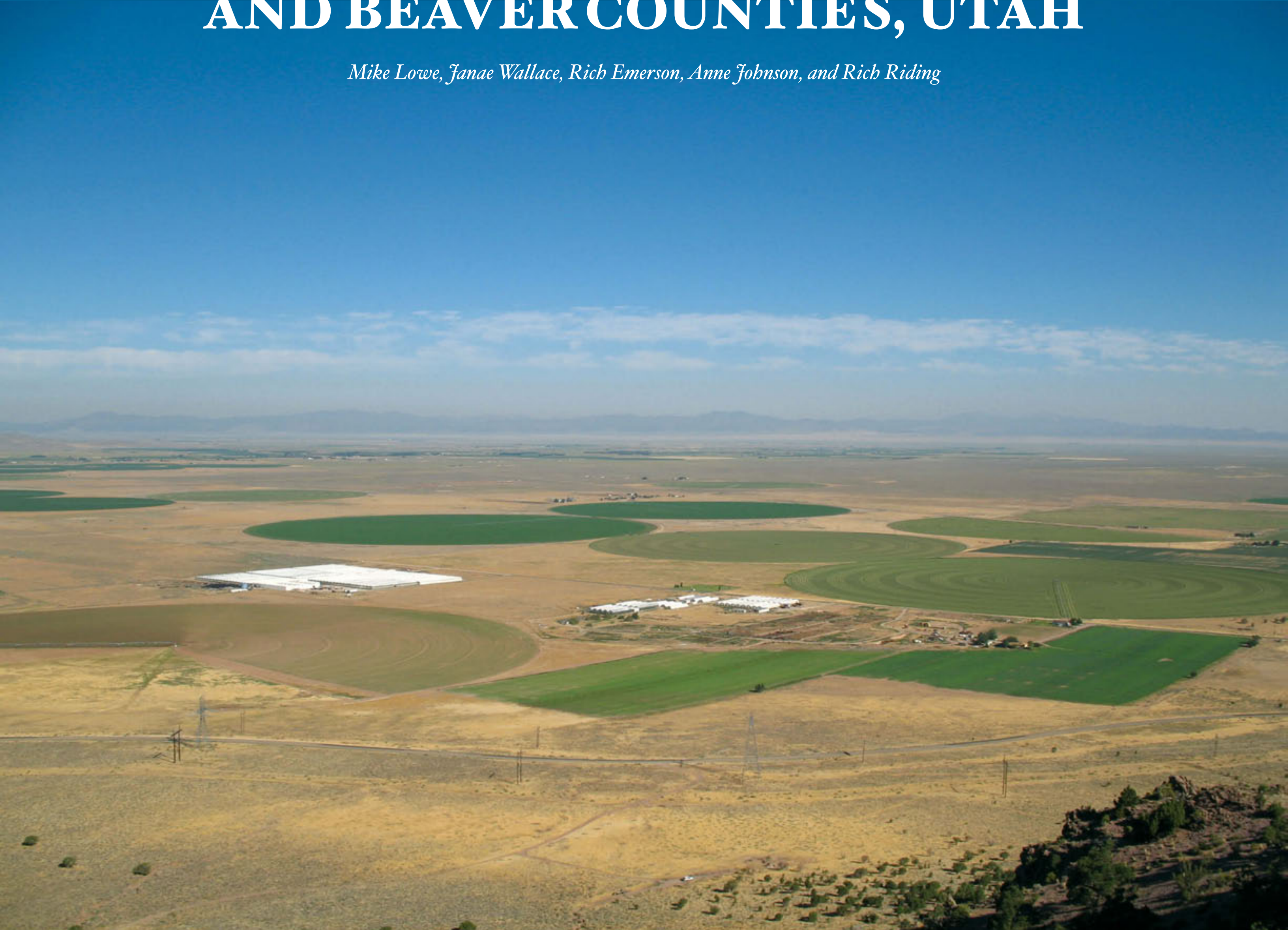
GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES, BERYL-ENTERPRISE AREA, IRON, WASHINGTON, AND BEAVER COUNTIES, UTAH

Mike Lowe, Janae Wallace, Rich Emerson, Anne Johnson, and Rich Riding



UTAH DNR GEOLOGICAL SURVEY

REPORT OF INVESTIGATION 266
UTAH GEOLOGICAL SURVEY
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Mike Lowe, Janae Wallace, and Rich Emerson

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Anne Johnson and Rich Riding

Utah Department of Agriculture and Food

Cover photo: *View looking NW across Escalante Valley toward Beryl. Geothermally heated greenhouses at Newcastle are in the foreground. Photo by Robert Blackett.*

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CONTENTS

FIGURES

TABLES

PLATES

GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES, BERYL-ENTERPRISE AREA, IRON, WASHINGTON, AND BEAVER COUNTIES, UTAH

Mike Lowe, Janae Wallace, Rich Emerson, Anne Johnson, and Rich Riding

ABSTRACT

The U.S. Environmental Protection Agency has recommended that states develop Pesticide Management Plans for four agricultural chemicals—alachlor, atrazine, metolachlor, and simazine—used in Utah as herbicides 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 in the basin-fill aquifer (bedrock is not evaluated) to agricultural pesticides in the Beryl-Enterprise area, Iron, Washington, and Beaver Counties, Utah. We used existing data to produce pesticide sensitivity and vulnerability maps by applying an attribute ranking system specifically tailored to the western United States using Geographic Information System analysis methods. This is a first 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 the Beryl-Enterprise area. Much of the Beryl-Enterprise area has moderate ground-water sensitivity to pesticides due to the presence of 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 the Beryl-Enterprise area. 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 the Beryl-Enterprise area.

Because of relatively high retardation (long travel times of pesticides in the vadose zone) and attenuation (short half-lives) of pesticides in the soil environment, pesticides applied to fields in the Beryl-Enterprise area likely do not present a serious threat to ground-water quality. To verify this conclusion, future ground-water sampling by the Utah Department of Agriculture and Food in the Beryl-Enterprise area should be concentrated in areas of high sensitivity or vulnerability. Sampling in the parts of the basin characterized by moderate sensitivity 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 (bedrock is not evaluated) of the Beryl-Enterprise area, Iron, Washington, and Beaver Counties, 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 aquifer in the Beryl-Enterprise area 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 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 the Beryl-Enterprise area, 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 made 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 updated 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

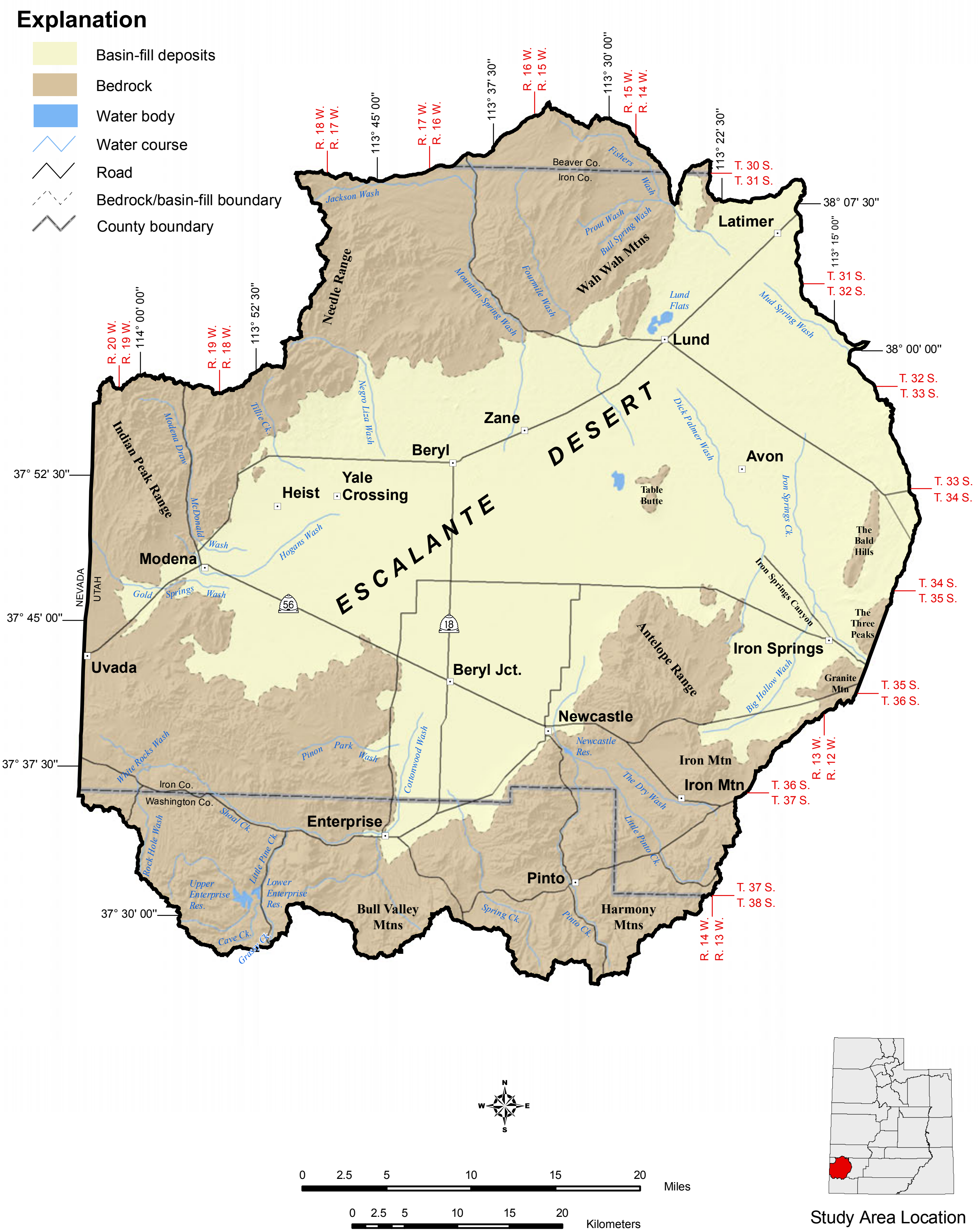

Figure 1. *Beryl-Enterprise area, Iron, Washington, and Beaver Counties, Utah, study area.*

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 had 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 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 [UDAF], 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 form 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 Villeneuve, 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 R309-200.5, Utah Administrative Code, and also in federal regulations (Title 40, Chapter 1, Part 141, National Primary Drinking Water Regulations; U.S. Environmental Protection Agency, 2006). 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 parts of the Beryl-Enterprise area 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 aquifer 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 aquifer.

PREVIOUS STUDIES

White (1932) reported on evapotranspiration by plants, estimates of water usage, and water levels in some wells for parts of southwestern Utah, including the Beryl-Enterprise area. Clyde (1941) estimated the extent and success of ground-water dependent agriculture for the Beryl area, and evaluated costs of ground water to farmers. Three progress reports to the Utah State Engineer provide descriptions of ground-water conditions in the Beryl-Enterprise area (Fix and others, 1950; Thomas and others, 1952; Waite and others, 1954). Connor and others (1958) compiled the quality of ground and surface water in Utah, including the Beryl-Enterprise area. Sandberg (1963) compiled ground-water data for several ground-water basins in southwestern Utah, including the Beryl-Enterprise area. Sandberg (1966) correlated the results of previous ground-water studies for several ground-water basins in southwestern Utah, including the Beryl-Enterprise area, to give a unified concept of ground-water conditions in those basins. Mower (1981) compiled ground-water data for the Beryl-Enterprise area. These data were used to produce the most recent comprehensive evaluation of ground-water conditions for the area (Mower and Sandberg, 1982). Burden and others (2005) evaluated water-level changes in wells in Utah from March 1970 to March 2005, including the Beryl-Enterprise area. Lund and others (2005) evaluated the origin and extent of earth fissures in Escalante Valley and the southern Escalante Desert. Thomas and Lowe (2007) mapped recharge and discharge areas for the basin-fill aquifer.

SETTING

Physiography

The Beryl-Enterprise area (figure 1) includes Escalante Valley and part of the Escalante Desert in southwest Utah. The larger community centers include Newcastle, Beryl Junction, Enterprise, Modena, Beryl, and Lund. The basin floor covers an area of about 890 square miles (2300 km^2).

The Beryl-Enterprise area is in the Tonoquints Volcanic section of the Basin and Range physiographic province (Stokes, 1977). The basin is bounded on the west by the Cedar Range, on the south by the Bull Valley Mountains; on the southeast by the Harmony Mountains and Antelope Range; on the east by a series of low hills; on the northeast by the Black Mountains; on the north by the Wah Wah Mountains, Indian Peak Range, and Needle Range; and on the northwest by the Paradise Mountains. This report covers only the part of the basin east of the Utah-Nevada state line, however the portion of the basin in Nevada appears to be underlain entirely by bedrock and not basin fill. Peaks in the drainage basin reach elevations of up to 8200 feet (2500 m) above sea level. The basin floor ranges in elevation from 5400 feet (1650 m) along the basin margin in Washington County to 5080 feet (1550 m) northwest of Lund. The generally uniform southwest to northeast slope of the basin floor is interrupted south of Lund by Table Butte (figure 1).

Little Pine, Spring, and Pinto Creeks are perennial streams draining the mountains in the southern part of the drainage basin (figure 1) (Mower and Sandberg, 1982). All other drainages are intermittent or ephemeral (Mower and Sandberg, 1982). In the southern part of the drainage basin, some of these ephemeral drainages can produce large floods, sometimes carrying debris several miles out onto the basin floor (Mower and Sandberg, 1982; Lund and others, 2005). Mud Spring Wash and Iron Springs Canyon are two gaps in the mountains on the east side of the drainage basin where surface flow into the Beryl-Enterprise area occurs during floods resulting from intense local rainstorms or from local snowmelt (Mower and Sandberg, 1982). The Beryl-Enterprise area is part of the Beaver River drainage basin, but there is no evidence that surface flow out of the Beryl-Enterprise basin through its lowest point northeast of Lund has occurred during the past several hundred years (Mower and Sandberg, 1982).

Bedrock in the Beryl-Enterprise area ranges in age from Cambrian to Tertiary (figure 2). Cambrian, Ordovician, and Mississippian sedimentary rocks are exposed in the Indian Peak Range and Wah Wah Mountains in the northern part of the study area. Jurassic and Cretaceous sedimentary rocks are exposed in the Bull Valley and Harmony Mountains, Iron Mountain, and The Three Peaks in the southern and southeastern parts of the study area. Tertiary igneous rocks (predominantly extrusive) are exposed in upland areas throughout the study area (Fix and others, 1950). Tertiary sedimentary rocks cover much of the uplands in the southern and southeastern part of the study area. Quaternary basalt is found in the uplands in the southern part of the study area. Extension, primarily during the Tertiary, along low- and high-angle normal faults deformed existing bedrock, forming basins that filled with locally derived sediments. The absence of prominent fault scarps in basin-fill deposits indicates that significant displacement along these faults has not occurred during the Holocene (Fix and others, 1950).

Unconsolidated to semi-consolidated basin fill consists primarily of interbedded alluvial and lacustrine deposits of Quaternary age (Mower and Sandberg, 1982) with eolian deposits also found in some areas (figure 2). The uppermost basin-fill deposits comprise the principal basin-fill and shallow unconfined aquifers, and consist of predominantly sand and gravel with some fine-grained clay and silt layers at the basin margins (Fix and others, 1950). Fine-grained clay and silt deposits become predominant towards the basin center, and deposits become semi-consolidated at depth (Mower and Sandberg, 1982). The basin-fill material is highly variable within short distances, and does not form well-defined aquifers or confining beds over large areas (Lofgren in Fix and others, 1950). Basin-fill thickness ranges from zero at the basin margins to likely more than 1000 feet (300 m) in the basin center (Mower and Sandberg, 1982). Normal-faults in the unconsolidated basin fill may exert strong control on ground-water movement and availability (Fix and others, 1950), but the effect of these structures on ground-water movement has not been evaluated in the Beryl-Enterprise area.

Climate

Four weather stations in the study area provide climatic data for different periods (Enterprise, 1954–92 period; Enterprise Beryl Junction, 1948–92 period; Lund, 1950–1967 period; and Modena, 1948–92 period), but only Enterprise Beryl Junction and Modena provide normal climatic data 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 11.4˚F (-11.4˚C) in January at Enterprise Beryl Junction and a normal maximum of 91.4˚F (33.0˚C) in July at Modena. The normal mean annual temperature ranges from 47.6˚F (8.7˚C) at Enterprise Beryl Junction to 49.1˚F (9.5˚C) at Modena. Normal annual precipitation ranges from 10.21 inches (25.93 cm) at Enterprise Beryl Junction to 10.32 inches (26.21 cm) at Modena. Normal annual evapotranspiration (using the Hargreaves equation [based on perennial rye grass or Alt fescue as reference crop]) ranges from 51.56 inches (130.96 cm) at Enterprise Beryl Junction to 52.06 (132.23 cm) at Modena. The average number of frost-free days ranges from 98 at Enterprise Beryl Junction to 113 at Modena.

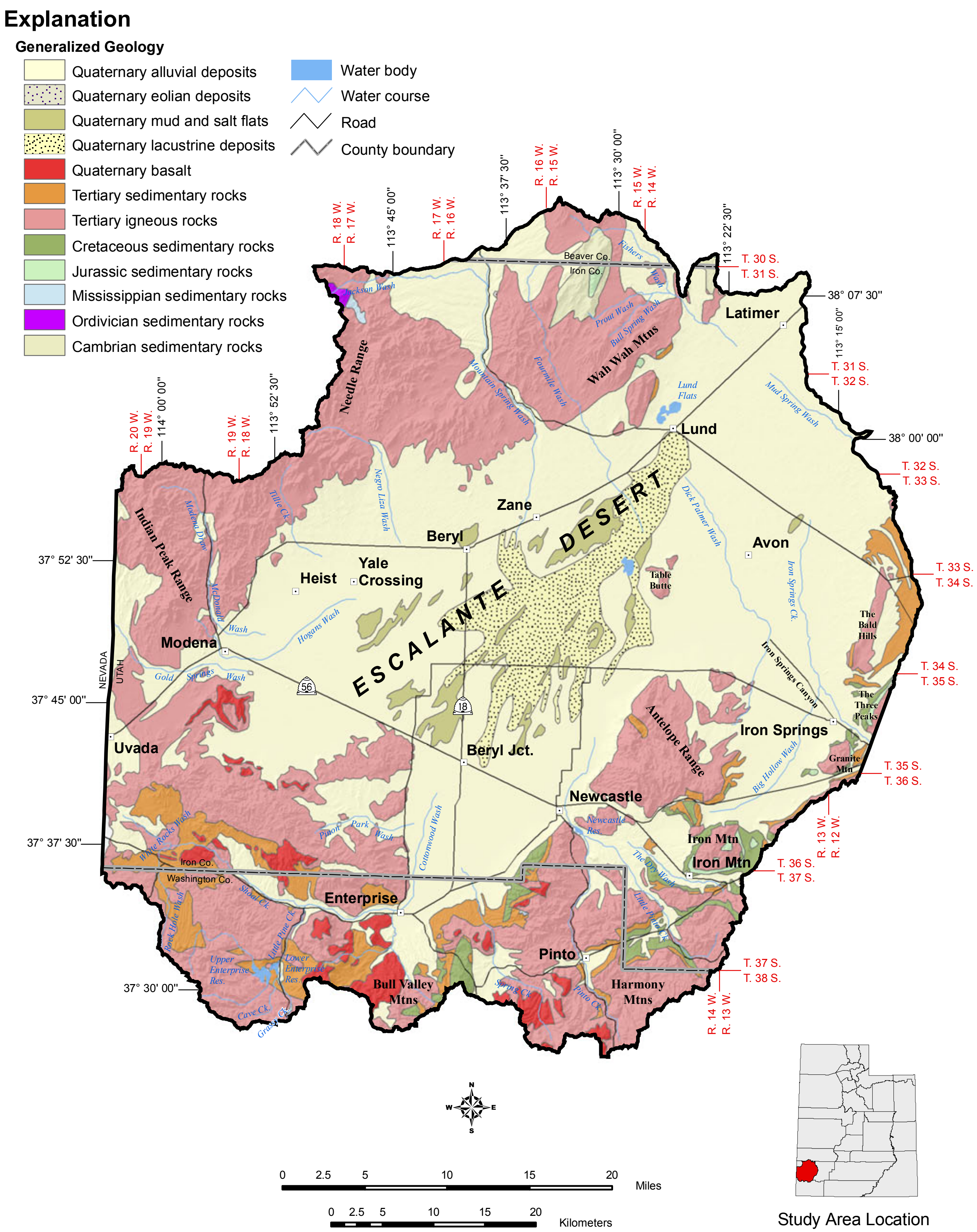

Figure 2. *Generalized geologic map, Beryl-Enterprise area, Iron, Washington, and Beaver Counties, Utah (modified from Hintze and others, 2000).*

Population and Land Use

The Beryl-Enterprise area is sparsely populated, but, like most areas in Utah, is experiencing an increase in population. The population of rural Iron County (i.e., excluding Brian Head, Cedar City, Enoch, Kanarraville, Paragonah, and Parowan), within which most of the study area lies, increased from 2882 in 1990 to 6321 in 2000 (Demographic and Economic Analysis Section, 2001), and by 2030 the population is expected to be 10,671 (Demographic and Economic Analysis Section, 2005). However, much of this population growth is likely to take place in eastern Iron County, outside of the study area.

The economy is dominated by agriculture, mainly cultivation of irrigated crops, but mining and rock collecting are also important sources of income (Travel Guides, 2006). Alfalfa has replaced potatoes as the most important crop, and dairies and feedlots have become an increasingly important source of income (Lund and others, 2005). Cultivated land is irrigated mostly by water wells (Mower and Sandberg, 1982).

GROUND-WATER CONDITIONS

Basin-Fill Aquifer

Ground water in the basin-fill aquifer in most of the Beryl-Enterprise area is under unconfined conditions (Fix and others, 1950). Unconfined conditions are to be expected along the basin margins, where basin-fill deposits consist predominantly of coarse-grained alluvial deposits and readily yield water to wells (Mower and Sandberg, 1982). But the lack of confined conditions over much of the central part of the basin, in spite of the predominance of fine-grained sediments, is unusual based on studies of other Utah basins (Fix and others, 1950). Most of the principal aquifer contains less than 25% sand and gravel, based on an examination of drillers' logs of water wells (Mower and Sandberg, 1982). The fine-grained sediments throughout much of the study area may be sufficiently impermeable to prevent the downward movement of ground water and precipitation (Fix and others, 1950), and a shallow unconfined aquifer overlies the principal aquifer in many areas of the basin center (figure 3). Most water wells in the Beryl-Enterprise area are greater than 300 feet (90 m) deep, and some wells are over 1200 feet (370 m) deep.

In the area between Modena and Enterprise, volcanic rocks of Tertiary age are saturated and hydraulically well connected to ground water in basin-fill deposits; Mower and Sandberg (1982) considered these rocks to be part of the principal aquifer, but herein we treat them as separate bedrock units.

Transmissivity of the principal basin-fill aquifer varies. Based on aquifer tests, Mower and Sandberg (1982, table 5) reported a range of 200 to 120,000 square feet per day (19–11,000 m^2/d) for wells in unconsolidated deposits. The largest value was from a well about midway between Enterprise and Beryl Junction. Specific yields calculated from the aquifer tests in the unconfined parts of the principal aquifer range from 0.0014 to 0.037 (Mower and Sandberg, 1982, table 5). Mower and Sandberg (1982) estimated the amount of ground water in storage in the principal basin-fill aquifer in 1978 to be 72 million acre-feet (89,000 hm^3).

Recharge to the basin-fill aquifer system (principal and shallow unconfined aquifers) in the Beryl-Enterprise area is from (1) precipitation in uplands surrounding the drainage basin, (2) infiltration from irrigated land, (3) precipitation on the basin floor, and (4) subsurface flow from other basins (Mower and Sandberg, 1982). Recharge from precipitation in the uplands, which occurs as either subsurface inflow from bedrock or infiltration from stream channels at the basin margins, was estimated to be about 31,000 acre-feet per year (38 hm^3/yr) in 1977 (Mower and Sandberg, 1982). Recharge from infiltration from farms was estimated to be 20% of the 81,400 acre feet (100 hm^3) of the irrigation water pumped from wells or diverted from streams in 1977 (Mower and Sandberg, 1982); this amounts to 16,300 acre-feet per year (20.1 hm^3/yr). Recharge from precipitation falling on the basin floor is low due to the low precipitation and high evapotranspiration rates noted in the Climate section above, and was estimated to be about 500 acre-feet per year (0.6 hm^3/yr) in 1977 (Mower and Sandberg, 1982). Subsurface inflow from Cedar Valley to the Beryl-Enterprise area through Mud Springs Wash and Iron Springs Canyon, based on estimates by Thomas and Taylor (1946), is about 320 acre-feet per year (0.39 hm^3/yr) (Mower and Sandberg, 1982). Mower and Sandberg (1982, table 6) estimated total recharge to the basin-fill aquifer system in 1977 at 48,000 acre-feet (59 hm^3).

Discharge from the basin-fill aquifer system in the Beryl-Enterprise area is by (1) ground-water withdrawal from wells, (2) evapotranspiration, and (3) subsurface outflow (Mower and Sandberg, 1982). Ground-water withdrawals from wells, mostly irrigation wells, was estimated to have increased from 3000 acre-feet per year (4 hm^3) in 1937 to 92,000 acre-feet per year (110 hm^3) in 1974, from the increasing importance of agriculture as a land use; well withdrawals decreased to 81,000 acre-feet per year (100 hm^3) in 1977 (Mower and Sandberg, 1982) following the change from flood irrigation to sprinkler irrigation on many farms. Mower and Sandberg (1982) noted that these estimates may be as much as 25% too low, based on data collected during 1961–77 by the Utah Division of Water Rights. Evapotranspiration in 1977 was estimated at 6000 acre-feet (7 hm^3) (Mower and Sandberg, 1982). This was a decrease from an average annual evapotranspiration of 26,000 acre-feet per year (32 hm^3/yr) estimated in 1927, caused by a decline in the potentiometric surface for the basin-fill aquifer system (Mower and Sandberg, 1982). Evapotranspiration may continue to decrease as average annual discharge continues to exceed average annual recharge. Mower and Cordova (1974) estimated subsurface flow of ground water out of the study area northeast of Lund to be about 1000 acre-feet per year

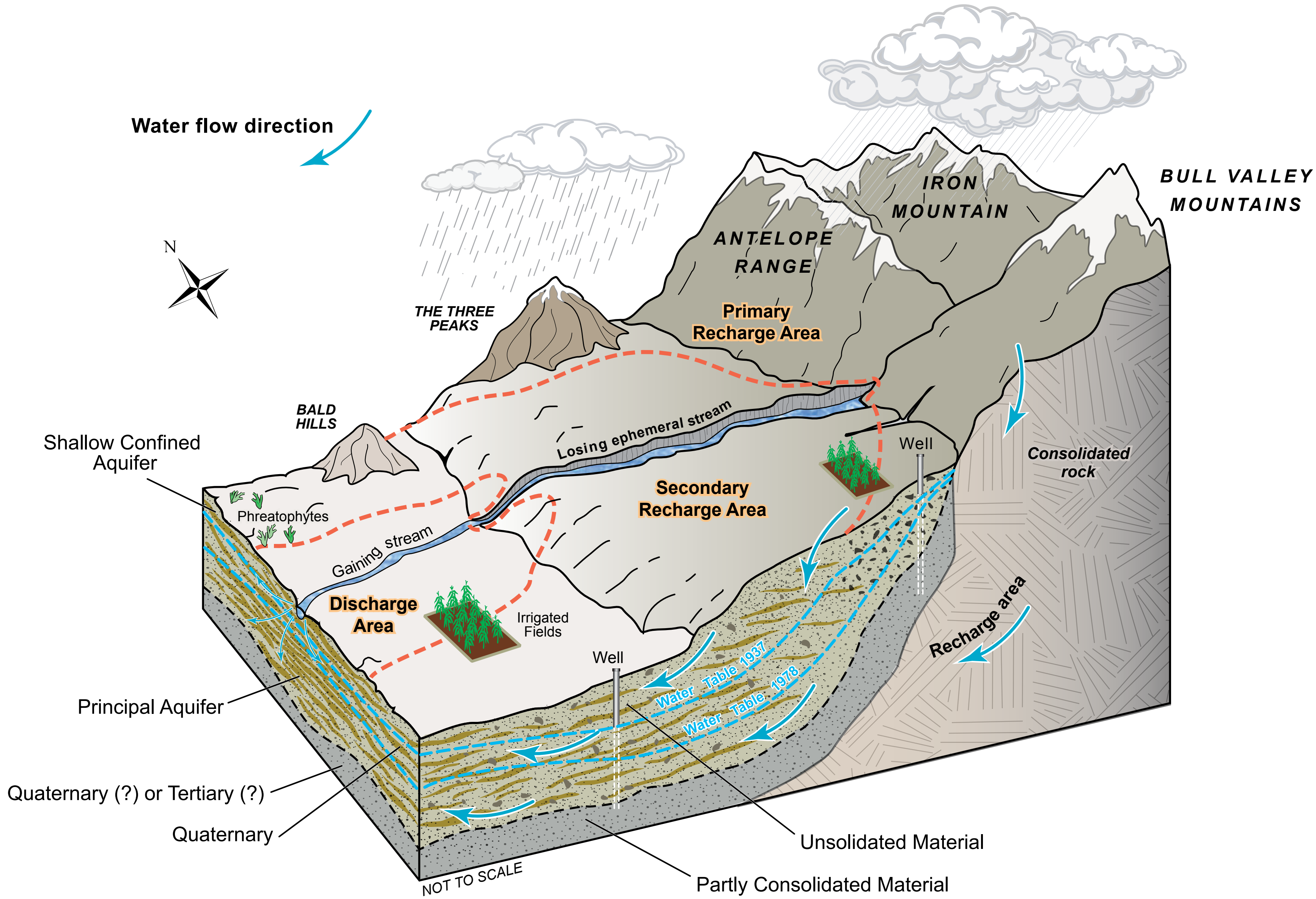

Figure 3. *Schematic block diagram showing recharge areas, location of the water table in 1937 and 1978, direction of ground-water movement, and discharge areas in the Beryl-Enterprise area (modified from Mower and Sandberg, 1982).*

(1 hm^3/yr). Mower and Sandberg (1982, table 8) estimated total discharge from the basin-fill aquifer in 1977 to be 88,000 acre-feet (110 hm^3).

Prior to large-scale water-well pumping in the Beryl-Enterprise area, ground-water flow in the principal aquifer was from the basin margins toward the basin center, and then to the northeast out of the study area (Fix and others, 1950). Large-scale water-well pumping, needed to support the predominantly agricultural land uses in this arid area, caused decline of the water table by more than 5 feet (1.5 m) over a 30 square-mile (80 km^2) area between 1945 and 1949 (Fix and others, 1950). By 1951, water-level declines of as much as 13 feet (4 m) were observed in some water wells in the southern end of the Beryl-Enterprise area (Thomas and others, 1952), and Fix and others (1950) attributed these declines to discharge from water wells exceeding natural replenishment to the principal aquifer. From 1951 to 1953, water levels in some wells in the central part of the basin declined an additional 5 feet (1.5 m) despite an above-average precipitation year in 1952 (Waite and others, 1954). Between 1952 and 1962, water-level declines of up to 32 feet (10 m) occurred in some wells in the southern part of the basin (Sandberg, 1966). For the period between 1937 to 1978, water levels in some wells in the southern part of the basin had declined as much as 70 feet (20 m) (Mower and Sandberg, 1982, figure 5), and had caused ground water in the southern part of the basin to flow towards the Beryl Junction area (Mower and Sandberg, 1982, plate 8) rather than northward. Figure 4 shows the change in water level between 1975 and 2005 (illustrating a consistent trend in water-level declines over time in the Beryl-Enterprise area). In addition to altering the configuration of the potentiometric surface, dewatering of the upper part of the principal aquifer and concomitant aquifer compaction may have caused ground-surface subsidence and resultant earth fissures, identified in the southern part of the basin following a flood in January 2005 (Lund and others, 2005).

Ground-Water Quality

Ground water in the Beryl-Enterprise area is generally suitable for domestic and stock use, except for hardness (Fix and others, 1950); hardness, which results mostly from calcium and magnesium concentrations in the water, is hard to very hard in most wells completed in the basin-fill aquifer. Based on data reported in Fix and others (1950), Sandberg (1966), and Mower (1981), total-dissolved-solids concentrations range from 232 to 5650 mg/L, and are highly variable throughout the study area (figure 5). The best quality ground water in the principal aquifer, having total-dissolved-solids concentrations of less than 375 mg/L, is found in a narrow belt along Shoal Creek south and west of Beryl Junction, and in the area east of Modena. The highest total-dissolved-solids concentrations in the principal aquifer are found in Zane northeast of Beryl, where ground water may have total-dissolved-solids concentrations exceeding 2000 mg/L (figure 5). Total-dissolved-solids concentrations tend to increase along ground-water flow paths and with depth. This is likely related to increased ground-water residence time allowing more opportunity to dissolve minerals from the basin-fill sediments. Water in the shallow unconfined aquifer generally has higher total dissolved solids concentrations than the underlying principal aquifer (Fix and others, 1950). Some wells in the study area have exceeded primary water-quality (health) standards for nitrate and fluoride, and some wells have exceeded secondary water-quality standard (taste, odor, etc.) for sulfate and chloride (Fix and others, 1950; Mower and Sandberg, 1982).

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 the Beryl-Enterprise area. The index-based model assigns ranges of attribute values and ranks the ranged attribute values as conducive or not conducive to ground-water contamination by pesticides. The process-based model incorporates physical and chemical processes through mathematical equations addressing the behavior of certain chemicals in the subsurface, in this case retardation and attenuation of pesticides, using methods developed by Rao and others (1985). No new fieldwork was conducted nor data collected as part of this project.

Ground-Water Sensitivity to Pesticide Pollution

Ground-water sensitivity to pesticides is determined by assessing natural factors favorable or unfavorable to the degradation of ground water by pesticides applied to or spilled on the land surface. Hydrogeologic setting (vertical ground-water gradient and presence or absence of confining layers), soil hydraulic conductivity, retardation of pesticides, attenuation of pesticides, and depth to ground water are the factors primarily determining ground-water sensitivity to pesticides in the Beryl-Enterprise area. 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

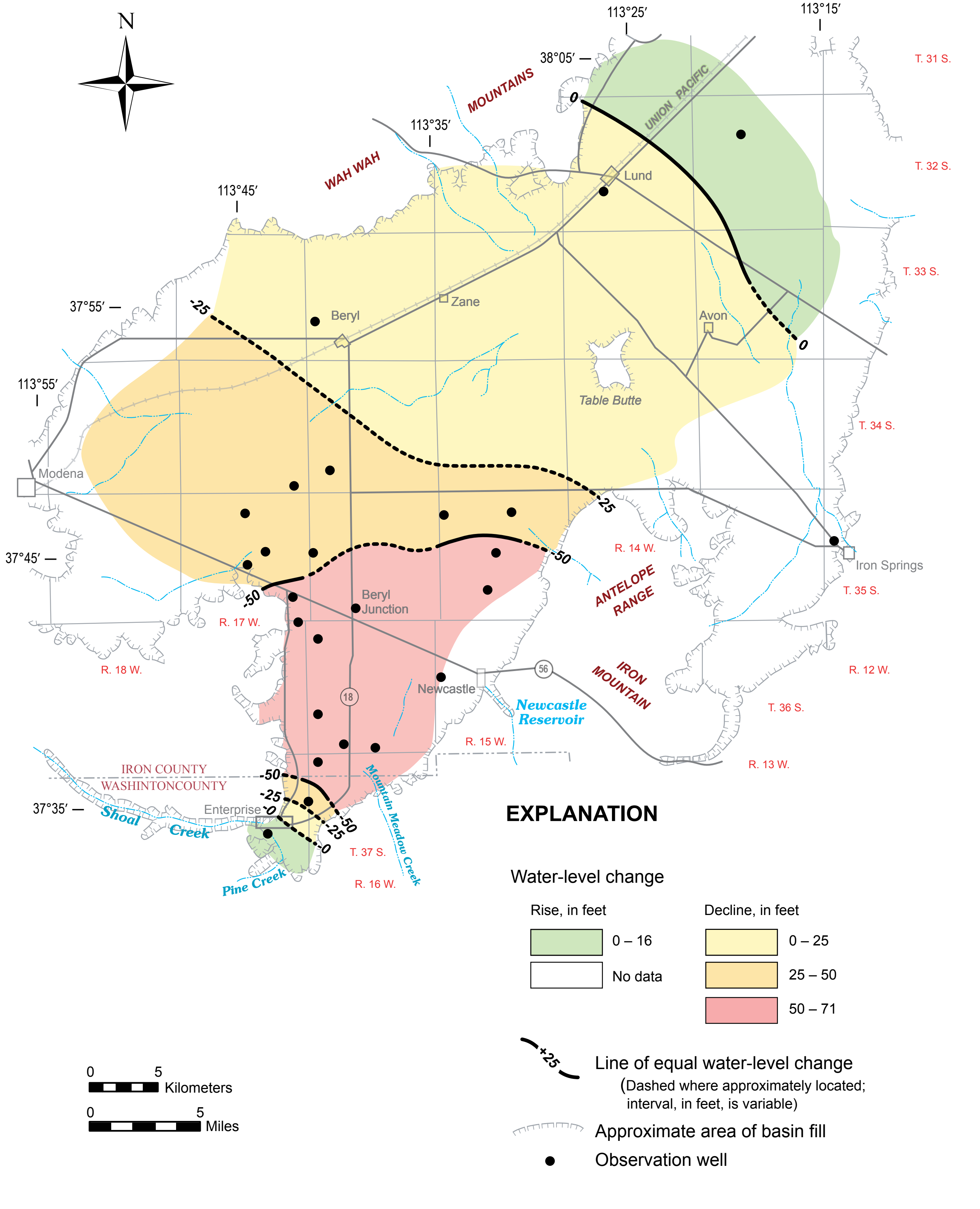

Figure 4. *Water-level change in the Beryl-Enterprise area from March 1975 to March 2005 (modified from Burden and others, 2005).*

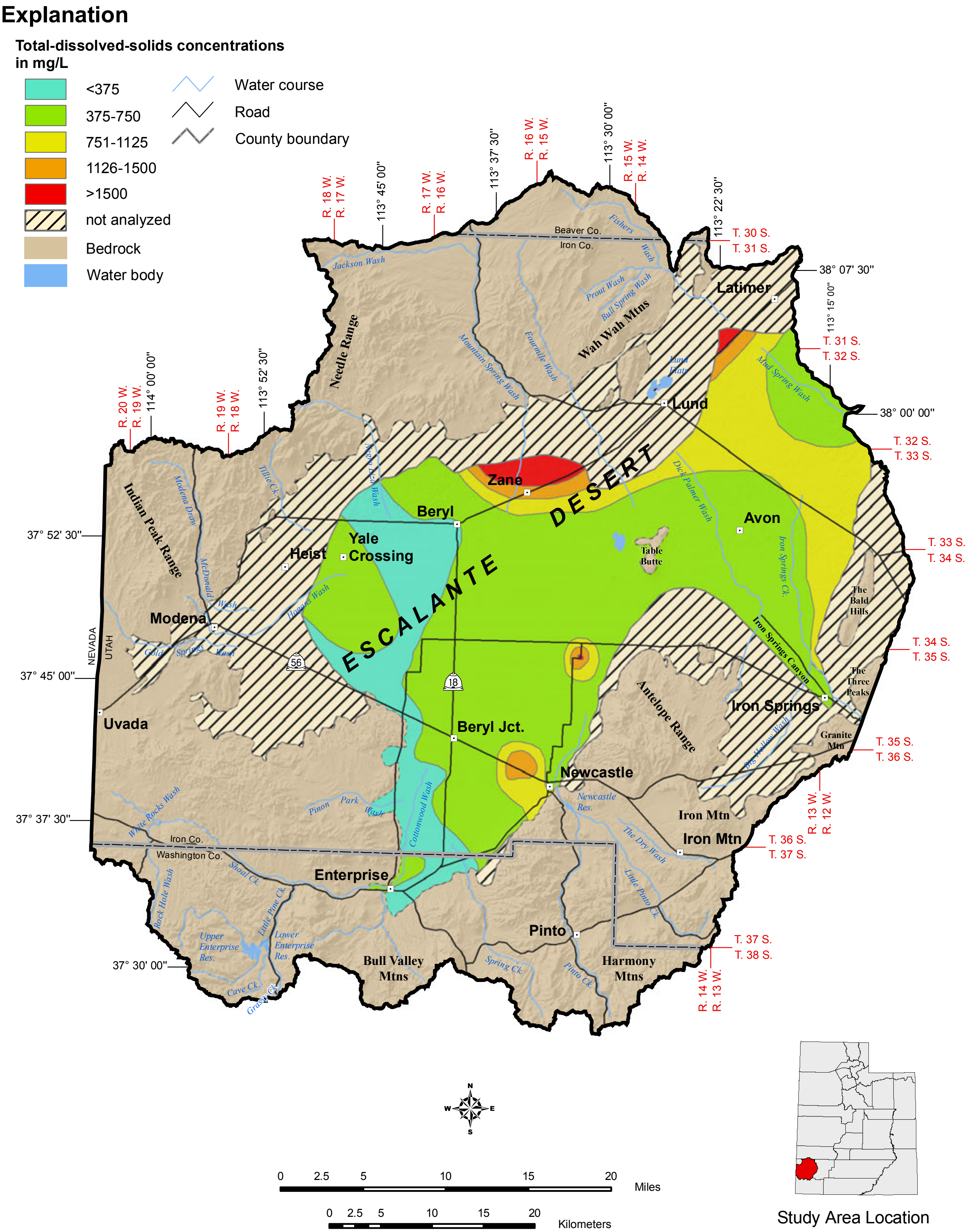

Figure 5. Total-dissolved-solids concentrations for the basin-fill aquifer, Beryl-Enterprise area, Iron, Washington, and Beaver Counties, Utah (modified from Mower and Sandberg, 1982).

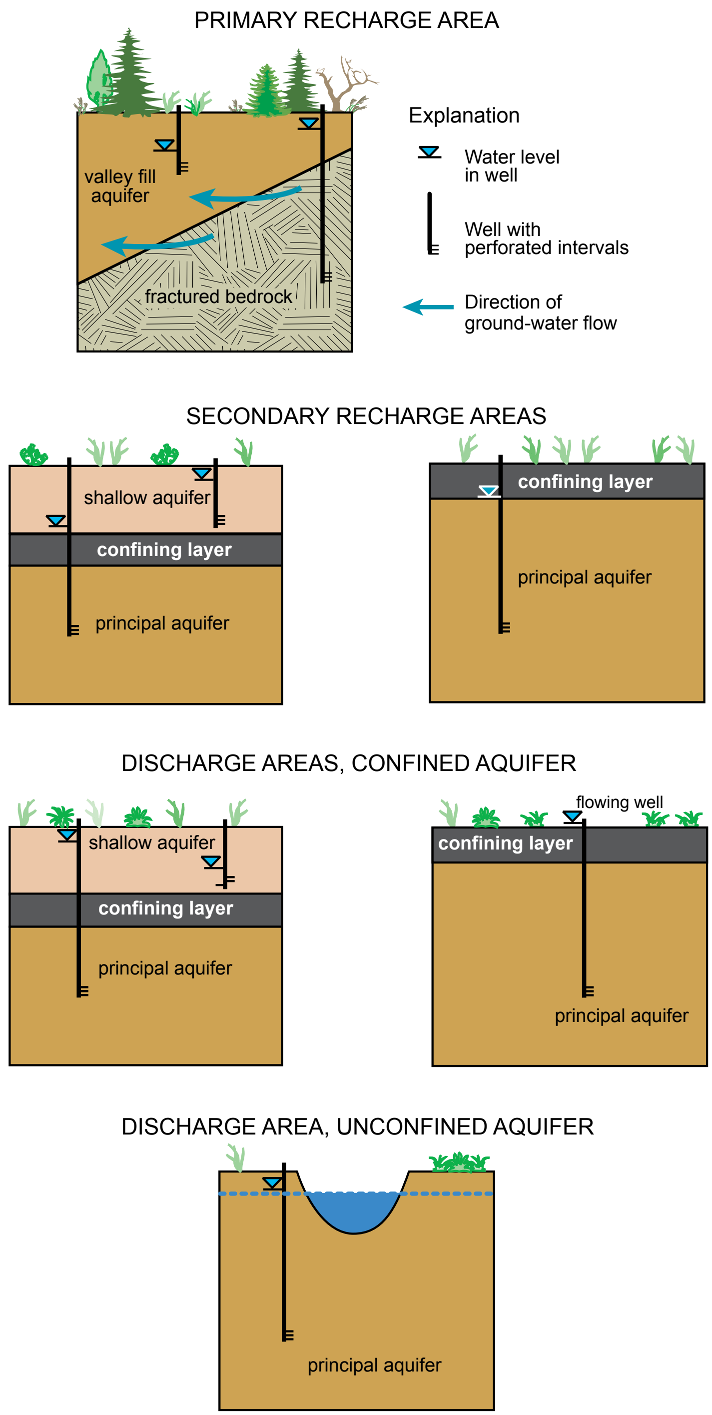

Figure 6. *Relative water levels in wells in recharge and discharge areas (modified from Snyder and Lowe, 1998).*

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.

Thomas and Lowe (2007) used drillers' logs of water wells in the Beryl-Enterprise area 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 logs is also problematic because levels in the shallow unconfined aquifer are commonly 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 the Beryl-Enterprise area consists of basin fill not containing confining layers (figure 6). 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 (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.

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; some flowing wells are shown 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. Discharge areas occur for unconfined aquifers where the water table intersects the land surface or stream channel. An understanding of the topography, surficial geology, and ground-water hydrology is necessary before using 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; Ulrich and others, 1960). 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) presented the following equation:

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

where:

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

Retardation factors typically range from (1 + 4Kd) to (1 + 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, 2005), which provides digitized data for some soil areas of the state of Utah, including the Beryl-Enterprise area, at a scale of 1:31,680. Data include derived values for bulk density, organic carbon fraction, and field capacity (table 2).

We set variables in equation 1 to values that represent conditions likely to be encountered in the natural environment (table 2) to establish a rationale for dividing high and low pesticide retardation for our GIS analysis, and we applied digital soil information unique to particular soil groups from SSURGO data for organic carbon. We used the organic carbon sorption distribution coefficient (table 3), at a pH of 7, for atrazine, the pesticide among the four having the least tendency to adsorb to organic carbon in the soil (Weber, 1994). We derived bulk density and field capacity from a soil texture triangle hydraulic properties calculator (Saxton, undated). To compute R_F values, we applied bulk density end members of 0.04 and 0.07 pounds per cubic inch (1.2 and 2.0 kg/L) and field capacity end members of 14 and 42%, which represent naturally occurring conditions in the Beryl-Enterprise area, and variable

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 (2005). 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 0.29 to 2.0%
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)	1.3–1.61 (1.4)	Variable and ranges from 0.29 to 2.0%
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 0.29 to 2.0%
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 0.29 to 2.0%
G	Gravel	2.0 and greater (less than 12)	2 (2)	0.29%**

* 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).*

	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

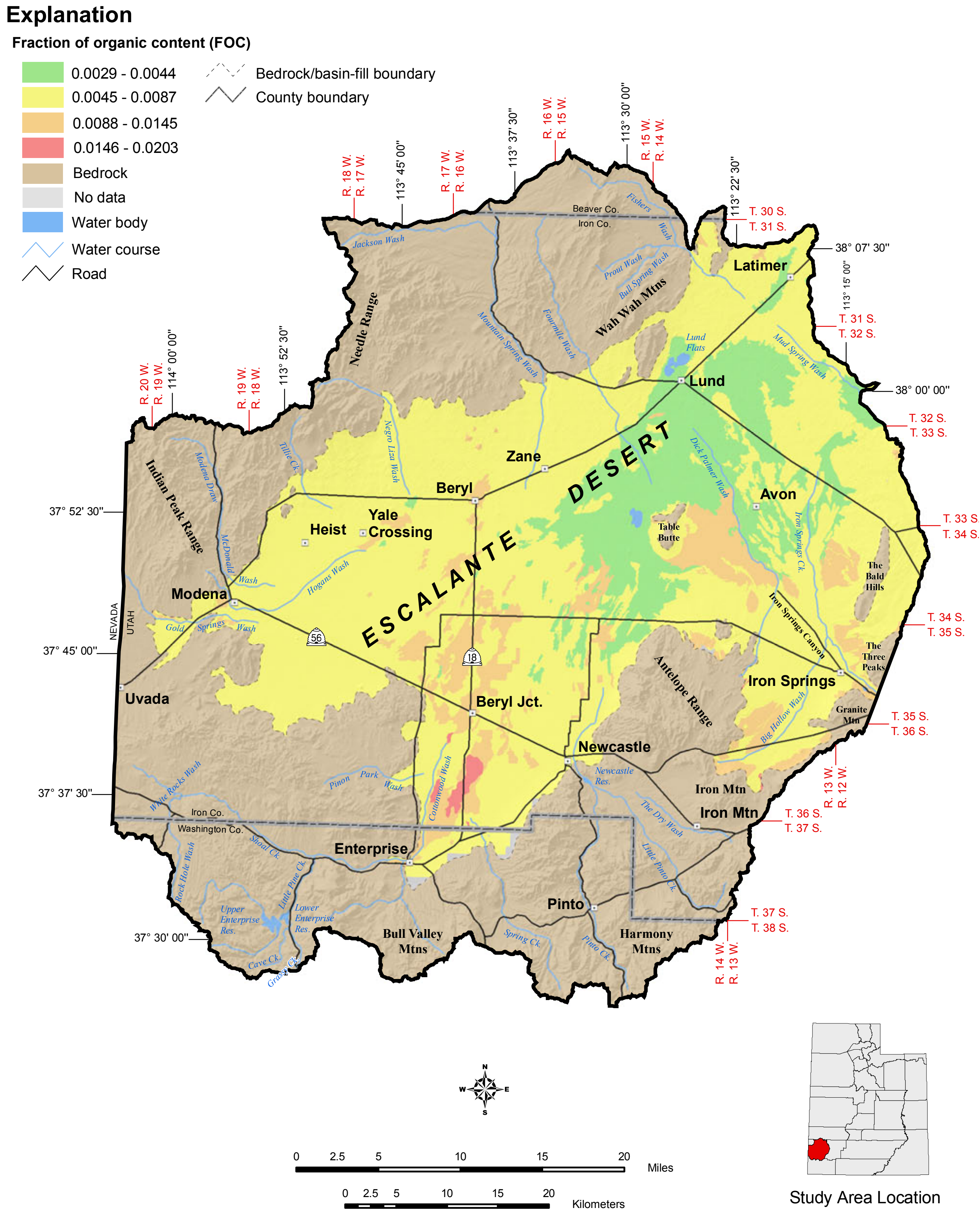

Figure 7. Fraction of organic content in soils in the Beryl-Enterprise area, Iron, Washington, and Beaver Counties, Utah (data from National Soil Survey Center, 2005).

soil organic carbon content using a water-table depth of 3 feet (1 m). Average organic carbon content in soils in the Beryl-Enterprise area is shown in figure 7 and ranges from 0.29 to 2.0%; 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 1.98 to 15.9. This means the highest relative velocity from our data is 0.5 and the lowest is 0.06; the former indicates pesticide in ground water moves at a rate about 50% that of ground water free of pesticides, whereas the latter indicates that pesticides in ground water are essentially immobile.

For the negligible net annual ground-water recharge from precipitation typical of the Beryl-Enterprise area, 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, 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) presented the following equation:

$$A_F = \exp(-0.693\ z\ R_F\ \theta_{FC}\ /q\ t_{½}) \qquad (2)$$

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
$t_{½}$ = pesticide half-life (years).

For this study, we calculated (using GIS analysis) net annual ground-water recharge by subtracting statewide mapped normal annual evapotranspiration (Jensen and Dansereau, 2001) for the 30-year period from 1971 to 2000 from mapped normal annual precipitation (Utah Climate Center, 1991) for the 30-year period from 1961 to 1990. Data from two different 30-year periods were used because normal annual precipitation GIS data are currently not available for the 1971 to 2000 period and normal annual evapotranspiration GIS data are not available for the 1961 to 1990 period. This analysis revealed that most of the moisture produced by precipitation is consumed by evapotranspiration in most parts of Utah, so that ground-water recharge from precipitation is relatively low in many areas of the state, including the Beryl-Enterprise area (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 the Beryl-Enterprise area, 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 the negligible net annual ground-water recharge typical of the basin-floor areas of the Beryl-Enterprise area, 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 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.

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 data from

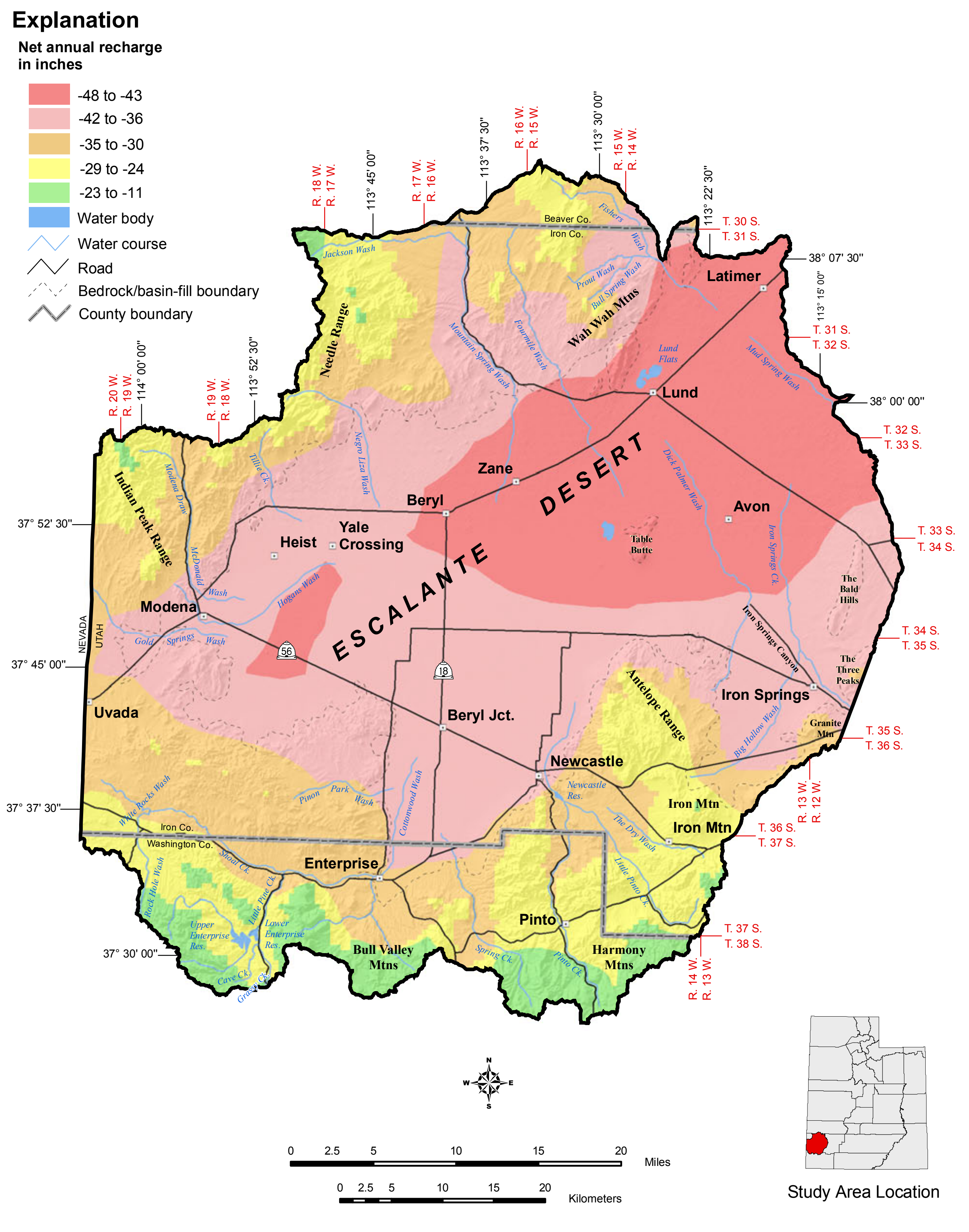

Figure 8. *Net annual ground-water recharge from precipitation in Beryl-Enterprise area, Iron, Washington, and Beaver Counties, Utah. Recharge calculated using data from the Utah Climate Center (1991) and Jensen and Dansereau (2001). Although net annual recharge may be negative in some areas, seasonally some recharge from precipitation may occur.*

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.

the Soil Survey Geographic (SSURGO) database (National Soil Survey Center, 2005), we delineated areas having ground water less than or equal to 3 feet (1 m) deep. We selected 3 feet (1 m) as the depth-to-ground-water attribute used to evaluate sensitivity of geographic areas to pesticides.

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 2001 Cedar-Beaver area land-use data.

Ground-Water Sensitivity

We consider ground-water sensitivity (intrinsic susceptibility) to be the principal factor determining the vulnerability of basin-fill aquifers in the Beryl-Enterprise area 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 or 5-meter (16-ft) resolution infrared satellite data and then field checked (Utah Division of Water Resources, 2009). The Cedar/Beaver inventory was conducted in 2001 (Utah Division of Water Resources, 2009). 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 or 5-meter (16 -ft) resolution infrared satellite data and then field checked (Utah Division of Water Resources metadata). The Cedar/Beaver inventory was conducted in 2001 (Utah Division of Water Resources, 2009). 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 grow-

Table 5. *Pesticide sensitivity and the attribute rankings used to assign sensitivity for the Beryl-Enterprise area, Iron, Washington, and Beaver Counties, 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="2">High</td><td rowspan="2">0</td><td rowspan="2">Low</td><td rowspan="2">0</td><td>Confined Aquifer Discharge Area</td><td>-4</td><td rowspan="2">Less than 1 inch/hour</td><td rowspan="2">1</td><td rowspan="2">Greater than 3 feet</td><td rowspan="2">1</td><td>Low</td><td>-2 to 0</td></tr>
<tr><td rowspan="2">Secondary Recharge Area</td><td rowspan="2">-1</td><td rowspan="2">Moderate</td><td rowspan="2">1 to 4</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 Unconfined Aquifer Discharge Area</td><td>2</td><td>High</td><td>5 to 8</td></tr>
</table>

Table 6. *Pesticide vulnerability and the attribute rankings used to assign vulnerability for the Beryl-Enterprise area, Iron, Washington, and Beaver Counties, Utah.*

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

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

Retardation/Attenuation

Retardation factors are variable and attenuation factors are ranked as low throughout the Beryl-Enterprise area; the low attenuation factors are due to net annual evapotranspiration exceeding net annual precipitation. The area is dominantly characterized by moderate to high retardation factors. Net annual recharge from precipitation is negative throughout the study area (figure 8). Although most recharge to the basin-fill aquifer is from subsurface inflow from bedrock or infiltration from stream channels at the basin margins, some recharge within the basin-floor area 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

Thomas and Lowe (2007) mapped ground-water recharge areas in the Beryl-Enterprise area (figure 9). The map shows that primary recharge areas, the areas most susceptible to contamination from pesticides applied to the land surface, comprise about 26% of the surface area of the basin-fill aquifer. Secondary recharge areas make up an additional 49% of the surface area of the basin-fill aquifers. Ground-water discharge areas in the Beryl-Enterprise area at the time most water wells were drilled make up 25% of the surface area of the basin-fill aquifer; because water levels in wells have greatly declined since most of these wells were drilled, the mapped discharge areas were considered secondary recharge areas for our pesticide sensitivity analysis (thus, 74% of the surface area of the basin-fill aquifer was considered secondary recharge areas).

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 (2005). Nearly 77% of the surface area of the basin-fill aquifer in the Beryl-Enterprise area has soil units mapped as having hydraulic conductivity greater than or equal to 1 inch (2.5 cm) per hour (figure 10). Less than 1% 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 (2005), 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. About 23% of the surface area of the basin-fill aquifer has soil units mapped as having hydraulic conductivities less than 1 inch (2.5 cm) per hour.

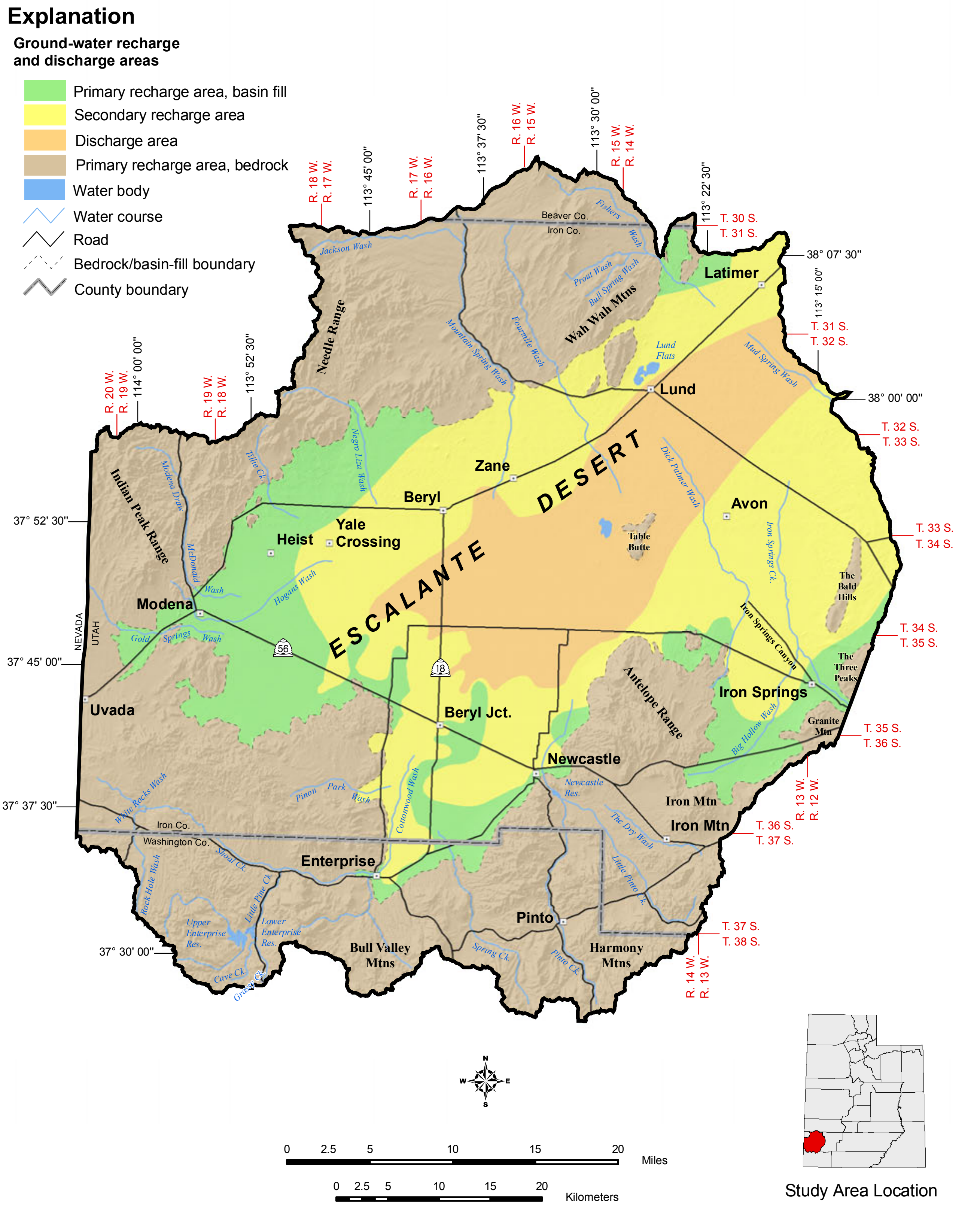

Figure 9. *Recharge and discharge areas in Beryl-Enterprise area, Iron, Washington, and Beaver Counties, Utah (data from Thomas and Lowe, 2007).*

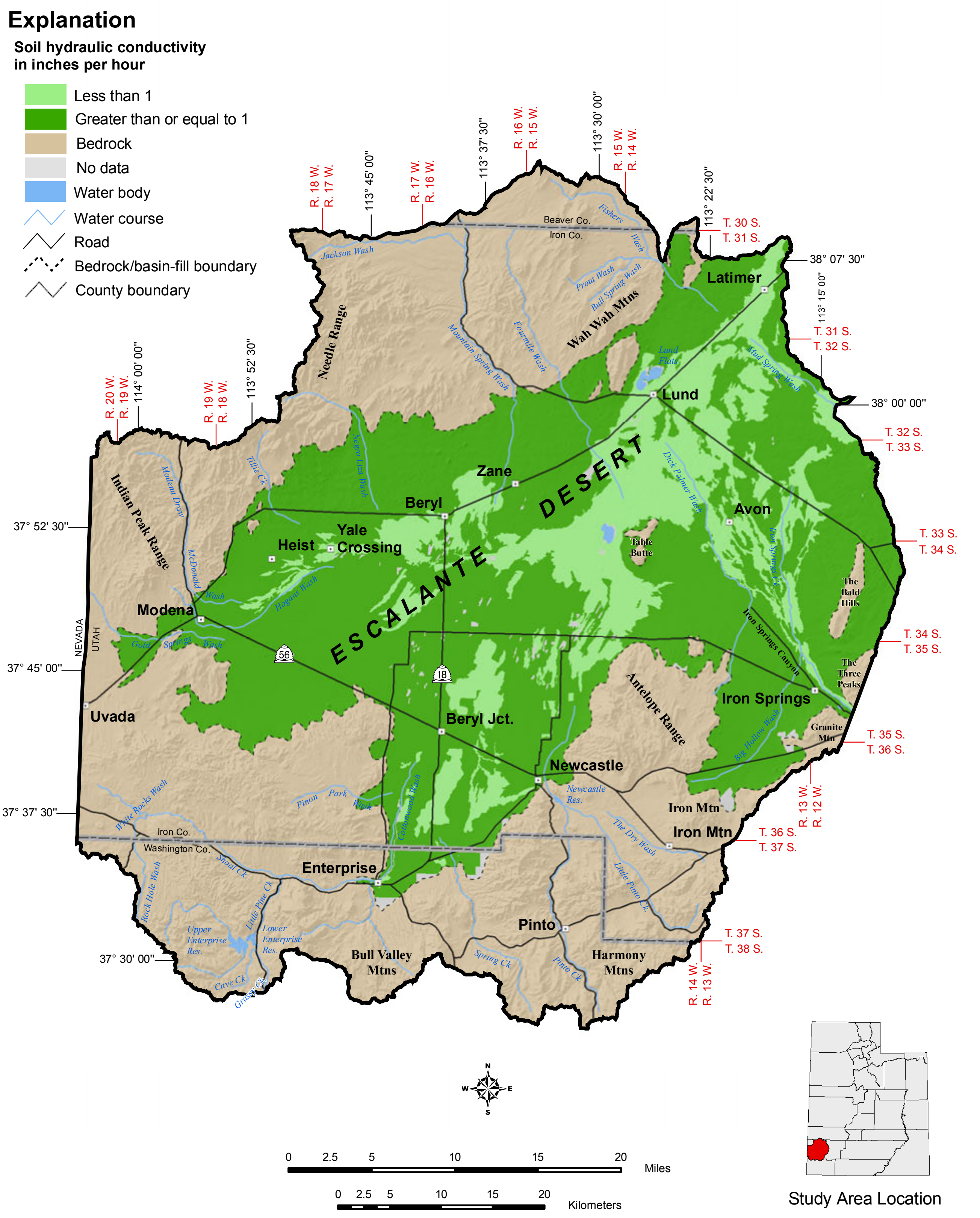

Figure 10. Soil hydraulic conductivity in Beryl-Enterprise area, Iron, Washington, and Beaver Counties, Utah (data from National Soil Survey Center, 2005).

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 ground-water data are from the National Soil Survey Center (2005). Less than 1% of the area overlying the basin-fill aquifer in the Beryl-Enterprise area has soil units mapped as having shallow ground water less than or equal to 3 feet (1 m) deep or has soil units for which depth to shallow ground-water values have not been assigned by the National Soil Survey Center (2005); soil units lacking depth to ground-water data were grouped into the less than or equal to 3 feet (1 m) deep category for analytical purposes to be protective of water quality (figure 11). Nearly 100% 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.

Pesticide Sensitivity Map

Plate 1 shows ground-water sensitivity (intrinsic susceptibility) to pesticides for the Beryl-Enterprise area, 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.

About 25% of the Beryl-Enterprise area is of high sensitivity (plate 1) because of high hydraulic conductivities. The remaining 75% of the study area is of moderate sensitivity.

Ground-Water Vulnerability

To assess ground-water vulnerability to pesticide contamination—the influence of human activity added to natural sensitivity—we assembled two attribute layers as intermediate steps. Pertinent statewide attribute layers include irrigated cropland and corn- and sorghum-producing areas in the Beryl-Enterprise area (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 the Beryl-Enterprise area. About 10% of the basin 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 south-central part of the Beryl-Enterprise 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 the Beryl-Enterprise area, constructed using the GIS methods and ranking techniques described above. The surrounding uplands are not included in the analysis because of shallow bedrock and mountainous terrain, and because they are not areas of significant agricultural activity.

Areas of high vulnerability are primarily in irrigated areas where ground-water sensitivity to pesticides is high. About 1% of the surface area of the basin-fill aquifer is mapped as having high vulnerability (plate 2). Of particular concern are areas adjacent to surface water or 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. About 99% of the surface area of the basin-fill aquifer is mapped as having moderate vulnerability.

CONCLUSIONS AND RECOMMENDATIONS

In the Beryl-Enterprise area, areas of irrigated land in primary recharge areas have the highest potential for water-quality degradation associated with surface application of pesticides. However, we believe pesticides likely do not represent a serious threat to ground-water quality in the basin-fill aquifer (bedrock is not evaluated as part of this study) because of the relatively high attenuation (short half-lives) of pesticides in water in the soil environment. We believe ground-water monitoring for pesticides should be concentrated in areas of high sensitivity or vulnerability. Sampling in the central parts of the basin characterized by moderate sensitivity should continue, but at a lower density than in the areas of higher sensitivity and vulnerability.

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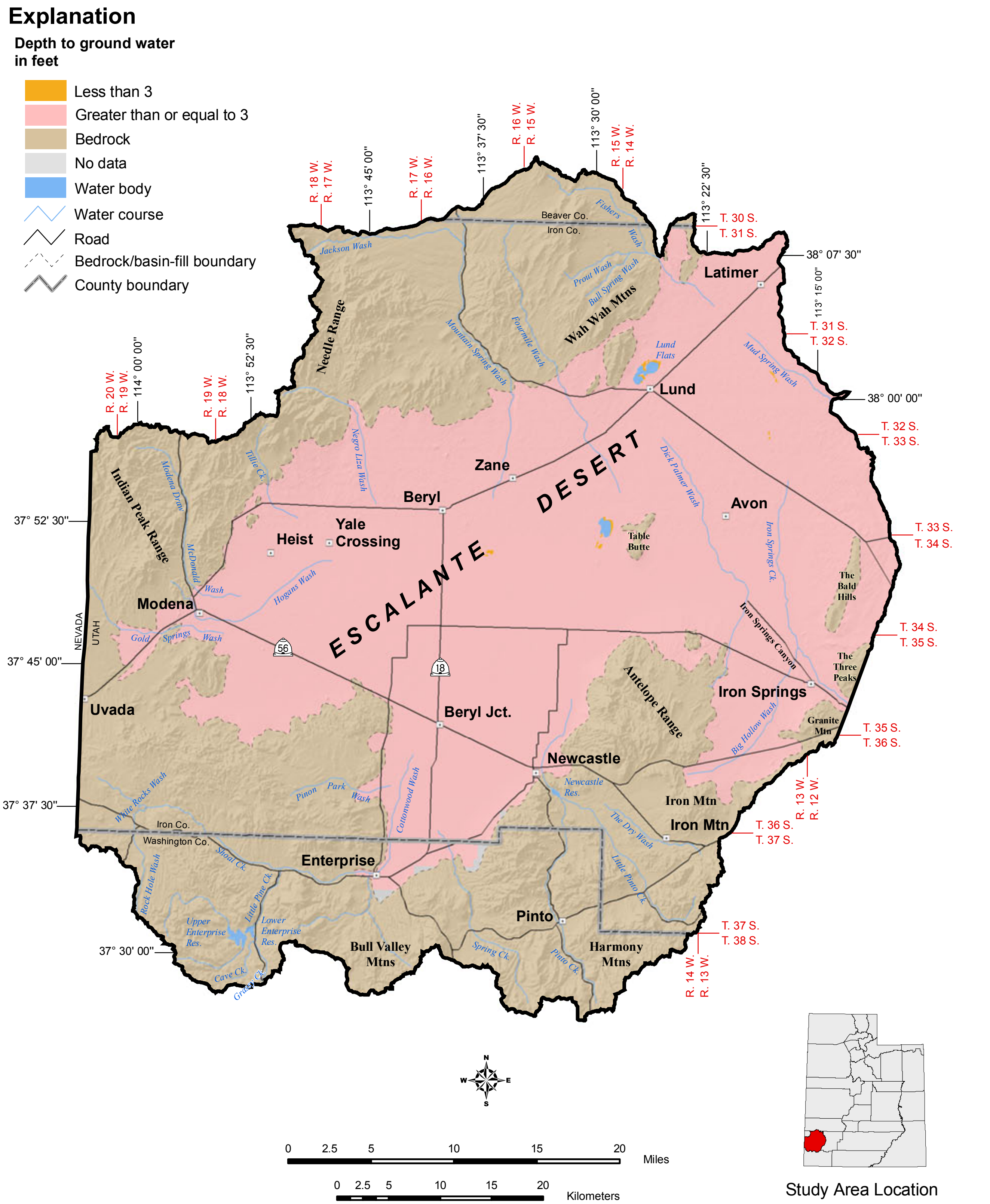

Figure 11. *Depth to shallow ground water in Beryl-Enterprise area, Iron, Washington, and Beaver Counties, Utah (data from National Soil Survey Center, 2005).*

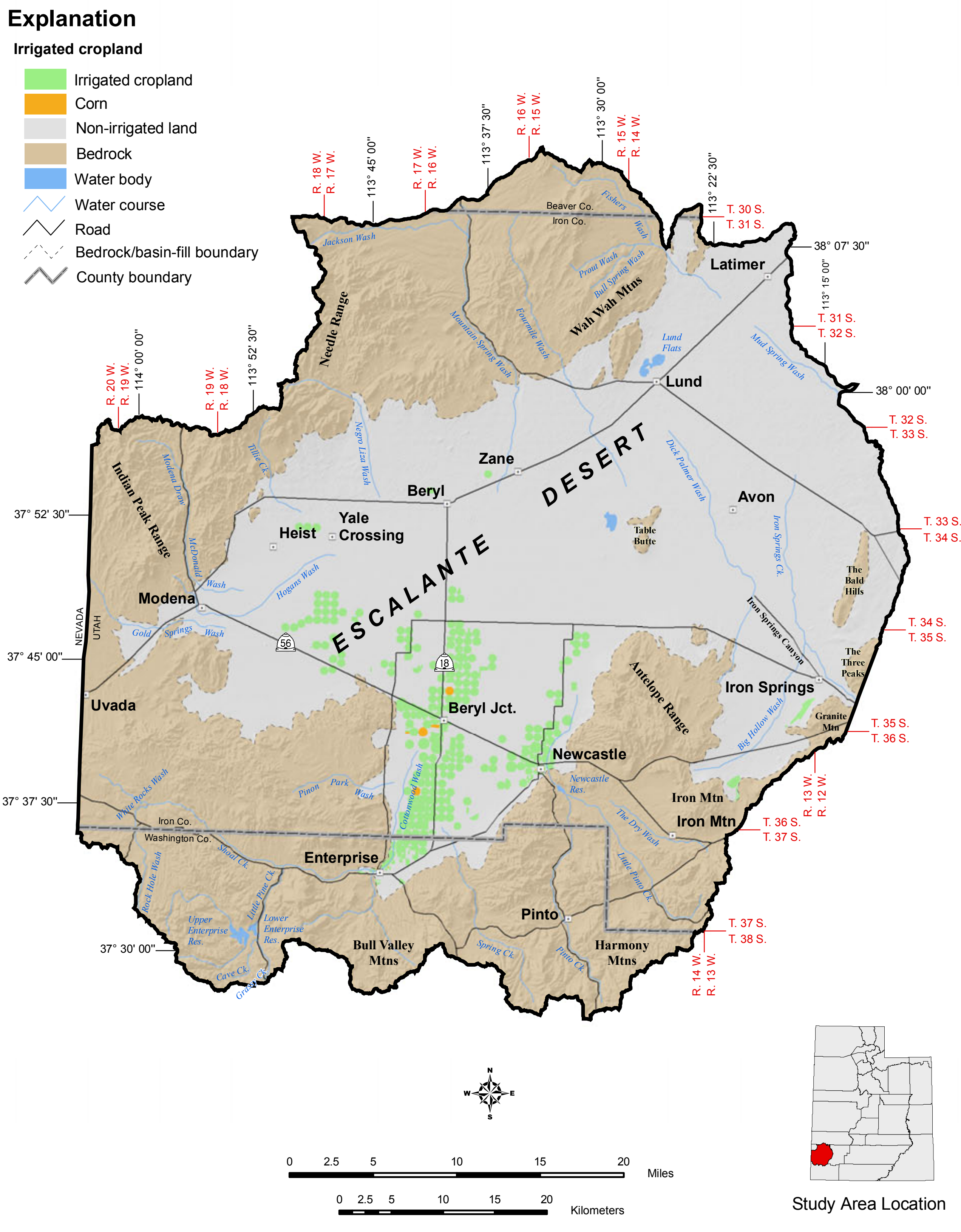

Figure 12. Irrigated and non-irrigated cropland in Beryl-Enterprise area, Iron, Washington, and Beaver Counties, Utah (data from Utah Division of Water Resources, 2009).

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Plate 1

GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES, BERYL-ENTERPRISE AREA, IRON, WASHINGTON, AND BEAVER COUNTIES, UTAH

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

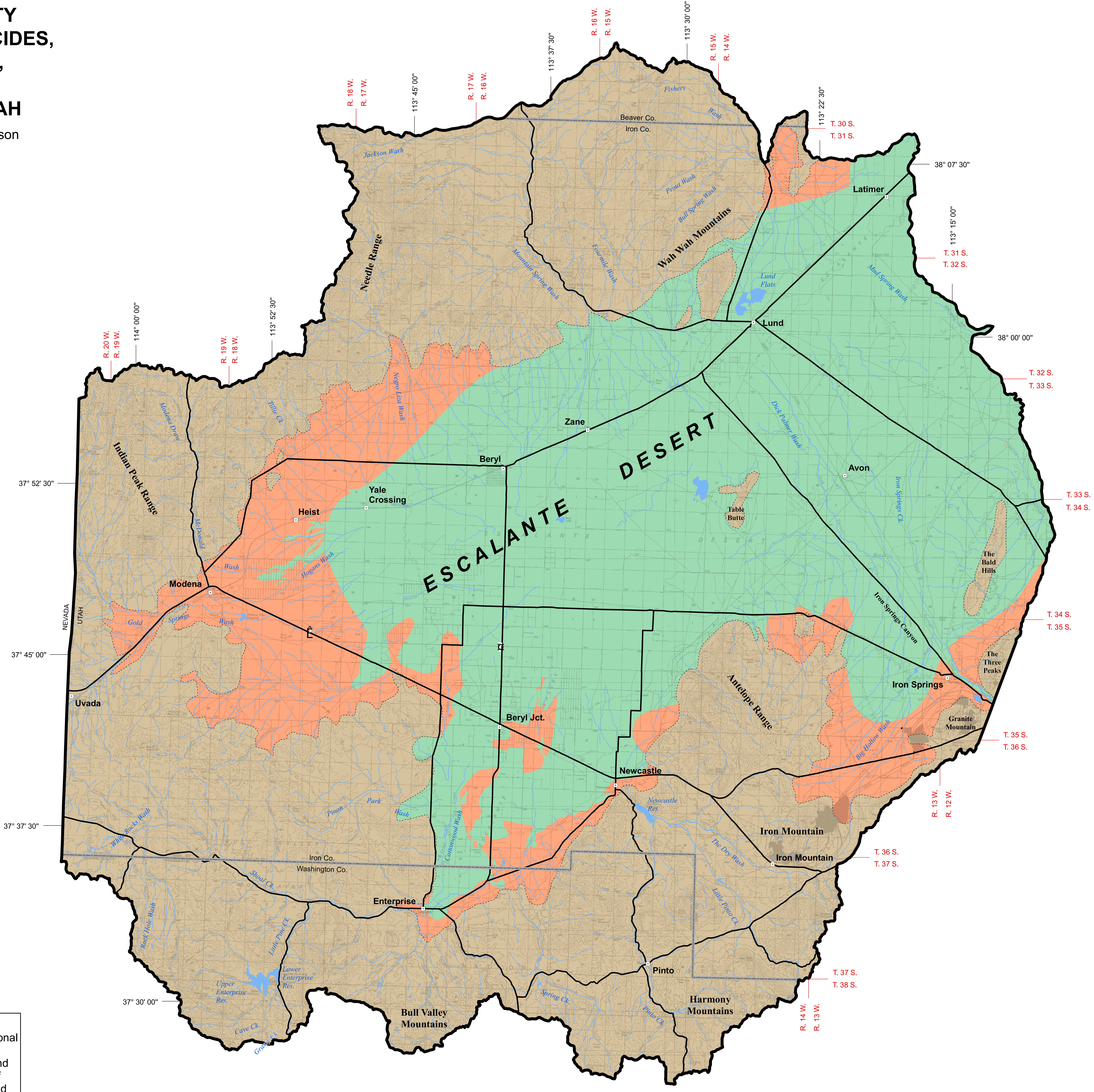
Report of Investigation 266
2009

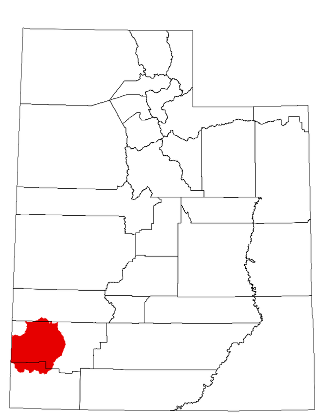
Explanation

Ground-Water Sensitivity Ranking

- Moderate
- High
- Bedrock
- Water body
- Perennial water course
- Intermittent water course
- Road
- Basin-fill boundary
- County boundary

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. Ground water vulnerability to pesticides is determined by assessing how ground-water sensitivity is modified by human activity.





Location of Study Area

This map is a GIS product derived from a recharge/discharge area map by Thomas and Lowe (2007), soil data from the National Soil Survey Center (2005), 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 (2009). 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.

0 1 2 4 6 8 10 Miles

0 1 2 4 6 8 10 Kilometers

1:165,000

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: Caliente (1978), Cedar City (1978) , St. George (1980), Wah Wah Mountains South (1980).

Plate 2

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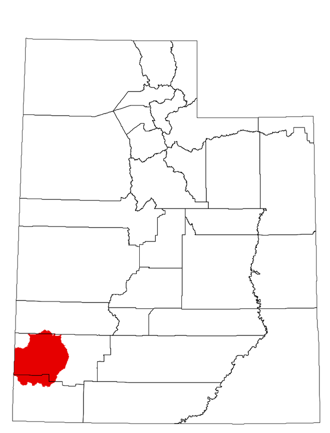

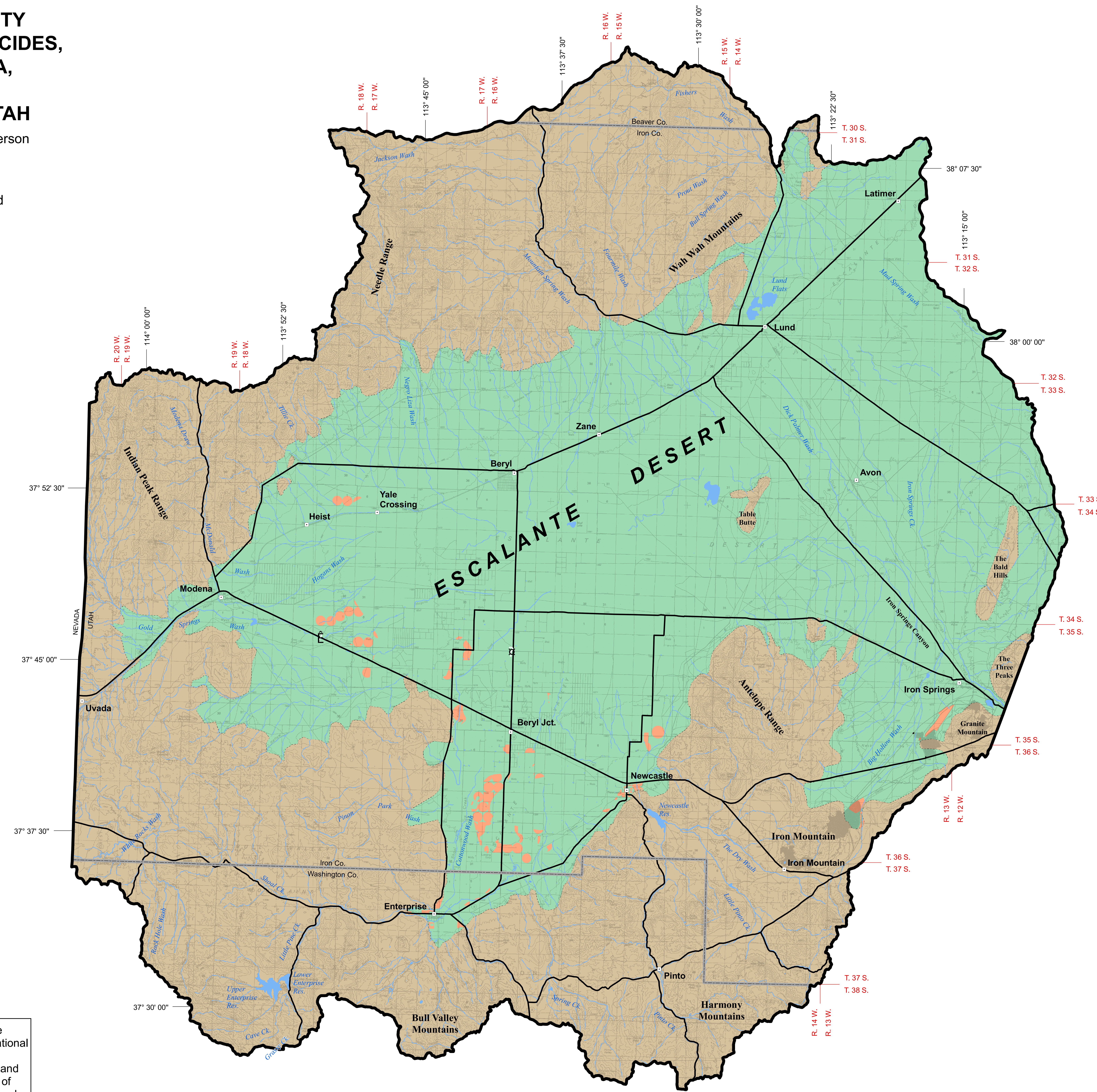

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