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

by

Mike Lowe, Janae Wallace, and Matt Butler, Utah Geological Survey

and

Rich Riding and Anne Johnson, Utah Department of Agriculture and Food

View to east of Tooele Valley from Deseret Peak. Army Depot in foreground, and Tooele City in background at base of Oquirrh Mountains.

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ABSTRACT

The U.S. Environmental Protection Agency has recommended that states develop Pesticide Management Plans for four agricultural chemical - - 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 Tooele Valley, Tooele 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 Tooele Valley. Much of the Tooele Valley has low ground-water sensitivity to pesticides due to prevalent protective clay layers above the principal aquifer and upward ground-water gradients in the northern end of the valley.

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 Tooele Valley. Areas of high vulnerability are primarily located 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 terrain 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 throughout Tooele Valley.

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 Tooele Valley likely do not present a serious threat to ground-water quality. To verify this conclusion, future ground-water sampling for pesticides in Tooele Valley 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) 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 vulnerability of ground water to agricultural pesticides in Tooele Valley, Tooele County, Utah (figure 1). This cooperative study, conducted by the Utah Geological Survey and the Plant Industry Division of the Utah Department of Agriculture and Food (UDAF), provides needed information on ground-water sensitivity and vulnerability to pesticides in the unconsolidated basin-fill aquifers of Tooele Valley. 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 Tooele Valley to agricultural pesticides.

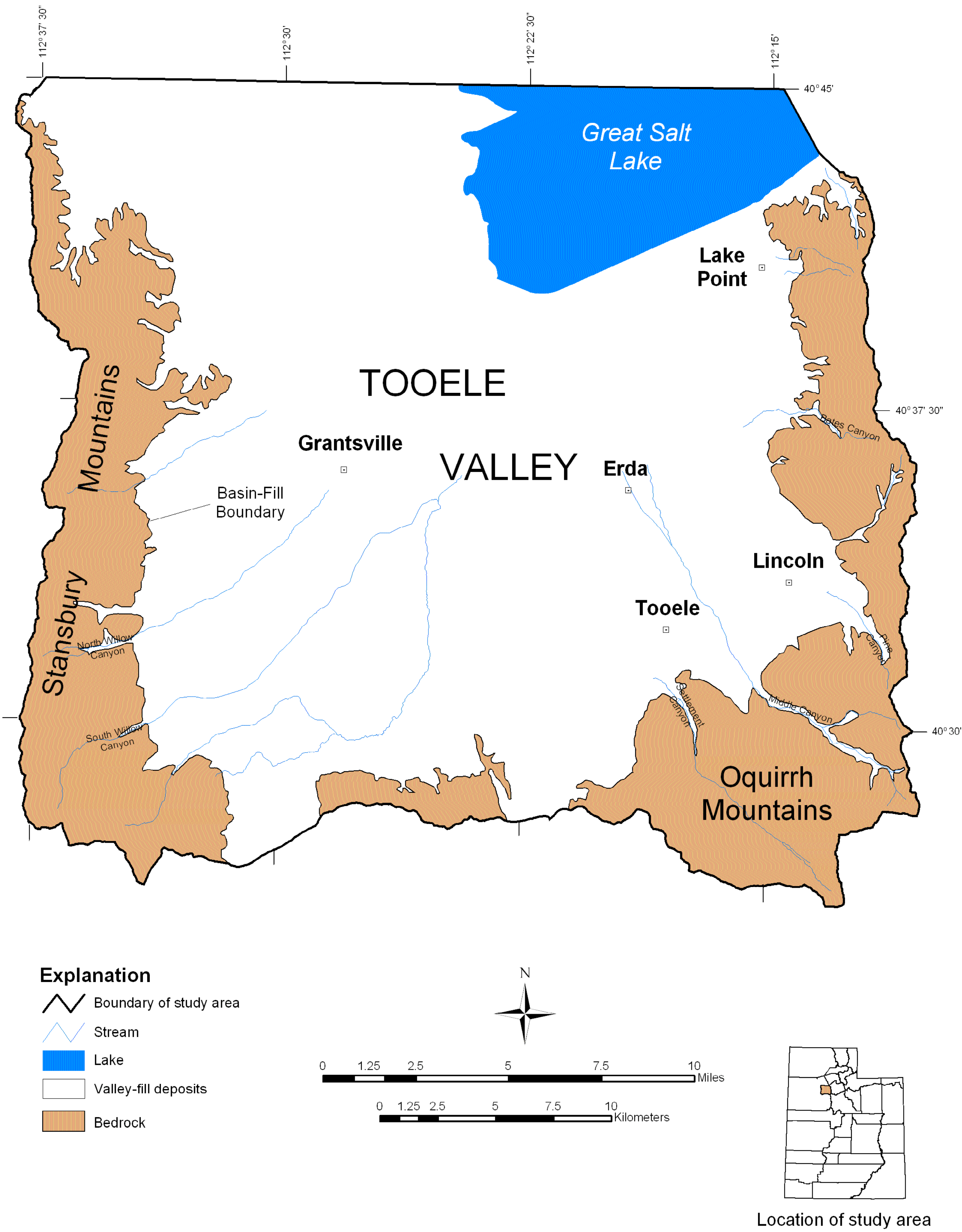

Figure 1. *Tooele Valley, Tooele County, Utah, study area.*

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 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 Tooele Valley, Tooele 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 UDAF.

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 protracted 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 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 based on our knowledge of the hydrogeology, and of the quality and types of data available; for example, we selected 3 feet (1 m) as the reference depth 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 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. 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 aquifer in over 2200 samples tested statewide (Quilter, 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 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 Tooele Valley 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

Early geologic studies of Tooele Valley included Gilbert's (1890) descriptions of geomorphic features related to Pleistocene Lake Bonneville, and Boutwell's (1905) investigations of stratigraphy, structure, and ore deposits in the Oquirrh Mountains. Subsequent geologic work included Gilluly's (1928) study of basin-and-range faulting along the west side of the Oquirrh Mountains, Gilluly's (1932) geologic map of the Stockton and Fairview quadrangles, Tooker and Roberts' (1970) study of upper Paleozoic rocks in the Oquirrh Mountains, and Tooker's (1980) map of the Tooele quadrangle. Rigby (1958) and Cook (1961) edited guidebooks to the geology of the Stansbury and Oquirrh Mountains, respectively, that included papers on structure, stratigraphy, and mineral deposits. Johnson (1958) conducted a gravity survey that included Tooele Valley. The U.S. Department of Agriculture Soil Conservation Service (now Natural Resources Conservation Service) mapped soils in the Tooele Valley area (unpublished data, 1989). Solomon (1993) mapped the Quaternary geology of Tooele Valley, and Solomon (1996) mapped the surficial geology of the Oquirrh fault zone. As part of a geologic hazards study that included Tooele Valley, Black and others (1999) produced a map showing depth to shallow ground water.

The first evaluation of ground-water conditions in Tooele Valley was Carpenter's (1913) regional-scale reconnaissance study. Thomas (1946) provided the first comprehensive study of ground-water conditions in Tooele Valley. Gates conducted a number of hydrogeologic studies in Tooele Valley in the 1960s, including an evaluation of possible buried faults affecting ground-water conditions in the Erda area (1962); a study of the hydrogeology of Middle Canyon in the Oquirrh Mountains (1963a); a compilation of selected hydrologic data for the valley (1963b); and a re-evaluation of Thomas' (1946) summary of the valley's ground-water resources (1965), including a summary of changes in ground-water conditions from 1941 to 1963. Gates and Keller (1970) produced a concise summary of ground-water conditions in Tooele Valley. Razem and Steiger (1981) produced an updated water budget for the principal aquifer system in Tooele Valley, and produced projected future ground-water conditions resulting from several water-management alternatives using the two-dimensional ground-water flow model of Razem and Bartholoma (1980). Ryan and others (1981) obtained hydrologic and geologic information on the basin-fill aquifer from test holes drilled in Tooele Valley. Stolp (1994) studied surface- and ground-water resources on southeastern Tooele Valley, including estimates of flows in streams and stream-channel deposits in Settlement and Middle Canyons from 1988 to 1990. The U.S. Army Corps of Engineers Hydrologic Engineering Center (1994) developed a three-dimensional ground-water flow model for the eastern part of the Tooele Army Depot. Bishop (1997) studied sources of nitrate in the east Erda area. Steiger and Lowe (1997) mapped recharge and discharge areas and studied the quality of ground water in Tooele Valley. Wallace and Lowe (1998) evaluated the potential impact of septic-tank soil absorption systems in Tooele Valley. Lowe and Wallace (1999) and Wallace (1999) classified ground-water quality based primarily on total-dissolved-solids concentrations in Tooele Valley; Wallace (1999) also mapped potential contaminant sources. Lambert and Stolp (1999) produced a three-dimensional, finite-difference, numerical ground-water flow model for Tooele Valley. Sheley and Yu (2000) conducted a seismic reflection and refraction survey near the mouth of Pine Canyon to determine the presence of a buried fault that might transport nitrate in ground water to the east Erda area. Burden and others (2000) reported on changes in water levels in the basin-fill aquifer of Tooele Valley from 1970 to 2000.

SETTING

Physiography

Tooele Valley (figure 1) is a north-south-trending valley with an area of about 250 square miles (650 km^2). Tooele Valley is in the Uintah Extension section of the Great Basin physiographic province, which is a subdivision of the Basin and Range Province (Stokes, 1977). Tooele Valley is bordered on the east, south, and west by the Oquirrh, South, and Stansbury Mountains, respectively, and by Great Salt Lake to the north (figure 1). Although perennial streams exist in Settlement Canyon in the Oquirrh Mountains and in Davenport, North and South Willow, and Box Elder Canyons in the Stansbury Mountains, they are diverted for irrigation just downstream from canyon mouths (Razem and Steiger, 1981) and surface flow does not reach Great Salt Lake.

Gravity data indicate that Tooele Valley is a broad collection of structural troughs and ridges within a larger graben-like structure (Johnson, 1958). This complex structure has up to 8,000 feet (2,400 m) of sediment in the northern end (Everitt and Kaliser, 1980). The Stansbury Mountains are a north-trending anticline which has been tilted to the east by movement along the Stansbury fault zone in Skull Valley (Rigby, 1958); the less active, west-dipping Broad Canyon fault bounds the east side of the Stansbury Mountains on the west side of Tooele Valley (Rigby, 1958; Helm, 1995, figure 3). The west-dipping Oquirrh fault zone bounds the eastern side of Tooele Valley; rock units in the Oquirrh Mountains have been tilted eastward by movement along this fault zone (Gilluly, 1932; Roberts and Tooker, 1961). The most recent movement along the Oquirrh fault zone occurred between 4,300 and 6,900 yr B.P. (Olig and others, 1996). Two possible faults, having no surface expression but possibly important to ground-water flow, have been inferred along the east side of Tooele Valley. Thomas (1946) inferred the presence of the Mill Pond fault based on the location of two springs, topography, and geology. Gates (1962) inferred the extension of the Occidental fault in the Oquirrh Mountains into the basin-fill deposits of Tooele Valley based on a gravity anomaly (Johnson, 1958), topography, and water-quality and water-level data.

The mountains surrounding Tooele Valley consist primarily of Cambrian to Tertiary sedimentary, metamorphic, and igneous rocks. The Oquirrh Mountains and South Mountain consist mostly of limestone and quartzite of the Pennsylvanian-Permian Oquirrh Group (Gates, 1965; Razem and Steiger, 1981). Although many formations of various lithologies crop out in the Stansbury Mountains, the thickest formations are the Oquirrh Group and the Cambrian Tintic Quartzite (Razem and Steiger, 1981).

The valley floor in Tooele Valley ranges in elevation from about 4,200 to 5,200 feet (1,280-1,590 m) and is underlain by various thicknesses of unconsolidated and semiconsolidated sediments made up of multiple discontinuous layers of silt, sand, and gravel (deposited in fluvial, alluvial-fan, and nearshore lacustrine environments) separated by layers of silt and clay (deposited in offshore lacustrine environments) (Steiger and Lowe, 1997). Basin margins are dominantly alluvial-fan deposits that grade into and interfinger with finer grained lacustrine deposits (Solomon, 1993). Pleistocene Lake Bonneville and Holocene Great Salt Lake lacustrine deposits are dominant in the central and northern parts of the valley (Gates and Keller, 1970; Solomon, 1993).

Climate

Three weather stations in the study area provide climatic data for different periods (Tooele, 1919-92 period; Bauer, 1948-59 period; and Grantsville, 1956-92), but only Tooele and Grantsville provide normal climatic data (precipitation data only at Grantsville) for the 1961-90 period. Because the normal climatic information represents a more complete data set, those values (taken from Ashcroft and others, 1992) are discussed herein. Temperatures reach a normal minimum of 19.5°F (-6.9°C) in January and a normal maximum of 88.5°F (31.4°C) in July, both at Tooele. The normal mean annual temperature at Tooele is 50.8°F (10.4°C). Normal annual precipitation ranges from 12.25 inches (31.12 cm) at Grantsville to 18.49 inches (46.96 cm) at Tooele. Normal annual evapotranspiration is 42.50 inches (107.95 cm) at Tooele. The average number of frost-free days is 164 at Tooele.

Population and Land Use

From 1990 to 2001, population in Tooele County increased from 26,581 to 44,431, a tie with Iron County for the second-highest average annual rate of population increase in Utah at 5.3 percent (Demographic and Economic Analysis Section, 2002). The projected population for Tooele County by 2020 is estimated at 80,938 (Demographic and Economic Analysis Section, 2000). Most Tooele County residents live in Tooele Valley, and residential development is the major land use in Tooele Valley, but agriculture is expected to remain prominent (Tooele County Engineering Department, 2003). Government, including Tooele Army depot (figure 2), is the largest source of employment in Tooele County. Many of the valley's residents commute to work at various locations along the Wasatch Front.

GROUND-WATER CONDITIONS

Basin-Fill Aquifers

Due to the complicated stratigraphic relationship between coarse-grained and fine-grained facies, the basin-fill aquifer consists of a complex multiple-aquifer system under both water-table and confined conditions (Gates, 1965) (figure 2). Confined conditions are dominant in the north-central part of the valley (Razem and Steiger, 1981). Unconfined conditions are present south and east of Tooele City and south and west of Grantsville (figure 2) (Steiger and Lowe, 1997). The confined aquifer is typically overlain by a water-table aquifer (Razem and Steiger, 1981). Thickness of the basin-fill aquifer varies from a few feet to 250 feet (80 m) at basin margins, to as much as 7100 feet (2160 m) in the northern part of the basin near Great Salt Lake (Steiger and Lowe, 1997).

Depth to ground water ranges from about 700 feet (210 m) at the mouth of Pine Canyon to near the ground surface proximal to Great Salt Lake (Bishop, 1997). In the Erda area, along the eastern margin of Tooele Valley, long-term water levels in wells declined from 1963 to 1967 and then rose until 1976 (Razem and Steiger, 1981). Razem and Steiger (1981) point out that, although long-term water-level trends correlate fairly well with long-term changes in precipitation, part of the water-level rise between 1972 and 1976 may be related to discharge of mine water down Pine Canyon because the rapid water-level rise did not occur in other parts of Tooele Valley. Long-term water levels in wells in the Grantsville area generally declined between 1955 and 1976 because long-term discharge exceeded long-term recharge (Razem and Steiger, 1981).

Ground-water flow in Tooele Valley is generally northwestward from the Oquirrh Mountains, northeastward from the Stansbury Mountains, and northward from South Mountain toward the valley center, and then north toward Great Salt Lake (Gates and Keller, 1970; Stolp, 1994). Bishop (1997) estimates the hydraulic gradient near the mountain front in the Pine Canyon area is about 100 feet per mile (19 m/km). In the east Erda area the hydraulic gradient is about 5 feet per mile (1 m/km) (Steiger and Lowe, 1997).

Recharge to the basin-fill aquifer is from (1) infiltration of precipitation and surface water, mostly in the mountains

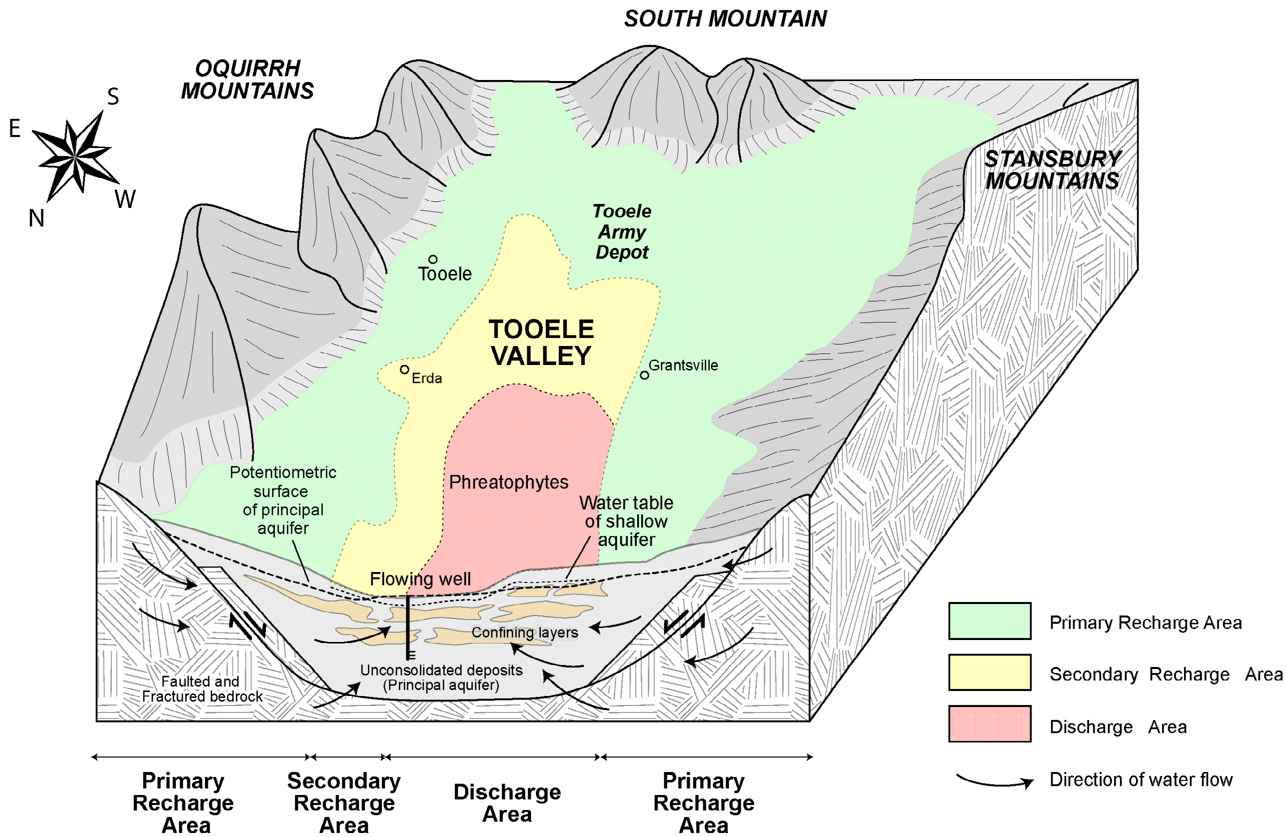

Figure 2. *Schematic block diagram showing ground-water conditions in Tooele Valley, Tooele County, Utah.*

and along valley margins, (2) underflow from consolidated rock along the margins of the valley, (3) subsurface flow from an adjacent valley to the north, (4) discharge from mines and tunnels, and (5) seepage from irrigated lands. Discharge is from evapotranspiration, well-water withdrawal, springs, and subsurface flow to Great Salt Lake (Gates and Keller, 1970; Razem and Steiger, 1981). According to Stolp (1994), average discharge approximates average recharge at 44,000 acre-feet per year (54,000,000 m^3/yr). Razem and Steiger (1981) provide a hydrologic budget for 1977 (table 2). Steiger and others (1996) report an average annual ground-water withdrawal of 28,000 acre-feet (35,000,000 m^3) from wells during 1991-95, accompanied by water-level increases for wells in northern, northwestern, and southeastern Tooele Valley, and water-level declines in all other wells.

Table 2. *1977 hydrologic budget for Tooele Valley (Razem and Steiger, 1981).*

Recharge type	Location	Amount (acre-feet)
Precipitation	Stansbury Mountains	19,300
Precipitation	Oquirrh Mountains	31,500
Precipitation	South Mountain	150
Subsurface flow	Rush Valley	5,000
TOTAL		55,950
Discharge type		**Amount (acre-feet)**
Springs		17,000
Evapotranspiration		23,000
Water wells		28,000
Subsurface flow to Great Salt Lake		3,000
TOTAL		71,000

Ground-Water Quality

Ground-water quality for Tooele Valley is variable and includes calcium-bicarbonate, calcium-magnesium-bicarbonate, and sodium-chloride types (Razem and Steiger, 1981). Additionally, ground water in some areas near Erda is of mixed types and sulfate is one of the major ions (Razem and Steiger, 1981). Total-dissolved-solids (TDS) concentrations in Tooele Valley range from 256 to 37,800 mg/L based on water-quality data collected between 1964 and 1995 (Steiger and Lowe, 1997). Average background TDS concentration is 1310 mg/L (Steiger and Lowe, 1997, tables 2 and 3). In general, recharge areas and basin margins are characterized by very good water quality (TDS concentration less than 500 mg/L). Water quality is more variable throughout the central part of the basin, where TDS concentrations range from less than 500 mg/L to greater than 3000 mg/L, and some areas near Great Salt Lake exceed 10,000 mg/L for TDS concentration (Steiger and Lowe, 1997).

Nitrate-plus-nitrite concentrations in the basin-fill aquifer range from less than 0.02 to 30.3 mg/L, with an average (background) concentration of 2.5 mg/L (Steiger and Lowe, 1997). Seven wells with water having nitrate concentrations exceeding 10 mg/L, the Utah ground-water quality standard, were identified in the east Erda area (Steiger and Lowe, 1997). The high nitrate concentrations range from 10.01 to 30.3 mg/L (Steiger and Lowe, 1997). These high nitrate levels are likely associated, at least partially, with contamination from septic-tank systems because fecal coliform bacteria have been found in water from one of the wells (Bishop, 1997). However, mining activities also may be a source of the nitrate contamination, especially if ground water does flow along the buried Occidental fault zone.

Concentrations of dissolved cadmium in water from three wells and one spring equaled or exceeded the ground-water quality standard of 5 µg/L in the 1970s, but concentrations in water from two of these wells were below the standard in 1985 (Steiger and Lowe, 1997). Concentrations of dissolved lead in water from six wells exceeded the ground-water quality standard of 15 µg/L, but concentrations in four of these wells later dropped below the standard (Steiger and Lowe, 1997). Ground water having concentrations above the ground-water quality standards for the volatile organic chemicals trichloroethylene and carbon tetrachloride, 5 µg/L for both, has been identified in the eastern part of Tooele Army Depot (Steiger and Lowe, 1997).

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 Tooele Valley. 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 Tooele 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 3. 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.

Steiger and Lowe (1997) used drillers' logs of water wells in Tooele 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 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 require 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, 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 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 Tooele Valley consists of the uplands along the margins of the basin, together with basin fill not containing confining layers (figure 3), 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

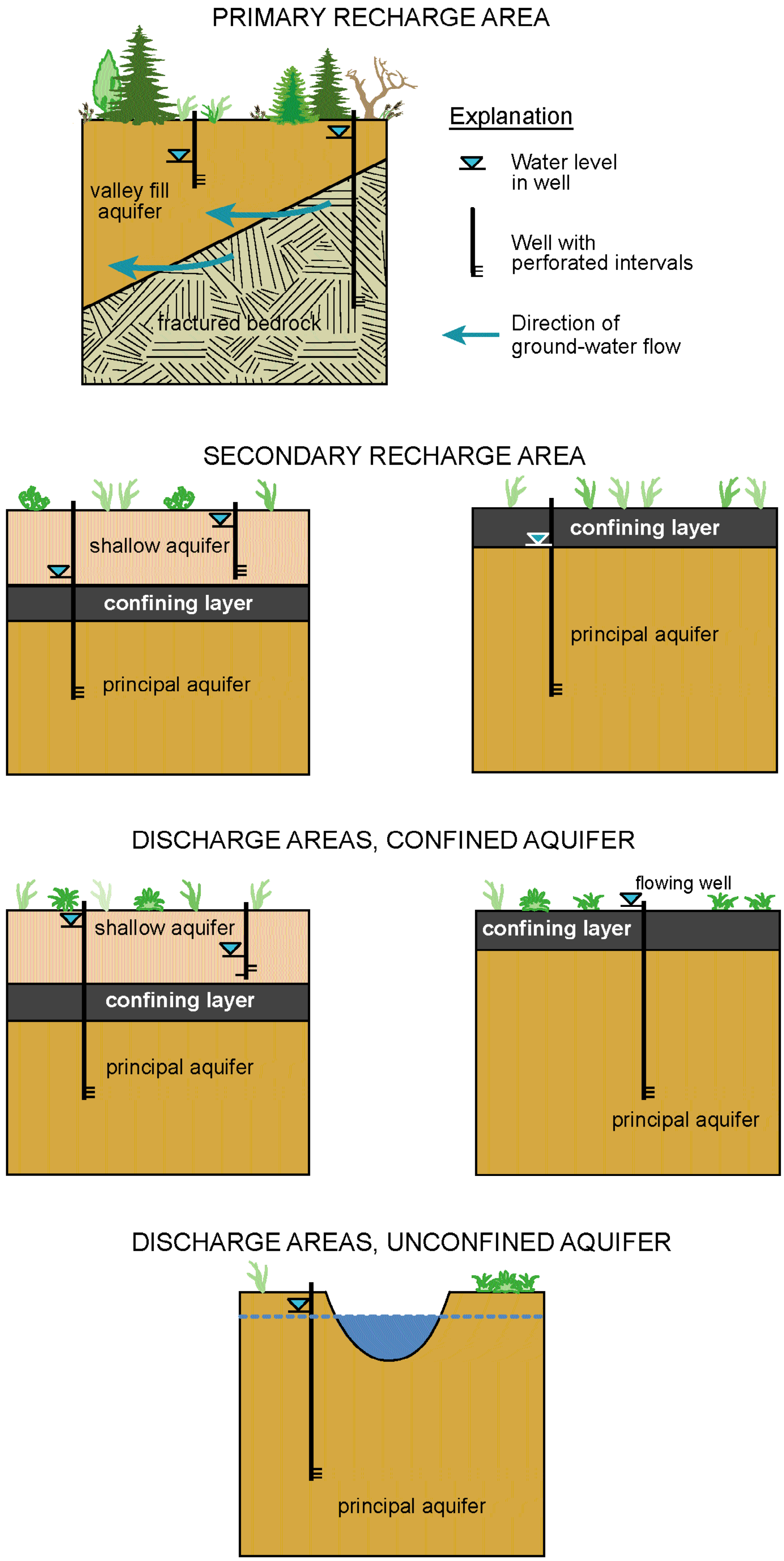

Figure 3. *Relative water levels in wells in recharge and discharge areas (modified from Snyder and Lowe, 1998).*

point where ground-water flow is upward (figure 3). 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 occur where the potentiometric surface in the principal aquifer system is below the ground surface.

Ground-water discharge areas, if present, generally occur 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 3). 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. We obtained values for hydraulic conductivity of soils 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; National Soil Survey Center, 1998). 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 more slowly through the soil 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);
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 (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 cation), 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, 1998), which provides digitized data for some soil areas of the state of Utah, including Tooele Valley, at a scale of 1:24,000. Data include derived values for bulk density, organic carbon fraction, and field capacity (table 3). For areas in the SSURGO database lacking information on hydrologic soil group, fraction of organic carbon, field capacity, and/or bulk density, we assigned values to them based on values from adjacent areas having similar geologic characteristics.

We set variables in equation 1 to values that represent conditions likely to be encountered in the natural environment (table 3) to establish a rationale for dividing high and low pesticide retardation for our GIS analysis, and we applied digital soil information unique for particular soil groups from SSURGO data for organic carbon. We used the organic carbon sorption distribution coefficient (table 4), 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 RF 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 Tooele Valley, and variable soil organic carbon content using a water depth of 3 feet (1 m). Average organic carbon content in soils

Table 3. *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 (1998). 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 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 0.2 to 2.6 %
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 0.2 to 2.6 %
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 0.2 to 2.6 %
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 0.2 to 2.6 %
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%

in Tooele Valley is shown in figure 4 and ranges from 0.2 to 2.6%; 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 1.6 to 38. This means the highest relative velocity from our data is 0.63 and the lowest, 0.03; the former indicates pesticide in ground water moves at a rate about 63 percent that of ground water free of pesticides, whereas the latter indicates that pesticides in ground water are essentially immobile.

Table 4. *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

A small percentage of pesticides traveling downward in vadose-zone material having an R_F of 1.6 could reach the water table at a depth of 3 feet (1 m) within one year if ground-water recharge amounted to 22.8 inches (58 cm) or greater during the year, which is the highest amount of recharge calculated for the mountains adjacent to Tooele Valley. When ground-water recharge is less than 13.8 inches (35 cm) per year, as is the case for the valley floors of Tooele Valley, no amount of pesticide 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, or less than or equal to 1.6.

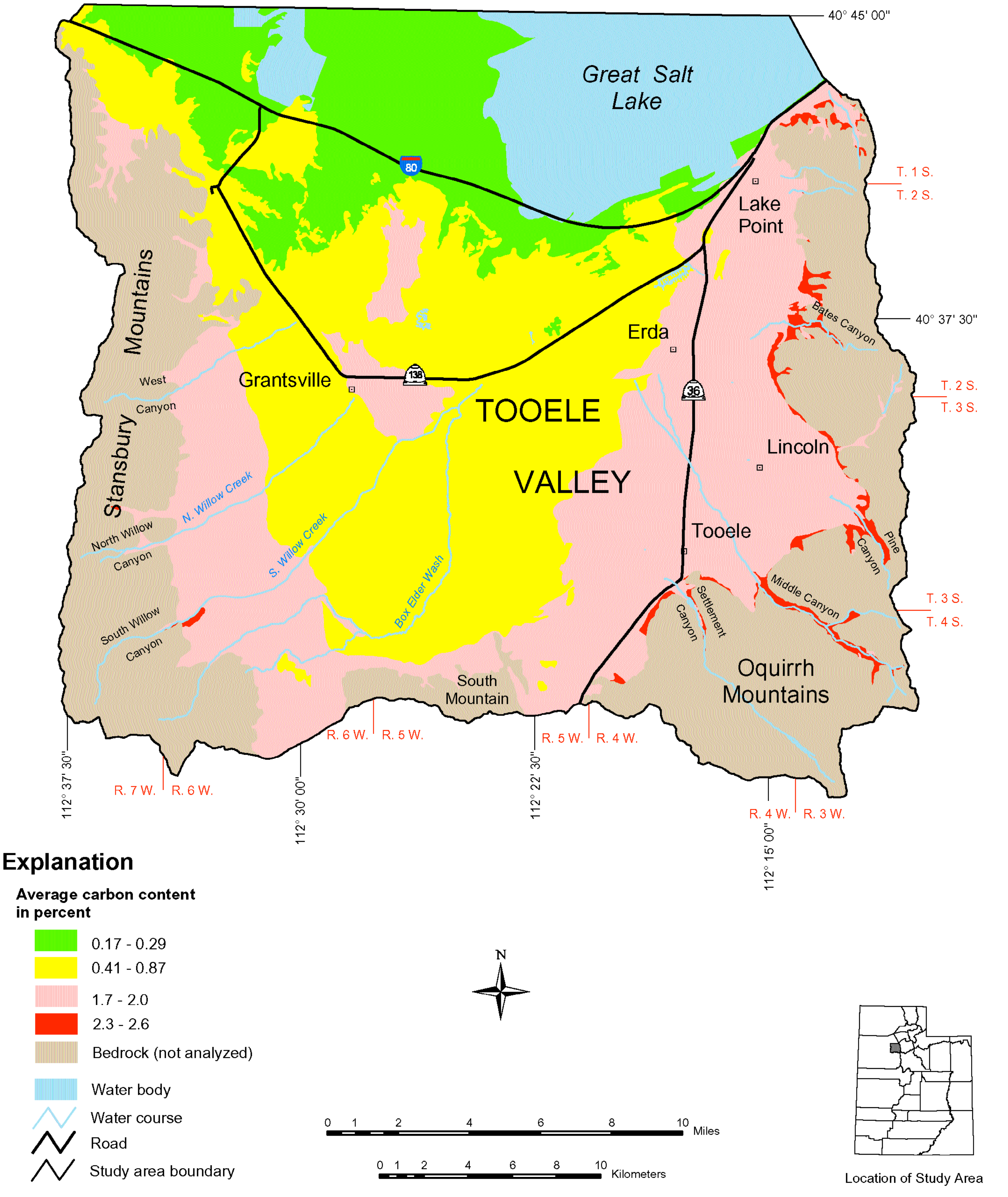

Figure 4. *Average organic carbon content in soils in Tooele Valley, Tooele County, Utah (data from National Soil Survey Center, 1998).*

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 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 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 not currently 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 the state, including Tooele Valley (figure 5). Therefore, ground-water recharge from precipitation is relatively low in many areas of Utah, including Tooele Valley. 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 Tooele 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 1.6, calculated as described above; the half-life for simazine (table 4), 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 negative net annual ground-water recharge values, as are typical of the valley-floor areas of Tooele Valley, 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) - - 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 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 5) 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 5. *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 with 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; National Soil Survey Center, 1998). 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," and "high" based on the sum of numerical values (rankings) assigned to hydrogeologic setting, soil hydraulic conductivity, soil retardation of pesti-

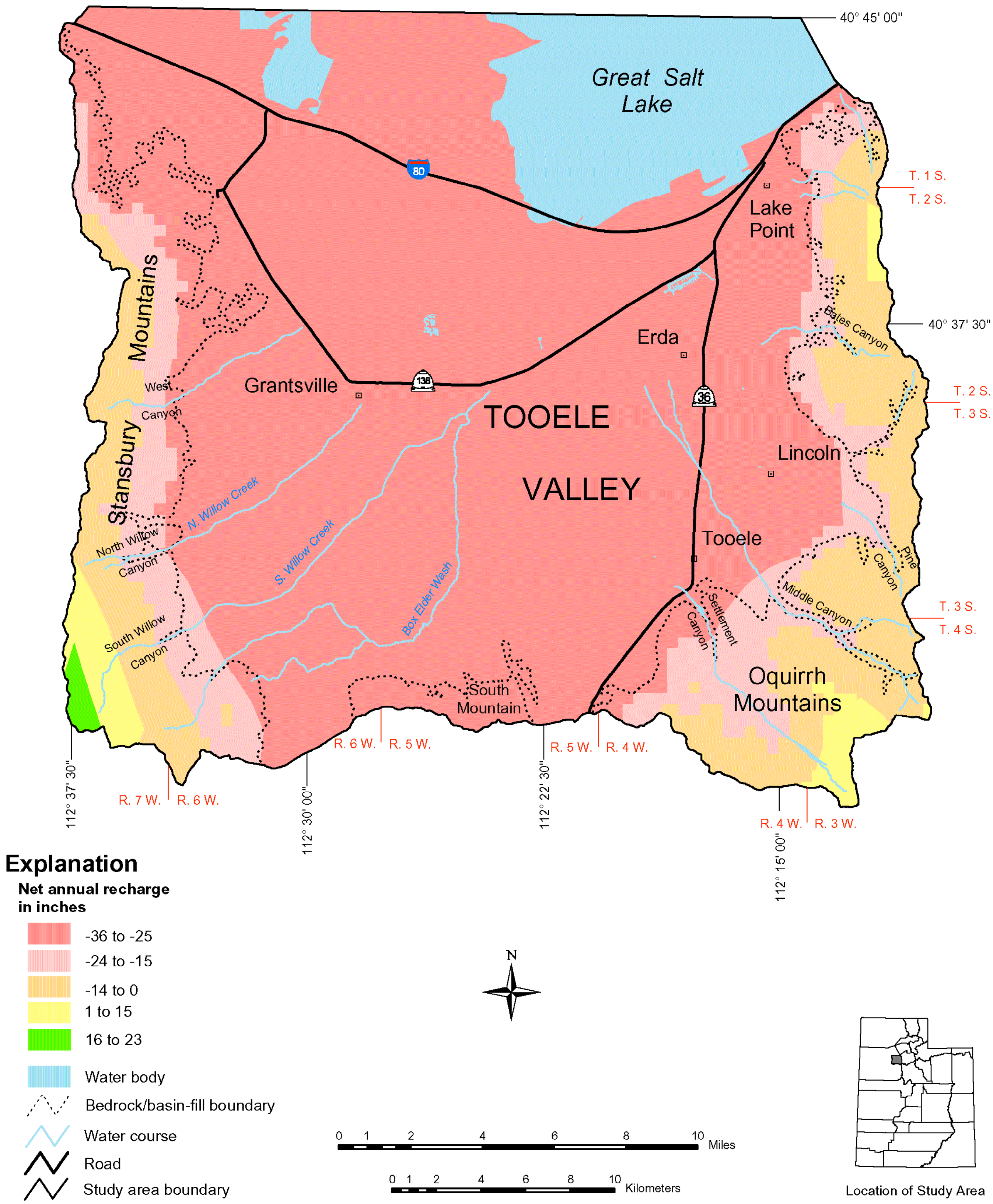

Figure 5. Net annual ground-water recharge from precipitation in Tooele Valley, Tooele County, Utah. Recharge calculated using data from the Utah Climate Center (1991) and Jensen and Dansereau (2001). Although net annual recharge may be negative in some areas, seasonally some recharge from precipitation may occur.

cides, soil attenuation of pesticides, and depth to shallow ground-water attributes as shown in table 6. 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 was assigned when the added numerical ranking ranged from –2 to 0, a sensitivity attribute of moderate was assigned when the added numerical ranking ranged from 1 to 4, and a sensitivity attribute of high was assigned when the added numerical ranking ranged 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 1997 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 Tooele Valley to degradation from agricultural pesticides. We assigned numerical values for low, moderate, and high sensitivity rankings as shown in table 7.

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 Tooele Valley inventory was conducted in 1997 (Utah Division of Water Resources metadata). All polygons having standard type codes beginning with IA were selected 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 Tooele Valley inventory was conducted in 1997 (Utah Division of Water Resources metadata). We selected all polygons with 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 7. Once again, 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

Table 6. *Pesticide sensitivity and attribute rankings used to assign sensitivity for Tooele Valley, Tooele County, Utah.*

<table>
<tr><th colspan="2">Pesticide Retardation Factor</th><th colspan="2">Pesticide Attenuation Factor</th><th colspan="2">Hydrogeologic Setting</th><th colspan="2">Soil Hydraulic Conductivity</th><th colspan="2">Depth to Ground Water</th><th colspan="2">Sensitivity</th></tr>
<tr><th>Attribute</th><th>Ranking</th><th>Attribute</th><th>Ranking</th><th>Attribute</th><th>Ranking</th><th>Attribute</th><th>Ranking</th><th>Attribute</th><th>Ranking</th><th>Attribute</th><th>Ranking</th></tr>
<tr><td rowspan="3">High</td><td rowspan="3">0</td><td rowspan="3">Low</td><td rowspan="3">0</td><td rowspan="2">Confined Aquifer Discharge Area</td><td rowspan="2">-4</td><td rowspan="3">Less than 1 inch/hour</td><td rowspan="3">1</td><td rowspan="3">Greater than 3 feet</td><td rowspan="3">1</td><td>Low</td><td>-2 to 0</td></tr>
<tr><td rowspan="3">Moderate</td><td rowspan="3">1 to 4</td></tr>
<tr><td rowspan="2">Secondary Recharge Area</td><td rowspan="2">-1</td></tr>
<tr><td rowspan="2">Low</td><td rowspan="2">1</td><td rowspan="2">High</td><td rowspan="2">1</td><td rowspan="2">Greater than or equal to 1 inch/hour</td><td rowspan="2">2</td><td rowspan="2">Less than or equal to 3 feet</td><td rowspan="2">2</td></tr>
<tr><td>Primary Recharge Area and Aquifer Discharge Area</td><td>2</td><td>High</td><td>5 to 8</td></tr>
</table>

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 6, and are described and summarized in the following sections.

Retardation/Attenuation

Retardation factors are variable and attenuation factors are ranked as low throughout the Tooele Valley 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 5). Most recharge that does occur 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

Steiger and Lowe (1997) mapped ground-water recharge areas in Tooele Valley (figure 6). Their map shows that primary recharge areas, the areas most susceptible to contamination from pesticides applied to the land surface, comprise about 53% of the surface area of the basin-fill aquifer. Secondary recharge areas make up 12% 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 35% 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 (1998). About 66% of the surface area of the basin-fill aquifer in Tooele Valley has soil units mapped as having hydraulic conductivity greater than or equal to 1 inch (2.5 cm) per hour (figure 7). About 26% 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 (figure 7). About 8% 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 (1998); these soil polygons 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. Depth to shallow ground-water data are from the National Soil Survey Center (1998). About 13% of the area overlying the basin-fill aquifer in Tooele Valley has soil units mapped as having depths to shallow ground water less than or equal to 3 feet (1 m) (figure 8). About 1% 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) (figure 8). About 86% of the surface area of the basin-fill aquifer has soil units mapped as having no data (figure 8). 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 Tooele 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.

Most of the area around Great Salt Lake (35%) 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. In these areas, 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 southern part of Tooele Valley, where soils have higher hydraulic conductivities, are areas of high sensitivity (plate 1). About 53% of the area overlying the valley-fill aquifer is mapped as having high sensitivity (plate 1). The remaining 12% 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 intermed-iate steps. Pertinent statewide attribute layers include irrigated cropland and corn- and sorghum-producing areas in Tooele Valley (figure 9). Using GIS methods as outlined in table 7, 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.

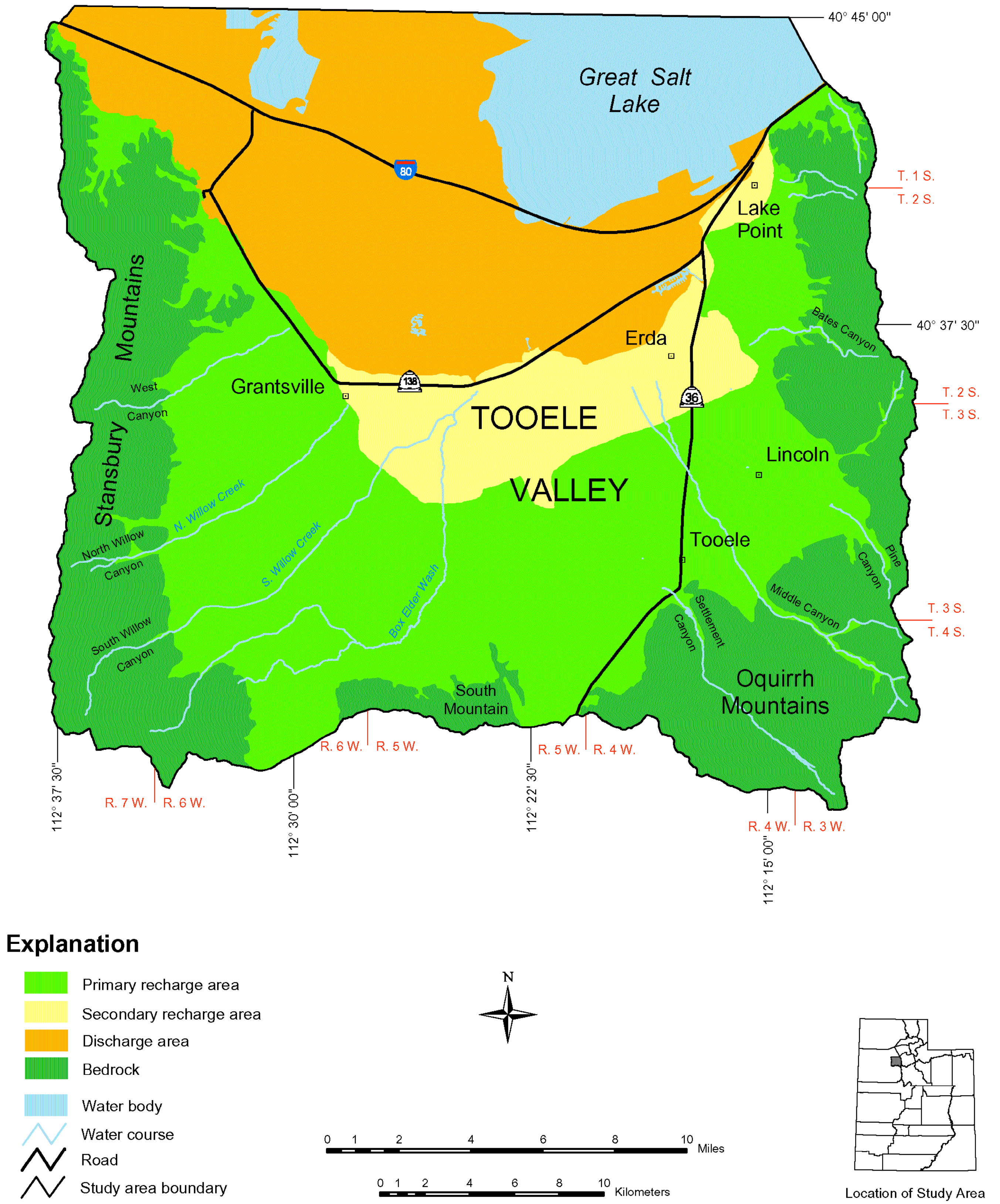

Figure 6. *Recharge and discharge areas in Tooele Valley, Tooele County, Utah (modified from Steiger and Lowe, 1997).*

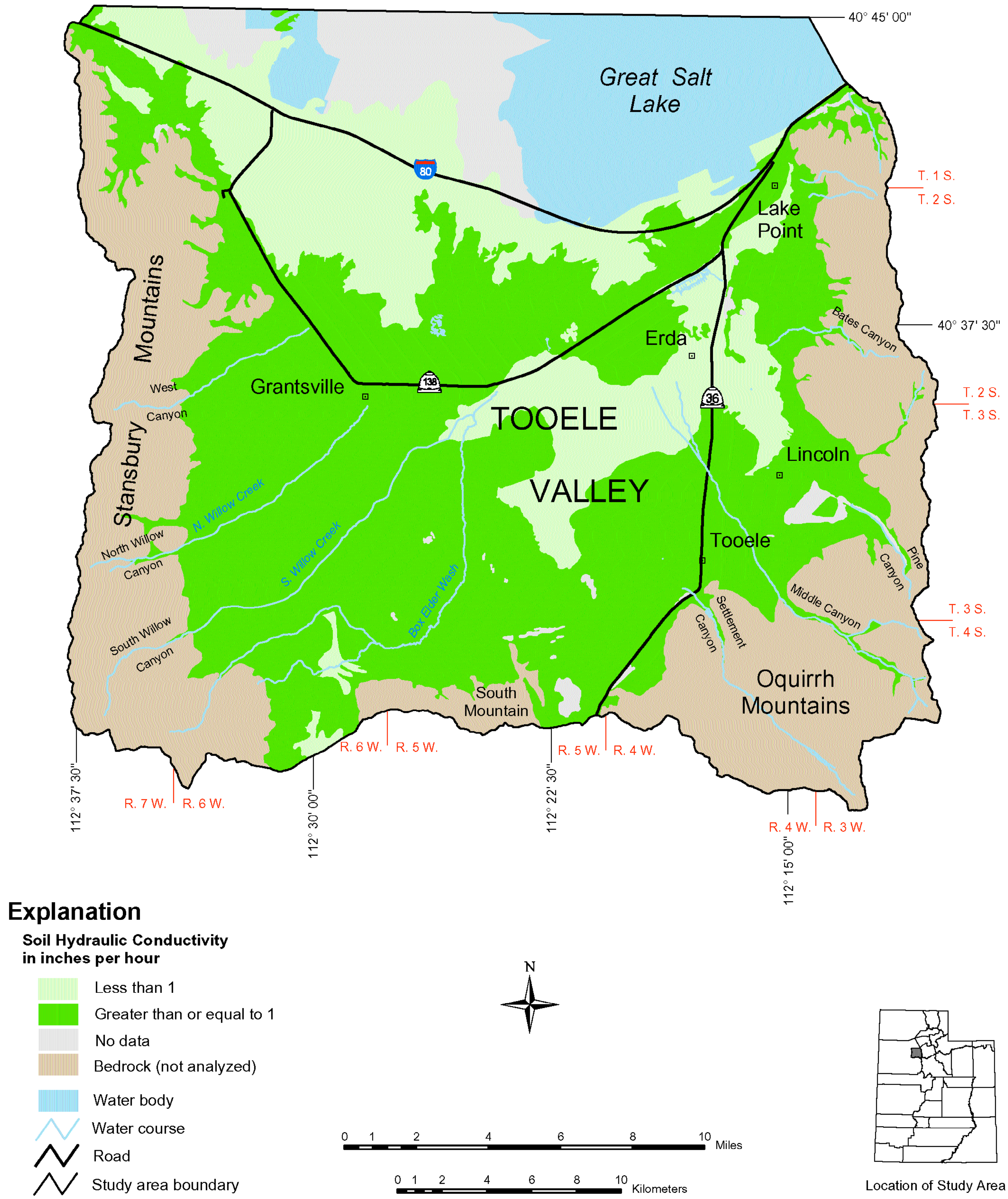

Figure 7. *Soil hydraulic conductivity in Tooele Valley, Tooele County, Utah (data from National Soil Survey Center, 1998).*

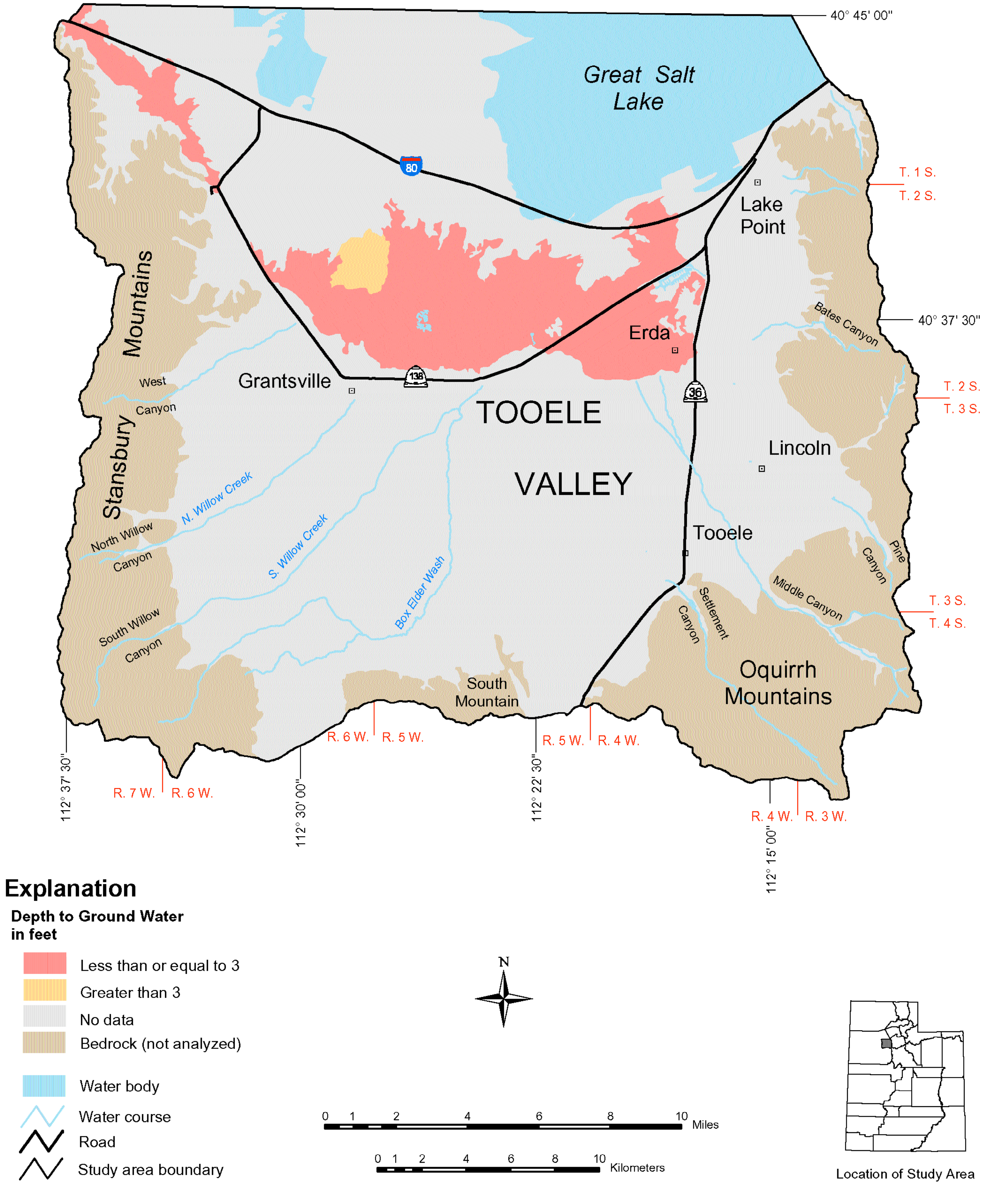

Figure 8. *Depth to shallow ground water in Tooele Valley, Tooele County, Utah (data from National Soil Survey Center, 1998).*

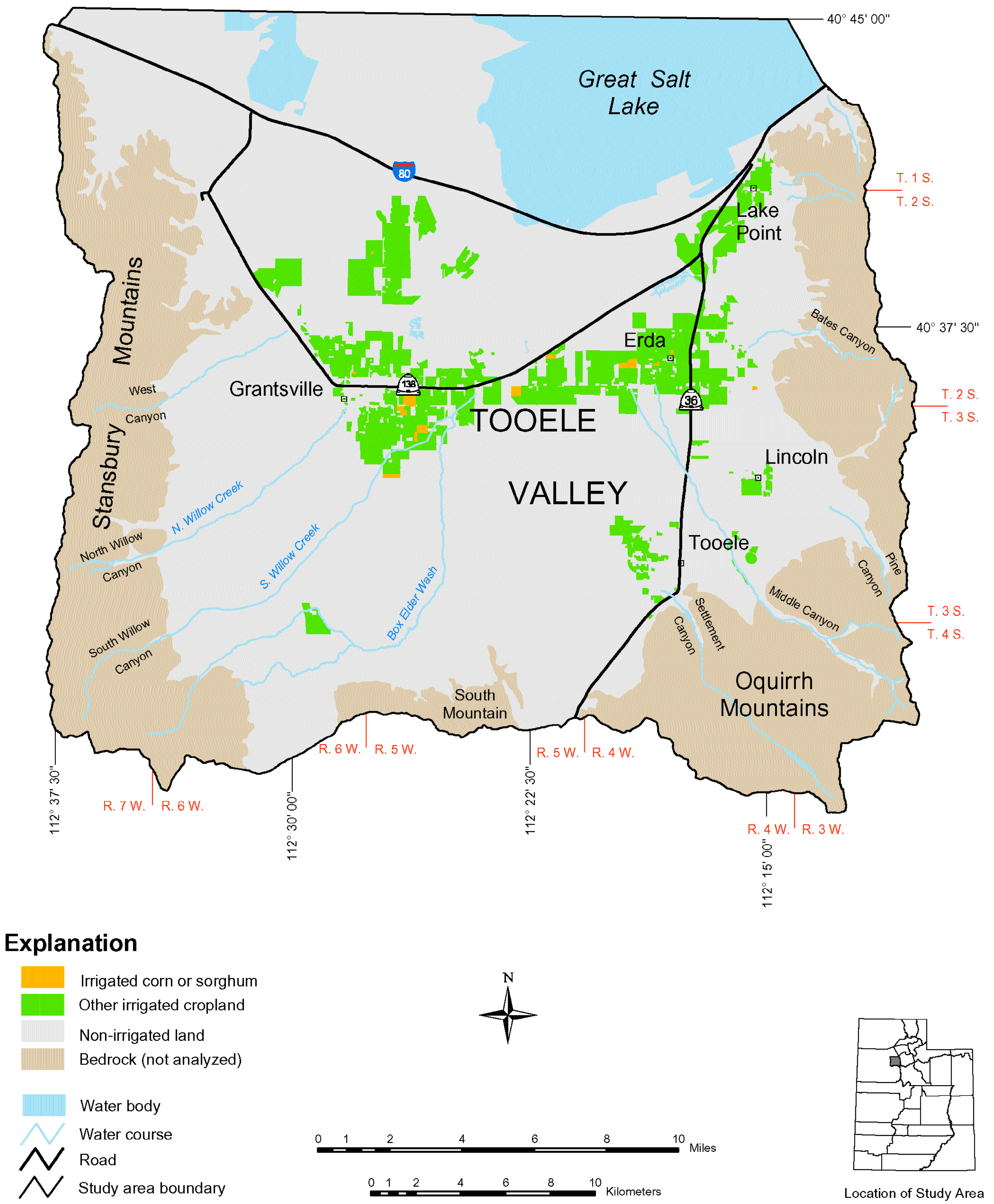

Figure 9. Irrigated and non-irrigated cropland in Tooele Valley, Tooele County, Utah (data from Utah Division of Water Resources, 1997). The pesticides addressed in this study are mainly applied to corn and sorghum.

Table 7. *Pesticide vulnerability and attribute rankings used to assign vulnerability for Tooele Valley, Tooele 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

Irrigated Cropland

Figure 9 shows irrigated cropland areas in Tooele Valley. About 9% of the valley floor is irrigated, and about 91% 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 central parts of the basin-floor area (figure 9). 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 contamination from pesticides of the basin-fill aquifer for Tooele valley, obtained using 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% 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 64% of the surface area of the basin-fill aquifer is mapped as having moderate vulnerability (plate 2). Low-sensitivity areas without irrigated cropland have low vulnerability to contamination associated with application or spilling of pesticides on the land surface. About 35% of the surface area of the basin-fill aquifer is mapped as having low vulnerability (plate 2).

CONCLUSIONS AND RECOMMENDATIONS

In Tooele Valley, areas of irrigated land where the ground-water table is near the land surface 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. However, we believe ground-water monitoring for pesticides should be concentrated in areas of moderate and high sensitivity or vulnerability, especially in those areas where corn or sorghum are grown. Sampling and testing in areas of the basins characterized by moderate sensitivity and moderate vulnerability (but without nearby corn or sorghum crops) should continue, but at a lower density than in the areas of higher sensitivity and vulnerability.

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Plate 1
Ground-Water Sensitivity to Pesticides in Tooele Valley, Tooele County, Utah
Miscellaneous Publication 04-3
Utah Geological Survey
2004

Plate 1

GROUND-WATER SENSITIVITY TO PESTICIDES IN TOOELE VALLEY, TOOELE COUNTY, UTAH

By Mike Lowe, Janae Wallace, and Matt Butler
Utah Geological Survey
and
Rich Riding and Anne Johnson
Utah Department of Agriculture and Food

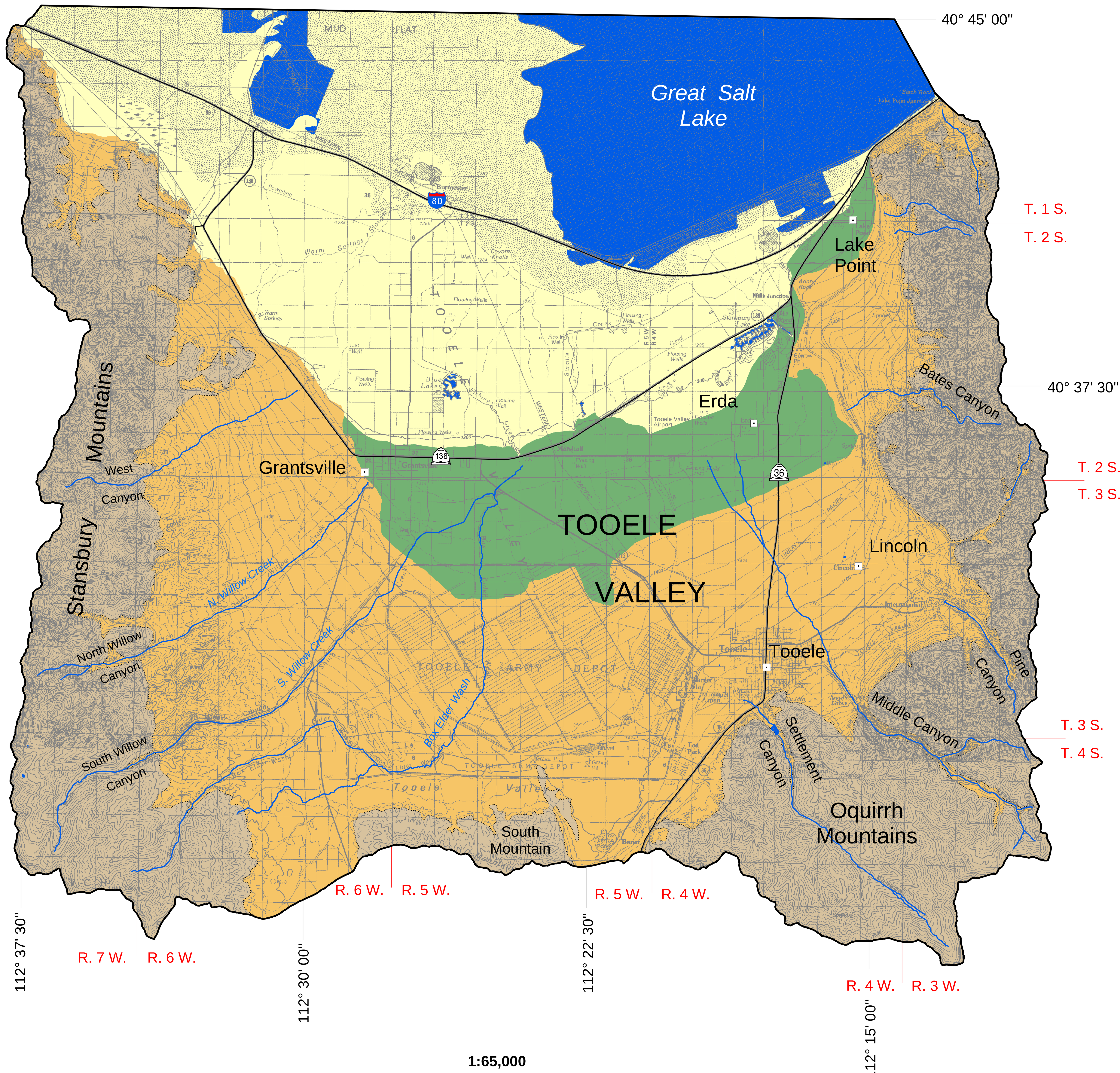
Miscellaneous Publication 04-3

Explanation

Ground-Water Sensitivity Ranking

- Low
- Moderate
- High
- Bedrock (not analyzed)

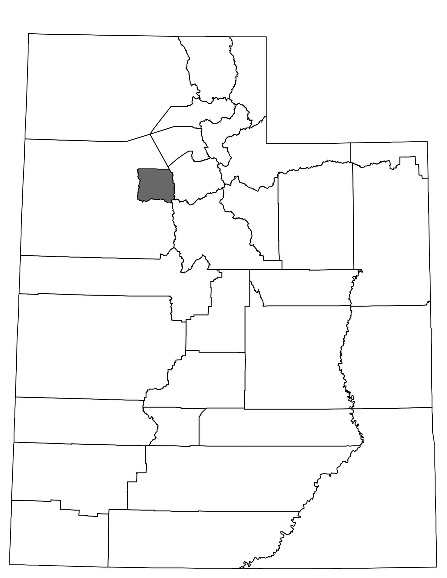
- Water body
- Water course
- Valley-fill boundary
- Road
- Study area boundary



1:65,000

0 1 2 4 6 8 10 Miles

0 1 2 4 6 8 10 Kilometers



Location of Study Area

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 (1997), 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 (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: NAD 27
Spheroid: Clarke 1866

Topographic base map from U. S. Geological Survey
1:100,000-scale digital images: Tooele (1997), Rush Valley (1997)

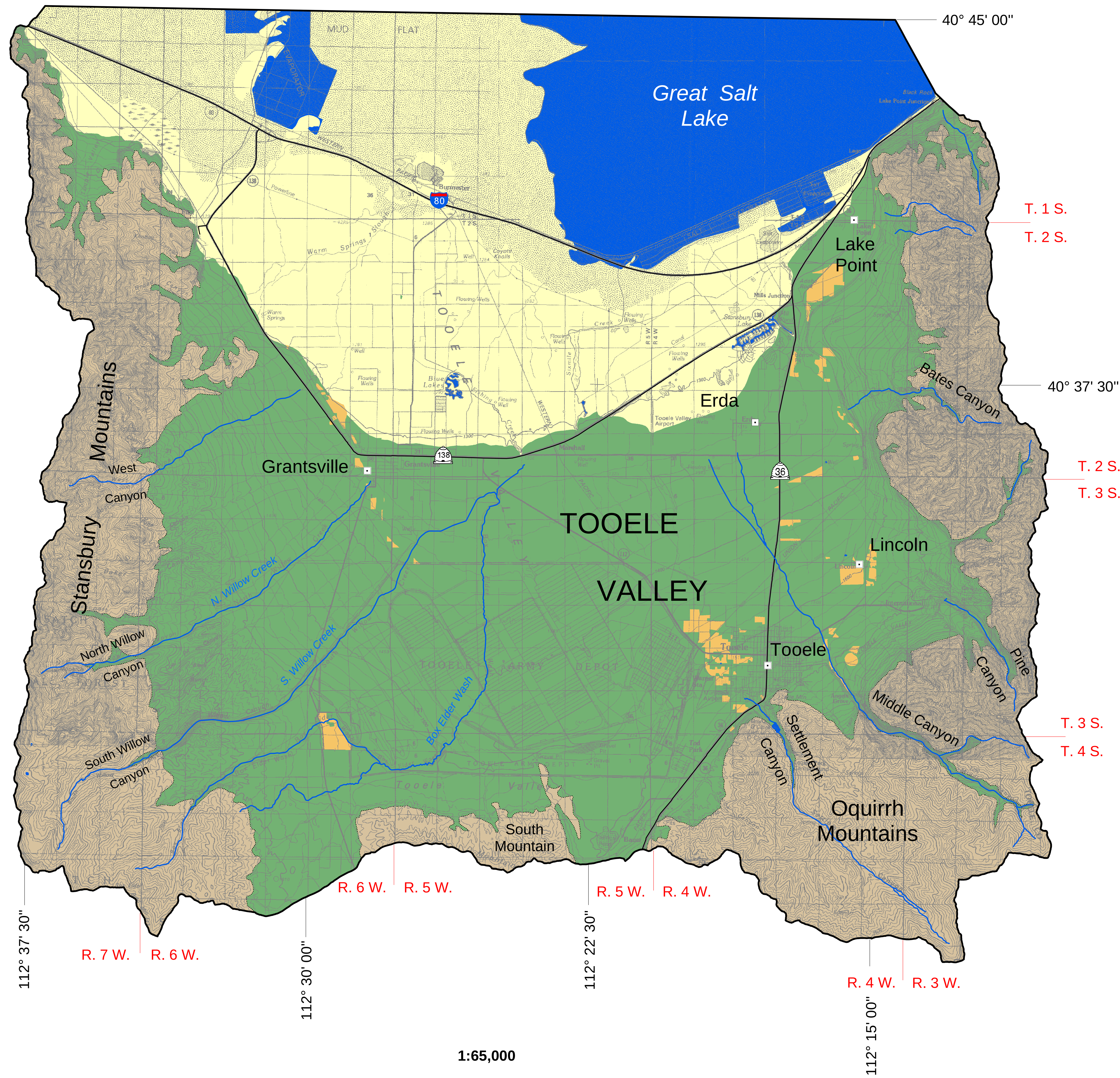
UTAH GEOLOGICAL SURVEY
UTAH GEOLOGICAL SURVEY a division of Department of Natural Resources

Plate 2

GROUND-WATER VULNERABILITY TO PESTICIDES IN TOOELE VALLEY, TOOELE COUNTY, UTAH

By Mike Lowe, Janae Wallace, and Matt Butler
Utah Geological Survey
and
Rich Riding and Anne Johnson
Utah Department of Agriculture and Food

Miscellaneous Publication 04-3

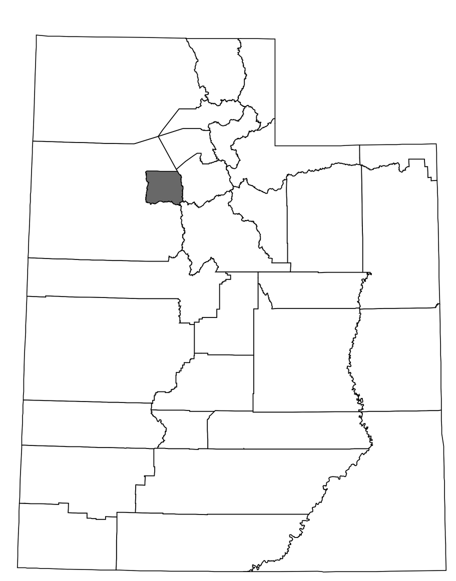


Explanation

Ground-Water Vulnerability Ranking

- Low Vulnerability
- Moderate Vulnerability
- High Vulnerability
- Bedrock (not analyzed)
- Water body
- Water course
- Valley-fill boundary
- Road
- Boundary of study area

N



Location of Study Area

1:65,000

0 1 2 4 6 8 10 Miles

0 1 2 4 6 8 10 Kilometers

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