GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES, SALT LAKE VALLEY, SALT LAKE COUNTY, UTAH

by

Mike Lowe, Janae Wallace, Neil Burk, and Justin Johnson, Utah Geological Survey

and

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MISCELLANEOUS PUBLICATION 05-7

UTAH GEOLOGICAL SURVEY

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Cover photo: Residential subdivision on former agricultural land near Kennecott waste dumps, Yosemite Gulch, southwest Salt Lake Valley. Photo by Barry Solomon.

ISBN 1-55791-733-7

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ABSTRACT

The U.S. Environmental Protection Agency has recommended 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, and to control weeds and undesired vegetation (such as along right-of-ways or utility substations). 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 Salt Lake County, 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 attempt 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 basin-fill deposits of Salt Lake County. Much of Salt Lake County has moderate ground-water sensitivity to pesticides due to prevalent protective clay layers within the basin-fill deposits.

Ground-water vulnerability to pesticides is determined by assessing how ground-water sensitivity is modified by human activity. 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 basin-fill deposits of Salt Lake County. 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 margins; 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 Salt Lake County.

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 Salt Lake County 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 Salt Lake County should be concentrated in areas of high sensitivity or vulnerability, typically along basin margins. Sampling in the central area of the basin characterized by low and moderate 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) has recommended 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 the sensitivity and vulnerability of ground water to agricultural pesticides in the basin-fill deposits of Salt Lake County, Utah (figure 1). 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 Salt Lake County to agricultural pesticides.

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 human activity. 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 hydraulic conductivity, bulk density, organic carbon content, and field capacity of soils. 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 basin-fill deposits of Salt Lake County, 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. No new fieldwork was conducted nor data collected as part of this project. This is a first attempt 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 digital soil maps used in this study are too generalized to accurately depict areas of soil versus 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 rock outcrop areas locally may not be reflected in our maps. To produce these maps, we needed to make some arbitrary decisions regarding the quality and 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 soils for applying pesticide retardation and attenuation equations.

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 re-evaluated today

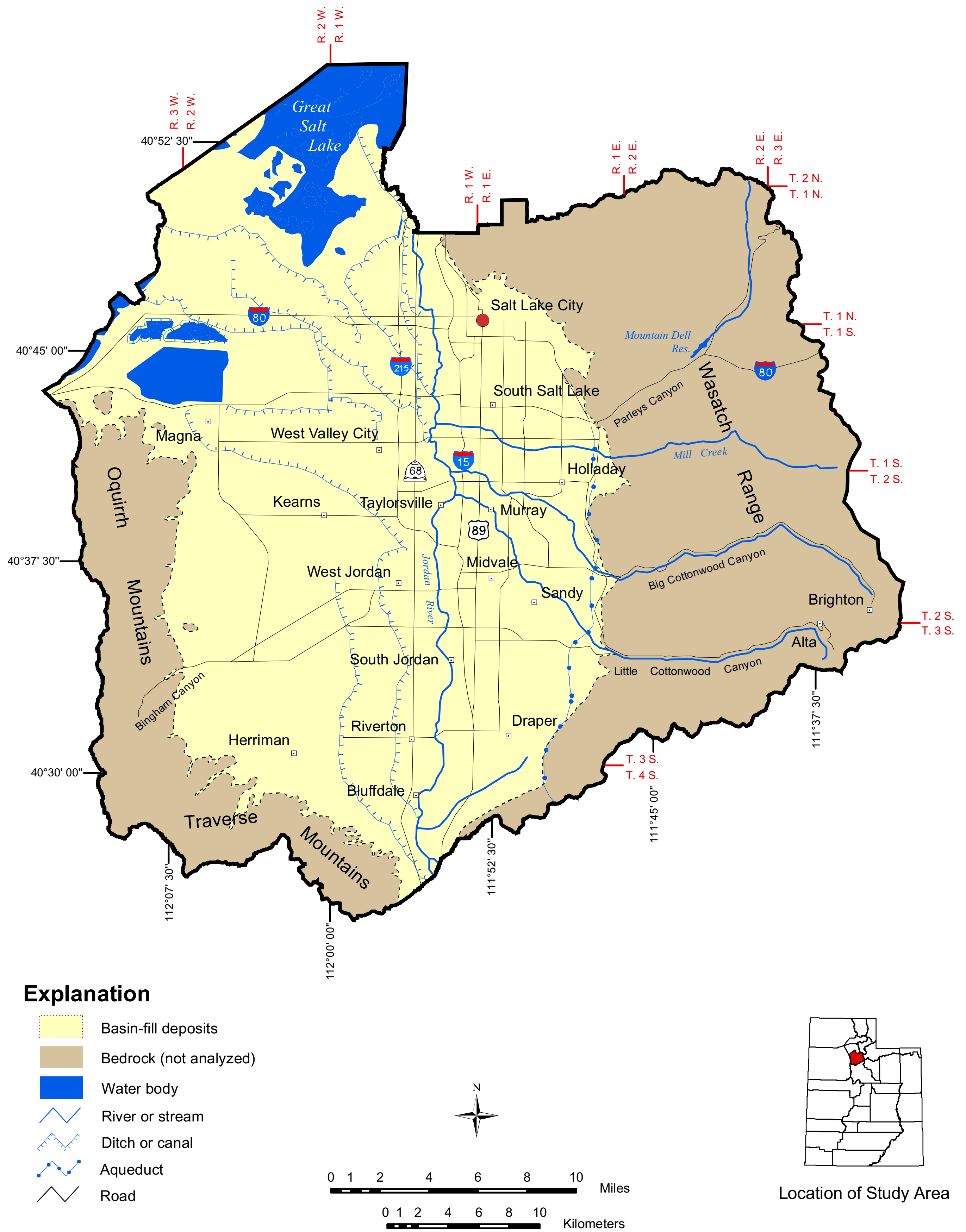

Figure 1. *Salt Lake Valley, Salt Lake County, Utah, study area.*

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. Utah's generic plan was approved by the EPA 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 drinking-water aquifer in over 2200 samples tested statewide (Quilter, 2004), although low levels of pesticides were detected in a 1998-2001 study of shallow ground water in the Great Salt Lake basin (Waddell and others, 2004). 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 µg/L
Atrazine	0.003 mg/L	3 µg/L
Metolachlor	—	—
Simazine	0.004 mg/L	4 µg/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 Salt Lake County 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

Richardson (1906) conducted the first investigation of ground-water conditions in Salt Lake Valley (also known as Jordan Valley); this study, which included Utah Valley, produced maps showing depth to ground water and the areas of flowing wells. Taylor and Leggette (1949) conducted a more thorough investigation that included many well records, and discussions of ground-water occurrence, recharge and discharge, and chemical quality. Lofgren (1952) discussed the status of ground-water development in Salt Lake Valley as of 1951. Marsell (1964) discussed water-supply issues as part of a comprehensive review of the geology of Salt Lake County. Marine and Price (1964) updated previous studies and subdivided the valley into ground-water districts for water-resource management purposes. Hely and others (1967, 1968, 1969) compiled hydrologic and climatalogic data that were used to produce a summary of ground-water hydrology in Salt Lake Valley (Mower, 1969a) and water resources in Salt Lake County (Hely and others, 1971). Arnow and Mattick (1968) evaluated the thickness of basin-fill deposits. Mower (1968) discussed ground-water discharge toward Great Salt Lake in basin-fill deposits. Mower (1969b) discussed ground-water inflow through channel fill in seven Wasatch Range canyons in Salt Lake County. Arnow and others (1970) used water-well logs to delineate the pre-Quaternary surface in Salt Lake Valley to be used as a general guide for water-well drilling. Mower (1970) discussed ground-water recharge to Salt Lake Valley from Utah Valley. Seiler and Waddell (1984) conducted an assessment of the shallow unconfined aquifer in Salt Lake Valley. Herbert and others (1985) conducted a seepage study of six canals in Salt Lake County. Waddell and others (1987a) evaluated the chemical quality of ground water in the basin-fill aquifer for the 1969-85 time period. Waddell and others (1987b) evaluated ground-water conditions in Salt Lake Valley with emphasis on predicted effects of increased withdrawals from wells. Thiros (1992) compiled selected hydrologic data for Salt Lake Valley with emphasis on data from the shallow unconfined aquifer and confining layers. Anderson and others (1994; see also Anderson and Susong, 1995) mapped ground-water recharge and discharge areas for the principal aquifers along the Wasatch Front, including the principal aquifer in Salt Lake Valley. Thiros (1995) investigated the chemical composition and movement of ground water, and the hydrologic properties of basin-fill material, to better understand the flow system in Salt Lake Valley. Lambert (1995a) produced a three-dimensional, finite-difference, numerical ground-water flow model for the basin-fill aquifer, which he (Lambert, 1995b) used to produce capture zones for selected public supply wells and simulate the movement of sulfate in ground water (Lambert, 1996). Burden and others (2000) described changes in ground-water conditions in Utah, including Salt Lake Valley, from 1970 to 2000. Waddell and others (2004) assessed water quality in the Great Salt Lake basins, including Salt Lake Valley.

Woodward and others (1974) mapped soils (scale 1:20,000) for Salt Lake County. Regional geologic maps covering the study area include the geologic map of Salt Lake County by Marsell and Threet (1964), the geologic map of the Tooele 1 x 2-degree quadrangle by Moore and Sorensen (1979), the geologic map of the Salt Lake City 30′ x 60′ quadrangle by Bryant (1990), the geologic map of the Salt Lake City segment of the Wasatch fault zone by Personius and Scott (1992), and the geologic map of the Oquirrh and Traverse Mountains by Tooker and Roberts (1998). Geologic quadrangle maps at 1:24,000 scale are shown on figure 2.

SETTING

Physiography

Salt Lake Valley is a north-south-trending valley located in north-central Utah southeast of Great Salt Lake. Salt Lake Valley is in the Salt Lake Valley segment of the Wasatch Front Valleys section of the Great Basin physiographic province (Stokes, 1977). The valley is bounded on the east and northeast by the central portion of the Wasatch Range, on

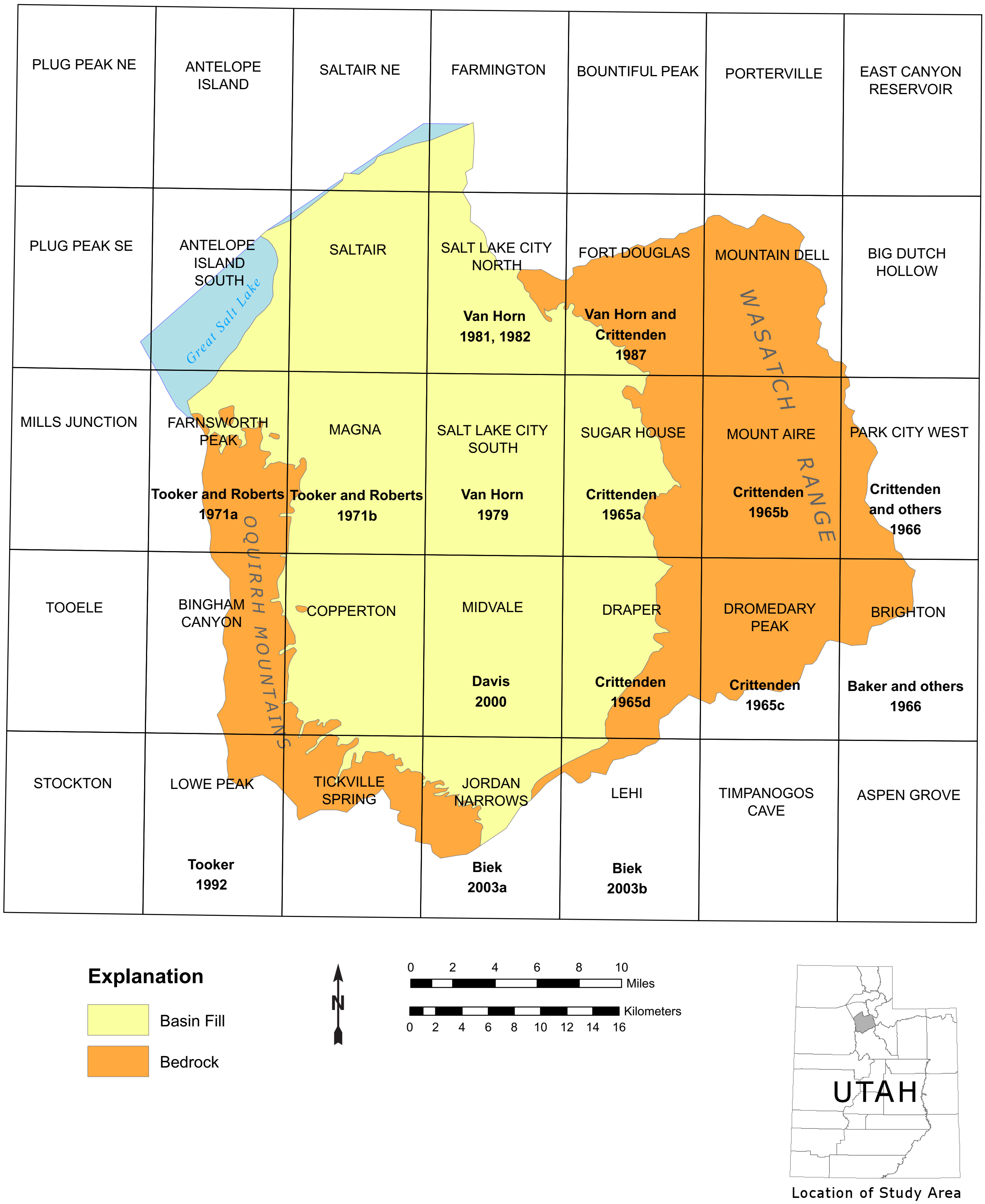

Figure 2. *Existing 1:24,000-scale geologic maps (author and publication date in bold) for Salt Lake County, Utah.*

the northwest by Great Salt Lake, on the west by the Oquirrh Mountains, and on the south by the Traverse Mountains. Elevations range from about 4200 feet (1280 m) in the lowest part of the valley near Great Salt Lake to more than 7000 feet (2130 m) in the Traverse Mountains, 9000 feet (2740 m) in the Oquirrh Mountains, and 11,000 feet (3350 m) in the Wasatch Range.

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

The mountains that surround the Salt Lake Valley are composed of rocks that range in age from Precambrian to Tertiary. The Wasatch Range consists of Precambrian, Paleozoic, Mesozoic, and Cenozoic sedimentary rocks that have been intruded by Tertiary granitic and dioritic stocks. The Oquirrh Mountains consist of Paleozoic sedimentary rocks, predominantly the Oquirrh Formation, and intrusive and extrusive Cenozoic rocks. The Traverse Mountains are composed of Paleozoic sedimentary rocks and Cenozoic volcanics.

The Salt Lake Valley is a graben that is bounded by faults on its east, west, and south sides. Sediments have been filling this graben since the Tertiary. The Tertiary and Quaternary basin fill is up to 4000 feet (1220 m) thick in some areas of the valley (Mattick, 1970), and consists of unconsolidated to semi-consolidated clay, silt, sand, gravel, tuff, and lava. Quaternary sediments in the upper part of the basin fill range from 0 to 2000 feet (0-610 m) thick (Arnow and others, 1970). The depositional sequence in the basin fill is complex (Marine and Price, 1964) due to alternating periods of lacustrine and interlacustrine conditions during the late Tertiary and Quaternary. During the lacustrine periods, or deep-lake cycles (figure 3), much of Salt Lake Valley was covered with water and offshore silt and clay were deposited in the central parts of the valley while deltaic (at the mouths of canyons) and nearshore sand and gravel were deposited along valley margins. During interlacustrine periods, sediments were deposited primarily as alluvial fans at canyon mouths and as fluvial-channel and floodplain sediments in the central parts of the valley. As a general rule, coarser grained sediments exist near valley margins and finer grained sediments exist in the middle and north end of the valley.

Climate

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

There are over 15 weather stations operated by the Utah Climate Center in Salt Lake County (Ashcroft and others, 1992). Based on data collected from those weather stations, Salt Lake Valley receives between 12 and 21 inches (30 and

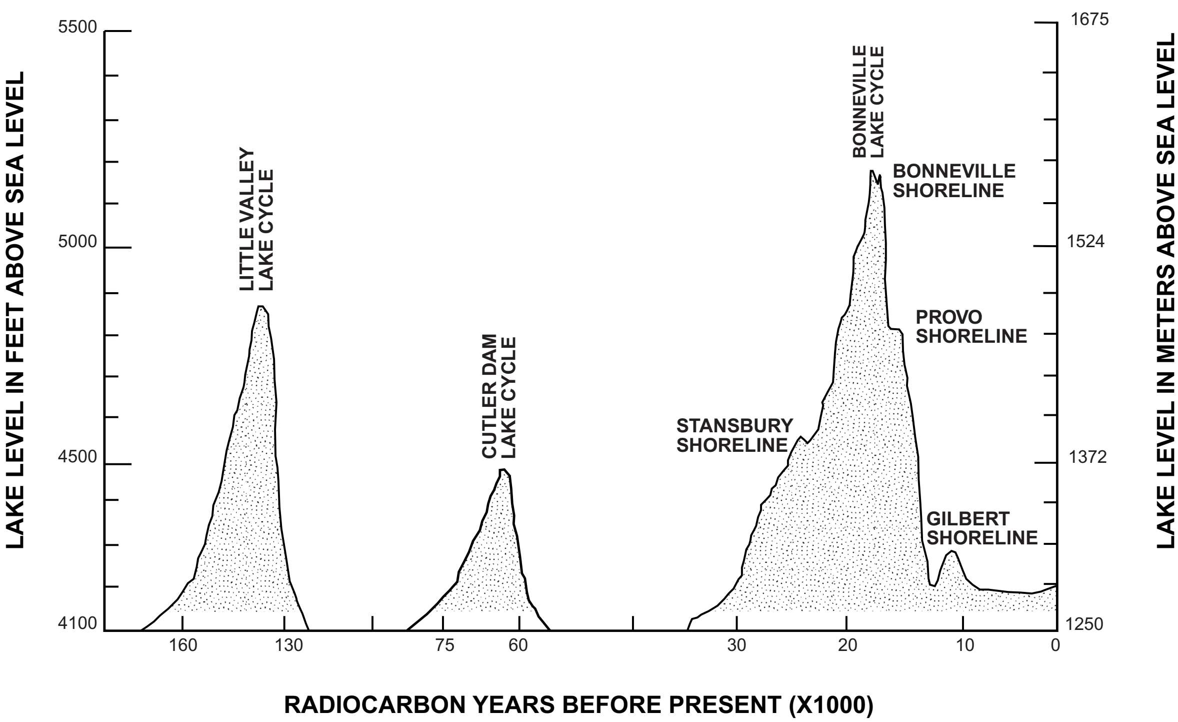

Figure 3. *Schematic diagram of probable lake levels in the Bonneville basin during the past 170,000 years. Modified from Machette and others (1992); note breaks in temporal scale.*

53 cm) of precipitation annually. Some anomalies exist, for example, the Magna station located on the west side of the valley (elevation 4310 feet [1314 m]) receives slightly less precipitation, which is reported to be 11.78 inches (29.92 cm) annually, than the other stations. The Riverton station, located in the south end of the valley, has an elevation of 4655 feet (1419 m) and receives 13.11 inches (33.30 cm) of precipitation annually, whereas the Draper station, located east of Riverton, has an elevation of 4630 feet (1411 m) and receives 21.01 inches (53.37 cm) of precipitation annually. Also, the Lower Mill Creek station, located in the east-central area of the county, has an elevation of 4959 feet (1512 m) and receives 20.20 inches (511.31 cm) of precipitation annually, and the Cottonwood Weir station located south of the Mill Creek station, has an elevation of 4960 feet (1,512 m), but receives 24.30 inches (61.72 cm) of precipitation annually. The mountains receive the most precipitation with the Alta station (elevation 8720 feet [2,658 m]) receiving 58.45 inches (148.46 cm) of precipitation annually. However, the Silver Lake at Brighton station has an elevation of 8741 feet (2664 m) and is located just east of Alta, but only receives 43.68 inches (110.95 cm) of precipitation annually (Ashcroft and others, 1992).

Temperatures in Salt Lake County are quite variable also, and like precipitation, temperatures are related to elevation, with the mountains being 10 to 15°F (5 to 8°C) cooler than the valley. To illustrate these extremes, the Salt Lake City Airport station has an elevation of 4221 feet (1287 m) and a normal maximum temperature, a normal minimum temperature, a normal mean temperature, and a record high temperature of 63.8, 40.3, 52.0, and 107°F (17.7, 4.6, 11.1, and 41.7°C), respectively. In contrast, the Alta station has an elevation 8720 feet (2658 m) and a normal maximum temperature, a normal minimum temperature, a normal mean temperature, and a record high temperature of 47.5, 28.3, 37.9, and 84°F (8.6, -2.1, 3.3, and 28.9°C), respectively (Ashcroft and others, 1992).

Evapotranspiration is dependent upon solar radiation, temperature, wind, and humidity, but does not directly correlate to elevation like temperature and precipitation, at least in Salt Lake County. The Draper station recorded the greatest evapotranspiration value of 48.54 inches (123.29 cm) and the Alta station recorded the lowest value of 29.48 inches (74.88 cm). However, most of the weather stations have evapotranspiration values between 42 and 48 inches (107 and 122 cm), including the Mountain Dell station (45.59 inches [115.80 cm]), which has an elevation of 5420 feet (1652 m) and is located in Parleys Canyon. The only other stations with lower evapotranspiration values are the Silver Lake station, Bingham Canyon station, and Bingham Canyon 2 NE station, which were 32.31, 37.16, and 41.37 inches (82.07, 94.39, and 105.08 cm), respectively (Ashcroft and others, 1992).

Population and Land Use

Salt Lake County has the largest county population in Utah, estimated at 940,465 in 2003 (Demographic and Economic Analysis Section, 2004). Salt Lake County residents make up 39.4% of Utah's total population of 2,385,358 (Demographic and Economic Analysis Section, 2004). Based on projections made in 2000, the population of Salt Lake County was expected to increase to 914,190, 1,028,508, 1,223,218, and 1,383,907 in 2005, 2010, 2020, and 2030, respectively (Demographic and Economic Analysis Section, 2000). This is an annual average increase in population of 1.6%; these estimates may be low – the projected population for 2005 has already been exceeded by over 26,000 in 2004. The increase in population in Salt Lake County between 1990 and 2000 was 23.8% (Demographic and Economic Analysis Section, 2001). Salt Lake County's population will continue to grow, although the rate of population increase may be difficult to predict.

Salt Lake Valley was permanently settled in 1847 by Mormon pioneers. Agriculture, the dominant land use then, is now practiced by relatively few in the valley (although many residents have gardens). Salt Lake City, being Utah's capital, is now a major metropolitan area with numerous types of businesses and industries. Most Salt Lake County residents (93.8%) live and work within the county (Demographic and Economic Analysis Section, 2003). Salt Lake County's largest employer is the University of Utah, followed by the State of Utah and the Granite and Jordan School districts, so local government agencies provide a substantial number of jobs (Salt Lake County Economic Development Department, undated). Much of the land in Salt Lake Valley and the surrounding benches is developed; not much open space exists within the valley. Residential and commercial development are major industries in the valley, so most existing open space is either being developed or is planned for development. However, the mountains surrounding the valley create a natural boundary for development, and have a considerable amount of open and natural space.

GROUND-WATER CONDITIONS

Basin-Fill Aquifers

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

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

Overlying the confined aquifer is an upper confining layer composed of individual Quaternary deposits of clay, silt, and fine sand that collectively create a single impermeable layer. The confining layer is between 40 and 100 feet

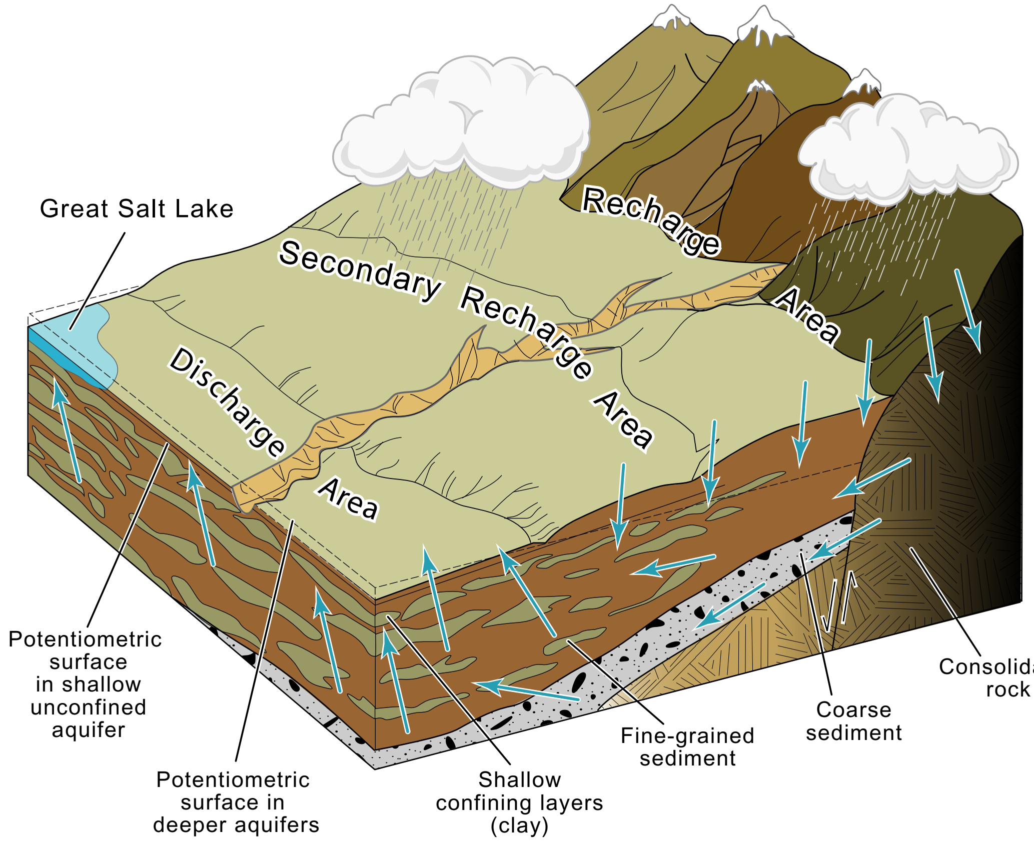

Figure 4. *Generalized block diagram showing water-bearing formations, probable direction of ground-water movement (arrows), and areas of recharge and discharge, Salt Lake County, Utah (modified from Hely and others, 1971, and Thiros, 1995).*

(12 and 30 m) thick, and the top of the layer is between 50 and 150 feet (15 and 46 m) below the land surface.

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

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

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

Transmissivity and storage coefficients range from 1000 to 50,000 feet squared per day (90-5000 m^2/d) and 0.15 to less than 0.0001 for the unconfined and confined parts of the principal aquifer, respectively (Hely and others, 1971). The transmissivity of the shallow unconfined aquifer ranges from 50 to 4000 feet squared per day (5-40 m^2/d) (Waddell and others, 1987b), and the storage coefficient is estimated to average 0.15 (Hely and others, 1971). The vertical hydraulic conductivity of the confining bed between the shallow unconfined and principal aquifer is estimated to average 0.025 feet per day (0.008 m/d) (Hely and others, 1971).

Water levels in wells completed in the principal aquifer generally declined in most parts of Salt Lake Valley between 1970 and 2000 (Burden and others, 2000), with the greatest declines in the central-eastern and southern parts of the valley (figure 5). Water levels rose in wells in the northwestern and northeastern parts of the valley during the same time period.

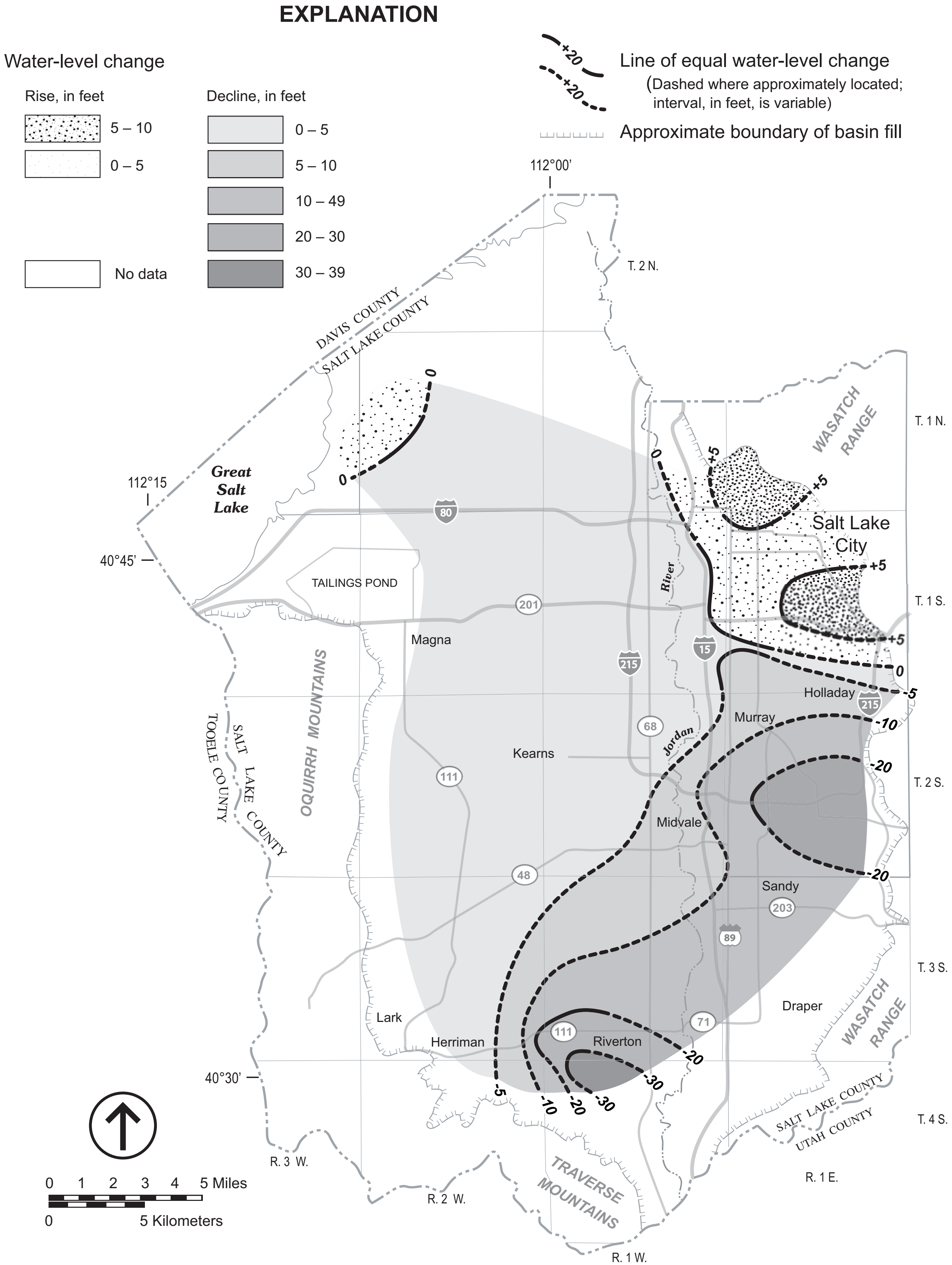

Figure 5. Change of water level in Salt Lake Valley from February 1970 to February 2000 (modified from Burden and others, 2000).

Ground-Water Quality

The chemical composition of ground water in Salt Lake Valley varies with location and depth, primarily due to quality of recharge sources and water-rock interactions as it moves through the aquifer. Most of the recharge occurs on the east side of the valley, and ground water in the principal aquifer typically has lower total dissolved-solids concentrations near the mouths of the larger streams (Big Cottonwood Creek, Little Cottonwood Creek) in southeastern Salt Lake Valley (Hely and others, 1971); calcium-magnesium-bicarbonate-type ground water is generally found in this part of the valley (Thiros, 1995). Both bicarbonate-type ground water and sodium-chloride-type ground water exist in the northwestern part of Salt Lake Valley (Thiros, 1995). Ground-water in the principal aquifer with the highest total-dissolved-solids concentrations is generally found in the vicinity of Great Salt Lake in the northwestern part of the valley (Hely and others, 1971). Based on wells completed in the principal aquifer from 1988 to 1992, the total-dissolved-solids concentrations ranged from 110 mg/L on the southeast side of the valley to 48,100 mg/L on the northwest side (Thiros, 1995). Ground water in the principal aquifer generally has lower total-dissolved-solids concentrations than water in the shallow unconfined aquifer (Hely and others, 1971).

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

Ground water between the mouth of Bingham Canyon and the Jordan River has been contaminated by seepage from evaporation ponds associated with mining activities (Hely and others, 1971). The contaminated ground water is acidic and has total-dissolved-solids concentrations as high as 75,000 mg/L (Waddell and others, 1987a). Ground water in the shallow unconfined and principal aquifer in the vicinity of South Salt Lake near the Jordan River has also been contaminated by leachate from uranium-mill tailings; ground water from this area has total-dissolved-solids concentrations as high as 21,000 mg/L, and is contaminated with chloride, sulfate, iron, and uranium (Waddell and others, 1987a). Volatile organic compounds and pesticides (primarily atrazine) are commonly found in monitoring wells completed in the shallow unconfined aquifers; most of the volatile organic compounds and all of the pesticides were below drinking water standards (Waddell and others, 2004).

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 basin-fill deposits in Salt Lake County. 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 Salt Lake Valley. 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 which typically show (1) primary recharge areas, (2) secondary recharge areas, and (3) discharge areas (Anderson and others, 1994). For our GIS analyses, we assigned hydrogeologic setting to one of these three categories, illustrated schematically in figure 6. 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 discharges 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 Salt Lake Valley 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 acquiring 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

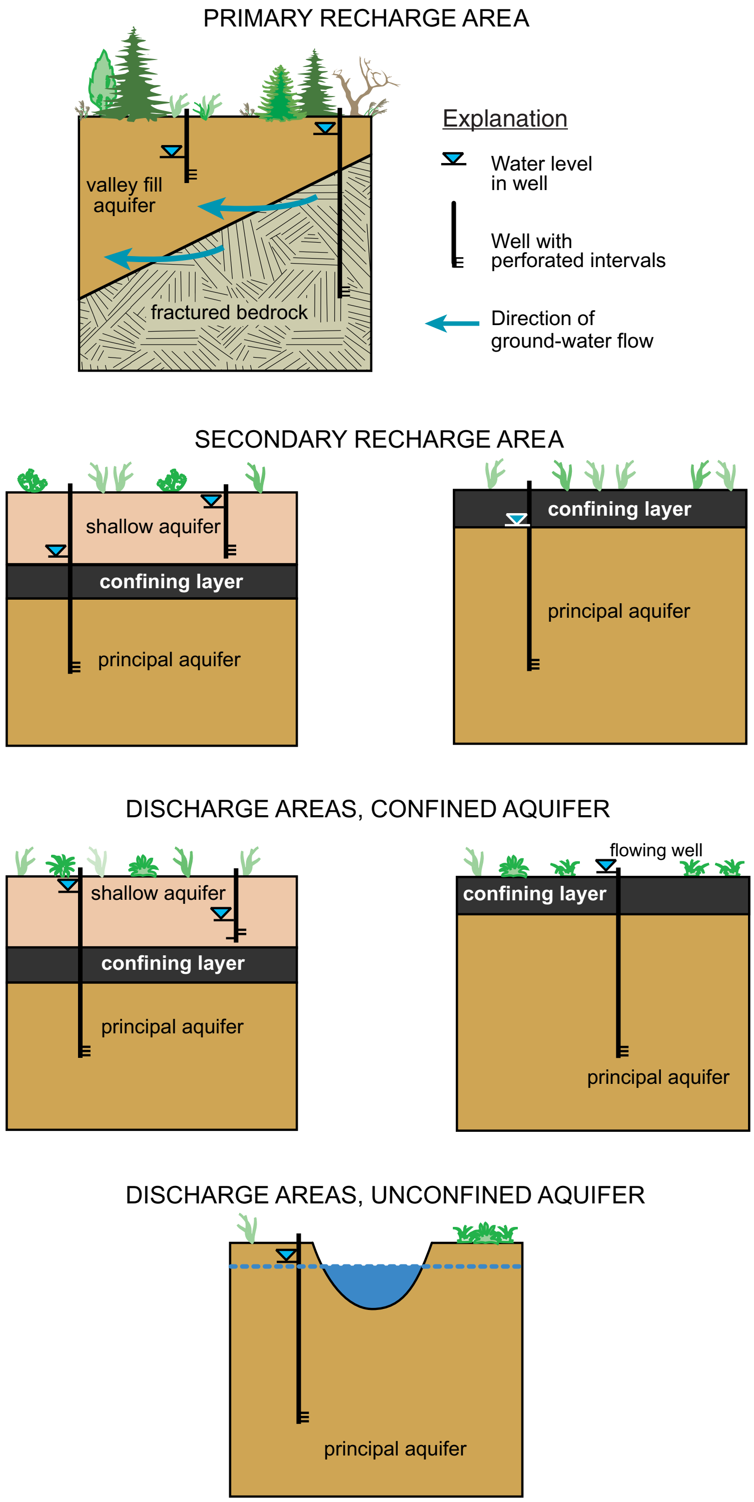

Figure 6. *Relative water levels in wells in recharge and discharge areas (modified from Snyder and Lowe, 1998).*

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; Anderson and Susong, 1995). 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 clay together with 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 Salt Lake Valley consists of the uplands along the margins of the basin, as well as basin fill not containing confining layers (figure 6), 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 confining layers exist, but ground-water flow maintains a downward component. Secondary recharge areas generally extend toward the center of the basin to the point where ground-water flow is upward (figure 6). 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 6). 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 secondary 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; Woodward and others, 1974). 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 hour GIS attribute ranking, described below under Results, 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 (R_F) 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 R_F 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);
ρb = 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 + 10Kd) (Freeze and Cherry, 1979), where Kd is the product of the organic carbon sorption distribution coefficient (K_{oc}) and the fraction of organic carbon (F_{oc}), 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 anion), move through the subsurface at the same rate as the ground water, whereas dissolved constituents in ground water having R_F values 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, 2004), which provides digitized data for some soil areas of the state of Utah, including Salt Lake Valley, 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

Table 2. Hydrologic soil groups, field capacity, bulk density, and fraction of organic carbon content generalized for Utah soils. Soil description and organic content from National Soil Survey Center (2004). 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 %)	Bulk Density Range (kg/L) (average)	Organic Carbon 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 7.0%
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 - 1.6 (1.4)	Variable and ranges from 0.3 to 7.0%
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 7.0%
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 7.0%
G	Gravel	2.0 and greater (less than 12)	2 (2)	0.3%**

* 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 the lowest value in the SSURGO data set.

Table 3. Pesticide organic carbon sorption distribution coefficients (K_{oc}) and half-lives (T ½) for typical soil pHs (data from Weber, 1994).

Herbicide	K_{oc}(L/kg)		T ½ (Days)		T ½ (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

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%, which represent naturally occurring conditions in Salt Lake Valley, and variable soil organic carbon content using a water-table depth of 3 feet (1 m). Average organic carbon content in soils in Salt Lake Valley is shown in figure 7 and ranges from 0.3 to 7.0%; 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 1.8 to 101. This means the highest relative velocity from our data is 0.56 and the lowest is 0.01; the former indicates pesticide in ground water moves at a rate about 56% that of ground water free of pesticides, whereas the latter indicates that pesticides in ground water are essentially immobile.

About 6% of pesticides traveling downward in vadose-zone material having an R_F of about 4 could reach the water table at a depth of 3 feet (1 m) within one year if ground-water recharge amounted to 24 inches (60 cm) or greater during the year, which is the highest amount of recharge recorded in the SSURGO data (National Soil Survey Center, 2004) for Salt Lake Valley. When ground-water recharge is less than 12 inches (30 cm) per year, as is the case for the valley floor in Salt Lake Valley, a negligible amount of pesticide (0.3%) will likely reach a depth of 3 feet (1 m) in a one-year period (see attenuation discussion below). For our GIS analysis, we divided pesticide retardation into two ranges: greater than, and less than or equal to 4.

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 travels, net annual ground-water recharge, half-life of the specific pesticide considered, and field capacity of the soil. Attenuation factors 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 (m);
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 Salt Lake Valley (figure 8). 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 basin-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 Salt Lake Valley, 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 4, 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%; and a bulk density value of 0.04 pounds per cubic inch (1.2 kg/L). For a net annual ground-water recharge of 0 inches, as is typical of the valley-floor areas of Salt Lake Valley, equation 2 results in an attenuation factor approaching 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 are 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.

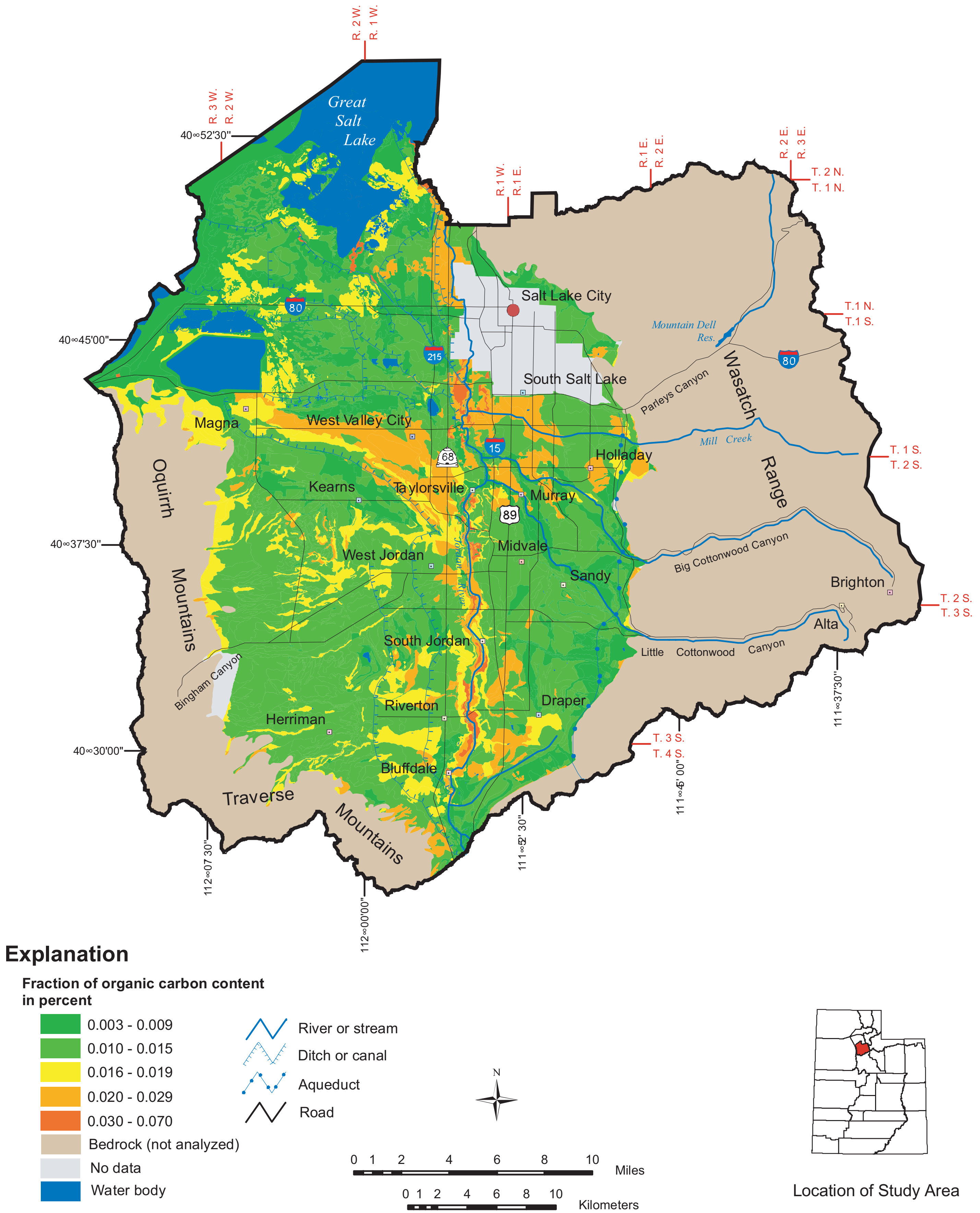

Figure 7. *Average organic carbon content in soils in Salt Lake Valley, Salt Lake County, Utah (data from National Soil Survey Center, 2004).*

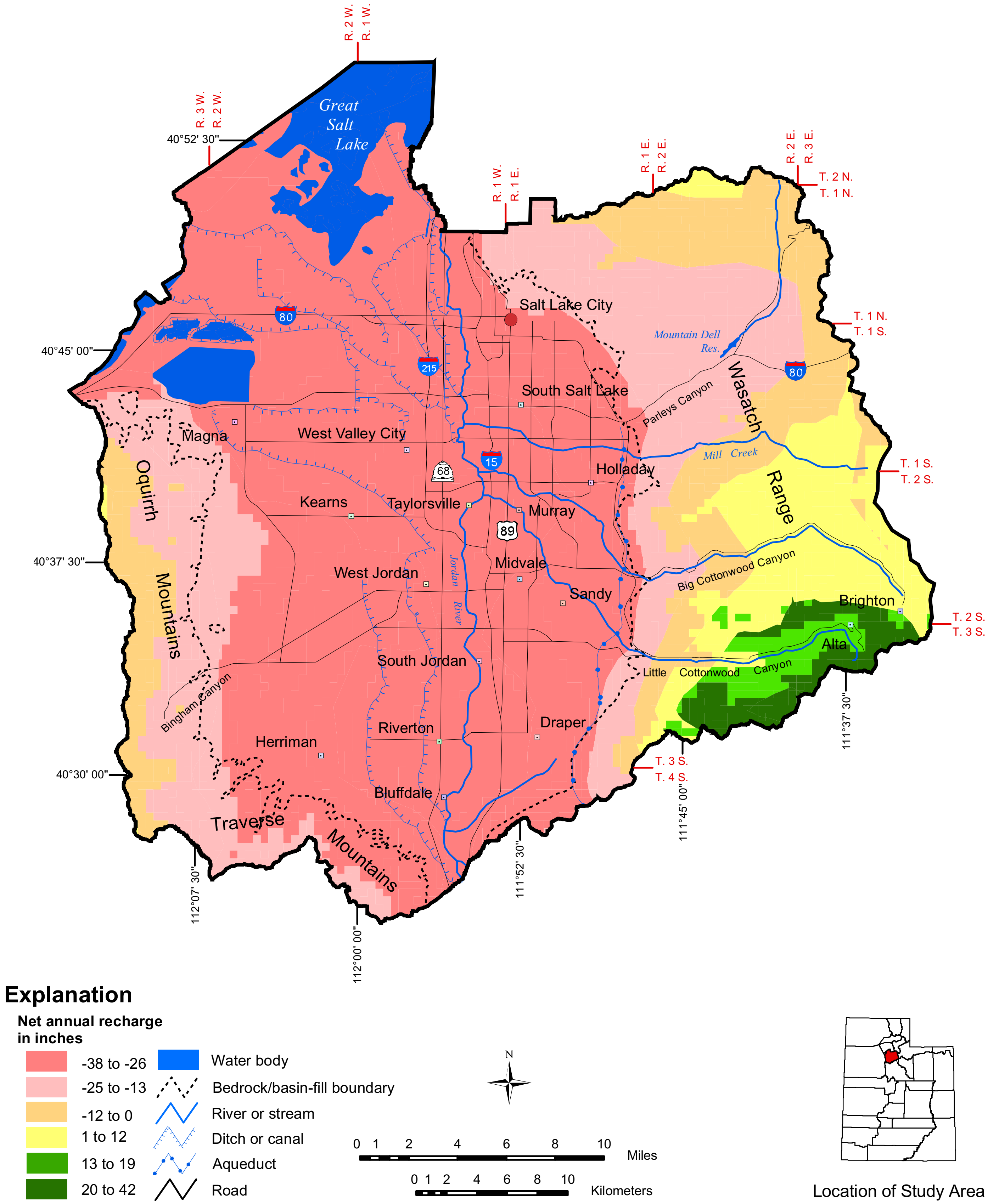

Figure 8. *Net annual ground-water recharge from precipitation in Salt Lake Valley, Salt Lake County, Utah. Recharge calculated using data from the Utah Climate Center (1991) and Jensen and Dansereau (2001). Although net annual recharge may be negative in some areas, seasonally some recharge from precipitation may occur.*

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; Woodward and others, 1974). 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, such as incorporated Salt Lake City and South Salt Lake, 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. Absolute 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 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 human activity. 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 1995 (lower Jordan River basin) 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 Salt Lake Valley to degradation from agricultural pesticides. Consequently, low, moderate, and high sensitivity rankings were assigned numerical values weighted more heavily than other factors, 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 lower Jordan River Basin inventory was conducted in 1995 (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

Table 5. *Pesticide sensitivity and the attribute rankings used to assign sensitivity for Salt Lake Valley, Salt Lake County, 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 Salt Lake Valley, Salt Lake County, 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). The lower Jordan River basin inventory was conducted in 1995 (Utah 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, absolute numerical ranking for each attribute category is arbitrary, but reflects the relative level of importance the attribute plays in determining vulnerability of ground water to contamination associated with 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 Salt Lake Valley; 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 8). Most recharge that occurs from precipitation is principally along the basin 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 Salt Lake Valley (figure 9) 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 29% of the surface area of the basin-fill aquifer. Secondary recharge areas make up an additional 29% 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 42% 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 (2004). About 35% of the surface area of the basin-fill aquifer in Salt Lake Valley has soil units mapped as having hydraulic conductivity greater than or equal to 1 inch (2.5 cm) per hour (figure 10). About 51% 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. About 14% 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 (2004); these soil polygons include incorporated Salt Lake City and South Salt Lake for which there are no soil survey data, 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

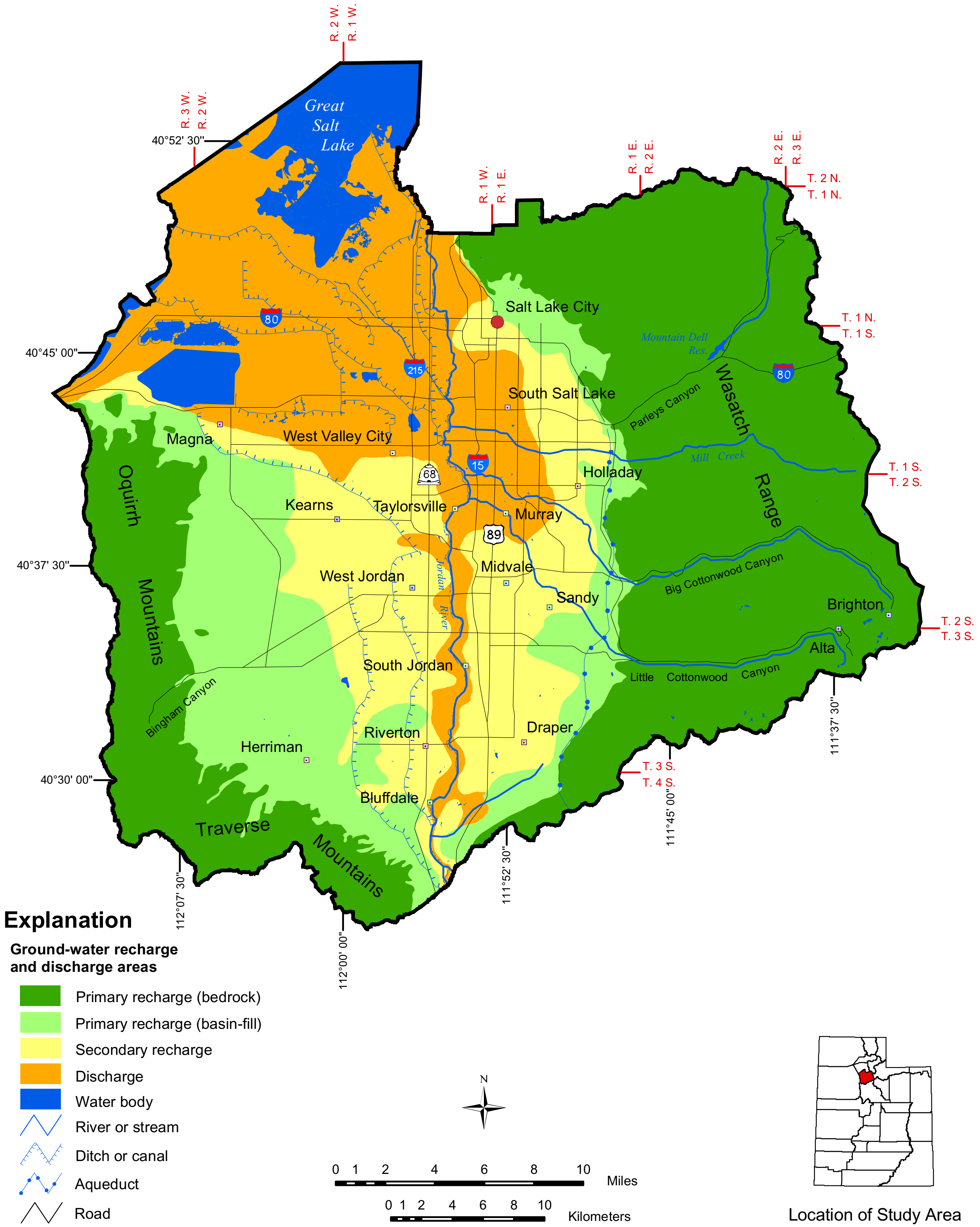

Figure 9. Recharge and discharge areas in Salt Lake Valley, Salt Lake County, Utah (from Anderson and others, 1994).

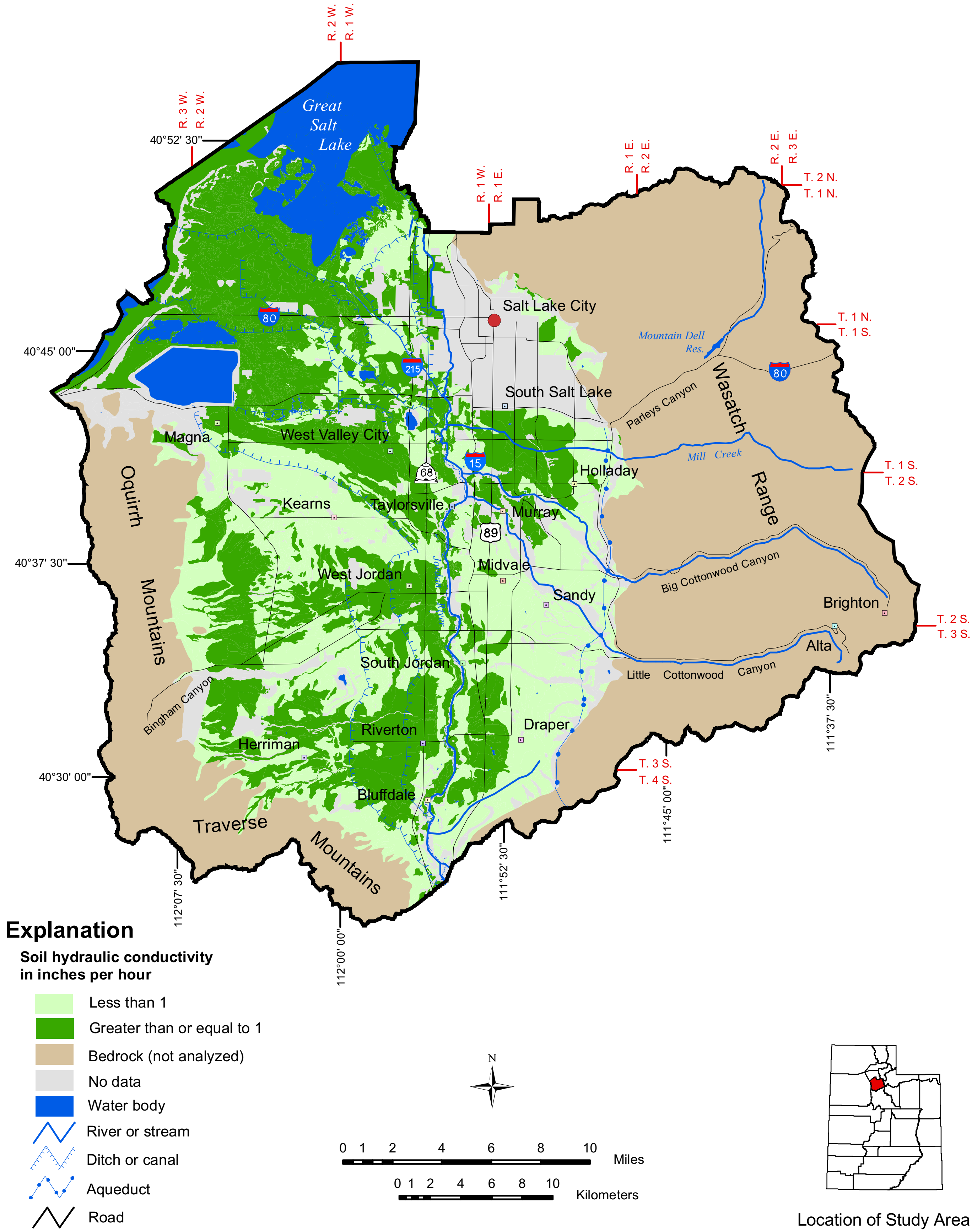

Figure 10. *Soil hydraulic conductivity in Salt Lake Valley, Salt Lake County, Utah (data from National Soil Survey Center, 2004).*

ground-water quality problems in areas of shallow ground water than where ground water is relatively deep. Depth to shallow ground-water data are from the National Soil Survey Center (2004).

About 25% of the area overlying the basin-fill aquifer in Salt Lake Valley has soil units mapped as having shallow ground water less than or equal to 3 feet (1 m) deep; these areas are primarily along Great Salt Lake, and along the Jordan River in the central part of the study area (figure 11). About 12% of the surface area of the basin-fill aquifer has soil units mapped as having shallow ground water greater than 3 feet (1 m) deep. About 63% of the surface area of the basin-fill aquifer has soil units for which no SSURGO data exist, including incorporated Salt Lake City and South Salt Lake. 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 Salt Lake Valley, 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.

Much of the northwestern part of Salt Lake Valley (8%) 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, where soils have higher hydraulic conductivities, are areas of high sensitivity (plate 1); this, combined with incorporated areas where soil data are not available, comprises about 26% of the basin-fill aquifer area. The remaining 66% 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 Salt Lake Valley (figure 12). 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

Figure 12 shows irrigated cropland areas in Salt Lake Valley. About 9% of the valley floor is irrigated cropland. 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 parts of the basin-floor area (figure 12). The use of pesticides on corn and sorghum crops increases the vulnerability of areas where these crops are grown from low to moderate.

Pesticide Vulnerability Map

Plate 2 shows ground-water vulnerability to contamination from pesticides of the basin-fill aquifer for Salt Lake Valley, 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 6% of the surface area of the basin-fill aquifer is mapped as having high vulnerability (plate 2), including incorporated Salt Lake City and South Salt Lake where soil data are not available. 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 86% 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 contamination associated with application or spilling of pesticides on the land surface. About 8% of the surface area of the basin-fill aquifer is mapped as having low vulnerability.

CONCLUSIONS AND RECOMMENDATIONS

In Salt Lake Valley, areas of irrigated land in primary recharge areas with potential shallow depths to ground water have the highest potential for water-quality degradation associated with surface application of pesticides. However, 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. We believe ground-water monitoring for pesticides should be concentrated in areas of moderate and high sensitivity or vulnerability, particularly in areas where corn or sorghum are grown. Sampling and testing in areas of the basin characterized by moderate sensitivity and moderate vulnerability should continue, but at a lower density than in the areas of higher sensitivity and vulnerability.

ACKNOWLEDGMENTS

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

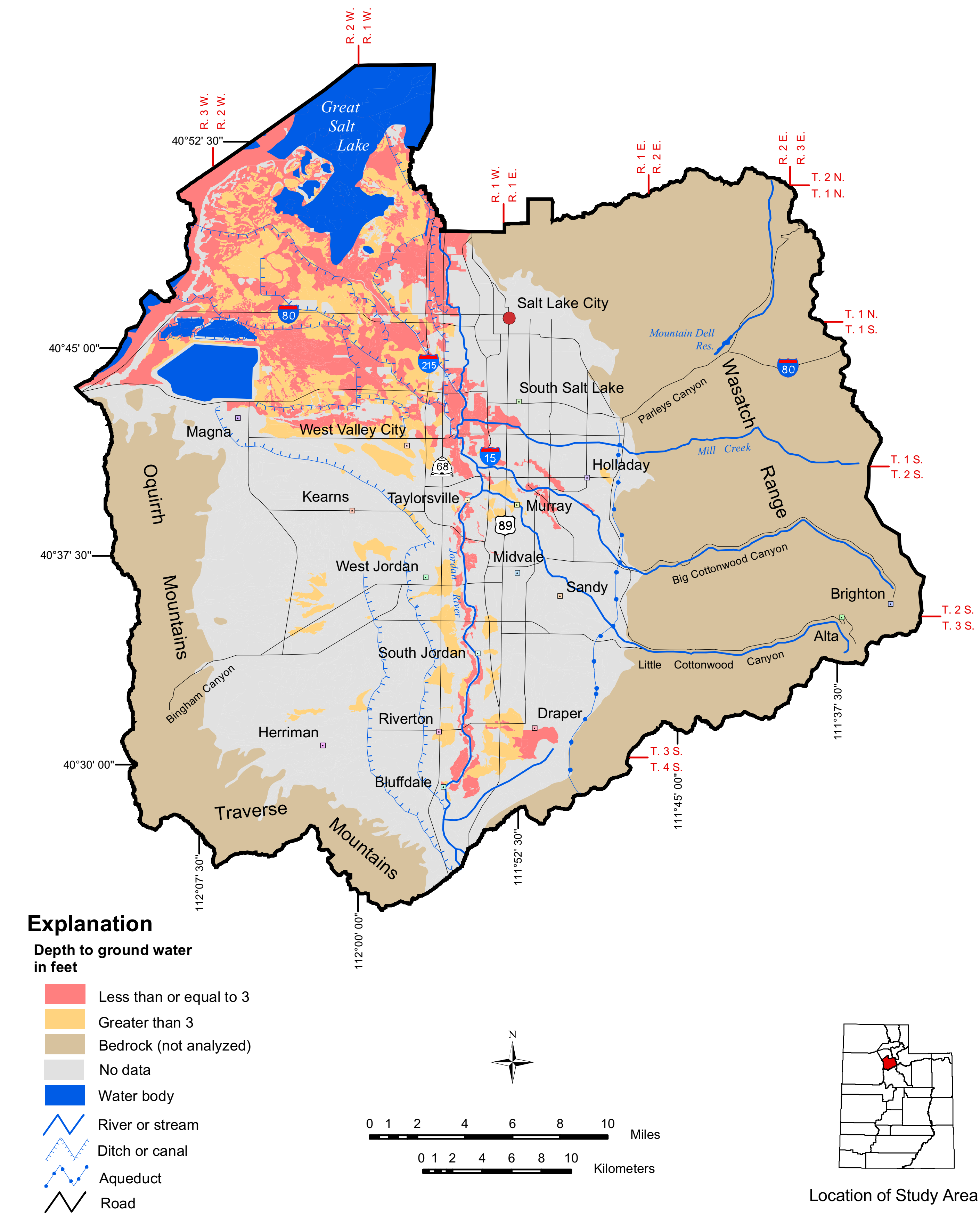

Figure 11. *Depth to shallow ground water in Salt Lake Valley, Salt Lake County, Utah (data from National Soil Survey Center, 2004).*

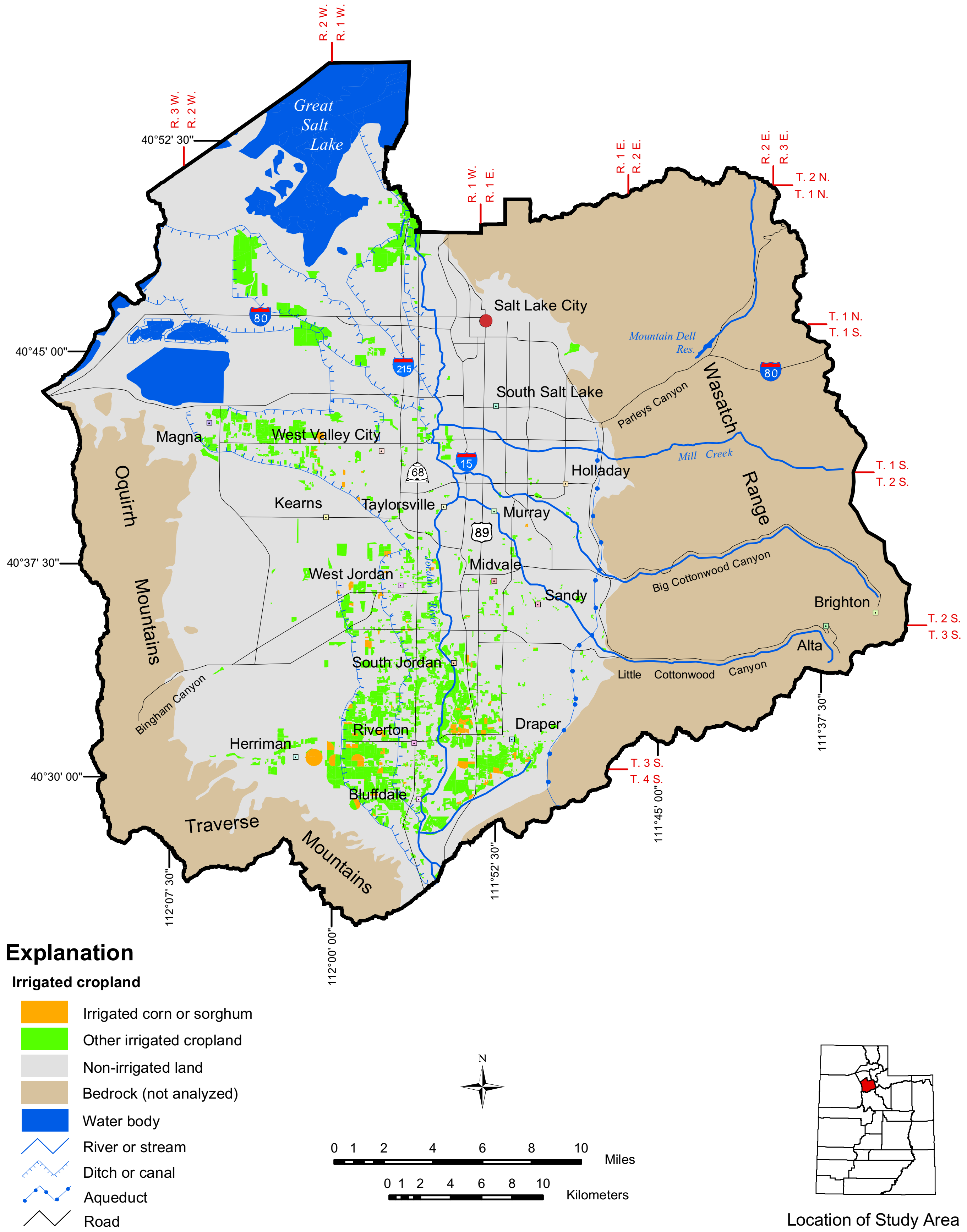

Figure 12. Irrigated and non-irrigated cropland in Salt Lake Valley, Salt Lake County, Utah, study area (unpublished data from Utah Division of Water Resources). The pesticides addressed in this study are mainly applied to corn and sorghum.

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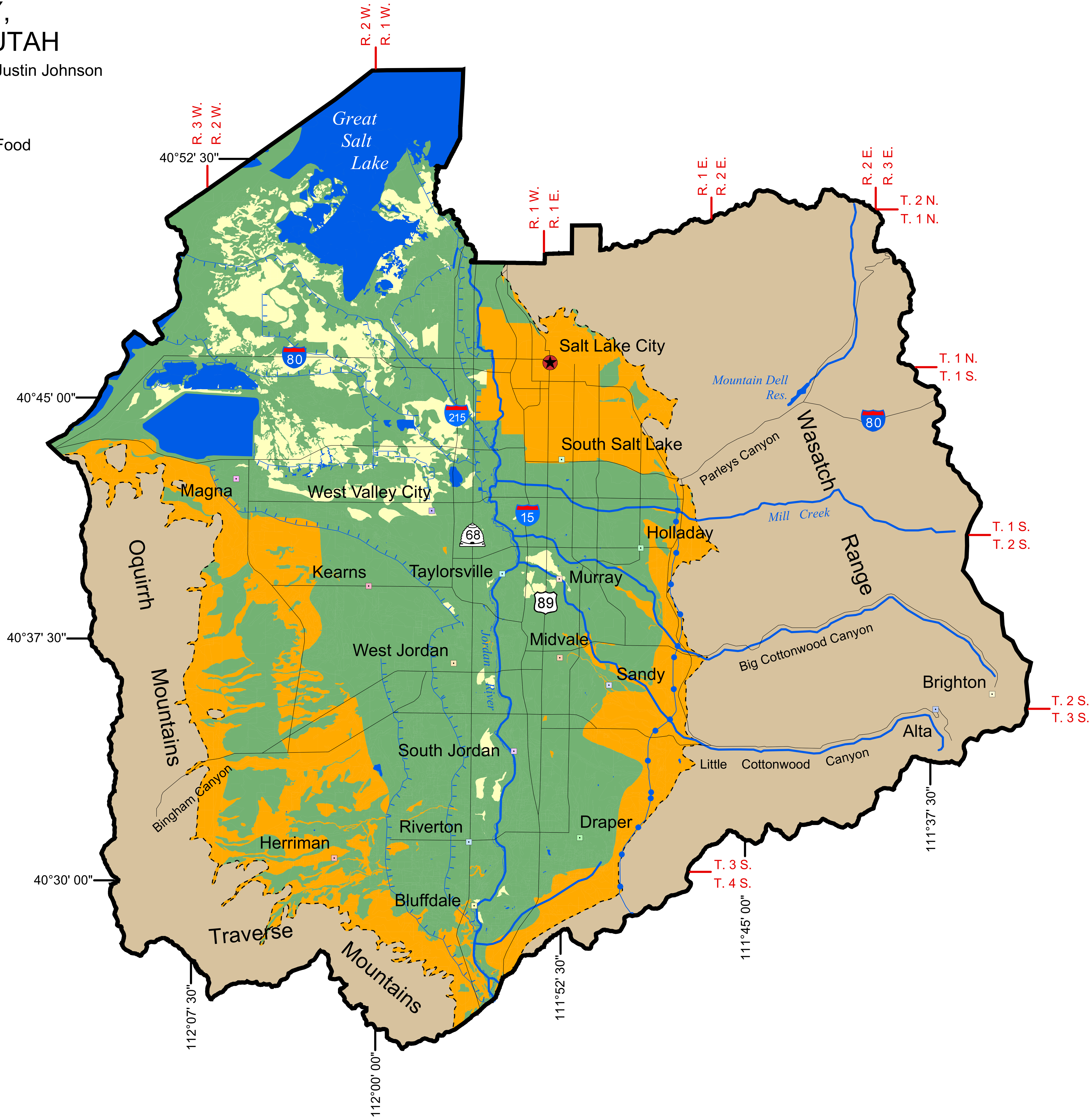
Plate 1

GROUND-WATER SENSITIVITY TO PESTICIDES IN SALT LAKE VALLEY, SALT LAKE COUNTY, UTAH

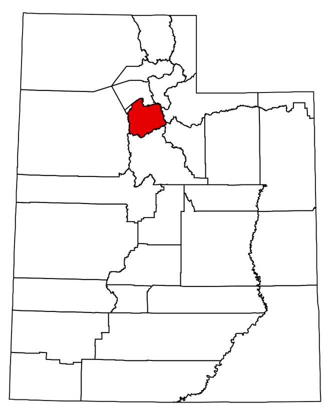
By Mike Lowe, Janae Wallace, Neil Burk, and Justin Johnson
Utah Geological Survey
and
Anne Johnson and Rich Riding
Utah Department of Agriculture and Food



Explanation

Ground-Water Sensitivity Ranking

- Low
- Moderate
- High
- Bedrock (not analyzed)
- Water body
- River or stream
- Ditch or canal
- Aqueduct
- Basin-fill boundary
- Road



Location of Study Area

0 1 2 4 6 8 10 Miles

0 1 2 4 6 8 10 Kilometers

1:120,000

Projection: UTM
Zone: 12
Units: Meters
Datum: NAD 83
Spheroid: GRS 1980

Topographic base map from U. S. Geological Survey 1:100,000-scale digital images: Provo (1986), Tooele (1979), Salt Lake City (1980), Rush Valley (1979)

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 (2002), precipitation data from the Utah Climate Center (1991), evapotranspiration data from Jensen and Dansereau (2001), and land-use data from the Utah Division of Water Resources (unpublished). 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.

Plate 2

GROUND-WATER VULNERABILITY TO PESTICIDES IN SALT LAKE VALLEY, SALT LAKE COUNTY, UTAH

By Mike Lowe, Janae Wallace, Neil Burk, and Justin Johnson
Utah Geological Survey
and
Anne Johnson and Rich Riding
Utah Department of Agriculture and Food

Explanation

Ground-Water Vulnerability Ranking

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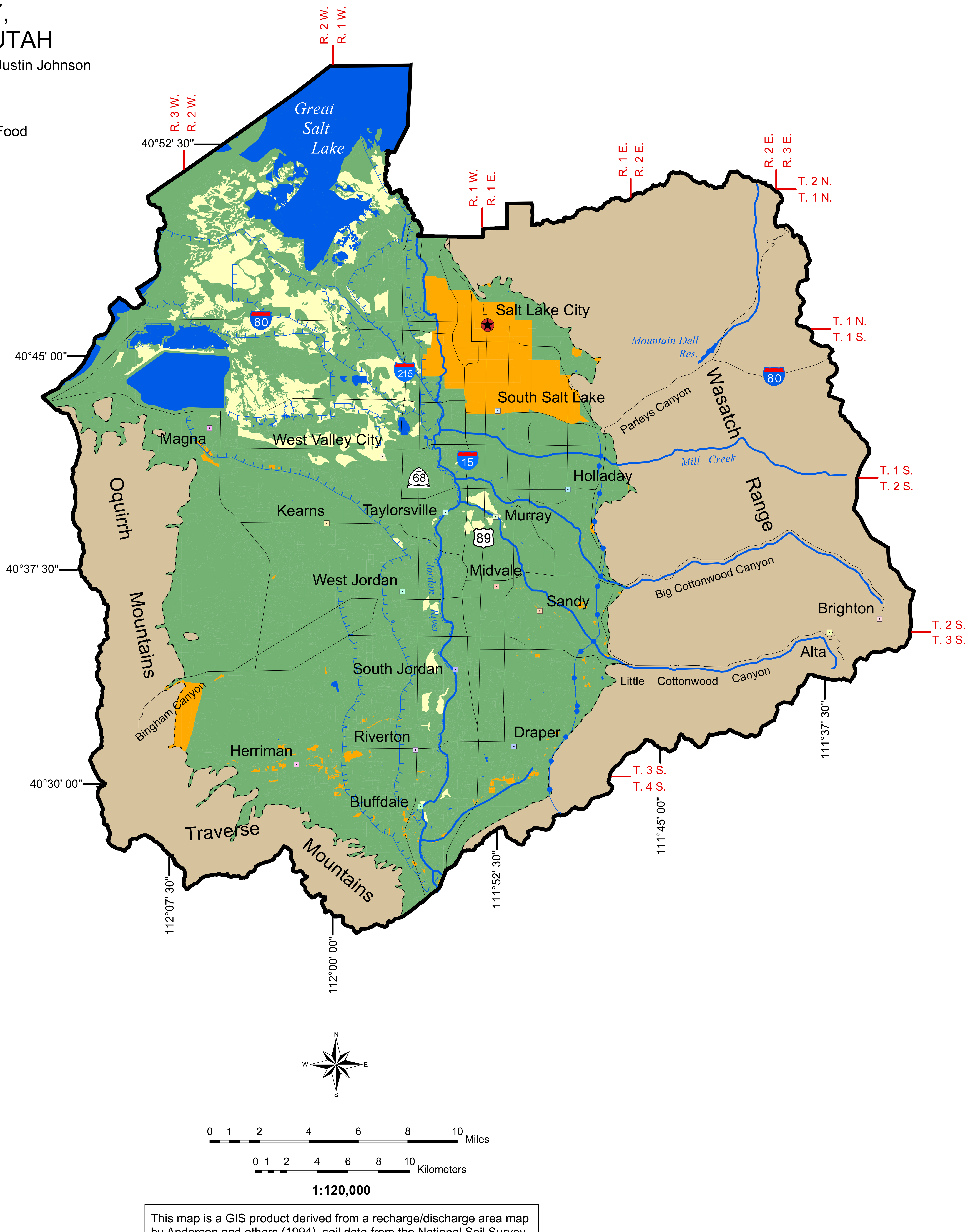

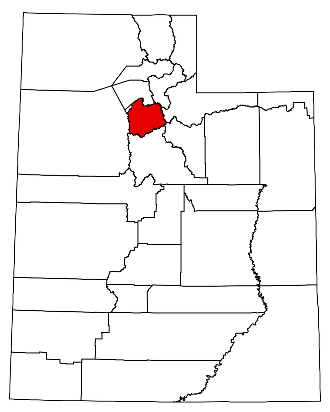

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