GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES, EAST SHORE AREA OF GREAT SALT LAKE, DAVIS AND WEBER COUNTIES, UTAH

by

Mike Lowe, Janae Wallace, and Matt Butler

Utah Geological Survey

MISCELLANEOUS PUBLICATION MP 04-1
UTAH GEOLOGICAL SURVEY
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Cover photo: Agricultural fields in East Shore area, Davis County, Utah. Photo by Mike Lowe.

ISBN 1-55791-700-0

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ABSTRACT

The U.S. Environmental Protection Agency is recommending that states develop Pesticide Management Plans for four agricultural chemicals – alachlor, atrazine, metolachlor, and simazine – herbicides used in Utah in the production of corn and sorghum. This report and accompanying maps are intended to be used as part of these Pesticide Management Plans to provide local, state, and federal government agencies and agricultural pesticide users with a base of information concerning sensitivity and vulnerability of ground water to agricultural pesticides in the east shore area of Great Salt Lake, Davis and Weber Counties, Utah. We used existing data to produce pesticide sensitivity and vulnerability maps by applying an attribute ranking system specifically tailored to the western United States using Geographic Information System analysis methods. This is a first cut at developing pesticide sensitivity and vulnerability maps; better data and tools may become available in the future so that better maps can be produced.

Ground-water sensitivity (intrinsic susceptibility) to pesticides is determined by assessing natural factors favorable or unfavorable to the degradation of ground water by any pesticides applied to or spilled on the land surface. Hydrogeologic setting (vertical ground-water gradient and presence or absence of confining layers), soil hydraulic conductivity, retardation of pesticides, attenuation of pesticides, and depth to ground water are the factors primarily determining ground-water sensitivity to pesticides in the east shore area of Great Salt Lake. Much of the east shore area has low ground-water sensitivity to pesticides due to prevalent protective clay layers.

Ground-water vulnerability to pesticides is determined by assessing how ground-water sensitivity is modified by the activities of humans. Ground-water sensitivity to pesticides, the presence of applied water (irrigation), and crop type are the three factors generally determining ground-water vulnerability to pesticides in the east shore area of Great Salt Lake. Areas of high vulnerability are located primarily in areas where irrigation occurs and ground-water sensitivity to pesticides is high. Of particular concern are areas where influent (losing) streams originating in mountainous areas cross the basin margin; streams in these areas are the most important source of recharge to the basin-fill aquifer and efforts to preserve water quality in streams at these points would help to preserve ground-water quality in the entire east shore area.

Because of relatively high retardation (long travel times of pesticides in the vadose zone) and attenuation (short half-lives) of pesticides in the soil environment, pesticides applied to fields in the east shore area of Great Salt Lake likely do not present a serious threat to ground-water quality. To verify this conclusion, future ground-water sampling by the Utah Department of Agriculture and Food in the east shore area should be concentrated in areas of moderate and high sensitivity or vulnerability, typically along basin margins. Sampling in the central area of the basin characterized by low sensitivity and vulnerability should continue, but at a lower density than in the areas of higher sensitivity and vulnerability.

INTRODUCTION

Background

The U.S. Environmental Protection Agency (EPA) recommends that states develop Pesticide Management Plans (PMPs) for four agricultural chemicals that in some areas impact ground-water quality. These chemicals – herbicides used in production of corn and sorghum – are alachlor, atrazine, metolachlor, and simazine. All four chemicals are applied to crops in Utah. In some areas of the United States where these crops are grown extensively, these pesticides have been detected as contaminants in ground water. Such contamination poses a threat to public health, wildlife, and the environment. In many rural and agricultural areas throughout the United States – and particularly in Utah – ground water is the primary source of drinking and irrigation water.

This report and accompanying maps provide federal, state, and local government agencies and agricultural pesticide users with a base of information concerning vulnerability of ground water to agricultural pesticides in the east shore area of Great Salt Lake, Davis and Weber Counties, Utah (figure 1). This study provides needed information on ground-water sensitivity and vulnerability to pesticides in the unconsolidated basin-fill aquifers of the east shore area. Geographic variation in sensitivity and vulnerability, together with hydrologic and soil conditions that cause these variations, are described herein; plates 1 and 2 show the sensitivity and vulnerability, respectively, of the unconsolidated basin-fill aquifers in the east shore area to agricultural pesticides.

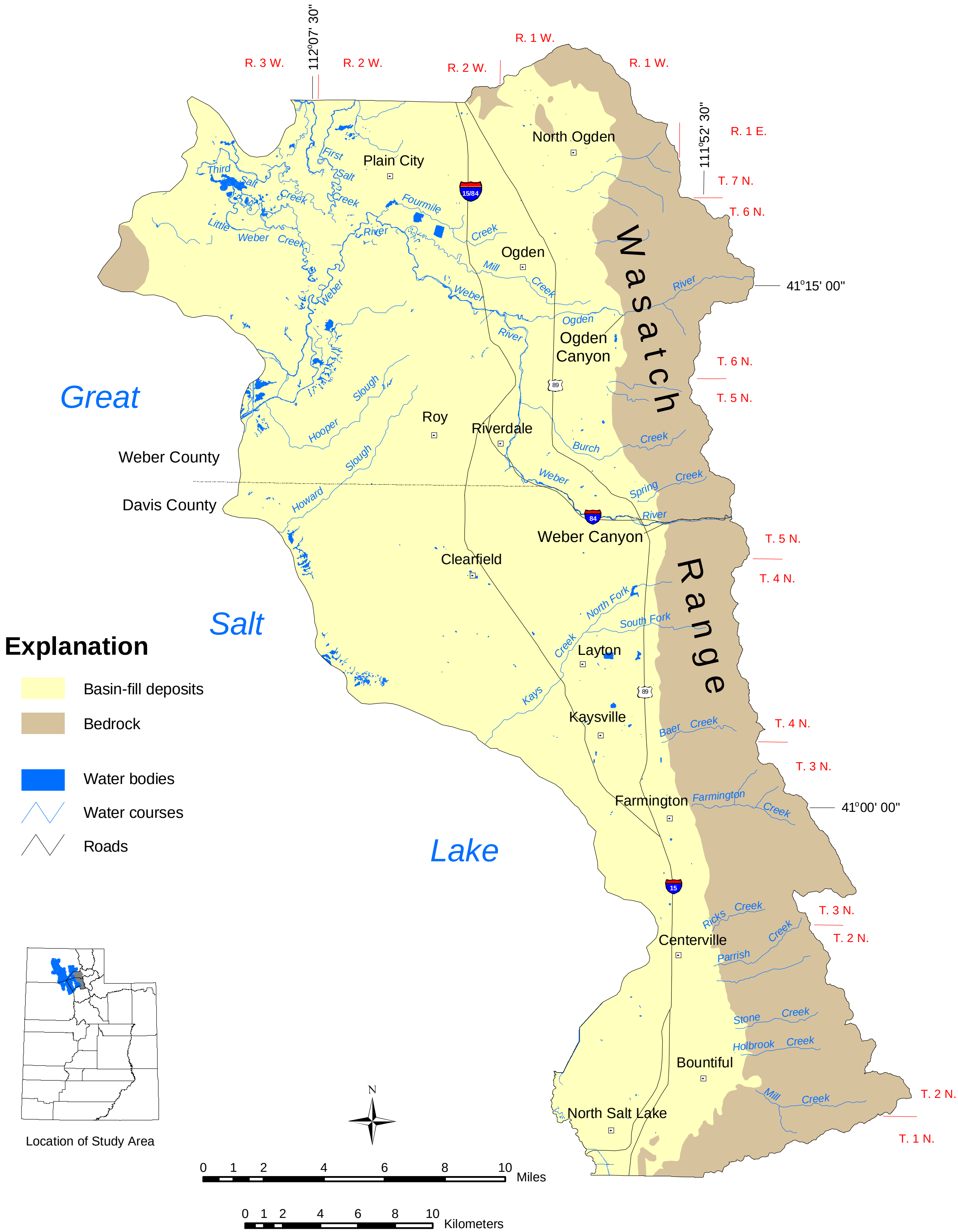


Figure 1. *East shore area of Great Salt Lake, Davis and Weber Counties, Utah, study area.*

Sensitivity to pesticides is determined by assessing natural factors favorable or unfavorable to the degradation of ground water by pesticides applied or spilled on the land surface, whereas vulnerability to pesticides is determined by assessing how ground-water sensitivity is modified by the activities of humans. For this study, sensitivity incorporates hydrogeologic setting, including vertical ground-water gradient, depth to ground water, and presence or absence of confining layers, along with the soils' hydraulic conductivity, bulk density, organic content, and field capacity. Sensitivity also includes the influence of pesticide properties such as the capacity of molecules to adsorb to organic carbon in soil and the half-life of a pesticide under typical soil conditions. Vulnerability includes human-controlled factors such as whether agricultural lands are irrigated, crop type, and amount and type of pesticide applied.

Purpose and Scope

The purpose of this project is to investigate sensitivity and vulnerability of ground-water resources in the east shore area of Great Salt Lake, Davis and Weber Counties, Utah, to contamination from agricultural pesticides. This information may be used by federal, state, and local government officials and pesticide users to reduce the risk of ground-water pollution from pesticides, and to focus future ground-water quality monitoring by the Utah Department of Agriculture and Food.

The project scope is limited to the use and interpretation of existing data to produce pesticide sensitivity and vulnerability maps through the application of Geographic Information System (GIS) analysis methods. This is a first cut at developing pesticide sensitivity and vulnerability maps; better data and tools may become available in the future so that better maps can be produced. For example, maps that show the quantity of recharge to aquifers in Utah are not available. We used a GIS coverage developed by subtracting average annual evapotranspiration from average annual precipitation to estimate average annual recharge from precipitation. This coverage provides a rough estimate of the largely elevation-controlled distribution of ground-water recharge, but does not account for recharge at low elevations during spring snowmelt or during prolonged storm events. Additionally, the 1:24,000-scale digital soil maps used in this study are too general to accurately depict areas of soil versus areas of bedrock outcrop. Because organic carbon in soils is one controlling factor determining the potential for pesticides to reach ground water, the higher sensitivity and vulnerability of these rock outcrop areas are not reflected in our maps. To produce these maps, we needed to make some arbitrary decisions regarding the quality and the types of data available based on our knowledge of the hydrogeology of the area; for example, we selected 3 feet (1 m) as the reference depth for applying pesticide retardation and attenuation equations. No new fieldwork was conducted nor data collected as part of this project.

GENERAL DISCUSSION OF PESTICIDE ISSUE

The information presented in this section was taken directly from Lowe and Sanderson (2003).

Introduction

Ground water is the primary source of water in many rural areas for human consumption, irrigation, and animal watering. Therefore, the occurrence of agricultural pesticides in ground water represents a threat to public health and the environment. Springs and drains flowing from contaminated aquifers may present a hazard to wildlife that live in or consume the water. When we better understand the mechanisms by which pesticides migrate into ground water, we are better able to understand what geographic areas are more vulnerable – and thus deserving of more concentrated efforts to protect ground water – than other less vulnerable areas. The ability to delineate areas of greater and lesser vulnerability allows us to apply mitigating or restrictive measures to vulnerable areas without interfering with the use of pesticides in the less vulnerable areas.

The rise of the United States as the world's foremost producer of agricultural products since the end of World War II may be attributed, in part, to widespread use of pesticides. Control of insect pests that would otherwise devour the developing crop, together with control of weeds that interfere with growth and optimum crop development, permit higher quality commodities in greater abundance at lower net cost. Effective use of pesticides often means the difference between profitability and financial ruin for an agricultural enterprise.

When evidence shows pesticides are degrading the environment, harming sensitive wildlife, or posing a public health threat, two regulatory courses of action are available: (1) ban further use of the offending chemical, or (2) regulate it so that judicious use mitigates the degradation or threat. Because the four subject herbicides play an essential role in crop production and profitability, banning them outright is unnecessarily severe if the desired environmental objectives can be met by regulation and more judicious use of these herbicides.

The case of DDT illustrates dilemmas faced by pesticide regulators. DDT was removed from widespread use in the United States in the 1970s because of its deleterious effects on bald eagles, ospreys, and peregrine falcons. Populations of these once-endangered species have recovered to a significant extent 25 years later (Environmental Defense Fund, 1997). An ongoing effort to extend the DDT ban worldwide is being hotly contested by advocates of its judicious use as a critical and inexpensive insecticide needed in developing countries to control mosquitoes that transmit the malaria parasite. It is further argued that, given the current regulatory apparatus, were the use of DDT to be reevaluated today under rigorous scientific and regulatory criteria, it would be restricted to specific uses rather than prohibited (Okosoni and Bate, 2001).

The EPA has developed guidelines and provided funding for programs to address the problem of pesticide contamination of ground water, including a generic PMP to be developed by state regulatory agencies having responsibility for pesticides. The EPA approved Utah's generic plan in 1997 (Utah Department of Agriculture and Food, 1997). Its implementation involves, among other things, establishing a GIS database containing results of analyses of samples collected from wells, springs, and drains showing concentrations of pesticides and other constituents that reflect water quality.

Implementation of the PMP also involves developing a set of maps showing varying sensitivity and vulnerability of ground water to contamination by pesticides.

Since its inception in 1994, the UDAF sampling program has revealed no occurrences of pesticide contamination in any aquifer in over 1,500 samples tested statewide (Quilter, 2001). Under the generic PMP, should an instance of pesticide contamination be found and verified, a chain of events to monitor and evaluate the contamination would begin that could culminate in cancellation or suspension of the offending pesticide's registration at the specific local level (Utah Department of Agriculture and Food, 1997). Identification of the appropriate area for pesticide registration, cancellation, or suspension requires the specific knowledge presented in this report and on the accompanying maps of varying sensitivity and vulnerability of ground water to pesticide contamination, conditions that result in these variations, and their geographic distribution.

Federal government agencies have been aware of the growing problem of pesticide contamination of ground water since the early 1980s. Cohen and others (1984) reviewed data from occurrences of 12 pesticides in ground water in 18 states, and Cohen and others (1986) reported at least 17 occurrences of pesticides in ground water in 23 states. By the early 1990s, EPA began formulating and implementing programs to address the problem.

In 1985, EPA published a standardized system for evaluating the potential for ground-water pollution on the basis of hydrogeologic setting (Aller and others, 1985). The method, known under the acronym DRASTIC, involves assigning numerical values to seven parameters and totaling a score. Under this system, the higher the score, the greater the assumed sensitivity of ground water to pesticide contamination. Ranges in the numerical score are easily plotted on GIS maps. Measured parameters include depth to the water table, recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity of the aquifer; the beginning letter of key words in these parameters forms the acronym DRASTIC. Eventually, many scientists concluded that this method is unreliable in some settings, and that it fails to consider the chemical characteristics of the potential contaminants and their interaction with soil and water in the vadose zone. As a result, no significant correlation exists between predicted pesticide detections and observed conditions (Banton and Villenueve, 1989). Other deficiencies with the DRASTIC method are that characteristics of the aquifer media have little bearing on the behavior of pesticides moving through soil in the vadose zone, that areas adjacent to effluent (gaining) rivers and streams are often incorrectly identified as being the most sensitive, and that soil media, impact of the vadose zone, and depth to the water table are all asking the same fundamental questions in different ways. The assigned numerical values in the DRASTIC method poorly represent variables as actually observed.

Rao and others (1985) developed indices for ranking the potential for pesticide contamination of ground water, which we have implemented in this study. The approach has been described as "a nice and widely acknowledged blend of process concepts and indexing methods. Conceptually the science is valid and the approach seems to work well" (Siegel, 2000). The method of Rao and others (1985) involves calculation of a retardation factor and an attenuation factor that characterize movement and persistence of pesticides in the vadose zone, respectively. These factors vary with different soil properties and different characteristics of specific pesticides. Equations for these indices enable calibration of hydrogeologic and other data to more realistically represent actual conditions. These indices, together with hydrogeologic data, provide the basis in this report for delineation of areas that are vulnerable to pesticide contamination of ground water.

Ground-Water Quality Standards

Maximum contaminant levels (MCLs) for pesticides in drinking water are established in R309-103-2.1, Utah Administrative Code, and also in 40 CFR 141.61. MCLs are given in table 1 below. Metolachlor is not listed in either regulation.

Table 1. *Maximum contaminant levels for pesticides in drinking water.*

Contaminant	Maximum Contaminant Level (MCL)	
Alachlor	0.002 mg/L	2 mg/L
Atrazine	0.003 mg/L	3 mg/L
Metolachlor	—	—
Simazine	0.004 mg/L	4 mg/L

Standards for crop irrigation and livestock watering have not been established. However, some crops would require even higher standards for herbicides than those set for human consumption to avoid crop damage.

Under Utah's PMP, if a pesticide is detected in ground water and confirmed by subsequent sampling and analysis as being greater than 25 percent of the established MCL, an administrative process begins that may eventually result in regulation or revocation of the pesticide's registration for use in the affected area as delineated in this report and the accompanying maps.

Ground-Water Contamination by Pesticides

The interplay between hydrogeologic setting, ground-water recharge, soil conditions, pesticide use, and pesticide behavior in the vadose zone determines whether ground water in a particular area is likely to become contaminated with pesticides. The type of pesticide being applied is a critical factor. Although pesticide use is highly variable and cannot be precisely monitored, the distribution of crop types and the quantities of pesticides sold to applicators may be used to obtain a general approximation. Ultimately, the only reliable method for detecting ground-water contamination by pesticides is an adequate ground-water monitoring program, with special emphasis on areas where these pesticides are being applied and where such application is most likely to impact ground water.

Vulnerability is determined on the basis of whether irrigation is used, what crops are being grown, and which pesticides are generally applied to particular crops. Areas of corn and sorghum production, in particular, would indicate areas where atrazine and similar herbicides might be used. Pesticide application should be monitored more closely in areas of corn and sorghum production than in other areas to ensure that these herbicides are not impacting ground water.

Mechanisms of Pollution

In areas of the east shore of Great Salt Lake where ground water is unconfined, degradation of the basin-fill aquifers by pesticides would occur whenever chemicals infiltrate through the vadose zone to the aquifer. In confined aquifer settings, pesticides would need to find pathways through confining layers to cause water-quality degradation. Thus, the ability of soils at the application site to retard or attenuate the downward movement of pesticides, and the hydrogeologic setting where the pesticides are applied, have a fundamental effect on the likelihood that a pesticide will travel downward to the basin-fill aquifer. Surface irrigation could cause a decrease in the retardation and attenuation of pesticides in some settings – especially in areas where corn or sorghum are grown – because the types of pesticides evaluated in this study are commonly applied to those crops. Withdrawal of water from the basin-fill aquifers via water wells could cause changes in vertical head gradient that may increase the potential for water-quality degradation. Also, the wells themselves, if not properly constructed, could provide pathways for pesticides to reach the basin-fill aquifers.

PREVIOUS STUDIES

Dennis and McDonald (1944) conducted an early study of ground-water conditions in the east shore area of Great Salt Lake. Thomas and Nelson (1948) studied the geology and ground-water conditions in the vicinity of Bountiful. Dennis (1952) evaluated ground-water recharge in the east shore area. Hamblin (1954) studied the geology and ground water conditions in northern Davis County. Feth and others (1966) conducted a comprehensive study of basin-fill deposits and hydrogeologic conditions in the northern Davis County and Weber County portions of 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. 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. Clyde and others (1984) constructed a ground-water model, which they used to evaluate the potential for diverting water from the Weber River at the mouth of Weber Canyon for use as a source of artificial recharge for the Weber Delta area. Clark and others (1990) reevaluated ground-water conditions in the east shore area and constructed a computer model for the northern Davis County and Weber County portions of the east shore aquifer to evaluate the effects of ground-water withdrawals. 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 Weber Delta district. 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. Burden and others (2000) described changes in ground-water conditions in Utah, including the east shore area, from 1970 to 2000. Yonkee and Lowe (in preparation) summarized ground-water conditions in the Ogden 7.5-minute quadrangle based on the ground-water reports discussed above; this summary provides the basis for the discussion of ground-water conditions presented herein.

Erickson and others (1968) mapped soils (scale 1:15,840) for Davis County and western Weber County. Regional geologic maps covering the study area include: a surficial geologic map along part of the Wasatch Front by Miller (1980, scale 1:100,000); a map of the Farmington Canyon Complex by Bryant (1984, scale 1:100,000); a map of the northern Wasatch Front compiled by Davis (1985, scale 1:100,000); and a map of surficial deposits along the Wasatch fault zone by Nelson and Personius (1993, scale 1:50,000). Geologic quadrangle maps at 1:24,000 scale are shown on figure 2.

SETTING

Physiography

The east shore area of Great Salt Lake is in the Ogden Valley segment of the Wasatch Front Valleys section of the Great Basin physiographic province (Stokes, 1977). The east shore area is a basin lowland extending northward from the Salt Lake salient to the town of Willard, Box Elder County, and from the western margin of the Wasatch Range to the eastern shore of Great Salt Lake (figure 1) (Clark and others, 1990); this report covers only that part of the east shore area south of the Box Elder County line. Elevation ranges from over 9,000 feet (2,700 m) for some peaks in the Wasatch Range to about 4,200 feet (1,280 m) at the shore of Great Salt Lake. The Weber and Ogden Rivers are the first- and second-largest streams in the east shore area, respectively, contributing 90 percent of the surface-water inflow (Clark and others, 1990, tables 3 and 4). The Ogden River is a tributary to the Weber River, as are Fourmile, Mill, and Burch Creeks in Weber County. Streams in Davis County are not tributaries to major river systems, but flow directly to Great Salt Lake. The major Davis County streams include Holms, Farmington, Ricks, Parrish, Centerville, Stone, and Mill Creeks (Clark and others, 1990, table 3). Dozens of other perennial, intermittent, and ephemeral streams flow westward from the Wasatch Range into the east shore area (Clark and others, 1990, table 4).

Rocks in the Wasatch Range east of the east shore area 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. A wide variety of rock types exist north of Burch Creek (figure 1), including the Precambrian Farmington Canyon Complex (described below) and Paleozoic limestone, dolomite, shale, and quartzite (Crittenden and Sorensen, 1985; Yonkee and Lowe, in preparation). South of Burch Creek, the Wasatch Range consists almost entirely of the Farmington Canyon Complex, a complex mixture of high-grade metamorphic and igneous rocks (Eardley, 1944;

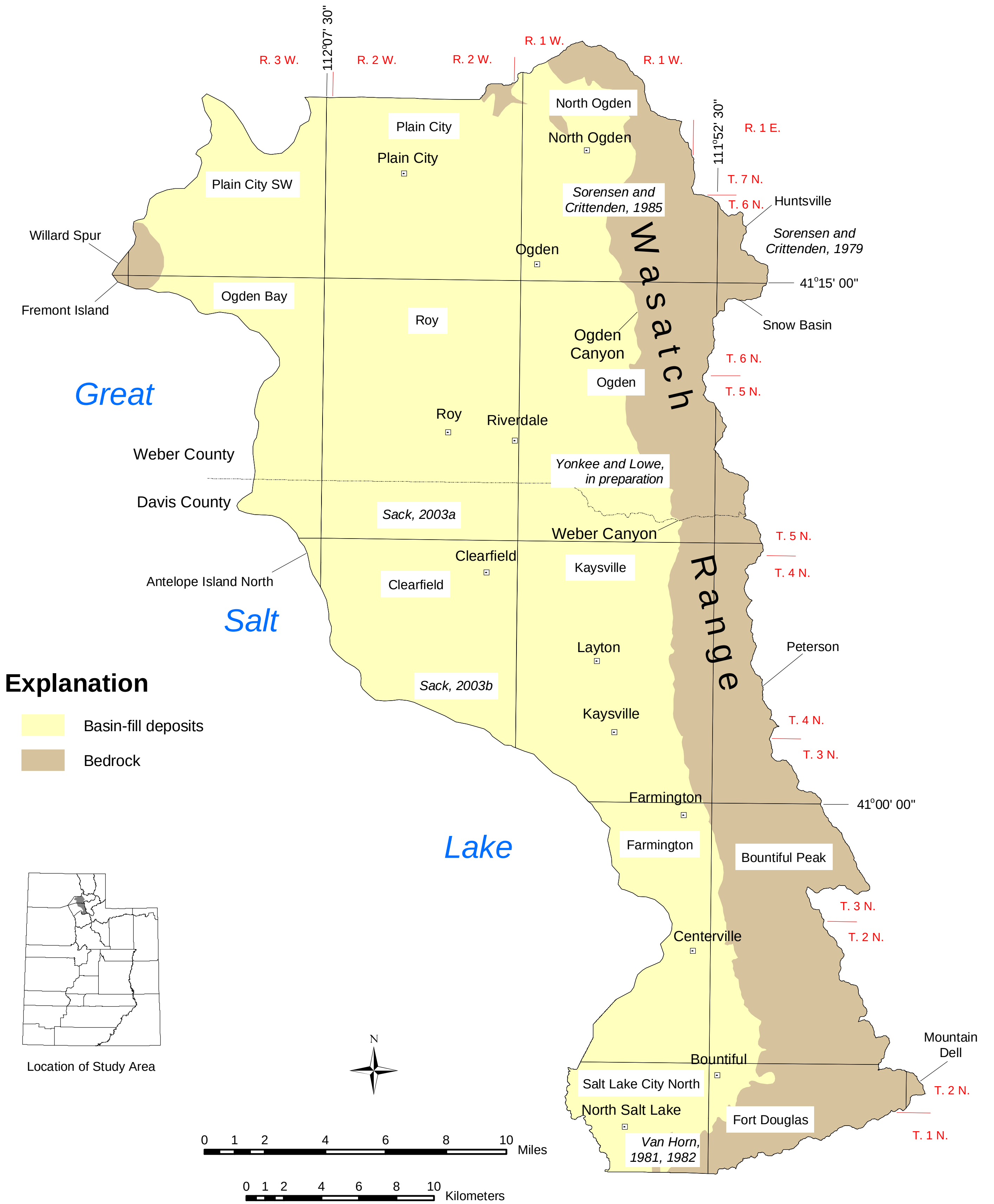


Figure 2. *Existing 1:24,000-scale geologic maps for the east shore area of Great Salt Lake, Davis and Weber Counties, Utah.*

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, in preparation). Tertiary conglomerate crops out on the Salt Lake salient (Van Horn, 1981).

The east shore area of Great Salt Lake is part of a north-south-trending structural graben that has been the site of accumulation of great thicknesses of sediment 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 up to 10,000 feet (3,000 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 those 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 Quaternary basin-fill sediments are the primary focus of this report because they comprise the principal ground-water aquifers.

The study area is within the hydrologically closed Lake Bonneville basin, and water flowing into this basin generally leaves it only by evapotranspiration. The Lake 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).

The Quaternary lacustrine and fluvial basin-fill deposits over much of the east shore of Great Salt Lake area can be divided into a lower interval, the Delta aquifer; a middle confining interval; the Sunset aquifer; and an upper confining interval (Feth and others, 1966). The lower interval was deposited partly in a marginal lacustrine environment and consists mostly of thin-bedded silt and fine sand (Sprinkel, 1993). The Delta aquifer consists mostly of fluvial, interbedded cobble to pebble gravel and gravelly sand. The middle confining interval consists mostly of thin-bedded silt and fine sand, with some layers of pebbly sand, deposited in marginal lacustrine and fluvial environments (Sprinkel, 1993). The Sunset aquifer consists of pebble gravel, pebbly sand, and well-sorted medium to coarse sand of fluvial origin (Sprinkel, 1993). The upper confining interval consists mostly of thin-bedded silt and sand likely deposited in a brackish lacustrine environment (Sprinkel, 1993). The deposits forming each of these aquifers gradually thin and become increasingly finer grained away from the canyon mouths.

Climate

Nine weather stations in the study area provide climatic data for different time periods (*Ogden Pioneer Powerhouse, 1902-92; *Ogden Sugar Factory, 1928-92; Ogden CAA Airport, 1948-52; Uintah, 1948-60; *Riverdale, 1928-91; Weber Basin Pump Plant 3, 1962-92; *Farmington USU Field Station, 1948-92; Farmington, 1948-65; and Bountiful-Val Verda, 1981-92), but only four (those with asterisks) provide normal climatic data for the 1961 to 1990 period. Temperatures reach a normal minimum of 17.3°F (-27.4°C) in January and a normal maximum of 92.1°F (33.4°C) in July, both at the Ogden Sugar Factory (Ashcroft and others, 1992). The normal mean annual temperature ranges from 46.6°F (8.1°C) at Riverdale to 51.5°F (10.8°C) at the Ogden Pioneer Powerhouse (Ashcroft and others, 1992). Normal annual precipitation ranges from 16.84 inches (42.77 cm) at the Ogden Sugar Factory to 22.73 inches (57.73 cm) at Farmington USU Field Station (Ashcroft and others, 1992). Normal annual evapotranspiration ranges from 45.15 inches (114.68 cm) at Ogden Pioneer Powerhouse to 46.73 inches (118.69 cm) at Farmington USU Field Station (Ashcroft and others, 1992). The average number of frost-free days ranges from 151 to 161 at the Riverdale and Ogden Pioneer Powerhouse, respectively (Ashcroft and others, 1992).

Population and Land Use

From 1990 to 2000, populations in Davis and Weber Counties increased by 27.2 and 24.1 percent (51,053 and 38,203 individuals), respectively (Demographic and Economic Analysis Section, 2001). The July 2001 population of Davis County was estimated at 244,845 (Demographic and Economic Analysis Section, 2002) with a projected population of 392,003 by 2030 (Demographic and Economic Analysis Section, 2000). The July 2001 population of Weber County was estimated at 200,567 (Demographic and Economic Analysis Section, 2002) with a projected population of 307,350 by 2030 (Demographic and Economic Analysis Section, 2000). Layton in Davis County and Ogden in Weber County are the largest cities, having 16,690 and 13,317 people in 2000, respectively (Demographic and Economic Analysis Section, 2001). Most people in Davis and Weber Counties live on the basin-fill deposits of the east shore area of Great Salt Lake.

Residential development is the main land use in Davis County and western Weber County, but agriculture is still a major land use, especially in western Weber County (Barry Burton, Davis County Community and Economic Development Department; G. Kelly Grier, Weber County Planning Department; verbal communications, July 29, 2003). Government is the largest source of employment in Davis and Weber Counties (Utah Division of Water Resources, 1997), probably primarily due to Hill Air Force Base, located in northern Davis County. Trade and services are the two next-largest sources of employment (Utah Division of Water Resources, 1997).

GROUND-WATER CONDITIONS

Basin-Fill Aquifers

Important ground-water resources in the Ogden area exist in unconsolidated to semiconsolidated Quaternary basin-fill deposits (Feth and others, 1966; Clark and others, 1990). 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). Basin-fill aquifers in Davis and Weber Counties west of the Wasatch Range are part of the east shore aquifer system, which can be divided into two somewhat separate hydrologic areas, the Weber Delta area and the Bountiful area (figure 3). The Weber Delta 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 the Great Salt Lake, and from Willard, in Box Elder County southward to Centerville (figure 3) (Feth and others, 1966; Clark and others, 1990; Gates, 1995); this report does not address the Box Elder County portion of the Weber Delta area. The Bountiful area covers about 40 square miles (100 km^2) extending from northern Centerville to the Salt Lake County line (figure 3).

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 4) (Anderson and others, 1994). Two principal aquifers, the Sunset and Delta, have been delineated in the central part of the Weber Delta 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 this aquifer 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). Tertiary basin fill deeper than about 1,500 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). Three much more poorly delineated confined aquifers, the shallow, intermediate, and deep "artesian" aquifers, are present in the Bountiful area; 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 (Thomas and Nelson, 1948).

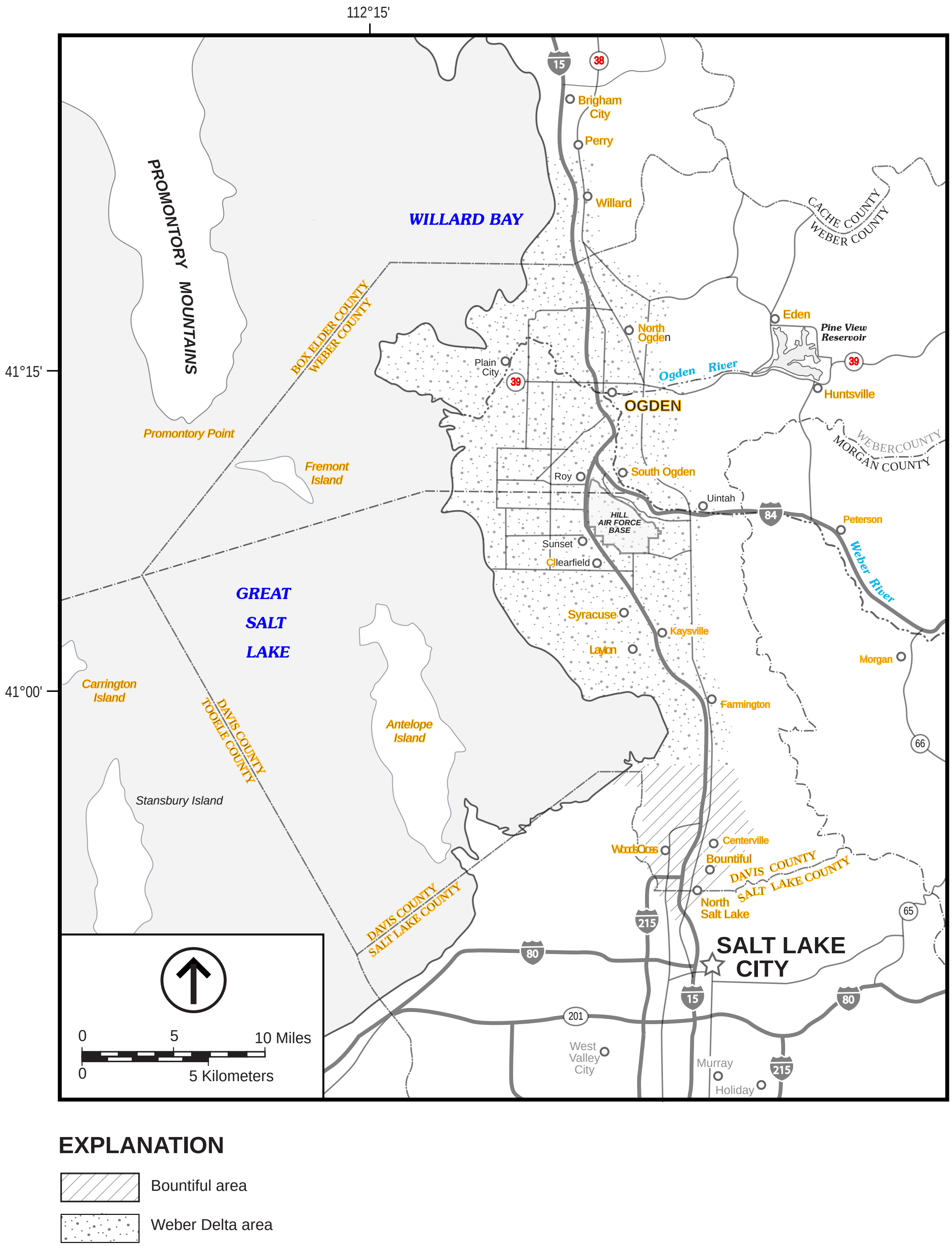
The ultimate source of ground water recharging the east shore aquifer system is precipitation in the drainage basin (Clark and others, 1990). Recharge enters the east shore aquifer system through channel seepage along losing stretches of streams; seepage from irrigated fields, lawns, and gardens; direct 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, especially near the mouth of Weber Canyon (Anderson and others, 1994). Subsurface inflow from bedrock along the mountain front and seepage from the Weber River and other perennial streams are probably the dominant recharge sources (Thomas and Nelson, 1948; Feth and others, 1966).

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

Ground-water flow in the east shore 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 Weber Delta area, the horizontal hydraulic gradient for deeper wells in the Delta aquifer is about 5 feet per mile (1 m/km) in most areas, and the horizontal hydraulic gradient for shallow wells in the Sunset aquifer is about 10 feet per mile (2 m/km) (Feth and others, 1966). The horizontal hydraulic gradient for wells in the shallow artesian aquifer in the Bountiful area is also about 5 feet per mile (1 m/km) in most areas (Thomas and Nelson, 1948). 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 Weber Delta area aquifer system range from 270 to 40,000 feet squared per day (25-3,700 m^2/d), based on 17 aquifer tests conducted between 1944 and 1956 (Feth and others, 1966, table 8). Transmissivity values for unconfined conditions near the mountain front in the Weber Delta area range from 4,000-5,300 feet squared per day (370-500 m^2/d), based on three aquifer tests conducted between 1944 and 1956 (Feth and others, 1966, table 8). Elastic storage coefficients for the Weber Delta 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 area, based on observed porosities and limited recharge tests (Feth and others, 1966). The Bountiful area aquifers likely exhibit similar values.

Seasonal ground water levels in the Weber Delta district generally rise in the spring during net recharge and decline in the summer, with greatest declines near the mountain front (Thomas and Nelson, 1948; Clark and others, 1990). Long-term water levels in the east shore aquifer system for most areas have declined slightly over time, probably related to increased withdrawals from wells for municipal and industrial use (Clark and others, 1990). From 1953 to 1985, ground-water levels declined an average of 27 feet (8 m) for wells in the confined part of the aquifer system in the Weber Delta area, with a maximum drop of 50 feet (15 m) near the principal pumping center for the aquifer system (Clark and others, 1990). From 1953 to 1985, water levels in the uncon-



EXPLANATION

Bountiful area

Weber Delta area

Figure 3. Location of the Weber Delta and Bountiful areas on the east shore of Great Salt Lake aquifer system, Box Elder, Davis, and Weber Counties, Utah (from Clark and others, 1990).

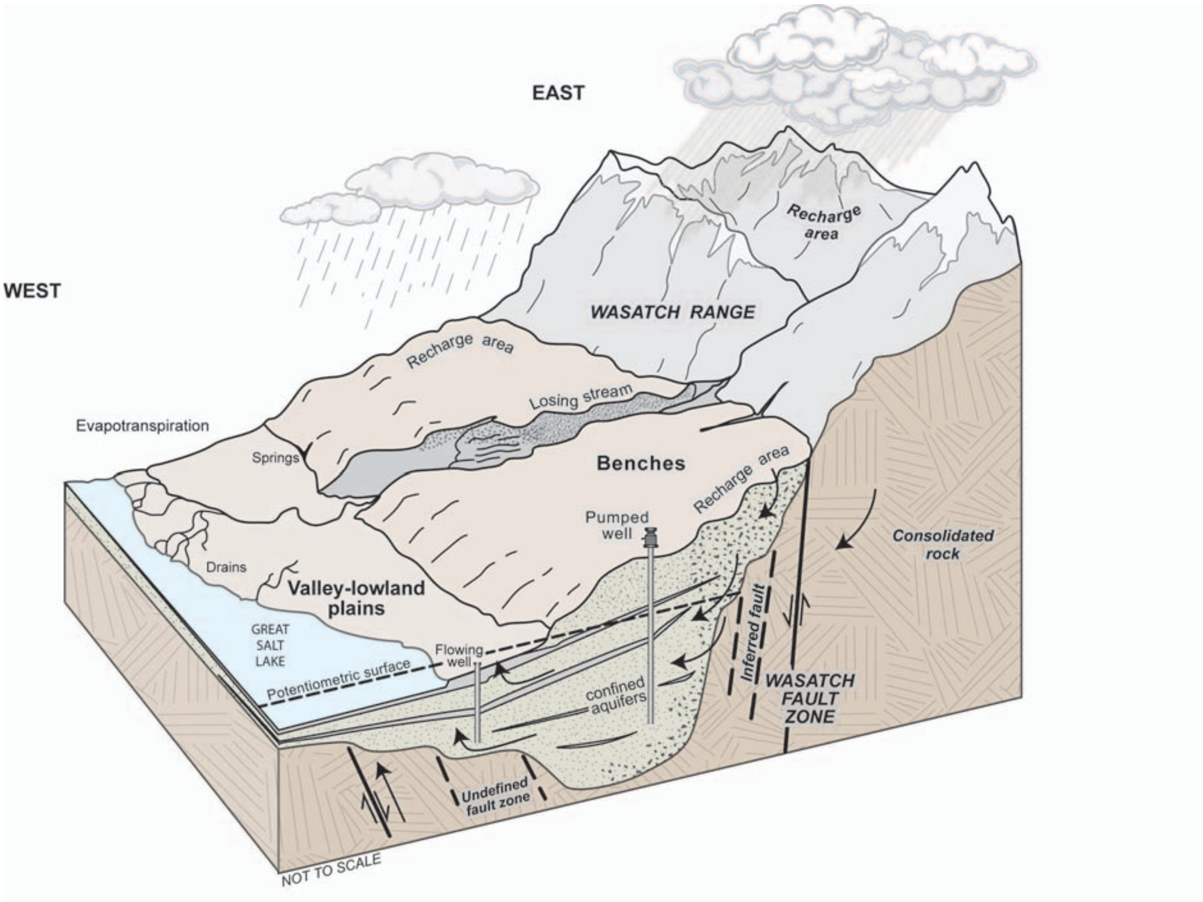


Figure 4. *Generalized block diagram showing water-bearing formations, probable directions of ground-water movement (arrows), and areas of recharge and discharge, east shore area of Great Salt Lake, Davis and Weber Counties, Utah (from Clark and others, 1990).*

fined part of the aquifer system in the Weber Delta area declined as much as 40 feet (12 m) in wells near the mouth of Weber Canyon (Clark and others, 1990), indicating that ground-water mining is a concern. The trend in declining water levels in the east shore aquifer system does not appear to have slowed; Burden and others (2000) documented water-level declines of up to 30.8 feet (9.4 m) from 1970 to 2000 (figure 5). Burden and others (2000) attribute the rise in water levels in the southern part of the Bountiful area from 1970 to 2000 (figure 5) to decreased local pumpage.

Ground-Water Quality

Ground-water quality in the east shore area aquifer system is generally good (figure 6), with total-dissolved-solids (TDS) concentrations ranging from 92 mg/L in the Weber Canyon area to 9,800 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 types in the east shore aquifer system are calcium-magnesium-bicarbonate, sodium-bicarbonate, sodium-chloride, and no predominant type (figure 6) (Smith and Gates, 1963; Feth and others, 1966; Bolke and Waddell, 1972; Clark and others, 1990). The calcium-magnesium-bicarbonate type 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 is found 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 occurs 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 9,000 mg/L TDS in the southwest North Ogden area (Smith and Gates, 1963, figure 8; Feth and others, 1966, figure 14). Mixed-type water exists in an area extending westward from Ogden Canyon and in the Bountiful/North Salt Lake area (figure 6), and contains from 500 to 1,000 mg/L TDS (Smith and Gates, 1963, figure 8; Feth and others, 1966, figure 14).

Concentrations of organic solvents, such as toluene and trichloroethane, exceeding ground-water quality standards (U.S. EPA, 2002) have been identified in the shallow unconfined aquifer in the Hill Air Force Base area south of Riverdale and are currently being remediated (Dalpias and others, 1989). Smaller plumes may also be present at other sites in the area, such as the Ogden Defense Depot west of Ogden.

Ground-water quality data from Smith (1961, table 3), Smith and Gates (1963, table 4), Feth and others (1966, table

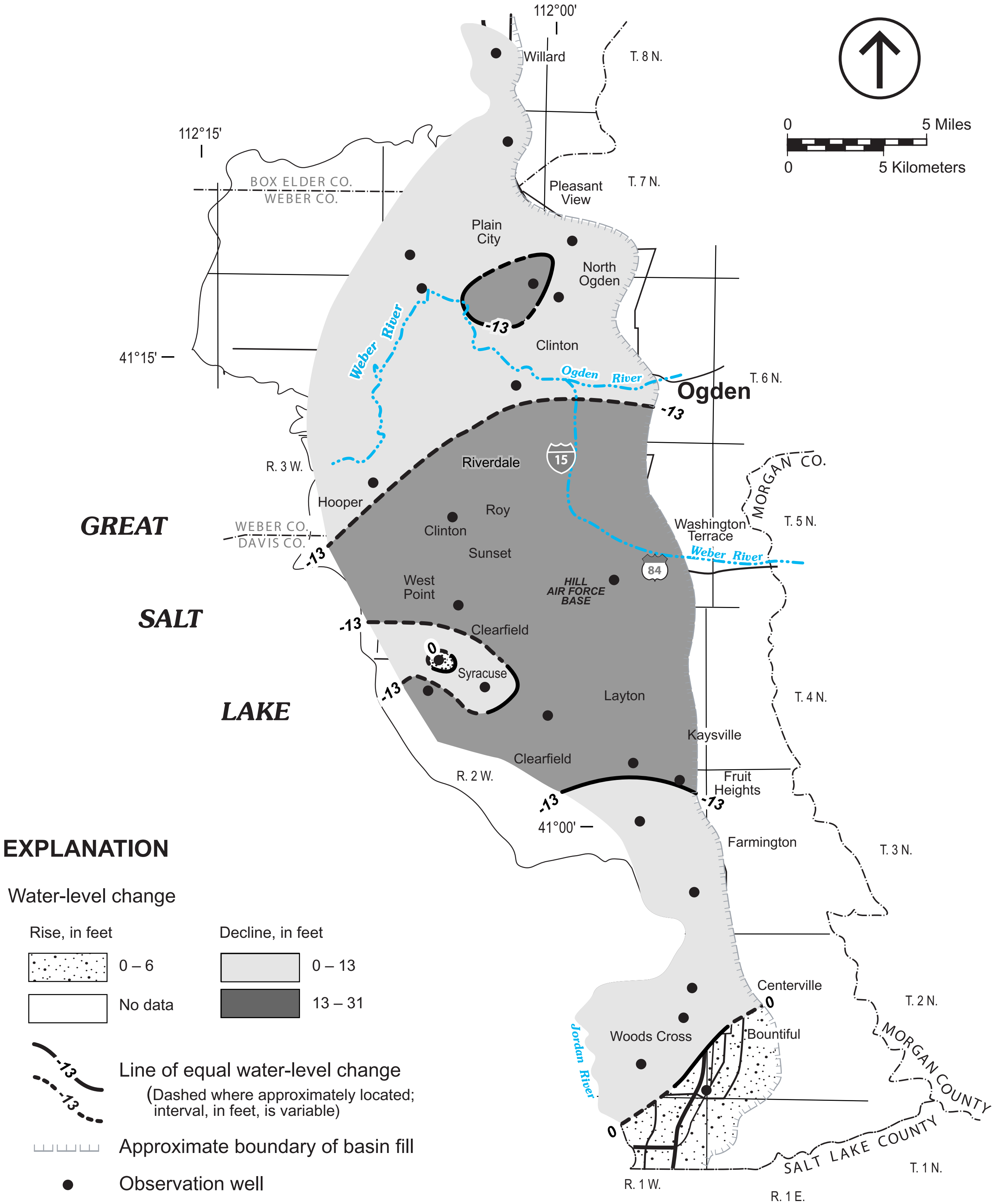


Figure 5. *Change of water level from March 1970 to March 2000, east shore area of Great Salt Lake (modified from Burden and others, 2000).*

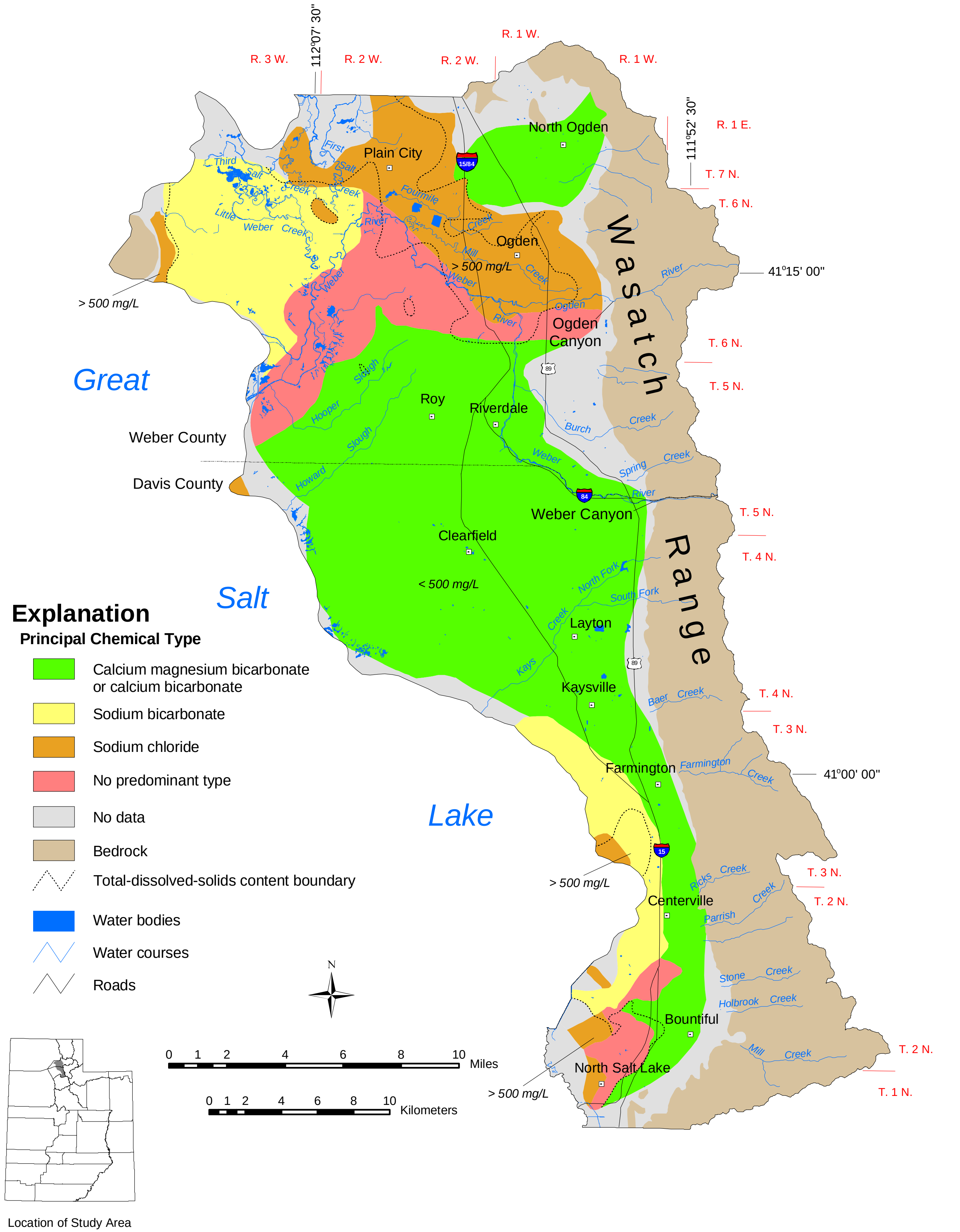


Figure 6. Ground-water quality types and areas with greater than or less than 500 mg/L total-dissolved-solids (TDS) concentrations, east shore area of Great Salt Lake, Davis and Weber Counties, Utah (modified from Bolke and Waddell, 1972).

9), Bolke and Waddell (1972, table 2), Plantz and others (1986, table 5), and Clark and others (1990, table 13) indicate that water samples from wells have exceeded U.S. EPA (2002) secondary ground-water quality standards for manganese in four wells in western Weber County; additionally, five wells have yielded ground-water with high nitrate concentrations (greater than or equal to the ground-water quality standard of 10 mg/L for nitrate).

METHODS

This study is limited to the use and interpretation of existing data to produce pesticide sensitivity and vulnerability maps through the application of GIS analysis methods. As outlined in Siegel (2000), we combine a process-based model with an index-based model to produce sensitivity and vulnerability maps for the east shore area of Great Salt Lake. The index-based model assigns ranges of attribute values and ranks the ranged attribute values as conducive or not conducive to ground-water contamination by pesticides. The process-based model incorporates physical and chemical processes through mathematical equations addressing the behavior of certain chemicals in the subsurface, in this case retardation and attenuation of pesticides using methods developed by Rao and others (1985). No new fieldwork was conducted nor data collected as part of this project.

Ground-Water Sensitivity to Pesticide Pollution

Ground-water sensitivity to pesticides is determined by assessing natural factors favorable or unfavorable to the degradation of ground water by pesticides applied to or spilled on the land surface. Hydrogeologic setting (vertical ground-water gradient and presence or absence of confining layers), soil hydraulic conductivity, retardation of pesticides, attenuation of pesticides, and depth to ground water are the factors primarily determining ground-water sensitivity to pesticides in the east shore area of Great Salt Lake. Sensitivity represents the sum of natural influences that facilitate the entry of pesticides into ground water.

Hydrogeologic Setting

Hydrogeologic setting is delineated on ground-water recharge-area maps that typically show: (1) primary recharge areas, (2) secondary recharge areas, and (3) discharge areas (Anderson and others, 1994). For our GIS anal-yses, we assigned hydrogeologic setting to one of these three categories, which are illustrated schematically in figure 7. Primary recharge areas, commonly the uplands and coarse-grained unconsolidated deposits along basin margins, do not contain thick, continuous, fine-grained layers (confining layers) and have a downward ground-water gradient. Secondary recharge areas, commonly mountain-front benches, have fine-grained layers thicker than 20 feet (6 m) and a downward ground-water gradient. Ground-water discharge areas are generally in basin lowlands. Discharge areas for unconfined aquifers occur where the water table intersects the ground surface to form springs, seeps, lakes, wetlands, or gaining streams (Lowe and Snyder, 1996). Discharge areas for confined aquifers occur where the ground-water gradient is upward and water is discharging to a shallow unconfined aquifer above the upper confining bed, or to a spring. Water from wells that penetrate confined aquifers may flow to the surface naturally. The extent of both recharge and discharge areas may vary seasonally and from dry years to wet years.

Anderson and others (1994) used drillers' logs of water wells in the east shore area of Great Salt Lake to delineate primary recharge areas and discharge areas, based on the presence of confining layers and relative water levels in the principal and shallow unconfined aquifers. Although this technique is useful for gaining a general idea of where recharge and discharge areas are likely located, it is subject to a number of limitations. The use of drillers' logs requires interpretation because of the variable quality of the logs.

Correlation of geology from well logs is difficult because lithologic descriptions prepared by various drillers are generalized and commonly inconsistent. Use of water-level data from well logs is also problematic because levels in the shallow unconfined aquifer are often not recorded and because water levels were measured during different seasons and years.

Confining layers are any fine-grained (clay and/or silt) layer thicker than 20 feet (6 m) (Anderson and others, 1994). Some drillers' logs show both clay and sand in the same interval, with no information describing relative percentages; these are not classified as confining layers (Anderson and others, 1994). If both silt and clay are checked on the log and the word "sandy" is written in the remarks column, then the layer is assumed to be a predominantly clay confining layer (Anderson and others, 1994). Some drillers' logs show both clay and gravel, cobbles, or boulders; these also are not classified as confining layers, although in some areas of Utah layers of clay containing gravel, cobbles, or boulders do, in fact, act as confining layers.

The primary recharge area for the principal aquifer system in the east shore area of Great Salt Lake consists of the uplands along the margins of the basin, together with basin fill not containing confining layers (figure 7), generally located along the mountain fronts. Ground-water flow in primary recharge areas has a downward component. Secondary recharge areas, if present, are locations where there are confining layers, but ground-water flow still has a downward component. Secondary recharge areas generally extend toward the center of the basin to the point where ground-water flow is upward (figure 7). The ground-water flow gradient, also called the hydraulic gradient, is upward when the potentiometric surface of the principal aquifer system is higher than the water table in the shallow unconfined aquifer (Anderson and others, 1994). Water-level data for the shallow unconfined aquifer are not abundant, but exist on some well logs. When the confining layer extends to the ground surface, secondary recharge areas exist where the potentiometric surface in the principal aquifer system is below the ground surface.

Ground-water discharge areas, if present, generally are at lower elevations than recharge areas. In discharge areas, the water in confined aquifers discharges to the land surface or to a shallow unconfined aquifer (figure 7). For this to happen, the hydraulic head in the principal aquifer system must be higher than the water table in the shallow unconfined aquifer. Otherwise, downward pressure from the shallow aquifer exceeds the upward pressure from the confined aquifer, creating a net downward gradient indicative of sec-

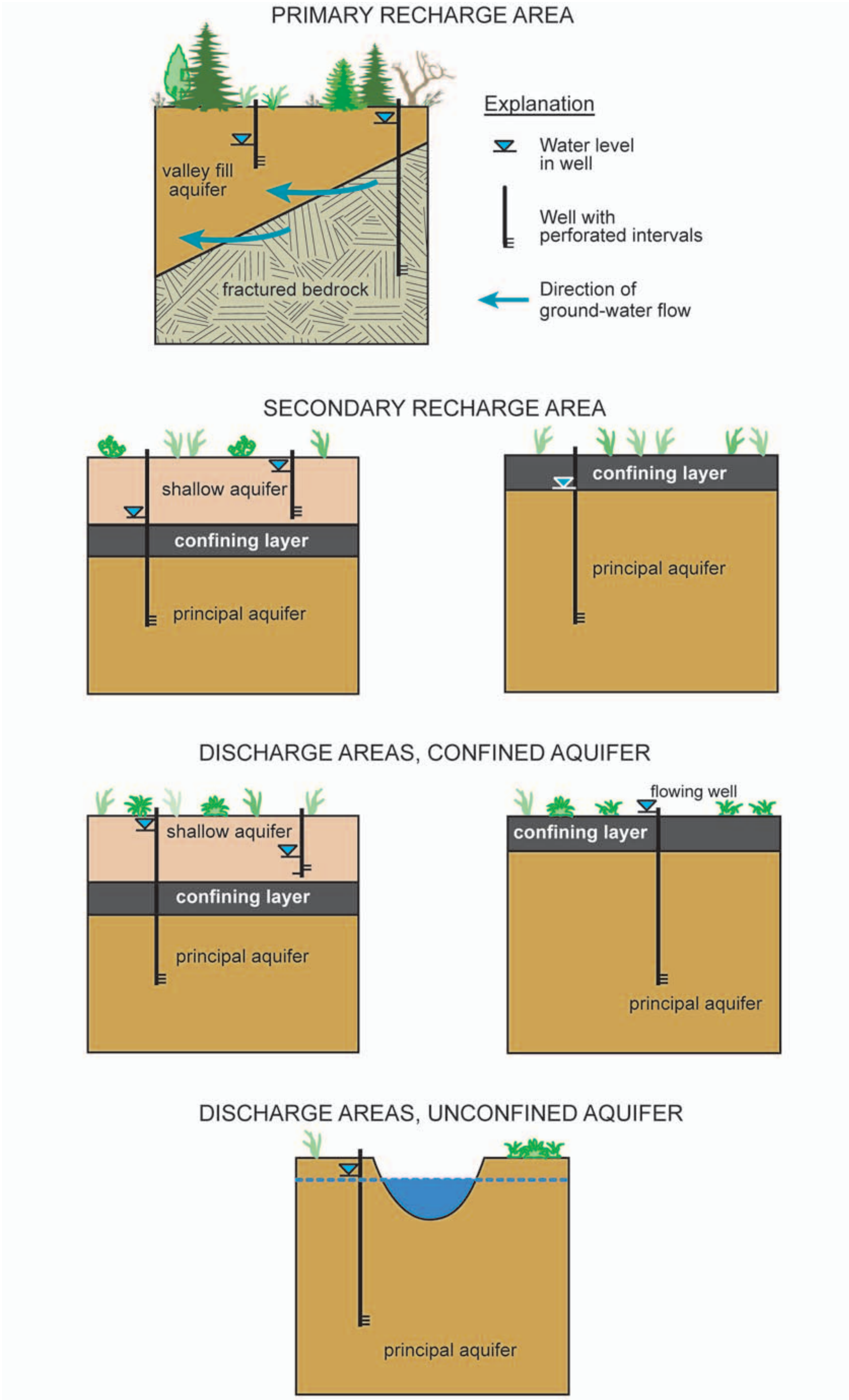


Figure 7. *Relative water levels in wells in recharge and discharge areas (modified from Snyder and Lowe, 1998).*

ondary recharge areas. Flowing (artesian) wells, indicative of discharge areas, are marked on drillers' logs and sometimes on U.S. Geological Survey 7.5-minute quadrangle maps. Wells with potentiometric surfaces above the top of the confining layer can be identified from well logs. Surface water, springs, or phreatophytic plants characteristic of wetlands can be another indicator of ground-water discharge. In some instances, however, this discharge may be from a shallow unconfined aquifer. An understanding of the topography, surficial geology, and ground-water hydrology is necessary before using these wetlands to indicate discharge from the principal aquifer system.

Hydraulic Conductivity of Soils

Hydraulic conductivity is a measure of the rate at which soils can transmit water. Even though fine-grained soils may have low transmissivities, water is nevertheless eventually transmitted. Values for hydraulic conductivity of soils were obtained from soil percolation tests and "permeability" (hydraulic conductivity) ranges assigned to soil units mapped by the U.S. Department of Agriculture's Soil Conservation Service (now Natural Resources Conservation Service; Erickson and others, 1968). For GIS analysis, we divided soil units into two hydraulic conductivity ranges: greater than or equal to, and less than, 1 inch (2.5 cm) per hour. We chose 1 inch (2.5 cm) per hour because it corresponds to the minimum allowable percolation rate for permitting septic tanks under Utah Division of Water Quality administrative rules. For areas having no hydraulic conductivity data, we applied the greater than or equal to 1 inch (2.5 cm) per minute GIS attribute ranking, described below, to be protective of ground-water quality.

Pesticide Retardation

Pesticide retardation is a measure of the differential between movement of water and the movement of pesticide in the vadose zone (Rao and others, 1985). Because pesticides are adsorbed to organic carbon in soil, they move through the soil slower than water; the relative rate of movement of pesticides depends on the proportion of organic carbon in the soil. This relatively slower movement allows pesticides to be degraded more readily by bacteria and chemical interaction than would be the case if they traveled at the same rate as pore water in the vadose zone. The retardation factor (RF) is a function of dry bulk density, organic carbon fraction, and field capacity of the soil and the organic carbon sorption distribution coefficient of the specific pesticide; a relatively low RF indicates a higher potential for ground-water pollution. Rao and others (1985) present the following equation:

$$R_F = 1 + (\rho_b F_{oc} K_{oc})/\theta_{FC} \qquad (1)$$

where:

R_F = retardation factor (dimensionless);
ρ_b = bulk density (kg/L);
F_{oc} = fraction, organic carbon;
K_{oc} = organic carbon sorption distribution coefficient (L/kg); and
θ_{FC} = field capacity (volume fraction).

Retardation factors typically range from (1 + 4Kd) to (1 + 10 Kd) (Freeze and Cherry, 1979), where Kd is the product of the organic carbon sorption distribution coefficient (K_{oc}) and the fraction of organic carbon, and based on typical unconsolidated sediment properties of dry bulk density (0.06-0.08 lb/in^3 [1.6-2.1 kg/L]) and porosity range (0.2 to 0.4). Dissolved constituents in ground water having low R_F values (around 1), such as nitrate (a relatively mobile cation), move through the subsurface at the same rate as the ground water, whereas dissolved constituents in ground water with R_F values that are orders of magnitude larger than one are essentially immobile (Freeze and Cherry, 1979). The relative velocity is the reciprocal of the retardation factor and describes the rate a mixture of reactive contaminant moves relative to solvent-free ground water.

For this study, we used data from the Soil Survey Geographic (SSURGO) database (National Soil Survey Center, 1994), which provides digitized data for some soil areas of the state of Utah, including the east shore area of Great Salt Lake, at a scale of 1:24,000. Data include derived values for bulk density, organic carbon fraction, and field capacity (table 2).

We set variables in equation 1 to values that represent conditions likely to be encountered in the natural environment (table 2) to establish a rationale for dividing high and low pesticide retardation for our GIS analysis, and we applied digital soil information unique to particular soil groups from SSURGO data for organic carbon. We used the organic carbon sorption distribution coefficient (table 3), at a pH of 7, for atrazine, the pesticide among the four having the least tendency to adsorb to organic carbon in the soil (Weber, 1994). We derived bulk density and field capacity from a soil texture triangle hydraulic properties calculator (Saxton, undated). To compute R_F values, we applied bulk density end members of 0.04 and 0.07 pounds per cubic inch (1.2 and 2.0 kg/L) and field capacity end members of 14 and 42 percent, which represent naturally occurring conditions in the east shore area of Great Salt Lake, and variable soil organic carbon content using a water depth of 3 feet (1 m). Average organic carbon content in soils in the east shore area of Great Salt Lake is shown in figure 8 and ranges from 0.3 to 4.4 percent; the mass fraction of organic carbon was computed by dividing the organic matter parameter in the SSURGO data by a conversion factor of 1.72 (Siegel, 2000). We then applied the organic carbon content end members to compute the extreme R_F values; equation 1 results in retardation factors ranging from 1.84 to 64. This means the highest relative velocity from our data is 0.54 and the lowest is 0.015; the former indicates pesticide in ground water moves at a rate about 54 percent that of ground water free of pesticides, whereas the latter indicates that pesticides in ground water are essentially immobile.

A small percentage (1%) of pesticides traveling downward in vadose-zone material having an R_F of 3.6 could reach the water table at a depth of 3 feet (1 m) within one year if ground-water recharge amounted to 11.8 inches (30 cm) or greater during the year, which is the highest amount of recharge calculated for the mountains in the east shore area of Great Salt Lake. When ground-water recharge is less than 9.8 inches (25 cm) per year, as is the case for the valley floors of the east shore area of Great Salt Lake, no amount of pesticide will likely reach a depth of 3 feet (1 m) in a one-

Table 2. Hydrologic soil groups, field capacity, bulk density, and fraction of organic content generalized for Utah soils. Soil description and organic content from National Soil Survey Center (1994). Field capacity based on sediment grain size calculated from a soil texture triangle hydraulic properties calculator (Saxton, undated). Bulk density from Marshall and Holmes (1988) and Saxton (undated).

Soil Group	Soil Description	Grain size (mm) (Field Capacity %) (average)	Bulk Density Range (kg/L)	Organic Content, Fraction (F_{oc})*
A	Sand, loamy sand, or sandy loam; low runoff potential and high infiltration rates even when thoroughly wetted; consists of deep, well to excessively drained sands or gravels with high rate of water transmission.	0.1 - 1 (14-21)	1.5 – 2 (1.75)	Variable and ranges from 0.3 to 4.4 %
B	Silt loam or loam; moderate infiltration rate when thoroughly wetted; consists of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures.	0.015 - 0.15 (25-28)	1.3 - 1.61 (1.4)	Variable and ranges from 0.3 to 4.4 %
C	Sandy clay loam; low infiltration rates when thoroughly wetted; consists of soils with layer that impedes downward movement of water; soils with moderately fine to fine structure.	0.01 - 0.15 (26)	1.3 – 1.9 (1.6)	Variable and ranges from 0.3 to 4.4 %
D	Clay loam, silty clay loam, sandy clay, silty clay, and/or clay; highest runoff potential of all soil groups; low infiltration rates when thoroughly wetted; consists of clay soils with a high swelling potential, soils with a permanent high water table, soils with a hardpan or clay layer at or near the surface, and shallow soils over nearly impervious material.	0.0001 - 0.1 (32-42)	1.2-1.3 (1.25)	Variable and ranges from 0.3 to 4.4 %
G	Gravel	2.0 and greater (less than 12)	2 (2)	0.1 %**

* F_{oc} is calculated from SSURGO organic matter data divided by 1.72 and is unique for soil polygons.
** No value for F_{oc} exists in the SSURGO database for gravel; we assigned a conservative value of 0.1%

Table 3. Pesticide organic carbon sorption distribution coefficients (K_{oc}) and half-lives ($T^{1/2}$) for typical soil pHs (data from Weber, 1994).

	K_{oc} (L/kg)		$T^{1/2}$ (Days)		$T^{1/2}$ (Years)
	pH 7	pH 5	pH 7	pH 5	
Atrazine	100	200	60	30	0.16
Simazine	200	400	90	—	0.25
Alachlor	170	—	20	60	0.05
Metolachlor	150	—	40	—	0.11

year period (see attenuation discussion below). For our GIS analysis, we divided pesticide retardation into two ranges: greater than, or less than or equal to 3.6.

Pesticide Attenuation

Pesticide attenuation is a measure of the rate at which a pesticide degrades under the same conditions as characterized above under pesticide retardation (Rao and others, 1985). The rate of attenuation indirectly controls the depth to which a pesticide may reasonably be expected to migrate, given the specific conditions. The attenuation factor (A_F) is a function of depth (vertically) or length (horizontally) of the soil layer through which the pesticide is traveling, net annual ground-water recharge, half-life of the specific pesticide considered, and field capacity of the soil. Attenuation factors

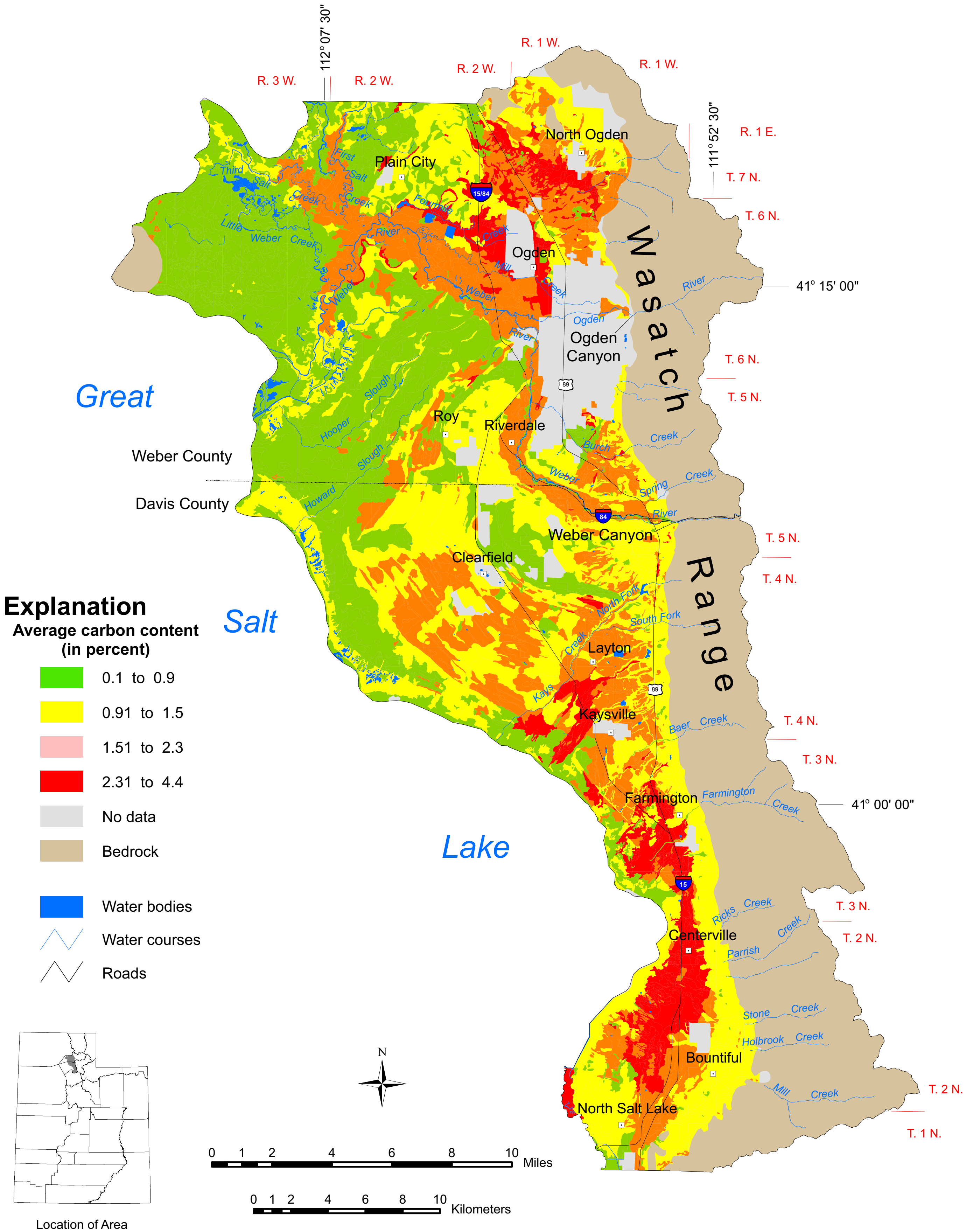


Figure 8. *Average organic carbon content in soils in the east shore area of Great Salt Lake, Weber and Davis Counties, Utah (data from National Soil Survey Center, 1994).*

range between 0 and 1 (Rao and others, 1985); note that high attenuation factors represent conditions of low attenuation. Rao and others (1985) present the following equation:

$$A_F = \exp(-0.693\ z\ R_F\ \theta_{FC} /q\ t_{1/2}) \qquad (2)$$

where:

A_F = attenuation factor (dimensionless);
z = reference depth (length);
R_F = retardation factor (dimensionless);
θ_{FC} = field capacity (volume fraction);
q = net annual ground-water recharge (precipitation minus evapotranspiration) (m); and
$t_{1/2}$ = pesticide half-life (years).

For this study, we calculated (using GIS analysis) net annual ground-water recharge by subtracting statewide mapped normal annual evapotranspiration (Jensen and Dansereau, 2001) for the 30-year period from 1971 to 2000 from mapped normal annual precipitation (Utah Climate Center, 1991) for the 30-year period from 1961 to 1990. Data from two different 30-year periods were used because normal annual precipitation GIS data are currently not available for the 1971 to 2000 period and normal annual evapotranspiration GIS data are not available for the 1961 to 1990 period. This analysis revealed that most of the moisture produced by precipitation is consumed by evapotranspiration in most parts of Utah, so that ground-water recharge from precipitation is relatively low in many areas of the state, including the east shore area of Great Salt Lake (figure 9). The only localities in which evapotranspiration is less than precipitation are high-elevation forested areas. These are typically the source areas for surface streams that flow to valleys at lower elevations where they infiltrate the valley-fill sediment, accounting for a large part of ground-water recharge. Irrigation is another component of ground-water recharge, but it is not easily measured, and is not evaluated in our analysis.

Using equation 2, we calculated attenuation factors for ranges of values common to soils in the east shore area of Great Salt Lake, similar to our approach for retardation, to delineate high and low pesticide attenuation factors for our GIS analysis. To represent naturally occurring conditions in this area that would result in the greatest sensitivity to ground-water contamination, we used a retardation factor of 3.6, calculated as described above; the half-life for simazine (table 3), the pesticide among the four with the longest half-life (Weber, 1994); a field capacity of 14 percent; and a bulk density value of 0.04 pounds per cubic inch (1.2 kg/L). For a net annual ground-water recharge value of 0 inches, as is typical of the valley-floor areas of the east shore of Great Salt Lake, equation 2 results in an attenuation factor that approaches 0. This means that at the above-described values for variables in the equation, none of the pesticide originally introduced into the system at the ground surface would be detected at a depth of 3 feet (1 m); therefore, no pesticides would reach ground water.

Although quantities of pesticides applied to the ground surface would intuitively seem to have a direct bearing on the amount of pesticide impacting ground water, Rao and others' (1985) equations do not support this. Note that the quantity of pesticide applied to the ground surface does not enter into either equation as a variable; the half-life of the pesticide, however, is essential. The half-life of a pesticide under typical field conditions remains fairly constant. The larger the quantity of pesticide that is applied, the greater the number of bacteria that develop to decompose and consume the pesticide over the same period of time. Furthermore, the quantity of pesticide needed to control weeds is quite small. The following recommended application rates (table 4) are provided by the manufacturers of the four herbicides evaluated as part of this study. Pre-emergent herbicides are typically applied once per year, either in the fall after post-season tillage or in early spring before weeds begin to germinate.

Table 4. *Maximum recommended application rates* for the four pesticides discussed in this report.*

Herbicide	**Max. Application rate (lbs. AI** per acre)**	**Time interval**
Atrazine	2.5	calendar year
Alachlor	4.05	pre-emergence
Metolachlor	1.9	pre-emergence
Simazine	4.0	pre-emergence

*Data derived from labeling documentation provided by manufacturers; latest update as of January 2001.
**Active ingredient.

Depth to Shallow Ground Water

The closer ground water is to the land surface the more sensitive it is to being degraded by pesticides. Based on soil mottling, water encountered in test pits, or other information, soils having shallow ground water seasonally less than or equal to 3 feet (1 m) deep is one attribute of soil units mapped by the Soil Conservation Service (now Natural Resources Conservation Service; Erickson and others, 1968). We selected 3 feet (1 m) as the depth-to-ground-water attribute used to evaluate sensitivity of geographic areas to pesticides. For areas where depth-to-ground-water data are not available in GIS format, we applied the less-than-3-feet (1 m) GIS attribute ranking, described below, to be protective of ground-water quality.

GIS Analysis Methods

We characterize pesticide sensitivity (intrinsic susceptibility) as "low," "moderate," or "high" based on the sum of numerical values (rankings) assigned to hydrogeologic setting, soil hydraulic conductivity, soil retardation of pesticides, soil attenuation of pesticides, and depth to shallowest ground-water attributes as shown in table 5. Numerical ranking for each attribute category is arbitrary, but reflects the relative level of importance the attribute plays in determining sensitivity of areas to application of agricultural pesticides; for instance, we believe hydrogeologic setting is the most important attribute with respect to ground-water sensitivity to pesticides, and therefore weighted this attribute three

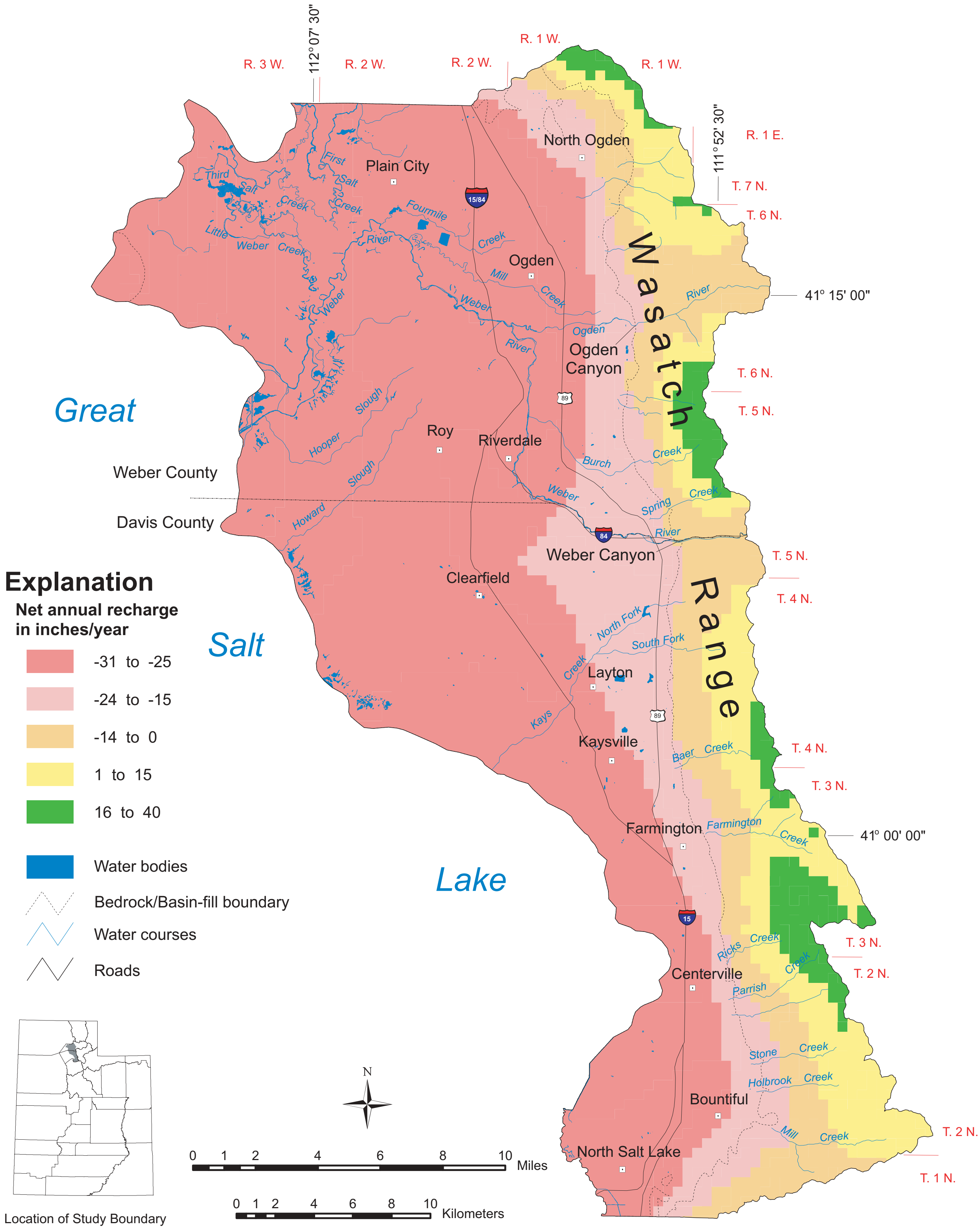


Figure 9. *Net annual ground-water recharge from precipitation in the east shore area of Great Salt Lake, Davis and Weber Counties, Utah. Recharge calculated using data from the Utah Climate Center (1991) and Jensen and Dansereau (2001). Although net annual recharge may be negative in some areas, seasonally some recharge from precipitation may occur.*

times more heavily than the other attribute categories. A sensitivity attribute of low is assigned when the summed ranking ranges from –2 to 0, a sensitivity attribute of moderate is assigned when the summed ranking ranges from 1 to 4, and a sensitivity attribute of high is assigned when the summed ranking ranges from 5 to 8.

Ground-Water Vulnerability to Pesticide Pollution

Ground-water vulnerability to pesticides is determined by assessing how ground-water sensitivity to pesticides is modified by the activities of humans. In addition to ground-water sensitivity to pesticides, the presence of applied water (irrigation) and crop type are the factors primarily determining ground-water vulnerability to pesticides. Our analysis is based on 1999 land-use data.

Ground-Water Sensitivity

We consider ground-water sensitivity (intrinsic susceptibility) to be the principal factor determining the vulnerability of the basin-fill aquifer in the east shore area of Great Salt Lake to degradation from agricultural pesticides. Consequently, low, moderate, and high sensitivity rankings were assigned numerical values as shown in table 6.

Irrigated Lands

We mapped irrigated lands from the Utah Division of Water Resources 1:24,000-scale Land Use/Water Related Use GIS data set. Areas of various water-use categories were mapped from either aerial photographs (pre-2000) or 5-meter (16-ft) resolution infrared satellite data and then field checked (Utah Division of Water Resources metadata). The east shore area of Great Salt Lake inventory was conducted in 1999 (Utah Division of Water Resources metadata). We used all polygons having standard type codes beginning with IA to produce the irrigated land coverage for this study. These data do not distinguish areas of sprinkler irrigation versus areas of flood irrigation; areas of flood irrigation are likely to be more vulnerable to degradation from pesticides than areas of sprinkler irrigation.

Crop Type

We mapped agricultural lands using the Utah Division of Water Resources 1:24,000-scale Land Use/Water Related Use GIS data set, which includes categories of crop types. Areas of various crop-type categories were mapped from either aerial photographs (pre-2000) or 5-meter (16 ft) resolution infrared satellite data and then field checked (Utah Division of Water Resources metadata). The east shore area of Great Salt Lake inventory was conducted in 1999 (Utah

Table 5. *Pesticide sensitivity and the attribute rankings used to assign sensitivity for the east shore area of Great Salt Lake, Davis and Weber Counties, Utah.*

Pesticide Retardation Factor		Pesticide Attenuation Factor		Hydrogeologic Setting		Soil Hydraulic Conductivity		Depth to Ground Water		Sensitivity	
Attribute	Ranking	Attribute	Ranking	Attribute	Ranking	Attribute	Ranking	Attribute	Ranking	Attribute	Ranking
High	0	Low	0	Confined aquifer discharge area	-4	Less than 1 inch/hour	1	Greater than 3 feet	1	Low	-2 to 0
				Secondary recharge area	-1					Moderate	1 to 4
Low	1	High	1	Primary recharge area and unconfined aquifer discharge area	2	Greater than or equal to 1 inch/hour	2	Less than or equal to 3 feet	2	High	5 to 8

Table 6. *Pesticide vulnerability and the attribute rankings used to assign vulnerability for the east shore area of Great Salt Lake, Davis and Weber Counties, Utah.*

Sensitivity		Corn/Sorghum Crops		Irrigated Land		Vulnerability	
Attribute	Ranking	Attribute	Ranking	Attribute	Ranking	Attribute	Ranking
Low	-2	No	0	No	0	Low	-2 to -1
Moderate	0					Moderate	0 to 2
High	2	Yes	1	Yes	1	High	3 to 4

Division of Water Resources metadata). We selected all polygons having standard type codes IA2a1 (corn), IA2a2 (sorghum), and IA2b5 (sweet corn; none in this category were in the data set) to produce the crop-type land coverage for this study, as these are the crop types to which the pesticides addressed are applied in Utah. Although the specific fields growing these crops may vary from year to year, the general areas and average percentages of these crop types likely do not.

GIS Analysis Methods

We characterize pesticide vulnerability as "low," "moderate," and "high" based on the sum of numerical values (rankings) assigned to pesticide sensitivity, areas of irrigated lands, and crop type as shown in table 6. Once again, numerical ranking for each attribute category is arbitrary, but reflects the relative level of importance the attribute plays in determining vulnerability of areas to application of agricultural pesticides. For instance, ground-water sensitivity to pesticides is the most important attribute with respect to ground-water vulnerability to pesticides, and therefore we weighted this attribute two times more heavily than the other attribute categories.

RESULTS

Ground-Water Sensitivity

To assess ground-water sensitivity (intrinsic susceptibility) to pesticide contamination, several GIS attribute layers were assembled as intermediate steps. Attribute layers include pesticide retardation/attenuation, hydrogeologic setting (recharge/discharge areas), hydraulic conductivity of soils, and depth to shallow ground water. Data from these attribute layers were used to produce a ground-water sensitivity map (plate 1) using GIS analysis methods as outlined in table 5, and are described and summarized in the following sections.

Retardation/Attenuation

Retardation factors are variable and attenuation factors are ranked as low throughout the east shore area; the low attenuation factors are due to net annual evapotranspiration exceeding net annual precipitation. The area is dominantly characterized by high retardation factors due to the prevalent silt/clay soil types. Net annual recharge from precipitation is negative in basin-floor areas (figure 9). Most recharge that occurs from precipitation is principally along the valley margins and likely occurs during spring snowmelt. Pesticides are generally applied after snowmelt. Up to several months may elapse between pesticide application and first irrigation, sufficient time for attenuation to occur before downward migration of pesticides in the vadose zone commences under the influence of irrigation.

Hydrogeologic Setting

Ground-water recharge areas in the east shore area of Great Salt Lake (figure 10) were mapped by Anderson and others (1994). Their map shows that primary recharge areas, the areas most susceptible to contamination from pesticides applied to the land surface, comprise about 11 percent of the surface area of the basin-fill aquifer. Secondary recharge areas make up 26 percent of the surface area of the basin-fill aquifer. Ground-water discharge areas, which provide extensive protection to the principal aquifer from surface contamination from the application of pesticides, make up 63 percent of the surface area of the basin-fill aquifer.

Hydraulic Conductivity of Soils

Surface application of pesticides is more likely to cause ground-water quality problems in areas where soils have higher hydraulic conductivity than in areas where hydraulic conductivity is low. Hydraulic conductivity data are from the National Soil Survey Center (1994). About 73 percent of the surface area of the basin-fill aquifer in the east shore area of Great Salt Lake has soil units mapped as having hydraulic conductivity greater than or equal to 1 inch (2.5 cm) per hour (figure 11). About 17 percent of the surface area of the basin-fill aquifer has soil units mapped as having hydraulic conductivity less than 1 inch (2.5 cm) per hour; these soil units are mainly along the shores of Great Salt Lake, and along the lower reaches of streams in the northern part of the study area. About 10 percent of the surface area of the basin-fill aquifer has soil units for which hydraulic conductivity values have not been assigned by the National Soil Survey Center (1994); these soil polygons are scattered throughout the study area, and were grouped into the greater than or equal to 1 inch (2.5 cm) per hour category for analytical purposes to be protective of water quality.

Depth to Shallow Ground Water

Surface application of pesticides is more likely to cause ground-water quality problems in areas of shallow ground water than where ground water is relatively deep. Depths to shallow ground-water data are from the National Soil Survey Center (1994). About 5 percent of the area overlying the basin-fill aquifer in the east shore area of Great Salt Lake has soil units mapped as having depths to shallow ground water less than or equal to 3 feet (1 m); these areas are primarily along Great Salt Lake, and along streams in the northern part of the study area (figure 12). About 36 percent of the surface area of the basin-fill aquifer has soil units mapped as having depths to shallow ground water greater than 3 feet (1 m). About 59 percent of the surface area of the basin-fill aquifer has soil units for which no SSURGO data exist. Areas without assigned depths to shallow ground water were grouped with the less than or equal to 3 feet (1 m) depth category for analytical purposes to be protective of water quality.

Pesticide Sensitivity Map

Plate 1 shows ground-water sensitivity (intrinsic susceptibility) to pesticides for the east shore area of Great Salt Lake, constructed using the GIS methods and ranking techniques described above. We analyzed only the basin-fill aquifer; the surrounding uplands are designated on plate 1 as "bedrock" and consist mainly of shallow or exposed bedrock in mountainous terrain.

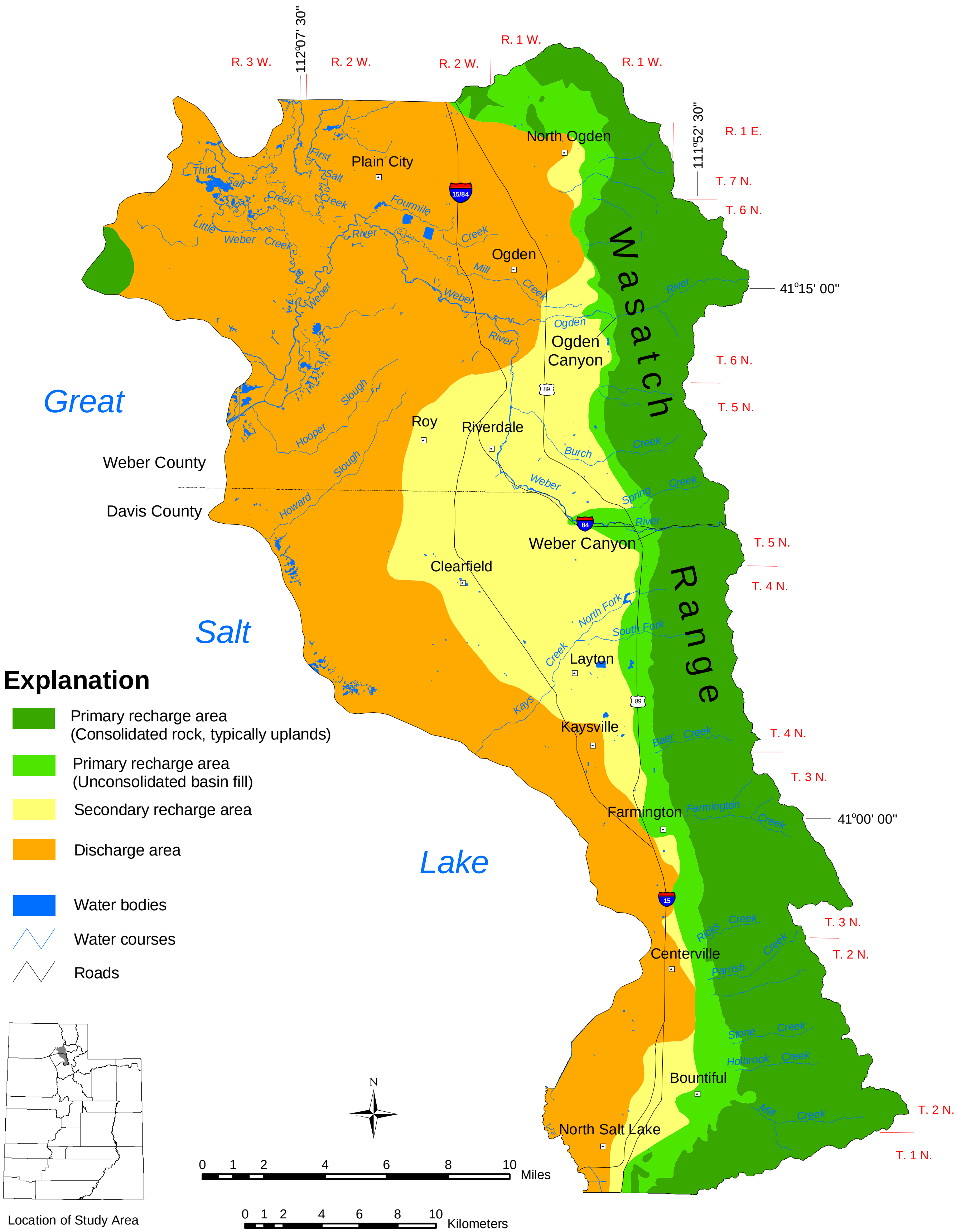


Figure 10. Recharge and discharge areas in the east shore area of Great Salt Lake, Davis and Weber Counties, Utah (from Anderson and others, 1994).

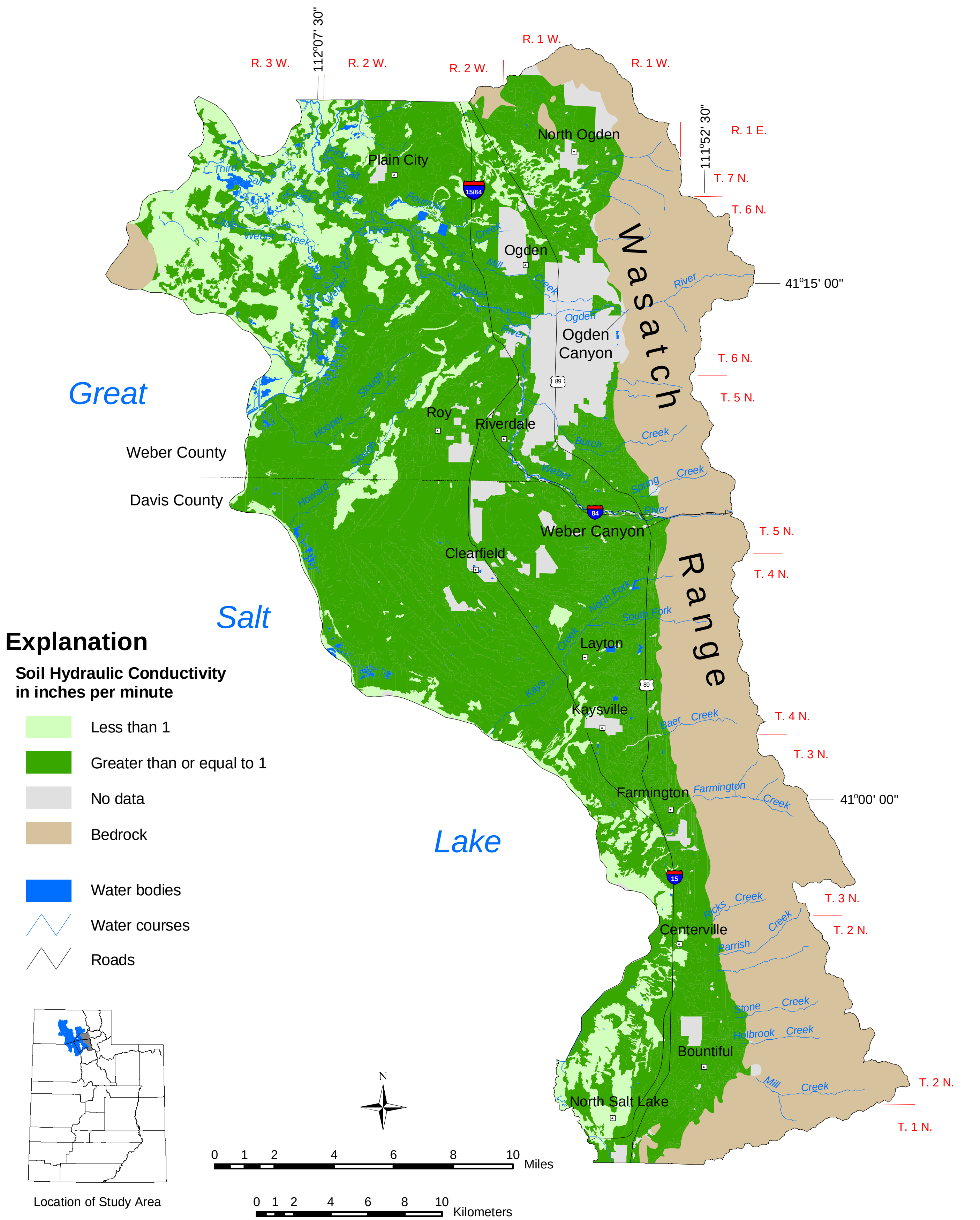


Figure 11. Soil hydraulic conductivity in the east shore area of Great Salt Lake, Davis and Weber Counties, Utah (data from National Soil Survey Center, 1994).

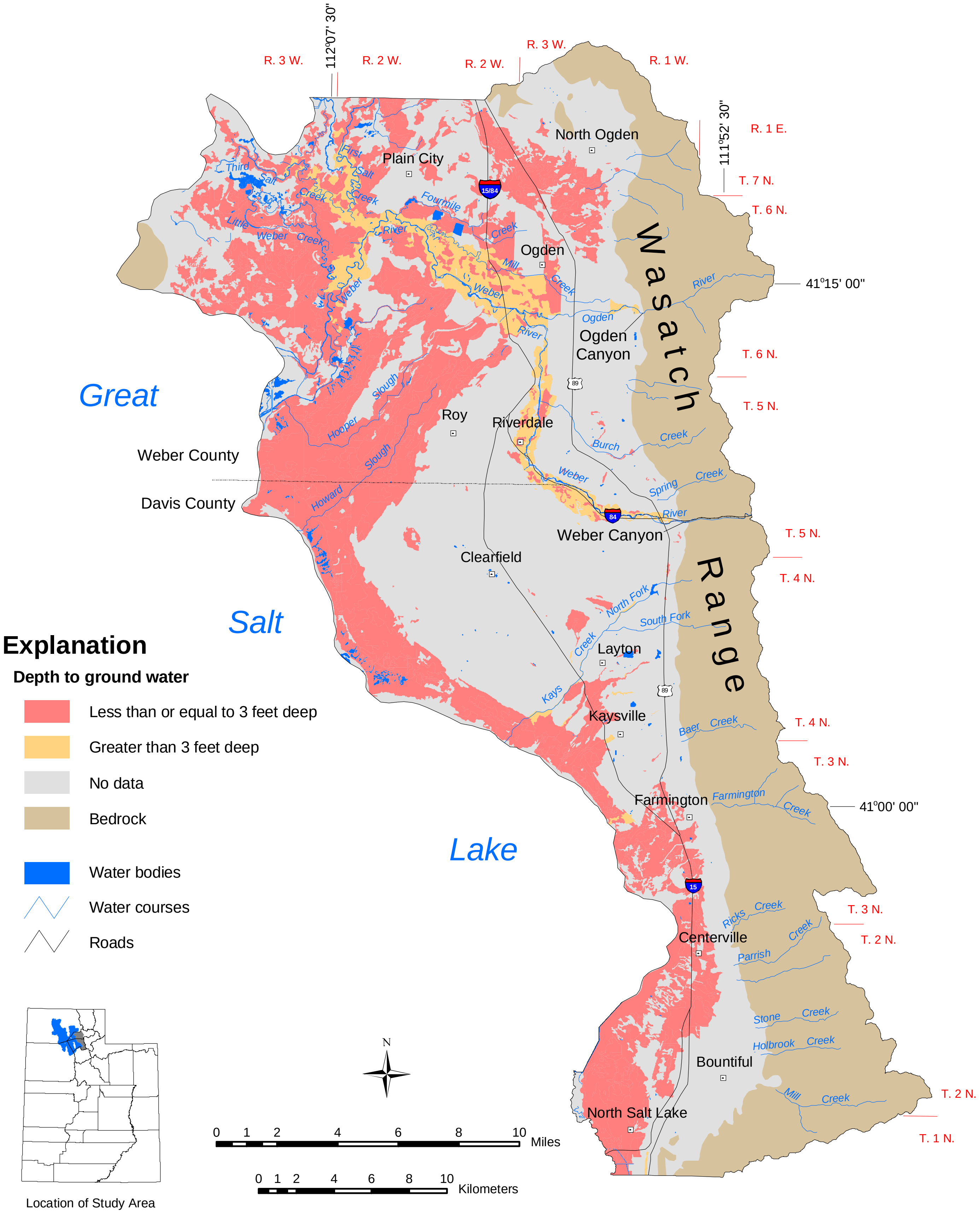


Figure 12. Depth to shallow ground water in the east shore area of Great Salt Lake, Davis and Weber Counties, Utah (data from National Soil Survey Center, 1994).

Most of the western part of the east shore area of Great Salt Lake (61 percent) is of low sensitivity (plate 1) because of the presence of protective clay layers and upward ground-water-flow gradients (discharge area hydrogeologic setting). Pesticides used in these areas are unlikely to degrade ground water. Also, pesticides spilled or misapplied have a much greater potential to contaminate surface water than ground water. Alluvial-fan areas along the basin margins and the northern part of the Weber Delta, where soils have higher hydraulic conductivities, are areas of high sensitivity (plate 1); this comprises about 14 percent of the basin-fill aquifer area. In these areas, pesticides spilled or misapplied have a much greater potential to contaminate surface water than ground water, because of relatively high retardation factors and low attenuation factors (low attenuation factors correspond to high attenuation). The remaining 25 percent of the study area is of moderate sensitivity.

Ground-Water Vulnerability

To assess ground-water vulnerability to pesticide contamination – the influence of human activity added to natural sensitivity – we assembled two attribute layers as intermediate steps. Pertinent statewide attribute layers include irrigated cropland and corn- and sorghum-producing areas in the east shore area of Great Salt Lake (figure 13). Using GIS methods as outlined in table 6, pertinent attribute layers, in turn, are combined with ground-water sensitivity, discussed in the previous sections, to produce a map showing ground-water vulnerability to pesticides (plate 2). The pertinent attribute layers irrigated cropland and corn and sorghum crops, along with ground-water sensitivity, are described in the following sections.

Irrigated Cropland

Irrigated cropland areas in the east shore area of Great Salt Lake are shown on figure 13. About 35 percent of the valley floor is irrigated, and about 65 percent is not. Irrigation is potentially significant because it is a source of ground-water recharge in the basin-fill aquifer.

Corn and Sorghum Crops

From the point of view of human impact, areas where corn and sorghum are grown are significant because the four herbicides considered in this report – alachlor, atrazine, metolachlor, and simazine – are used to control weeds in these crops. Corn and sorghum crops are mainly grown in the western portions of the basin-floor area (figure 13). The use of pesticides on corn and sorghum crops raises the vulnerability of areas where these crops are grown from low to moderate.

Pesticide Vulnerability Map

Plate 2 shows ground-water vulnerability to pesticides of the basin-fill aquifer for the east shore area of Great Salt Lake, constructed using the GIS methods and ranking techniques described above. The surrounding uplands are not included in the analysis because of shallow bedrock and mountainous terrain, and because they are not areas of significant agricultural activity.

Areas of high vulnerability are primarily in irrigated areas where ground-water sensitivity to pesticides is high. About 1 percent of the surface area of the basin-fill aquifer is mapped as having high vulnerability (plate 2). Of particular concern are areas where ground water is shallow, as these are the areas most likely to be impacted by pesticide pollution. Areas of moderate vulnerability coincide, in general, with non-irrigated areas of moderate or high sensitivity, or irrigated areas where ground-water sensitivity to pesticides is low. About 43 percent of the surface area of the basin-fill aquifer is mapped as having moderate vulnerability. Low-sensitivity areas without irrigated cropland have low vulnerability to application or spilling of pesticides to the land surface. About 56 percent of the surface area of the basin-fill aquifer is mapped as having low vulnerability.

CONCLUSIONS AND RECOMMENDATIONS

In the east shore area of Great Salt Lake, areas of irrigated land where the ground-water table is close to the land surface have the highest potential for water-quality degradation associated with surface application of pesticides. However, because corn and sorghum are generally not grown in the east shore area, and because of the relatively high attenuation (short half-lives) of pesticides in water in the soil environment, pesticides likely do not represent a serious threat to ground-water quality. However, should corn or sorghum begin to be grown in the east shore area, we believe ground-water monitoring for pesticides should be increased, and should be concentrated in areas of moderate and high sensitivity or vulnerability. Sampling and testing in areas of the basins characterized by moderate sensitivity and moderate vulnerability should continue, but at a lower density than in the areas of higher sensitivity and vulnerability. The maps and accompanying report are based on analyses of 1:24,000 or smaller scale data and are not meant for site-specific evaluations.

ACKNOWLEDGMENTS

This project was funded by the U.S. Environmental Protection Agency. Critical review comments were provided by Kimm Harty, Charles Bishop, and Mike Hylland, Utah Geological Survey. Kim Nay, Utah Geological Survey, produced some of the computer drawings for the project.

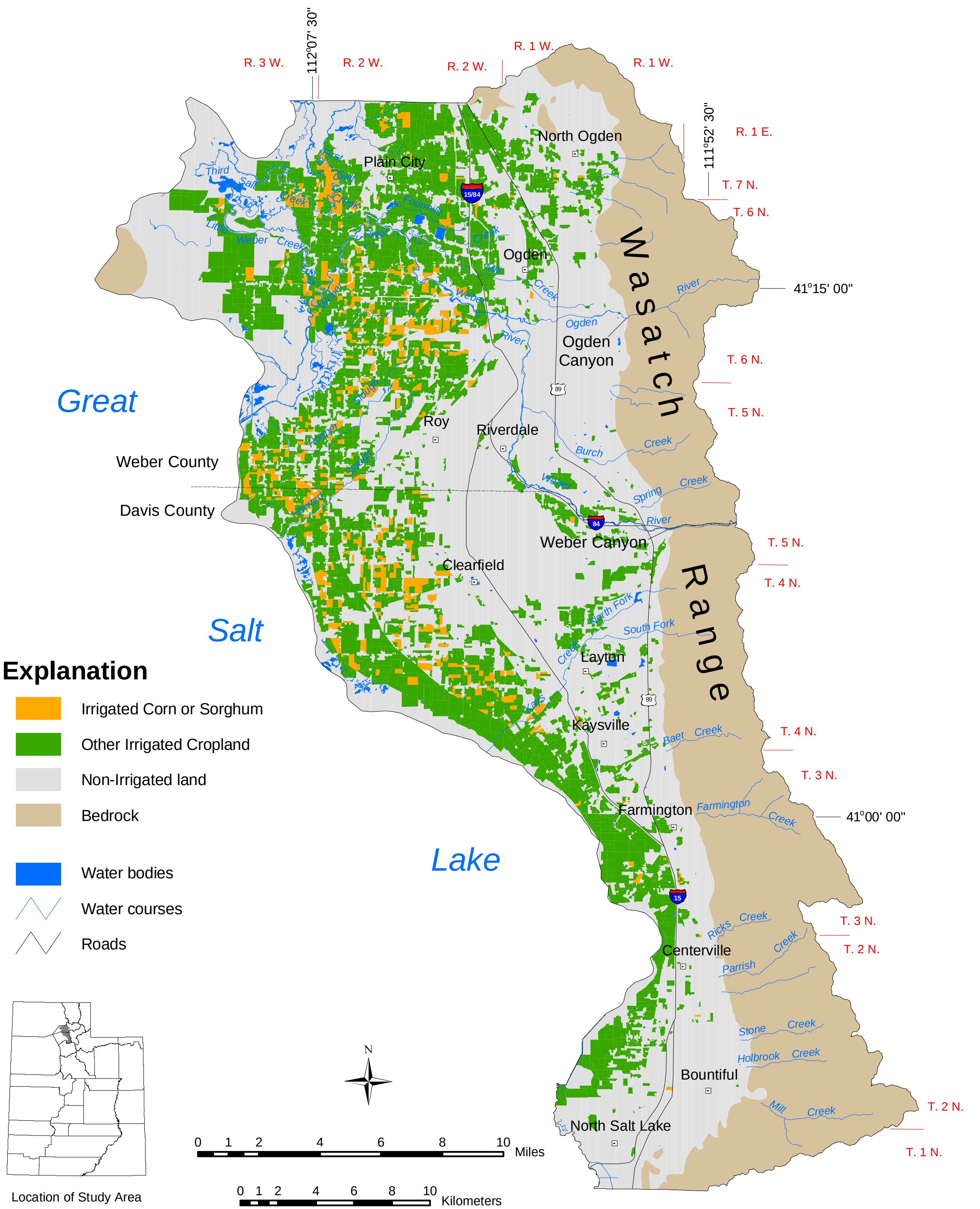


Figure 13. Irrigated and non-irrigated cropland in the east shore area of Great Salt Lake, Davis and Weber Counties, Utah (data from Utah Division of Water Resources, 1995). The pesticides being addressed in this study are mainly applied to corn and sorghum.

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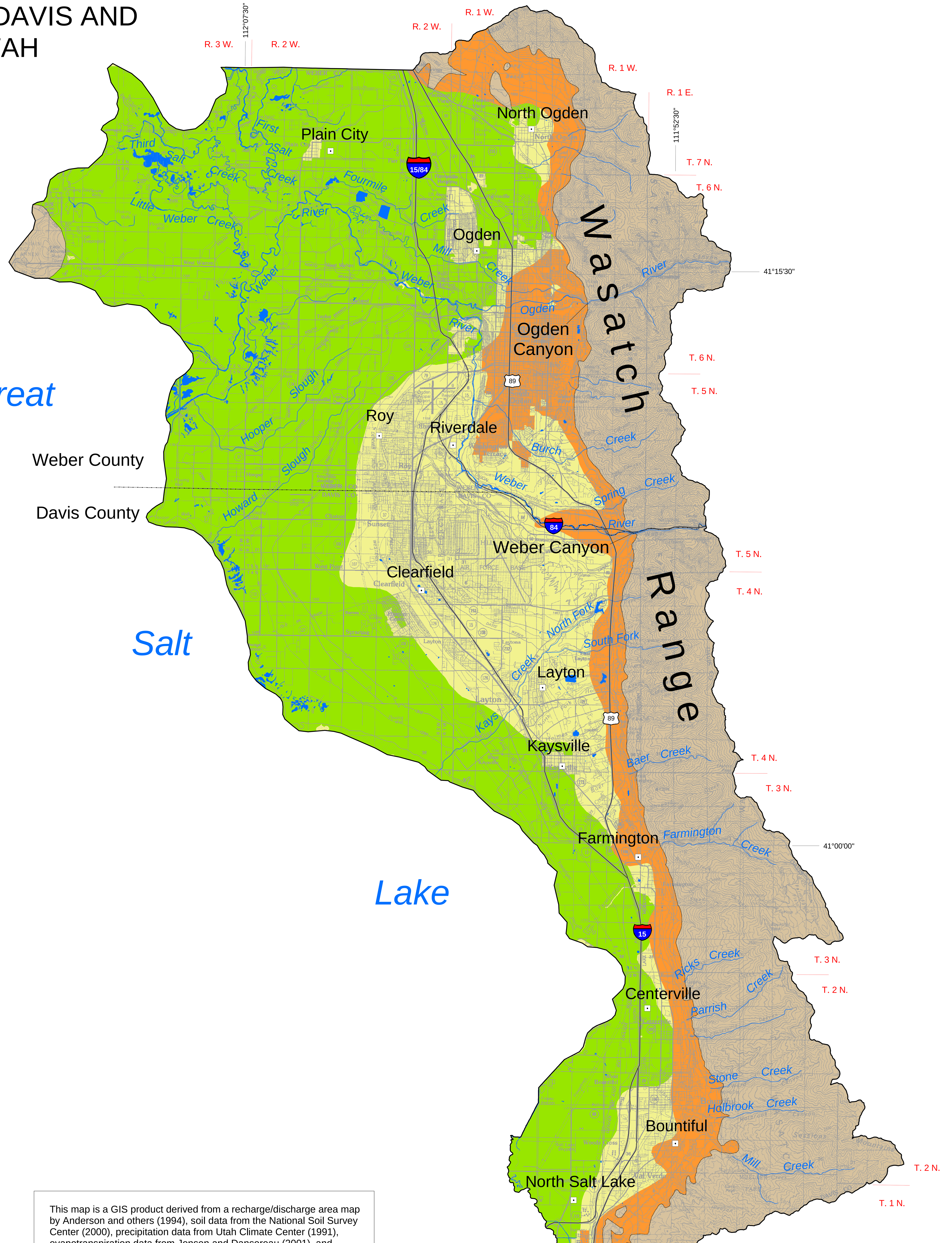
Plate 1

GROUND-WATER SENSITIVITY TO PESTICIDES IN THE EAST SHORE AREA OF GREAT SALT LAKE, DAVIS AND WEBER COUNTIES, UTAH

by Mike Lowe, Janae Wallace, and Matt Butler



Explanation

Pesticide sensitivity ranking

- Low sensitivity
- Moderate sensitivity
- High sensitivity
- Bedrock (not analyzed)
- Water bodies
- Water courses
- Valley-fill boundary
- Roads
- Study boundary

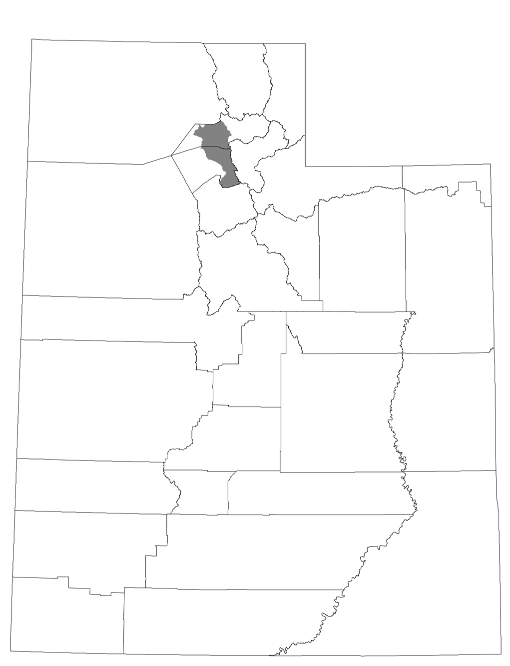
N

1:75,000

0 1 2 4 6 8 10 Miles

0 1 2 4 6 8 10 Kilometers

Contour Interval 200 Feet



Location of Study Area Boundary

This map is a GIS product derived from a recharge/discharge area map by Anderson and others (1994), soil data from the National Soil Survey Center (2000), precipitation data from Utah Climate Center (1991), evapotranspiration data from Jensen and Dansereau (2001), and land-use data from the Utah Division of Water Resources (1995). No additional fieldwork was performed or data collected.

This map is based on 1:24,000 or smaller scale data and should not be used for site-specific evaluations.

Projection: UTM
Zone: 12
Units: Meters
Datum: NAD27
Spheroid: Clarke 1866

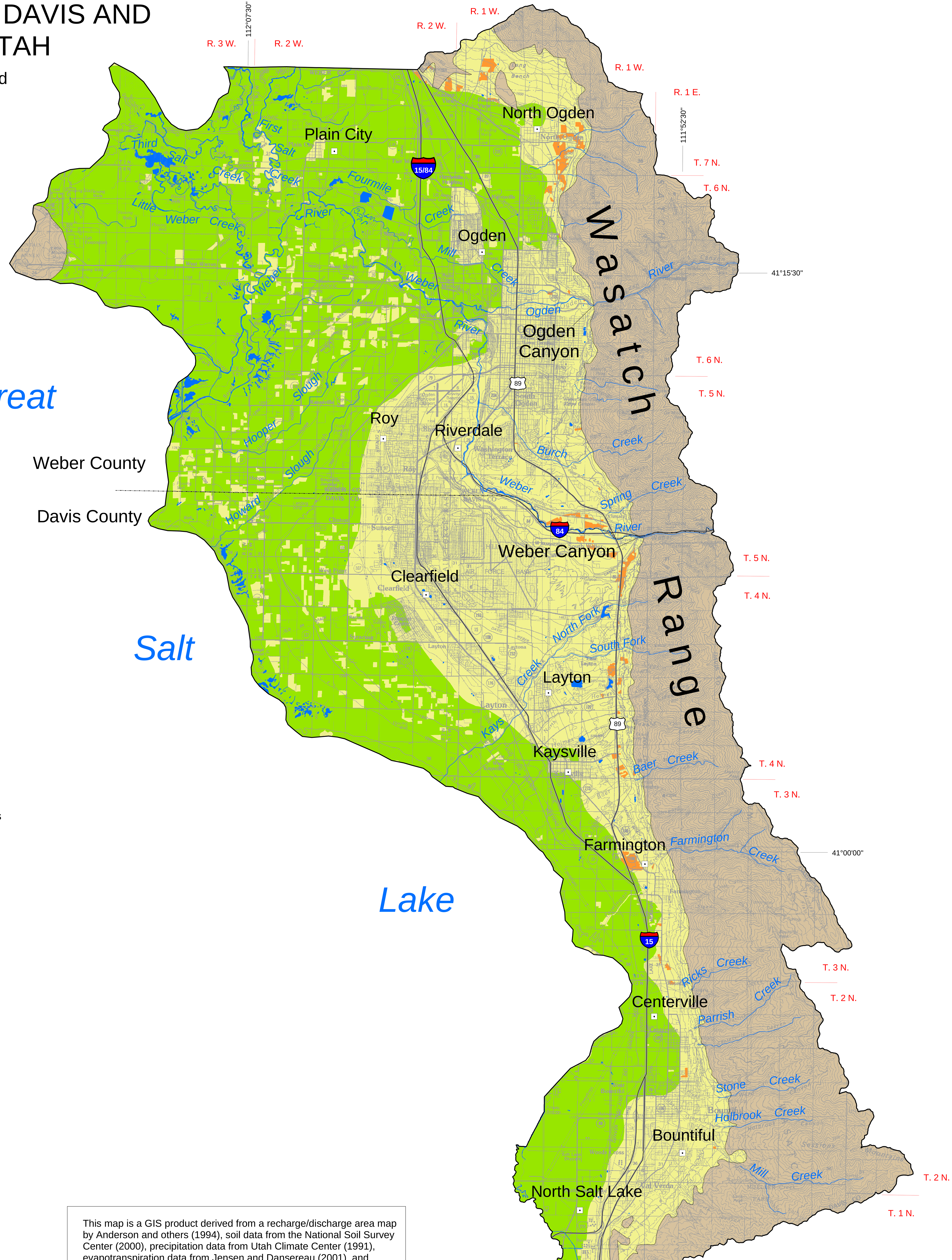
Topographic base map from United States Geological Survey
1:250,000-scale images: Salt Lake City (1970), Brigham City (1970), and Ogden (1982)

UTAH GEOLOGICAL SURVEY
UTAH GEOLOGICAL SURVEY a division of Department of Natural Resources

Plate 2

GROUND-WATER VULNERABILITY TO PESTICIDES IN THE EAST SHORE AREA OF GREAT SALT LAKE, DAVIS AND WEBER COUNTIES, UTAH

by Mike Lowe, Janae Wallace, and Matt Butler



Explanation

Pesticide vulnerability ranking

- Low vulnerability
- Moderate vulnerability
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- Bedrock (not analyzed)
- Water bodies
- Water courses
- Valley-fill boundary
- Roads
- Study boundary

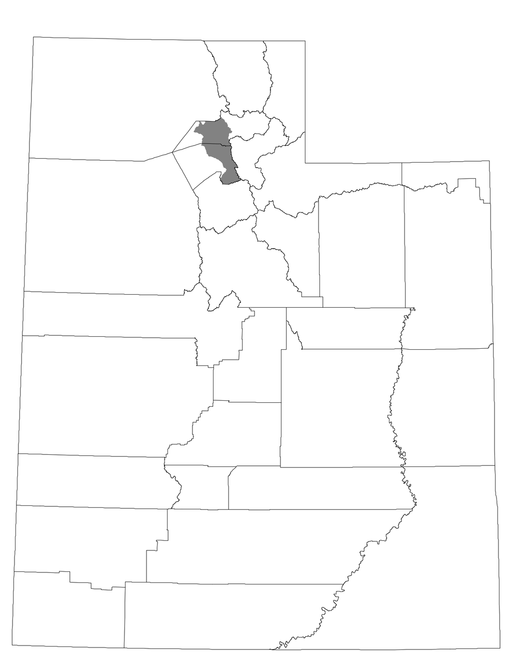
N

1:75,000

0 1 2 4 6 8 10 Miles

0 1 2 4 6 8 10 Kilometers

Contour Interval 200 Feet



Location of Study Area Boundary

This map is a GIS product derived from a recharge/discharge area map by Anderson and others (1994), soil data from the National Soil Survey Center (2000), precipitation data from Utah Climate Center (1991), evapotranspiration data from Jensen and Dansereau (2001), and land-use data from the Utah Division of Water Resources (1995). No additional fieldwork was performed or data collected.

This map is based on 1:24,000 or smaller scale data and should not be used for site-specific evaluations.

Projection: UTM
Zone: 12
Units: Meters
Datum: NAD27
Spheroid: Clarke 1866

Topographic base map from United States Geological Survey
1:250,000-scale images: Salt Lake City (1970), Brigham City (1970), and Ogden (1982)

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