring 2005: Salt Lake City, Utah Governor's Office of Planning and Budget, 8 p.

Dennis, P.E., 1952, Ground-water recharge in the East Shore area, Utah: U.S. Geological Survey Open-File Report, 17 p.

Dennis, P.E., and McDonald, H.R., 1944, Ground water in the vicinity of Ogden, Utah: U.S. Geological Survey Open-File Report, 106 p.

Eardley, A.J., 1944, Geology of the north-central Wasatch Mountains: Geological Society of America Bulletin, v. 55, p. 819-894.

Eardley, A.J., 1955, Tertiary history of north-central Utah, *in* Eardly, A.J., editor, Tertiary and Quaternary geology of the eastern Bonneville Basin: Utah Geological Society Guidebook to the Geology of Utah, No. 10, p. 37-44.

Erickson, A.J., Wilson, L., Hughie, V.K., Nielson, W., and Chadwick, R.S., 1968, Soil survey of the Davis-Weber area, Utah: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with Utah Agricultural Experiment Station, 149 p.

Feth, J.H., Barker, D.A., Moore, L.G., Brown, R.J., and Veirs, C.E., 1966, Lake Bonneville–geology and hydrology of the Weber Delta district, including Ogden, Utah: U.S. Geological Survey Professional Paper 518, 76 p.

Gates, J.S., 1995, Description and quantification of the groundwater basins of the Wasatch Front, Utah, *in* Lund, W.R., editor, Environmental and engineering geology of the Wasatch Front region: Utah Geological Association Publication 24, p. 221-248.

Glenn, W.E., Chapman, D.S., Foley, D., Capuano, R.M., Cole, D., Sibbett, B., and Ward, S.H., 1980, Geothermal exploration program, Hill Air Force Base, Weber County, Utah: Salt Lake City, Earth Science Laboratory, University of Utah Research Institute, prepared for U.S. Department of Energy, Division of Geothermal Energy, contract no. DE-AC07-78ET28392, 77 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model – User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hunt, R.J., Krabbenhoft, D.P., and Anderson, M.P., 1996, Groundwater inflow measurements in wetland systems: American Geophysical Union, Water Resources Research, vol. 32, no. 3, p. 495-507.

Lock, P.A., 1994, Utah's wetland workbook: Salt Lake City, Utah Division of Wildlife Resources, 63 p.

Lowe, M., Kirby, S.M., and Harty, K.M., 2008, Geologic map of the Farmington 7.5-minute quadrangle, Davis and Salt Lake Counties, Utah: Salt Lake City, Utah Geological Survey contract deliverable to the U.S. Geological Survey, scale 1:24,000.

Lowe, M., Wallace, J., and Butler, M., 2004, Ground-water sensitivity and vulnerability to pesticides, east shore area of Great Salt Lake, Davis and Weber Counties, Utah: Utah Geological Survey Miscellaneous Publication 04-1, 28 p., scale 1:75,000, CD-ROM.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chapter A1.

McNeil, B.R., and Smith, R.B., 1992, Upper crustal structure of the northern Wasatch Front, Utah, from seismic reflection and gravity data: Utah Geological Survey Contract Report 92-7, 62 p.

Miller, D.M., 1991, Mesozoic and Cenozoic evolution of the northeastern Great Basin, *in* Shaddrick, D.R., Kizis, J.A., and Hunsaker, E.L., III, editors, Geology and ore deposits of the northeastern Great Basin: Geological Society of Nevada Field Trip No. 5, p. 43-73.

Miller, R.D., 1980, Surficial geologic map along part of the Wasatch Front, Great Salt Lake Valley, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1198, scale 1:100,000.

Mitsch, W.J., and Gosselink, J.G., 2000, Wetlands: New York, John Wiley and Sons, 920 p.

National Wildlife Federation, 1989, A citizen's guide to protecting wetlands: Washington, D.C., National Wildlife Federation, 64 p.

Nelson, A.R., and Personius, S.F., 1993, Surficial geologic map of the Weber segment, Wasatch fault zone, Weber and Davis Counties, Utah: U.S. Geological Survey Map I-2199, scale 1:50,000.

Plantz, G.G., Appel, C.L., Clark, D.W., Lambert, P.M., and Puryear, R.L., 1986, Selected hydrologic data from wells in the East Shore area of the Great Salt Lake, Utah, 1985: Utah Hydrologic-Data Report No. 45, 75 p.

Seiler, R.L., Skorupa, J.P., Naftz, D.L., and Nolan, B.T., 2003, Irrigation-induced contamination of water, sediment, and biota in the western United States – Synthesis of data from the National Irrigation Water Quality Program: U.S. Geological Survey Professional Paper 1655, 123 p.

Smith, R.E., 1961, Records and water-level measurements of selected wells and chemical analyses of ground water, East Shore area, Davis, Weber, and Box Elder Counties, Utah: Utah State Engineer Basic-Data Report No. 1, 35 p.

Smith, R.E., and Gates, J.S., 1963, Ground-water conditions in the southern and central parts of the East Shore area, Utah, 1953-1961: Utah Geological and Mineral Survey Water Resources Bulletin 2, 48 p.

Sprinkel, D.A., 1993, Amoco's advanced drilling technology retrieves a deep core from Lake Bonneville sediments, Davis County: Utah Geological Survey, Survey Notes, v. 26, no. 1, p. 10-15.

Stokes, W.L., 1977, Subdivisions of the major physiographic provinces in Utah: Utah Geology, v. 4, no. 1, p. 1 17.

Thomas, H.E., and Nelson, W.B., 1948, Ground water in the East Shore area, Utah; part 1, Bountiful district, Davis County: Utah State Engineer Technical Publication 5, *in* State of Utah 26th Biennial Report of the State Engineer, p. 52-206.

U.S. Army Corps of Engineers, 1987, Corps of Engineers wetlands delineation manual: Vicksburg, Mississippi, U.S. Army Corps of Engineers Waterways Experiment Station, Technical Report Y-87-1, 100 p.

U.S. Environmental Protection Agency, 2003, Wetland functions and values: Online, http://www.epa.gov/watertrain/wetlands/, accessed January 3, 2005.

U.S. Environmental Protection Agency, 2008, Current drinking water standards: Online, http://www. epa.gov/safewater/mcl.html, accessed June 9, 2008.

U.S. Fish and Wildlife Service, 1994, U.S. Fish and Wildlife Service manual 660FW 1, wetlands policy and action plan: Online, http://www.fws.gov/policy/660fw1.html, accessed November 3, 2005.

Utah Department of Transportation, 2007, Legacy Nature Preserve comprehensive water management plan: Salt Lake City, Section 404 permit #200350493 by SWCA Environmental Consultants, 9 p.

Utah Division of Water Quality, 1998, Aquifer classification guidance document: Salt Lake City, unpublished Utah Division of Water Quality report, 9 p.

Utah Division of Water Resources, 1997, Utah State Water Plan, Weber River basin: Salt Lake City, unpublished Utah Division of Water Resources report, variously paginated.

Utah Division of Water Resources, 2001, Utah State Water Plan, West Desert basin: Salt Lake City, Utah Division of Water Resources report, variously paginated.

Utah Division of Water Resources, 2007, Drought in Utah–learning from the past–preparing for the future: Salt Lake City, unpublished Utah Division of Water Resources report, 124 p.

Utah Division of Water Rights, 2006a, Ground-water management plan for the Bountiful sub-area of the east shore area: Online, http://waterrights.utah.gov/wrinfo/mmplan/ugw/bountfl.htm, accessed September 30, 2008.

Utah Division of Water Rights, 2006b, Ground-water management plan for the Weber Delta sub-area of the east shore area: Online, http://waterrights.utah.gov/wrinfo/mmplan/ugw/web_del.htm, accessed September 30, 2008.

Utah Division of Wildlife Resources, 2006, Farmington Bay Wildlife Management Area: Online, http://wildlife.utah.gov/habitat/farmington_bay.php, accessed March 21, 2008.

Van Horn, R., 1981, Geologic map of pre-Quaternary rocks of the Salt Lake City North quadrangle, Davis and Salt Lake Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1330, scale 1:24,000.

Waddell, K.M., and Fields, F.K., 1977, Model for evaluating the effects of dikes on the water and salt budget of Great Salt Lake, Utah: Utah Geological and Mineral Survey Water-Resource Bulletin 21, 54 p.

Wang, H.F., and Anderson, M.P., 1982, Introduction to groundwater modeling–finite difference and finite element methods: New York, W.H. Freeman and Company, 237 p.

Willis, G.C., and Jensen, M.E., 2000, Tertiary rocks of Antelope Island, Davis County, northern Utah, *in* King, J.K., and Willis, G.C., editors, The geology of Antelope Island: Utah Geological Survey Miscellaneous Publication 00-1, p. 49-70.

Winter, T.C., 1981, Uncertainties in estimating the water balance of lakes: American Water Resource Association, Water Resources Bulletin, vol. 17, no. 1, p. 82-115.

Yonkee, W.A., and Lowe, M., 2004, Geologic map of the Ogden 7.5-minute quadrangle, Weber and Davis Counties, Utah: Utah Geological Survey Map 200, 42 p., scale 1:24,000.

Yonkee, W.A., Willis, G.C., and Doelling, H.H., 2000, Petrology of Precambrian rocks of the Farmington Canyon Complex, Antelope Island, Utah, *in* King, J.K., and Willis, G.C., editors, The geology of Antelope Island: Utah Geological Survey Miscellaneous Publication 00-1, p. 5-36.

Zoback, M.L., 1983, Structure and Cenozoic tectonism along the Wasatch fault zone, Utah, *in* Miller, D.M., Todd, V.R., and Howard, K.A., editors, Tectonic and stratigraphic studies of the eastern Great Basin: Geological Society of America Memoir 157, p. 3-26.

APPENDICES

APPENDIX A

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 substance 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 B.1. *Cowardin wetlands classification of the Farmington Bay area wetlands.*

System	Subsystem	Class	Regime	Abbreviation	Acres/Hectares	% In Study Area
Palustrine	None	Emergent - Characterized by erect, rooted, herbaceous hydrophytes present for most of the growing season in most years. Usually dominated by perennial plants.	Temporarily Flooded - Surface water is present for brief periods during growing season, but the water table usually lies well below the soil surface. Plants that grow both in uplands and wetlands may be characteristic of this water regime.	PEMA	617.4/249.9	1.47%
			Seasonally Flooded - Surface water is present for extended periods especially early in the growing season, but is absent by the end of the growing season in most years. The water table after flooding ceases is variable, extending from saturated to the surface to a water table well below the ground surface.	PEMC	3180.3/1287	7.56%
			Semipermanently Flooded - Surface water persists thoughout the growing season in most years. When surface water is absent, the water table is usually at or very near the land's surface.	PEMF	3155.7/1277.1	7.50%
			Temporarily Flooded - Same as above. Permanently Flooded - Water covers the land surface throughout the year in all years.	PEMAH	76/30.8	0.18%
			Intermittently Exposed - Surface water is present throughout the year except in years of extreme drought. Excavated Wetland.	PEBGX	110.2/44.6	0.26%
			Semipermanently Flooded/Permanently Flooded - Same as above.	PEMFH	3088.9/1250	7.34%
		Unconsolidated Bottom - Includes all wetlands and deepwater habitats with at least 25% cover of particles smaller than stones (less than 6-7 cm), and a vegetative cover less than 30%.	Semipermanently Flooded - Same as above.	PUBF	89.6/36.3	0.21%
			Semipermanently Flooded/Permanently Flooded - Same as above.	PUBFH	128.5/52	0.31%
			Intermittently Exposed - Surface water is present throughout the year except in years of extreme drought. Permanently Flooded - Same as above.	PUBGH	76/30.8	0.18%
		Unconsolidated Shore - Includes all wetland habitats having three characteristics: (1) unconsolidated substrates with less than 75% areal cover of stones, boulders, or bedrock; (2) less than 30% areal cover of vegetation other than pioneering plants; and (3) any of the following water regimes: irregularly exposed, regularly flooded, irregularly flooded, seasonally flooded, temporarily flooded, intermittently flooded, saturated, seasonal-tidal, temporary-tidal, or artificially flooded.	Temporarily Flooded - Same as above.	PUSA	154/62.3	0.37%
			Temporarily Flooded/Permanently Flooded - Same as above.	PUSAH	98.5/39.9	0.23%
		Emergent/Unconsolidated Shore - Same as above.	Temporarily Flooded - Same as above.	PEM/USA	1117/452	2.65%
			Permanently Flooded/Temporarily Flooded - Same as above.	PEM/USAH	54.6/22.1	0.13%
				Total Palustrine	11946.7/4834.7	28.39%

Table B.1. *(continued)*

System	Subsystem	Class	Regime	Abbreviation	Acres/Hectares	% In Study Area
Lacustrine	2 Littoral -- All wetland habitats in the Lacustrine system. Extends from shoreward boundary to 2 m (6.6 ft) below annual low water or to the maximum extent of nonpersistent emergents, if these grow at depths greater than 2 m (6.6 ft).	Aquatic Bed - Includes wetlands and deepwater habitats dominated by plants that grow principally on or below the surface of the water for most of the growing season in most years. Aquatic beds generally occur in water less than 2 meters (6.6 feet) deep.	Intermittently Exposed/Permanently Flooded - Same as above.	L2ABGH	188.2/76.2	0.45%
		Aquatic Bed/Unconsolidated Bottom - Same as above.	Intermittently Exposed/Permanently Flooded - Same as above.	L2AB/UBGH	1214.8/491.6	2.89%
		Unconsolidated Bottom - Same as above.	Semipermanently Flooded - Same as above.	L2UBF	45.2/18.3	0.11%
			Intermittently Exposed - Same as above.	L2UBG	217.8/88.1	0.52%
			Intermittently Exposed - Same as above. Excavated wetland.	L2UBGX	57.8/23.4	0.14%
			Semipermanently Flooded/Permanently Flooded - Same as above.	L2UBFH	305.7/123.7	0.73%
			Intermittently Exposed/Permanently Flooded - Same as above.	L2UBGH	805/325.8	1.91%
		Unconsolidated Shore - Same as above.	Temporarily Flooded - Same as above.	L2USA	6947.4/2811.5	16.51%
			Seasonally Flooded - Same as above.	L2USC	20143/8151.6	47.87%
			Permanently Flooded/Temporarily Flooded - Same as above.	L2USAH	209.2/84.7	0.50%
				Total Lacustrine	30134.1/12194.9	71.63%

Classification system from Cowardin and others, 1979

Mapping by U.S. Fish and Wildlife Service for the National Wetland Inventory 2001

APPENDIX C

Water-Quality Data

Table C.1. *Water-quality data for the Farmington Bay wetlands area, Davis County, Utah*

Site ID	Well Depth (feet)	Sample Date	Nitrogen NO2 + NO3 dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Field Tempera-ture, (°C)	Field, Specific Conductance (µS/cm)	Lab, Specific Conduct-ance (µmhos)	pH, lab	pH field	Aluminum, dissolved (µg/L)	Arsenic, dissolved (µg/L)	Barium, dissolved (µg/L)	Bicarbon-ate (mg/L)
#5FB	5	11/17/06	2.16	5992.00	11.00	9.20	10650.00	8.50	7.80	<100.0	66.505	<100.0	1005.0
#1FB	5	11/8/06	<0.1	1328.00	14.90	2.61	2260.00	8.17	7.50	38.143	188.65	308.99	1298.0
#2FB	5	11/17/06	<0.1	30644.00	8.40	47.0	>12000	8.95	8.10	<30.0	617.16	<100.0	3956.0
#3FB	5	11/17/06	<0.1	5550.00	7.90	12.18	9390.00	8.65	3.40	<30.0	113.84	113.12	2434.0
#4FB	5	11/17/07	<0.1	47490.00	11.90	77.90	>12000	7.41	2.90	509.01	<50.0	<100.0	706.0
#3FB	5	6/12/07	<0.1	—	—	—	>12000	9.21	—	—	—	—	2394.0
#2FB	5	6/12/07	0.9	—	—	—	>12000	—	—	—	—	—	—

Table C.1. *(continued)*

Site ID	Cadmium, dissolved (µg/L)	Calcium, dissolved (mg/L)	Carbon dioxide (mg/L)	Carbonate (mg/L)	Chloride (mg/L)	Chromium, dissolved (µg/L)	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)
#5FB	<1.0	26.40	5.00	26.00	2380.0	<5.0	521.0	<12.0	0.00	<20.0	<3.0	121.0	113.51
#1FB	<1.0	92.20	14.00	0.00	180.0	7.4895	639.0	<12.0	0.00	27.50	<3.0	192.0	29.268
#2FB	2.3536	11.70	7.00	307.00	12550.0	<5.0	225.0	41.688	0.00	5270.00	<3.0	266.0	36.118
#3FB	1.0205	23.20	14.00	76.00	1550.0	<5.0	127.0	13.888	0.00	<20.0	<3.0	130.0	53.089
#4FB	<20.0	125.00	8.00	0.00	27000.0	<50.0	347.0	63.227	0.00	42.00	<20.0	988.0	<20.0
#3FB	—	—	2	—	2240.0	—	149.0	—	—	—	—	—	—
#2FB	—	—	—	—	3630.0	—	0.0	—	—	—	—	–	—

Table C.1. *(continued)*

Site ID	Mercury, dissolved (µg/L)	Phosphate, total (mg/L)	Potassium, dissolved (mg/L)	Selenium, dissolved (µg/L)	Silver, dissolved (µg/L)	Sodium, dissolved (mg/L)	Sulfate (mg/L)	Total Alkalinity (mg/L)	Total Hardness (mg/L)	Total Suspended Solids (mg/L)	Turbidity, (NTU)	Zinc, dissolved (µg/L)	Data source
#5FB	<0.2	1.70	126.0	N0	<5.0	2010.0	628.0	868.0	563.7	182.0	129.0	<30.0	UGS
#1FB	<0.2	0.244	40.1	<1.0	<5.0	207.0	37.2	1064.0	1020.0	320.0	130.0	<30.0	UGS
#2FB	<0.2	5.15	252.0	1582.00	2.653	9470.0	3240.0	3756.0	1123.6	10580.0	>10000.0	<30.0	UGS
#3FB	<0.2	2.41	164.0	NO	<5.0	1940.0	555.0	2122.0	592.8	1204.0	733.0	<30.0	UGS
#4FB	<0.2	1.36	882.0	1.025	<50.0	16300.0	2270.0	579.0	4377.0	129.2	236.0	<0.2	UGS
#3FB	—	17.6	—	—	—	—	983.0	2493.0	—	2060.0	856.0	—	UGS
#2FB	—	10.3	—	—	—	—	2070.0	0.0	—	67400.0	>10000.0	—	UGS

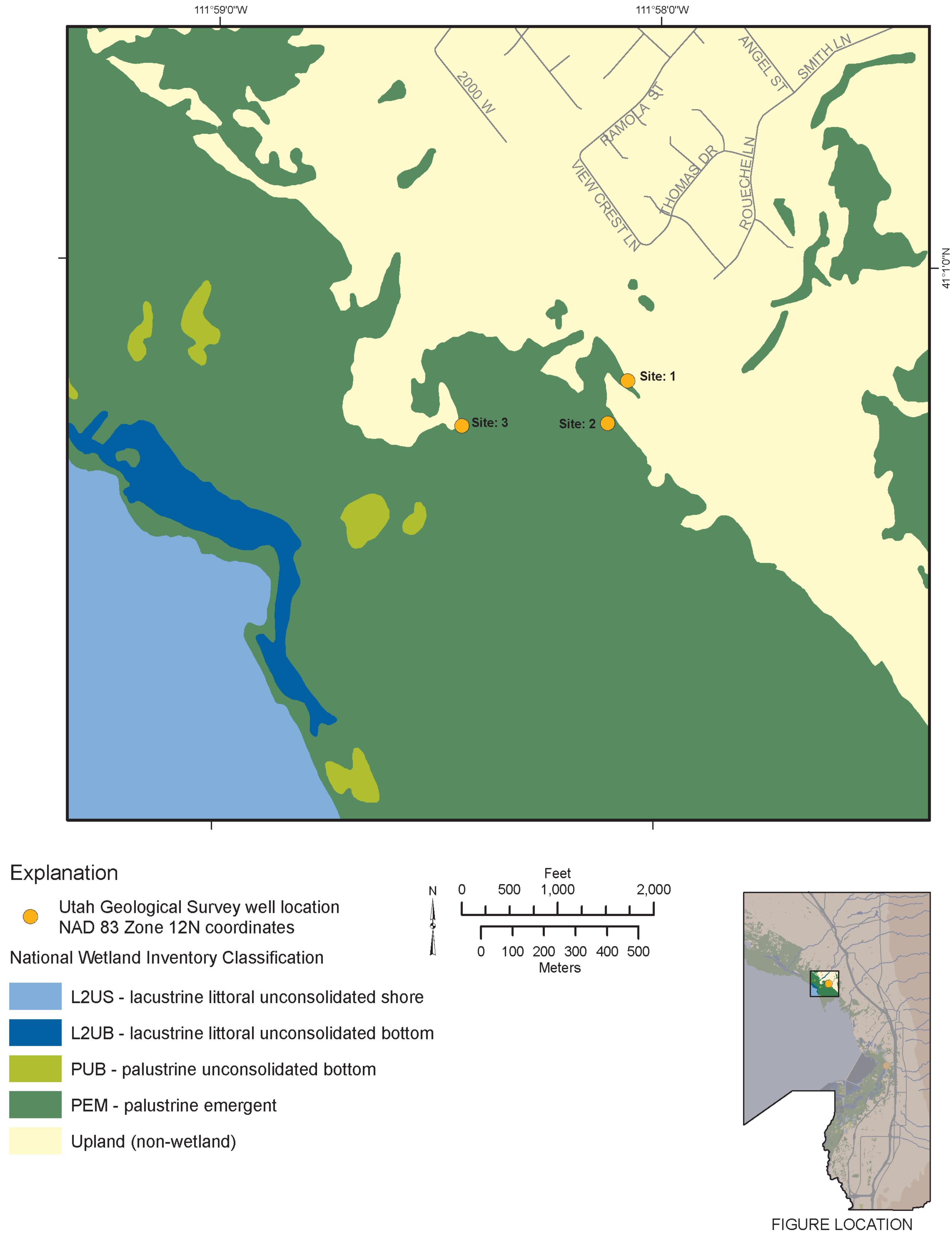
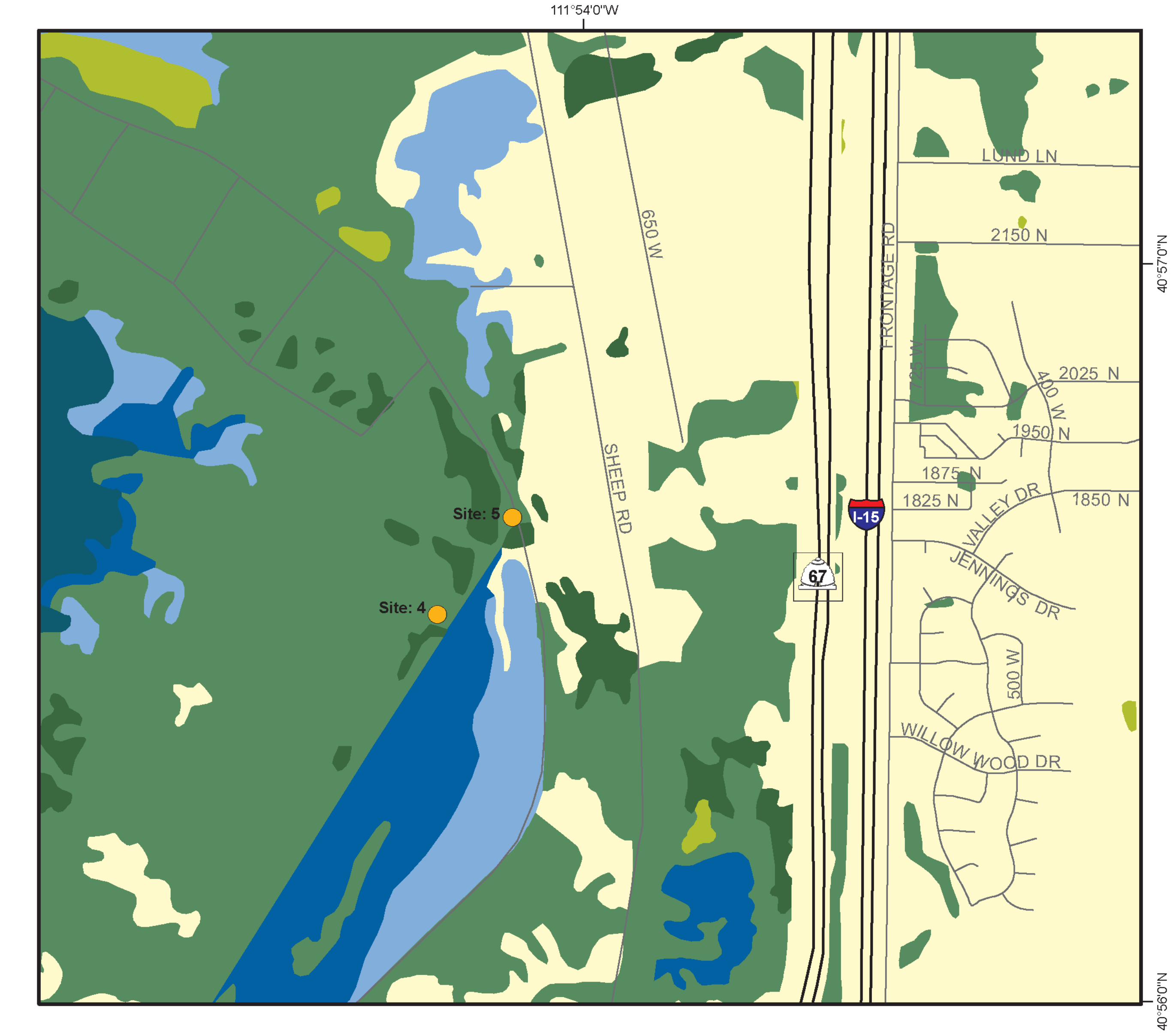


Figure C-1. *Location of wells 1-3.*

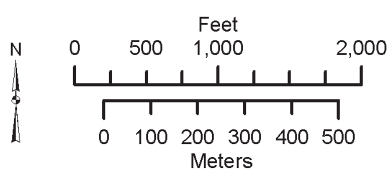


Explanation

Utah Geological Survey well location
NAD 83 Zone 12N coordinates

National Wetland Inventory Classification

- L2US - lacustrine littoral unconsolidated shore
- L2UB - lacustrine littoral unconsolidated bottom
- L2AB - lacustrine littoral aquatic bed
- PUB - palustrine unconsolidated bottom
- PEM - palustrine emergent
- PUS - palustrine unconsolidated shore
- Upland (non-wetland)



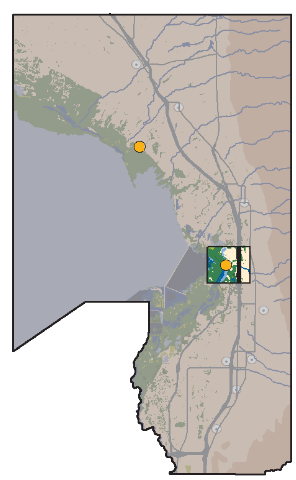


FIGURE LOCATION

Figure C-2. *Location of wells 4-5.*