GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES, MOAB–SPANISH VALLEY, GRAND AND SAN JUAN COUNTIES, UTAH

by

Mike Lowe, Janae Wallace, and J. Scott Horn, Utah Geological Survey
and
Anne Johnson and Rich Riding, Utah Department of Agriculture and Food

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Cover photo: View of Moab–Spanish Valley looking west. Photo by Janae Wallace.

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ABSTRACT

The U.S. Environmental Protection Agency has recommended that states develop Pesticide Management Plans for four agricultural chemicals—alachlor, atrazine, metolachlor, and simazine—herbicides used in Utah in the production of corn and sorghum, and to control weeds and undesired vegetation (such as along right-of-ways or utility substations). This report and accompanying maps are intended to be used as part of these Pesticide Management Plans to provide local, state, and federal government agencies and agricultural pesticide users with a base of information concerning sensitivity and vulnerability of ground water to agricultural pesticides in Moab–Spanish Valley, Grand and San Juan 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 valley-fill deposits of Moab–Spanish Valley. Much of Moab–Spanish Valley has high ground-water sensitivity to pesticides due to a lack of protective clay layers and a downward ground-water gradient within the valley-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 valley-fill deposits of Moab–Spanish Valley. 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 valley margins; streams in these areas are the most important source of recharge to the valley-fill aquifer, and efforts to preserve water quality in streams at these points would help to preserve ground-water quality in Moab–Spanish 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 Moab–Spanish Valley 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 Moab–Spanish Valley should be concentrated in areas of high sensitivity or vulnerability. Sampling in the northwestern parts of the valley characterized by low and moderate sensitivity and vulnerability should continue, but at a lower density than in the areas of higher sensitivity and vulnerability.

INTRODUCTION

Background

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

This report and accompanying maps provide federal, state, and local government agencies and agricultural pesticide users with a base of information concerning the sensitivity and vulnerability of ground water to agricultural pesticides in the valley-fill deposits of Moab–Spanish Valley, Grand and San Juan 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 valley-fill aquifer in Moab–Spanish Valley to agricultural pesticides.

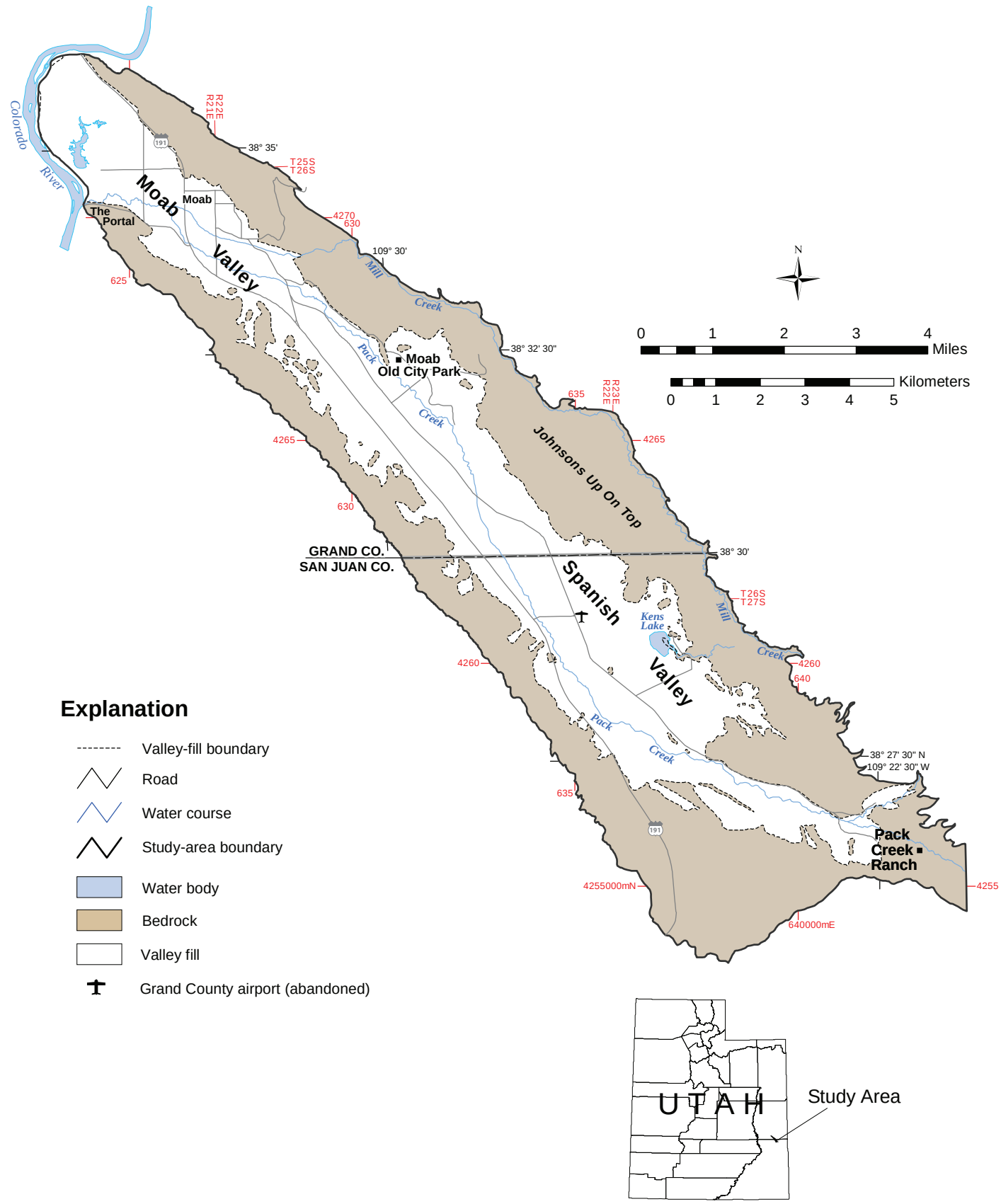


***Figure 1**. Moab–Spanish Valley study area, Grand and San Juan Counties, Utah.*

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 valley-fill deposits of Moab–Spanish Valley, 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 and financial ruin for an agricultural enterprise.

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

The case of DDT illustrates dilemmas faced by pesticide regulators. DDT was removed from widespread use in the United States in the 1970s because of its deleterious effects on bald eagles, ospreys, and peregrine falcons. Populations of these once-endangered species have recovered to a significant extent 25 years later (Environmental Defense Fund, 1997). An ongoing effort to extend the DDT ban worldwide is being hotly contested by advocates of its judicious use as a critical and inexpensive insecticide needed in developing countries to control mosquitoes that transmit the malaria parasite. It is further argued that, given the current regulatory apparatus, were the use of DDT to be re-evaluated today 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 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 R309-200.5, 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.

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.

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

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 Moab–Spanish Valley where ground water is unconfined, degradation of the valley-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 valley-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 valley-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 valley-fill aquifer.

PREVIOUS STUDIES

Geologic mapping in the Moab–Spanish Valley area includes Weir and others (1961), Doelling (1985, 2001, 2004), and Doelling and others (1995, 2002). Hydrogeologic studies relevant to Moab–Spanish Valley were conducted by Sumsion (1971), Weir and others (1983), Blanchard (1990), Freethey and Cordy (1991), Steiger and Susong (1997), Eisinger and Lowe (1999), Downs and Kovacs (2000), Wallace and others (2003), Kirby (2005), and Lowe and others (2007). Lammers (1991) mapped soils in the Moab–Spanish Valley area.

SETTING

Physiography

Moab–Spanish Valley is a northwest-trending valley in the Colorado Plateau physiographic province (Stokes, 1977), and is about 14 miles (23 km) long and averages 1.25 miles (2 km) wide with an area of about 18 square miles (47 km^2) (figure 1). The rectilinear valley is an elongate, crag-walled trough bounded on the northeast and southwest by sandstone mesas and cuestas. Moab–Spanish Valley ranges in elevation from about 3950 feet (1200 m) at the Colorado River near The Portal in the northwest to about 6100 feet (1860 m) in the upper reaches of Pack Creek within valley-fill material (figure 1); the drainage basin reaches 12,646 feet (3855 m) in elevation at Mount Mellenthin to the east of the study area.

Moab–Spanish Valley is in the 144 square-mile (373 km^2) drainage basin for Mill and Pack Creeks on the west side of the La Sal Mountains to the east of the study area (Sumsion, 1971). Mill and Pack Creeks and their tributaries flow west and northwestward from the La Sal Mountains into Moab–Spanish Valley and, ultimately, the Colorado River, which cuts the northwest end of Moab–Spanish Valley at The Portal (figure 1). Mill and Pack Creeks are perennial streams, but parts of the Pack Creek channel are dry except during periods of heavy runoff because flow is diverted for irrigation (Sumsion, 1971). Pack Creek enters Moab–Spanish Valley at its southeast end and flows generally northwest. The diversion for Pack Creek is located just below the crossing of the road to Pack Creek Ranch south of the Loop Road; the diversion ditch crosses under the Loop Road, travels west on its north side, then flows north into Kens Lake (Lance Christie, Grand County resident, written communication, May 28, 2003). Mill Creek enters the valley near Moab and flows across the valley-fill deposits for about 2.5 miles (4 km) before it is joined by Pack Creek on the west side of Moab. Mill Creek is a gaining stream throughout its length; Pack Creek is a gaining stream just north of Kerby Lane after a long, dry stretch; the old diversion fed a now-abandoned ditch west of the now-abandoned in San Juan County and along its lower reaches below Moab Old City Park (figure 1) (Lance Christie, Grand County resident, written communication, May 28, 2003).

Structurally, Moab–Spanish Valley is part of a regionally extensive, collapsed salt anticline (Doelling and others, 2002). The Pennsylvanian Paradox Formation, which underlies the Paradox basin region, contains thick salt layers deposited under marine conditions (Hintze, 1988). As these salt layers were buried by younger sediments, they became mobile and formed a diapir under present-day Moab–Spanish Valley. Due to differences in the specific gravity of salt and bedrock, the diapir rose, folding overlying rocks into an anticline. The subsequent uplift of the Colorado Plateau in the late Tertiary resulted in high rates of erosion and allowed ground and surface water to contact and dissolve the salt layers from the core of the anticline (Doelling and others, 2002). Subsequently, the overlying rock strata collapsed and eroded, forming the inverted topography of Moab–Spanish Valley in the core of the anticline. High-angle normal fault systems that developed as a result of the collapse of the salt diapir are present along both margins of Moab–Spanish Valley (Doelling and others, 2002).

Geologic units surrounding Moab–Spanish Valley include Pennsylvanian, Permian, Triassic, Jurassic, and Cretaceous sedimentary rocks (figure 2) (Doelling, 2001, 2004; Doelling and others, 2002). Small outcrops of Pennsylvanian Paradox Formation caprock (gypsum, gypsiferous mudstone, and black shale) exist along the northwest and northeast margins of Moab–Spanish Valley near Moab. A limited exposure of sandstone and conglomerate of the Permian Cutler Formation crops out along the northwest margin of Moab–Spanish Valley. Triassic Chinle and Moenkopi Formations, undivided, are exposed at the base of the cliffs in the northwest end of Moab–Spanish Valley northwest of Moab; the Moenkopi Formation includes sandstone, silty sandstone, and minor siltstone and conglomerate (Doelling, 2001). Sandstone, siltstone, conglomeratic sandstone, and mudstone

Explanation

Faults

Normal, dashed where approximately located

Folds

Anticline, showing plunge direction, dashed where approximately located

Syncline, showing plunge direction, dashed where approximately located

Quaternary Deposits

- Qagy — Younger alluvial gravel deposits
- Qal — Stream alluvium
- Qaf — Alluvial-fan deposits
- Qat — Terrace deposits
- Qea — Mixed eolian and alluvial deposits
- Qmt — Talus and colluvium
- Qms — Slumps and landslides
- Qat — Older alluvial gravel deposits
- bx — Collapsed breccia

Cretaceous Rocks

- Kms — Sandstone beds in Mancos Shale
- Km — Mancos Shale
- Kd — Dakota Sandstone
- Kbc — Burro Canyon Formation

Jurassic Rocks

- Jmb — Brushy Basin Member of Morrison Formation
- Jms — Salt Wash Member of Morrison Formation
- Jsmt — Tidwell Member of Morrison Formation and Summerville Formation, undivided
- Jsms — Summerville Formation and Tidwell and Salt Wash Members of Morrison Formation
- Jcdm — Moab Member of Curtis Formation
- Jes — Slick Rock Member of Entrada Sandstone
- Jcd — Dewey Bridge Member of Carmel Formation
- Jn — Navajo Sandstone
- Jk — Kayenta Formation
- Jw — Wingate Sandstone

Triassic Rocks

- TRc — Chinle Formation

Pennsylvanian Rocks

- IPpc — Paradox Formation caprock

- Roads
- Water course
- Study-area boundary
- Water body

Projection UTM
Zone 12
Units Meters
Datum NAD27
Spheroid Clarke 1866

Geologic data compiled from the published
Moab 30' X 60' and the LaSal 30' X 60' 1:100,000-scale quadrangles

Figure 2. *Generalized geologic map, Moab–Spanish Valley area, Grand and San Juan Counties, Utah. (compiled from Doelling, 2001, 2004; and Weir and others, 1961).*

of the Triassic Chinle Formation are exposed along both margins the northwest end of Moab–Spanish Valley (Doelling, 2001). The Wingate Sandstone is exposed in the cliffs above these Triassic units in the northwest two-thirds of the valley (Doelling, 2001). Sandstones of the Jurassic Kayenta and Navajo Formations are exposed in the cliffs and/or cap the cuestas and mesas in much of the Moab–Spanish Valley area (Doelling, 2001). The Wingate, Kayenta, and Navajo Formations form the Glen Canyon Group where they cannot be differentiated (Doelling, 2001), and also form the Glen Canyon aquifer, an important source of ground water, especially along the northwest margin of Moab–Spanish Valley. Younger rock units are exposed in the southeastern end of Moab–Spanish Valley, including siltstone and sandstone of the Jurassic Carmel Formation; sandstone and mudstone of the Jurassic Entrada Sandstone; mudstone, sandstone, and thin limestone of the Jurassic Morrison Formation; sandstone and conglomerate of the Cretaceous Burro Canyon Formation; sandstone and conglomerate of the Cretaceous Dakota Sandstone; and shale, siltstone, and sandstone of the Cretaceous Mancos Shale (Doelling, 2004).

The valley fill of Moab–Spanish Valley consists mainly of stream, alluvial-fan, mass-movement, and wind-blown deposits (figure 2) (Doelling, 2001). Modern alluvium at the northwest end of Moab–Spanish Valley consists of channel-fill and low terrace deposits of sand, silt, and clay, with local lenses of gravel, deposited by the Colorado River (Doelling and others, 1995, 2002). Alluvium along Mill Creek and Pack Creek consists mainly of silty sand with abundant pebble and cobble gravel in active channels; the gravel clasts include both locally derived sedimentary rocks and intrusive igneous rocks from the La Sal Mountains (Doelling and others, 1995, 2002). Late Pleistocene to early Holocene stream deposits form the floor of Moab–Spanish Valley and are generally poorly to well-sorted sand, silt, and clay, with some gravel lenses; these deposits are up to 30 feet (9 m) thick and contain larger percentages of fine-grained material than the underlying older alluvium (Doelling and others, 1995, 2002). Older alluvium consists of river and stream gravels, alluvial-fan deposits, and possibly some eolian interbeds, and is at least 406 feet (124 m) and possibly up to 450 feet (137 m) thick (Doelling and others, 1995, 2002). Alluvial-fan deposits form apron-like slopes along the northwest and southeast sides of Moab–Spanish Valley and consist mainly of poorly sorted, generally unstratified, muddy to sandy cobble gravel with boulders common in the upper reaches of the fans (Doelling and others, 1995, 2002). Talus and colluvium, consisting of rock-fall blocks, angular boulders, gravel, sand, silt, and clay exist along steep slopes below most cliffs in the study area (Doelling and others, 1995, 2002), and landslide deposits are mapped in the far southeast end of the valley (Weir and others, 1961; Doelling, 2004); landslide composition depends on the nature of the geologic unit from which slide material is derived. Well-sorted, unstratified to cross-bedded windblown sand deposits cover surfaces and fill hollows at many locations along the margins of Moab–Spanish Valley (Weir and others, 1961; Doelling, 2001, 2004).

Climate

Average annual precipitation in the Moab–Spanish Valley drainage basin increases with altitude and ranges from about 8 inches (20 cm) at the Colorado River to more than 30 inches (76 cm) in the La Sal Mountains (Blanchard, 1990). The Moab weather station, at an elevation of 4021 feet (1,226 m), provides the following information (Ashcroft and others, 1992). Normal annual precipitation from 1961 to 1990 was 9.00 inches (22.9 cm). Summer precipitation is typically in the form of brief, localized, intense thunderstorms, whereas winter precipitation is of longer duration, less localized and intense, and falls primarily as snow at higher elevations (Blanchard, 1990). Temperature ranges from a record high of 114°F (45.6°C) to a record low of -29°F (-33.9°C) for the 1893 to 1992 period of the weather station's existence. Normal mean annual temperature from 1961 to 1990 was 56.8°F (13.8°C). Average annual evapotranspiration was 6.3 times greater than precipitation for the period of record. Because of the brevity of precipitation events and higher evapotranspiration rates in the summer, most recharge to ground-water aquifers takes place during spring snowmelt (Blanchard, 1990).

Population and Land Use

Moab–Spanish Valley is an increasingly popular site for vacation and retirement homes, and a growing tourist industry provides employment for many valley residents. The result is population growth and a decrease in agricultural land use. Moab–Spanish Valley includes Moab, the County Seat of Grand County, and a portion of unincorporated San Juan County. In 2000, the population of Moab was 4779, and the population of all unincorporated areas of San Juan County was 9293 (Demographic and Economic Analysis Section, 2001); by 2030, these populations are expected to increase to 5719 and 10,923, respectively (Demographic and Economic Analysis Section, 2000).

GROUND-WATER CONDITIONS

Valley-Fill Aquifers

Ground water in Moab–Spanish Valley occurs in two types of aquifers: (1) fractured bedrock, and (2) valley-fill deposits (figure 3). The valley-fill aquifer is the principal focus of this report. Once the principal source of all ground water used in Moab–Spanish Valley (Sumsion, 1971), the valley-fill deposits now provide water used mostly for irrigation and for some domestic water supply (Steiger and Susong, 1997). The valley fill, predominately stream alluvium and alluvial-fan deposits, is 400 to 450 feet (120–140 m) thick in northwestern Moab–Spanish Valley near the Colorado River (Doelling and others, 1995, 2002). These deposits were estimated by Sumsion (1971), based on selected drillers' logs of water wells, to have a textural composition of about 7 percent clay, 4 percent silt, 50 percent sand, and 39 percent gravel. The average thickness of saturated sediments in Moab–Spanish Valley is about 70 feet (20 m) (Sumsion, 1971). Moab–Spanish Valley had over 200 wells completed in unconsolidated deposits by the late 1960s (Sumsion, 1971); these wells range in depth from 30 to 300 feet (9–90 m) (Gloyn and others, 1995; Lowe, 1996) and have water yields ranging from 8 to 1000 gallons per minute (0.5–60 L/sec) (Sumsion, 1971). The average transmissivity

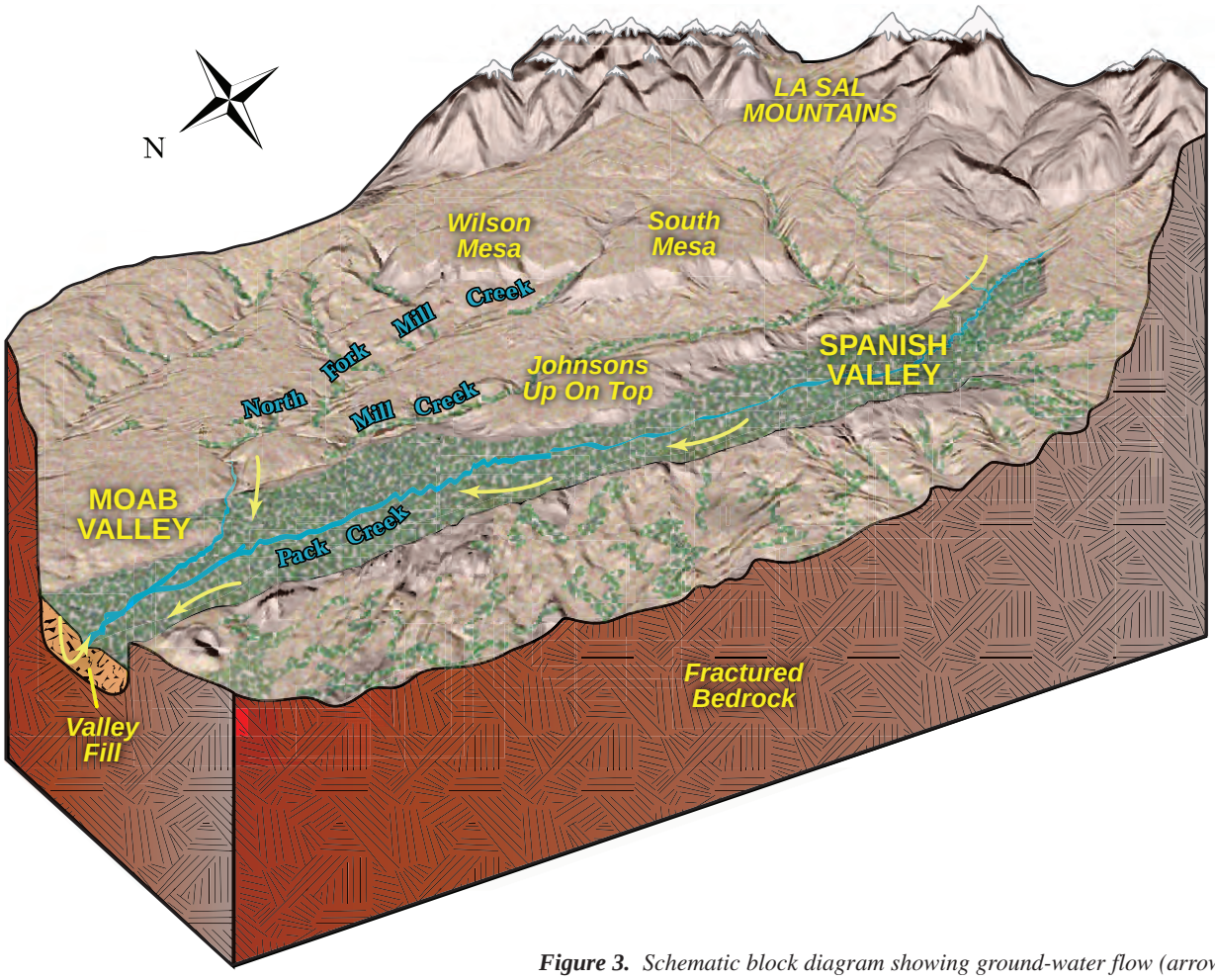


Figure 3. *Schematic block diagram showing ground-water flow (arrows indicate direction of flow in the valley-fill aquifer) in Moab–Spanish Valley.*

for the Moab–Spanish Valley valley-fill aquifer is estimated at approximately 10,000 square feet per day (900 m^2/d) (Sumsion, 1971). Sumsion (1971) estimated approximately 200,000 acre-feet (250 hm^3) of recoverable water in storage in the Moab–Spanish Valley valley-fill aquifer.

Moab–Spanish Valley is floored by Quaternary age unconsolidated deposits of the valley-fill aquifer. Near the Colorado River northwest of Moab, unconsolidated deposits rest directly on caprock of the Paradox Formation and are greater than 400 feet (122 m) thick (Lowe and others, in preparation). Southeast of Moab, valley fill thins to approximately 150 feet (46 m) and lies on Triassic rocks (Doelling and others, 2002). Throughout the remainder of Spanish Valley, unconsolidated deposits rest primarily on Middle and Lower Jurassic rocks including the Glen Canyon Group (Lowe and others, in preparation). In the central and southeast portions of Spanish Valley, valley fill is thicker along the valley axis with several pockets over 200 feet (61 m) thick along strike (Lowe and others, in preparation). Southeast of Kens Lake, valley-fill depth is unconstrained but is inferred to shallow southeastward along the valley axis and toward the valley margins.

Depth to ground water ranges from near land surface at the northwest end of Moab–Spanish Valley to over 180 feet (50 m) at the abandoned Grand County Airport (Sumsion, 1971, plate 2). Based on an average saturated thickness of valley fill of 70 feet (20 m) and an estimated specific yield of 0.25, Sumsion (1971) estimated the average volume of ground water stored in the valley-fill aquifer to be about 200,000 acre-feet (250 hm^3). Ground-water flow in the valley-fill aquifer is generally to the northwest (figure 4) (Steiger and Susong, 1997). Sumsion (1971) estimated the hydraulic gradient to be 0.013 to the northwest at the northwest end of Moab–Spanish Valley; the hydraulic gradient flattens to about 0.08 at the abandoned Grand County Airport (Sumsion, 1971, plate 2).

Recharge in the La Sal Mountains is ultimately the source of recharge to the valley-fill aquifer in Moab–Spanish Valley. Most of the recharge to the valley-fill aquifer is from springs and subsurface flow from the Glen Canyon aquifer, principally along the northeast side of the valley (Sumsion, 1971), and from direct precipitation and infiltration of water from Pack Creek and Kens Lake (Steiger and Susong, 1997). Sources of discharge in Moab–Spanish Valley include out-

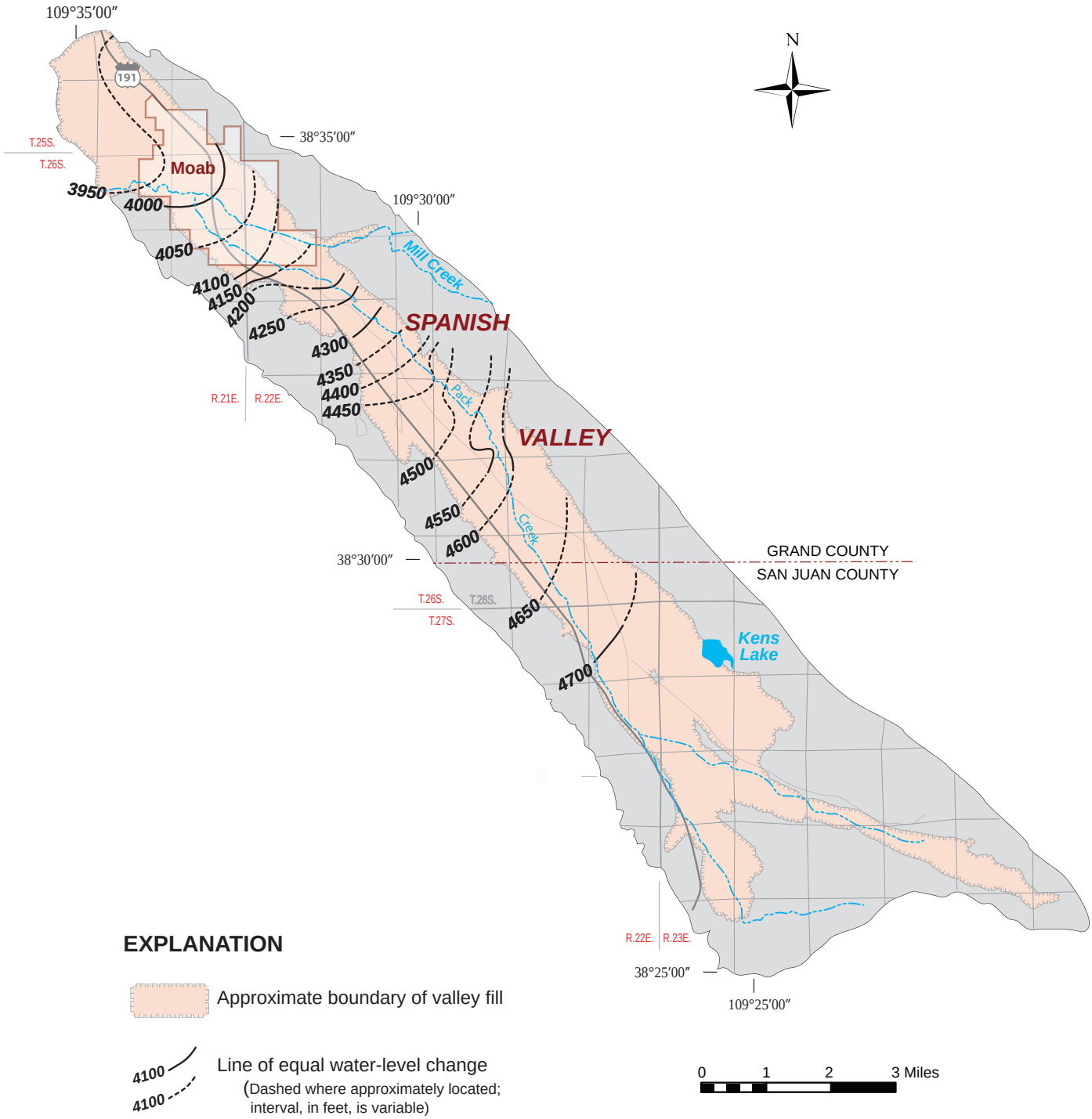


Figure 4. *Potentiometric contours of water levels for the valley-fill aquifer, Moab–Spanish Valley, Grand and San Juan Counties, Utah (modified from Sumsion, 1971).*

flow to the Colorado River; evapotranspiration by phreatophytes and hydrophytes; and consumptive use of ground water for irrigation, public supply, domestic purposes, and sewage treatment (Sumsion, 1971).

Ground-Water Quality

Ground-water quality in Moab–Spanish Valley is generally good and is suitable for most uses. The Moab–Spanish Valley unconsolidated aquifer generally yields calcium-bicarbonate-type or calcium-sulfate-bicarbonate-type ground water (Sumsion, 1971).

Based on data from ground-water samples from the 63 wells and one surface-water site, TDS in the valley-fill aquifer of Moab–Spanish Valley range from 140 to 1818 mg/L (figure 5), with only 4 wells exceeding 1000 mg/L TDS and an overall average TDS concentration of 690 mg/L (Lowe and others, in preparation). The higher TDS concentrations exist in the central part of Moab–Spanish Valley on the west side of Pack Creek (figure 5); the higher TDS concentrations may be due to (1) upward leakage of higher TDS ground water along the Moab fault, (2) contact with pre-Jurassic rocks that contain more soluble materials than the Glen Canyon Group which underlies the valley-fill in most other areas of Moab–Spanish Valley, or (3) a combination of 1 and 2 (Lowe and others, in preparation). The lower TDS concentrations found on the east side of Moab–Spanish Valley (figure 5) are likely the result of higher quality water discharging from the Glen Canyon aquifer and mixing locally with water in the valley-fill aquifer (Steiger and Susong, 1997).

Sumsion (1971) reported nitrate concentrations in the Moab–Spanish Valley unconsolidated aquifer of up to 26 mg/L, more than twice the ground-water quality (health) standard of 10 mg/L (U.S. Environmental Protection Agency, 2002). Steiger and Susong (1997) reported that dissolved nitrate-plus-nitrite concentrations for ground water in Moab–Spanish Valley ranged from 0.04 to 5.87 mg/L, and suggested nitrate-plus-nitrite concentrations of greater than 3 mg/L in an area in the central portion of the valley resulted from human activities. This is an area where domestic wastewater is or, until recently, was disposed of using septic tank soil-absorption systems.

Based on the data from 63 wells completed in the valley-fill aquifer, three wells exceeded primary water-quality standards for the metals lead, silver, and selenium; four wells exceeded water-quality standards for radionuclides alpha (3 wells), beta (2 wells), radium (1 well), and uranium (1 well) (Lowe and others, in preparation); no pesticides from any of the wells sampled for pesticides were detected (Quilter, 2001). Sixteen wells exceeded secondary ground-water quality standards for iron (1 well) and sulfate (15 wells).

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 valley-fill deposits in Moab–Spanish 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 Moab–Spanish Valley. Sensitivity represents the sum of natural influences that facilitate the entry of pesticides into ground water.

Hydrogeologic Setting

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

Lowe and others (in preparation) used drillers' logs of water wells in Moab–Spanish Valley to delineate primary recharge areas and discharge areas, based on the presence of confining layers and relative water levels in the principal and shallow unconfined aquifers. Although this technique is useful for acquiring a general idea of where recharge and discharge areas are likely located, it is subject to a number of limitations. The use of drillers' logs requires interpretation because of the variable quality of the logs. Correlation of geology from well logs is difficult because lithologic descriptions prepared by various drillers are generalized and commonly inconsistent. Use of water-level data from well

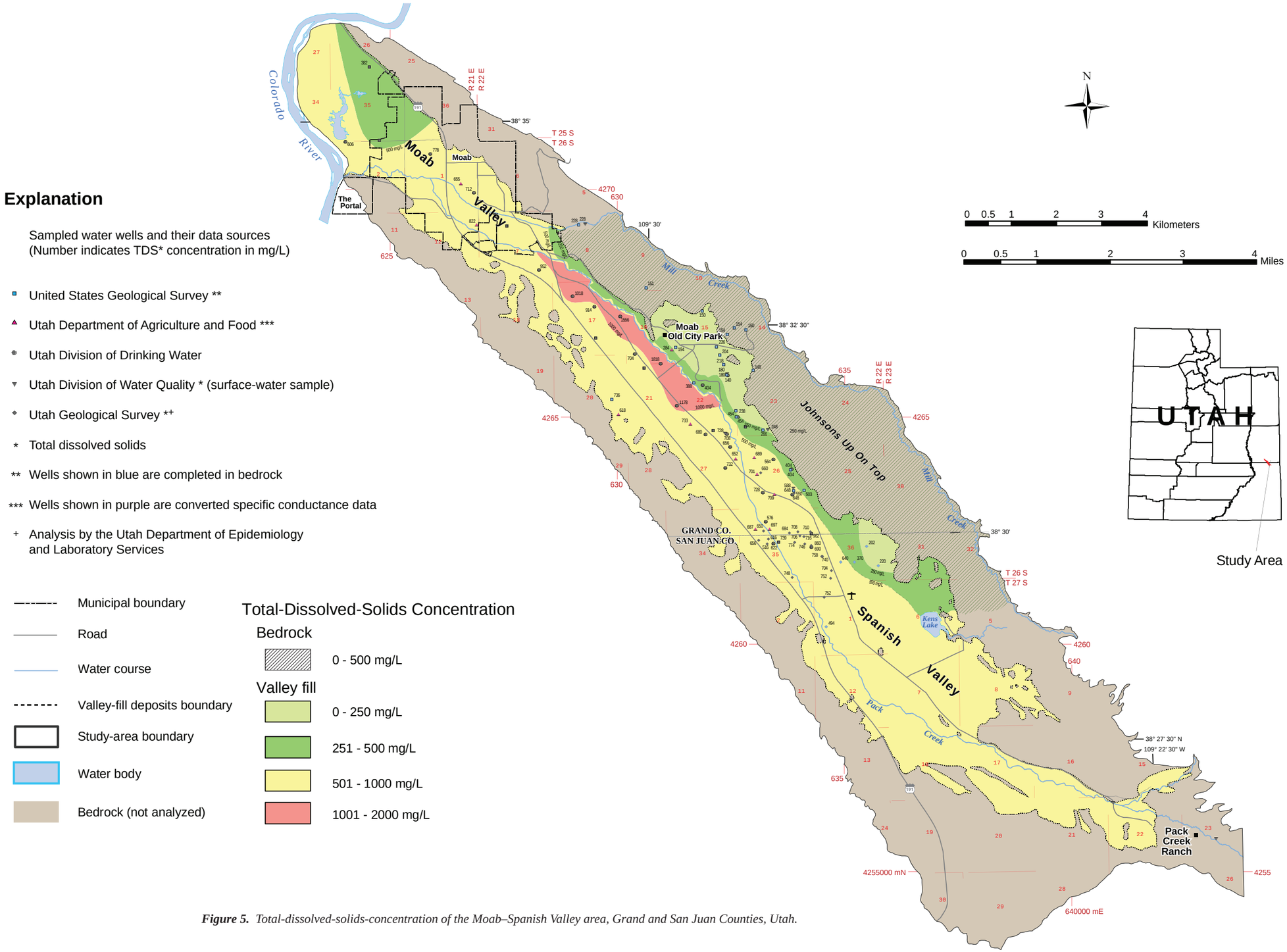


Figure 5. *Total-dissolved-solids-concentration of the Moab–Spanish Valley area, Grand and San Juan Counties, Utah.*

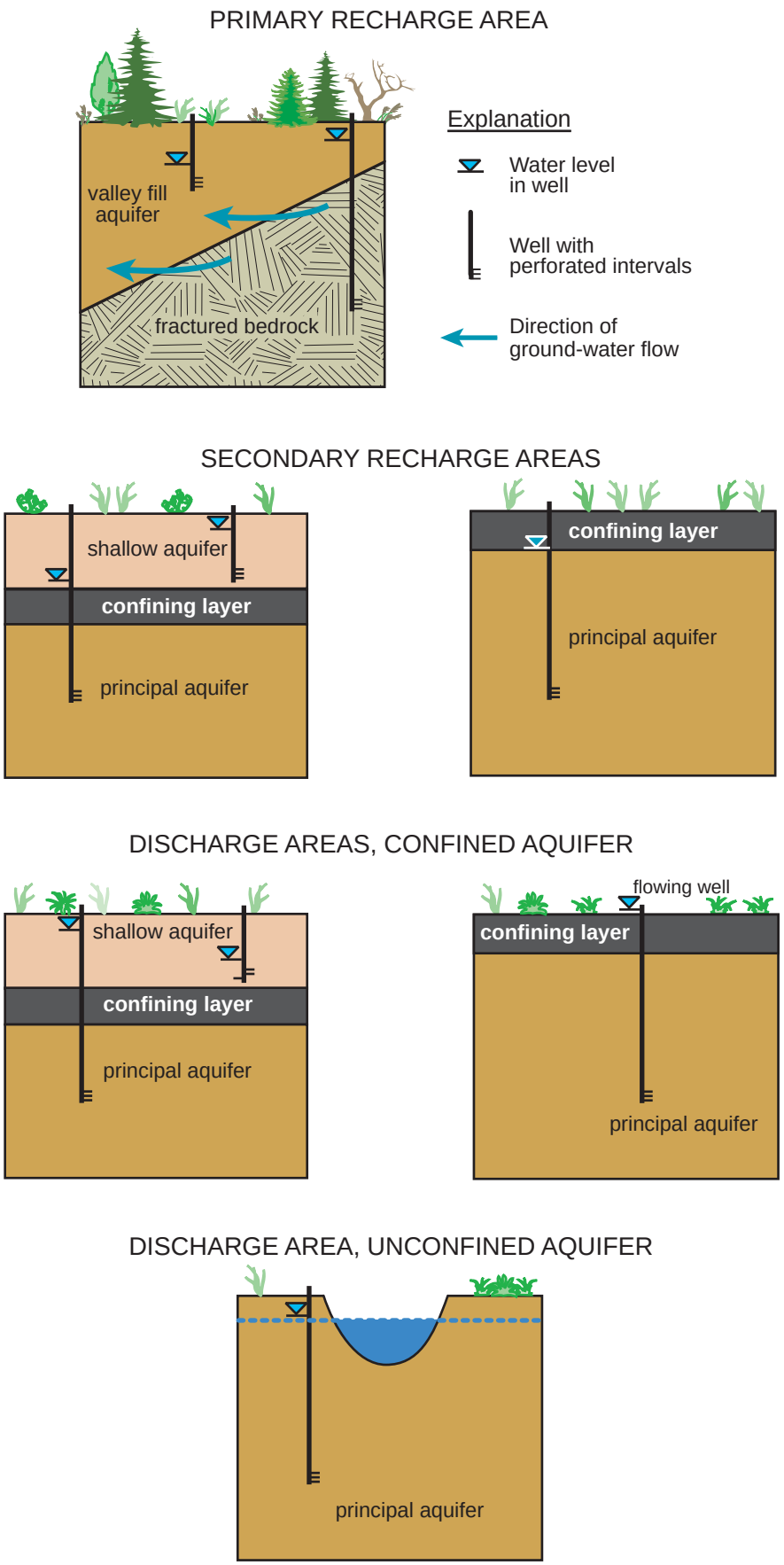


Figure 6. *Relative water levels in wells in recharge and discharge areas (modified from Snyder and Lowe, 1998).*

logs is also problematic because levels in the shallow unconfined aquifer are 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 Moab–Spanish Valley consists of valley 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; Lammers, 1991). 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[g/cm^3]);
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 Moab–Spanish Valley, at a scale of 1:24,000. Data include derived values for bulk density, organic carbon fraction, and field capacity (table 2).

We set variables in equation 1 to values that represent conditions likely to be encountered in the natural environment (table 2) to establish a rationale for dividing high and low pesticide retardation for our GIS analysis, and we applied digital soil information unique to particular soil groups from SSURGO data for organic carbon. We used the organic carbon sorption distribution coefficient (table 3), at a 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 Moab–Spanish Valley, and variable soil organic carbon content using a water-table depth of 3 feet (1 m). Average organic carbon content in soils in Moab–Spanish Valley is shown in figure 7 and ranges from 0.15 to 1.2%; 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 1.4 to 18. This means the highest relative velocity from our data is 0.7 and the lowest is 0.06; the former indicates pesticide in ground water moves at a rate about 70% 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 Moab–Spanish 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, 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 character-

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 0.15 to 1.2%
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 0.15 to 1.2%
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 0.15 to 1.2%
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 0.15 to 1.2%
G	Gravel	2.0 and greater (less than 12)	2 (2)	0.15%**

* 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 disbribution 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

ized 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:

$$AF = \exp(-0.693\ z\ RF\ \theta FC/q\ T_{½}) \qquad (2)$$

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/yr); 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 Moab–Spanish Valley (figure 8). The only localities in which evapotranspiration is less than precipitation are high-elevation forested areas. These are typically the source areas for surface streams that flow to valleys at lower elevations where they infiltrate the basin-fill sediment, accounting for a large part of ground-water recharge. Irrigation is another component of ground-water recharge, but it is not easily measured, and is not evaluated in our analysis.

Using equation 2, we calculated attenuation factors for ranges of values common to soils in Moab–Spanish Valley, similar to our approach for retardation, to delineate high and low pesticide attenuation factors for our GIS analysis. To represent naturally occurring conditions in this area that would result in the greatest sensitivity to ground-water contamination, we used a retardation factor of 4, calculated as described above; the half-life for simazine (table 3), the pesticide among the four with the longest half-life (Weber, 1994); a field capacity of 14%; and a bulk density value of 0.04 pounds per cubic inch (1.2 kg/L). For the negligible net annual ground-water recharge typical of the valley-floor areas of Moab–Spanish Valley, equation 2 results in an attenuation factor approaching 0. This means that at the above-described values for variables in the equation, none of the pesticide originally introduced into the system at the ground surface would be detected at a depth of 3 feet (1 m); therefore, no pesticides would reach ground water.

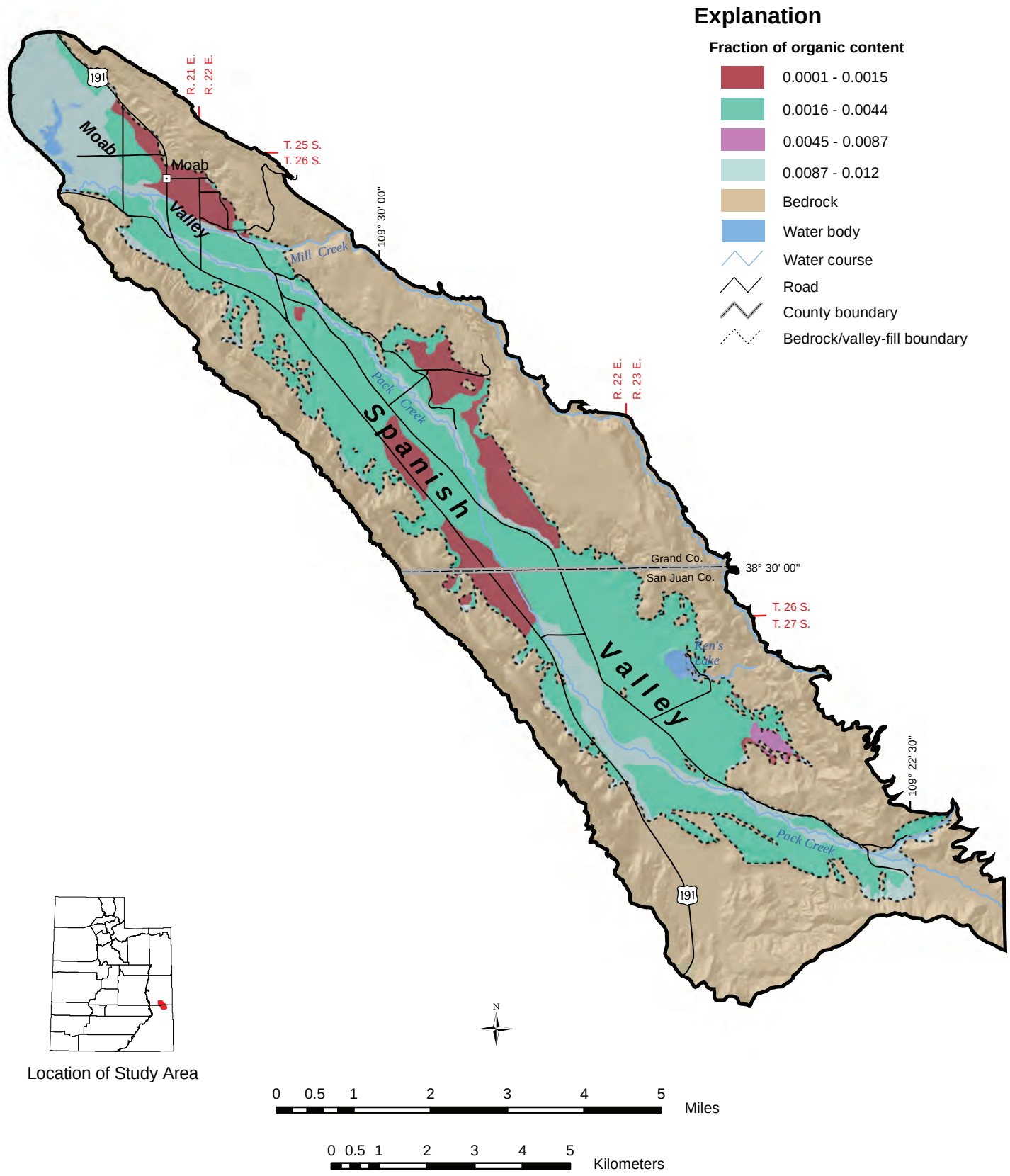
Although quantities of pesticides applied to the ground surface would intuitively seem to have a direct bearing on the amount of pesticide impacting ground water, Rao and others' (1985) equations do not support this. Note that the quantity of pesticide applied to the ground surface does not enter into either equation as a variable; the half-life of the pesticide, however, is essential. The half-life of a pesticide under typical field conditions remains fairly constant. The larger the quantity of pesticide that is applied, the greater 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 potentiometric-surface (water-levels in wells) and mapping from Sumsion, (1971) and ground-surface elevations from U.S. Geological topographic maps, 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



Location of Study Area

Figure 7. *Average organic carbon content in soils in Moab–Spanish Valley, Grand and San Juan Counties, Utah (data from National Soil Survey Center, 2005).*

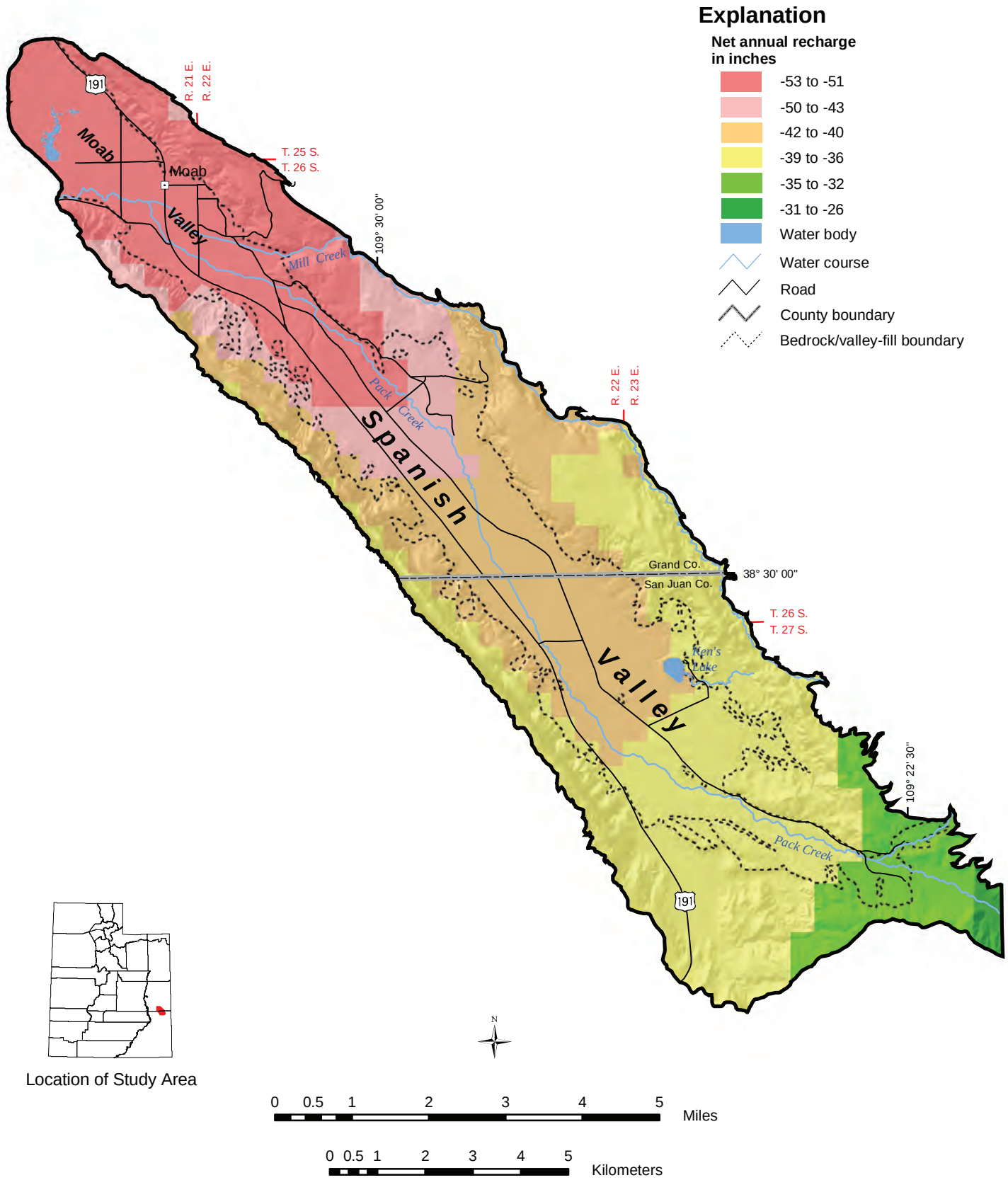


Figure 8. *Net annual ground-water recharge from precipitation in Moab–Spanish Valley, Grand and San Juan Counties, Utah. Recharge calculated using data from the Utah Climate Center (1991) and Jensen and Dansereau (2001). Although net annual recharge may be negative, seasonally some recharge from precipiation 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.

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 1999 southeast Colorado River basin 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 Moab–Spanish Valley to degradation from agricultural pesticides. Consequently, low, moderate, and high sensitivity rankings were assigned numerical values weighted more heavily than other factors, as shown in table 6.

Irrigated Lands

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

Crop Type

We mapped agricultural lands using the Utah Division of Water Resources 1:24,000-scale Land Use/Water Related Use GIS data set, which includes categories of crop types. Areas of various crop-type categories were mapped from either aerial photographs (pre-2000) or 5-meter (16 ft) resolution infrared satellite data and then field checked (Utah Division of Water Resources metadata). The southeast Colorado River basin inventory was conducted in 1999 (Utah Division of Water Resources metadata). We selected all polygons having standard type codes IA2a1 (corn), IA2a2 (sorghum), and IA2b5 (sweet corn; none in this category were in the data set) to produce the crop-type land coverage for this study, as these are the crop types to which the pesticides addressed are applied in Utah. Although the specific fields growing these crops may vary from year to year, the general areas and average percentages of these crop types likely do not.

GIS Analysis Methods

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

RESULTS

Ground-Water Sensitivity

To assess ground-water sensitivity (intrinsic susceptibility) to pesticide contamination, 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 attrib-

Table 5. *Pesticide sensitivity and the attribute rankings used to assign sensitivity for Moab–Spanish Valley, Grand and San Juan Counties, Utah.*

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

Table 6. *Pesticide vulnerability and the attribute rankings used to assign vulnerability for Moab–Spanish Valley, Grand and San Juan 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

ute 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 Moab–Spanish Valley; 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 valley-fill aquifer is from springs and subsurface flow from the Glen Canyon aquifer and from direct precipitation and infiltration of water from Pack Creek and Kens Lake, some recharge within the valley-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

Lowe and others (in preparation) mapped ground-water recharge areas in Moab–Spanish Valley (figure 9). The map shows that primary recharge areas, the areas most susceptible to contamination from pesticides applied to the land surface, comprise about 92% of the surface area of the valley-fill aquifer. Secondary recharge areas make up an additional 1% of the surface area of the valley-fill aquifers. Ground-water discharge areas in Moab–Spanish Valley are areas where the water-table at least seasonally intercepts the ground surface; these areas are highly vulnerable to surface contamination from the application of pesticides and make up 7% of the surface area of the valley-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 (2005). Nearly 100% of the surface area of the valley-fill aquifer in Moab–Spanish Valley 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 valley-fill aquifer has soil units for which hydraulic conductivity values have not been assigned by the National Soil Survey Center (2004), and were grouped into the greater than or equal to 1 inch (2.5 cm) per hour category for analytical purposes to be protective of water quality.

Depth to Shallow Ground Water

Surface application of pesticides is more likely to cause ground-water quality problems in areas of shallow ground water than where ground water is relatively deep. We developed a depth to ground-water map (figure 11) by comparing potentiometric surface data for ground water in wells with land-surface elevation from U.S. Geological Survey topographic quadrangle maps. About 6% of the area overlying the valley-fill aquifer in Moab–Spanish Valley has soil units mapped as having shallow ground water less than or equal to 3 feet (1 m) deep; these areas are primarily along Mill and Pack Creeks southeast of Moab (figure 11). About 94% of the surface area of the valley-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 Moab–Spanish Valley, constructed using the GIS methods and ranking techniques described above. We analyzed only the valley-fill aquifer; the surrounding uplands are designated on plate 1 as “bedrock” and consist mainly of shallow or exposed bedrock in mountainous terrain.

About 99% of Moab–Spanish Valley is of low sensitivity (plate 1) because of the lack of protective clay layers and high hydraulic conductivities. The remaining 1% of the study area is of moderate sensitivity.

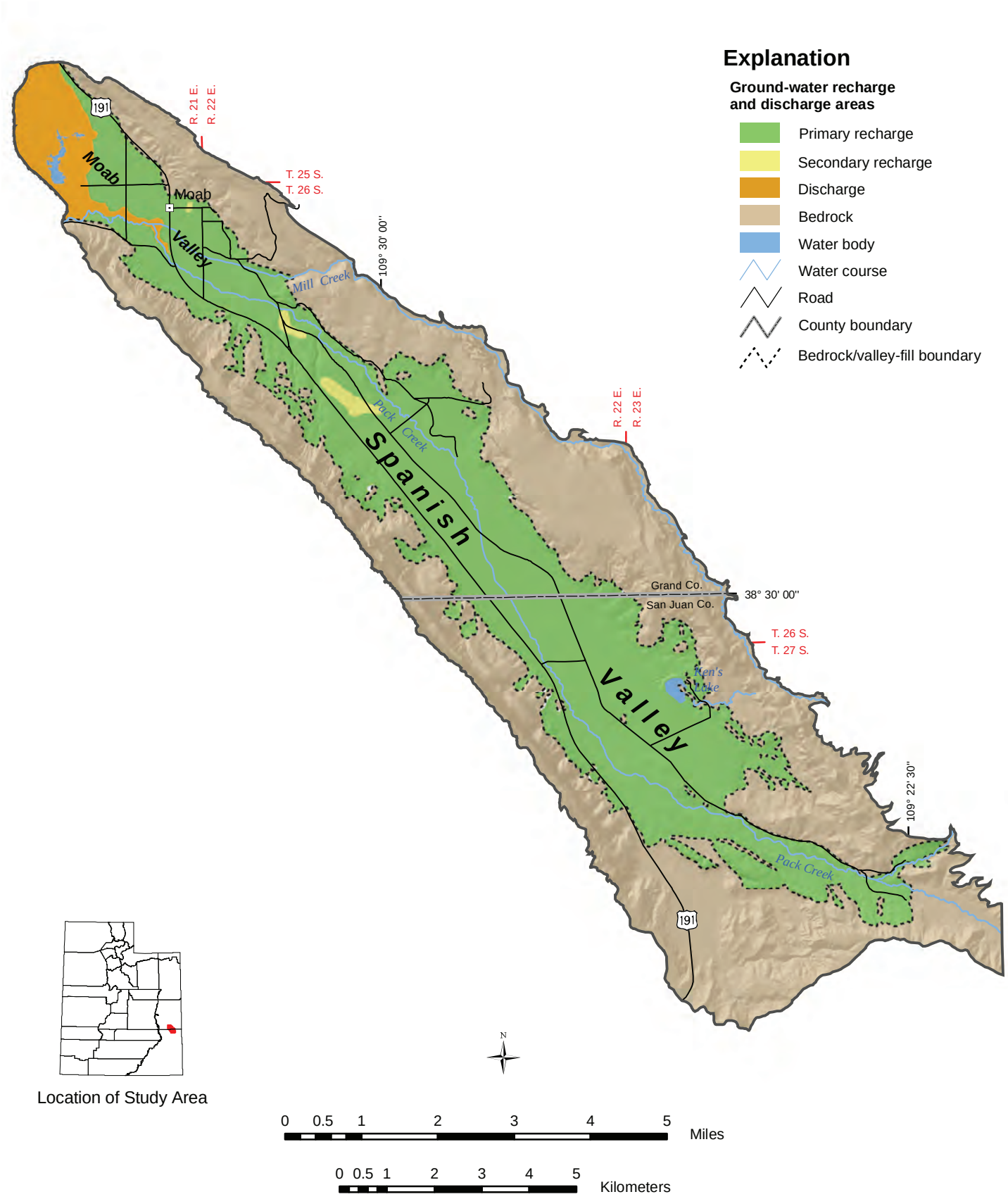


Figure 9. *Reharge and discharge areas in Moab–Spanish Valley, Grand and San Juan Counties, Utah (Lowe and others, 2007).*

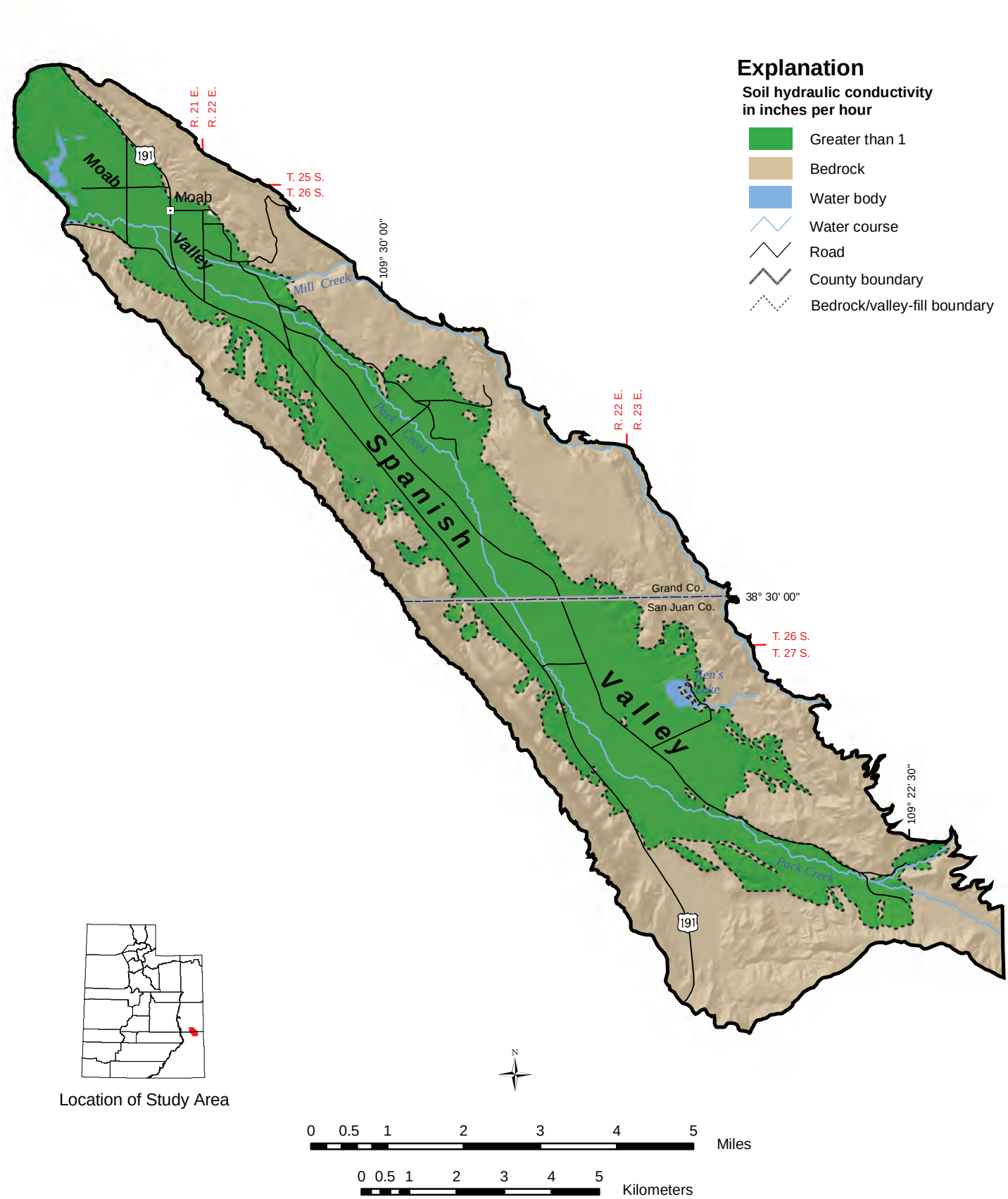


Figure 10. *Soil hydraulic conductivity in Moab–Spanish Valley, Grand and San Juan Counties, Utah (data from National Soil Survey Center, 2005).*

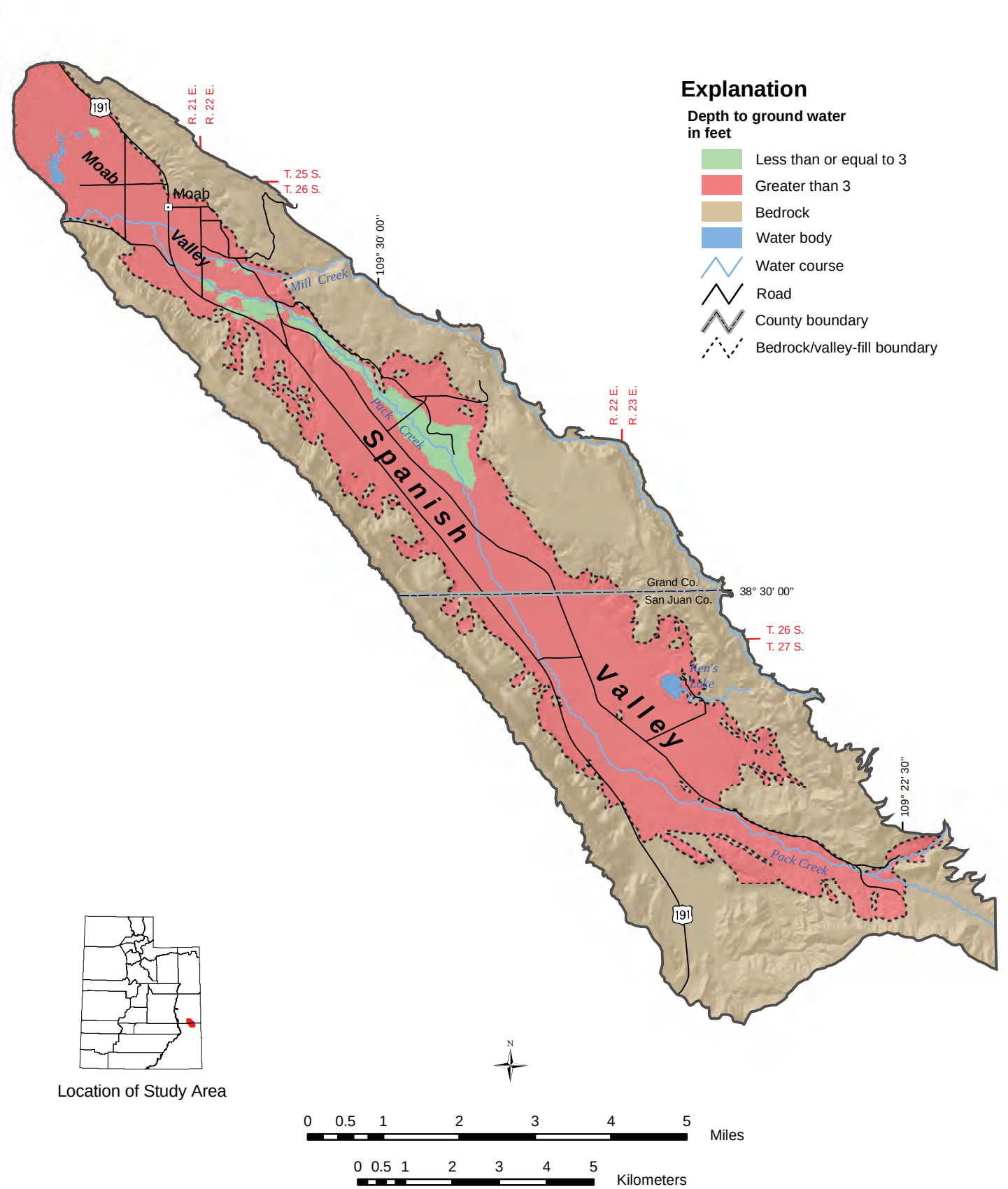


Figure 11. *Depth to shallow ground water in Moab–Spanish Valley, Grand and San Juan Counties, Utah (based on water-level data from Sumsion, 1971).*

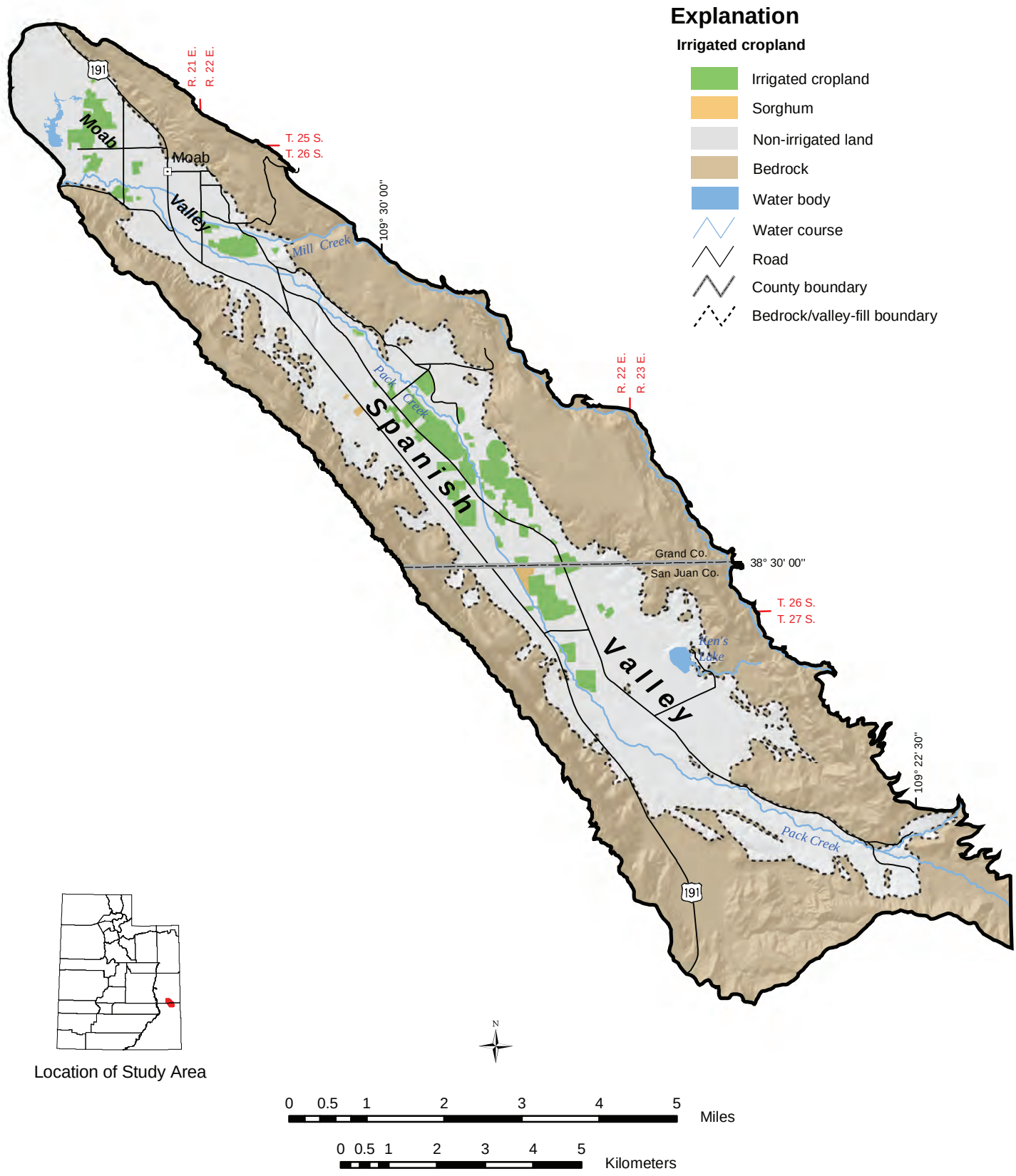


Figure 12. *Irrigated and non-irrigated cropland in Moab–Spanish Valley, Grand and San Juan Counties, Utah (unpublished data from Utah Division of Water Resources).*

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 Moab–Spanish Valley (figure 12). Using GIS methods as outlined in table 6, pertinent attribute layers, in turn, are combined with ground-water sensitivity, discussed in the previous sections, to produce a map showing ground-water vulnerability to pesticides (plate 2). The pertinent attribute layers (irrigated cropland, and corn and sorghum crops), along with ground-water sensitivity, are described in the following sections.

Irrigated Cropland

Figure 12 shows irrigated cropland areas in Moab–Spanish Valley. About 10% of the valley floor is irrigated cropland. Irrigation is potentially significant because it is a source of ground-water recharge in the valley-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. Sorghum crops are mainly grown along U.S. Highway 191 in Grand County and in San Juan County near the County Line (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 valley-fill aquifer for Moab–Spanish Valley, constructed using the GIS methods and ranking techniques described above. The surrounding uplands are not included in the analysis because of shallow bedrock and mountainous terrain, and because they are not areas of significant agricultural activity.

Areas of high vulnerability are primarily in irrigated areas where ground-water sensitivity to pesticides is high. About 16% of the surface area of the valley-fill aquifer is mapped as having high vulnerability (plate 2), including areas where hydraulic conductivity data are not available. 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, or irrigated areas where ground-water sensitivity to pesticides is low. About 84% of the surface area of the valley-fill aquifer is mapped as having moderate vulnerability.

CONCLUSIONS AND RECOMMENDATIONS

In Moab–Spanish Valley, areas of irrigated land in primary recharge areas and unconfined aquifer discharge areas with potential shallow depths to ground water, have the highest potential for water-quality degradation associated with surface application of pesticides. However, for the valley-fill deposits outside of the unconfined aquifer discharge areas, we believe pesticides likely do not represent a serious threat to ground-water quality 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 moderate and high sensitivity or vulnerability. Sampling and testing in areas of the basin characterized by moderate sensitivity and moderate vulnerability should continue, but at a lower density than in the areas of higher sensitivity and vulnerability.

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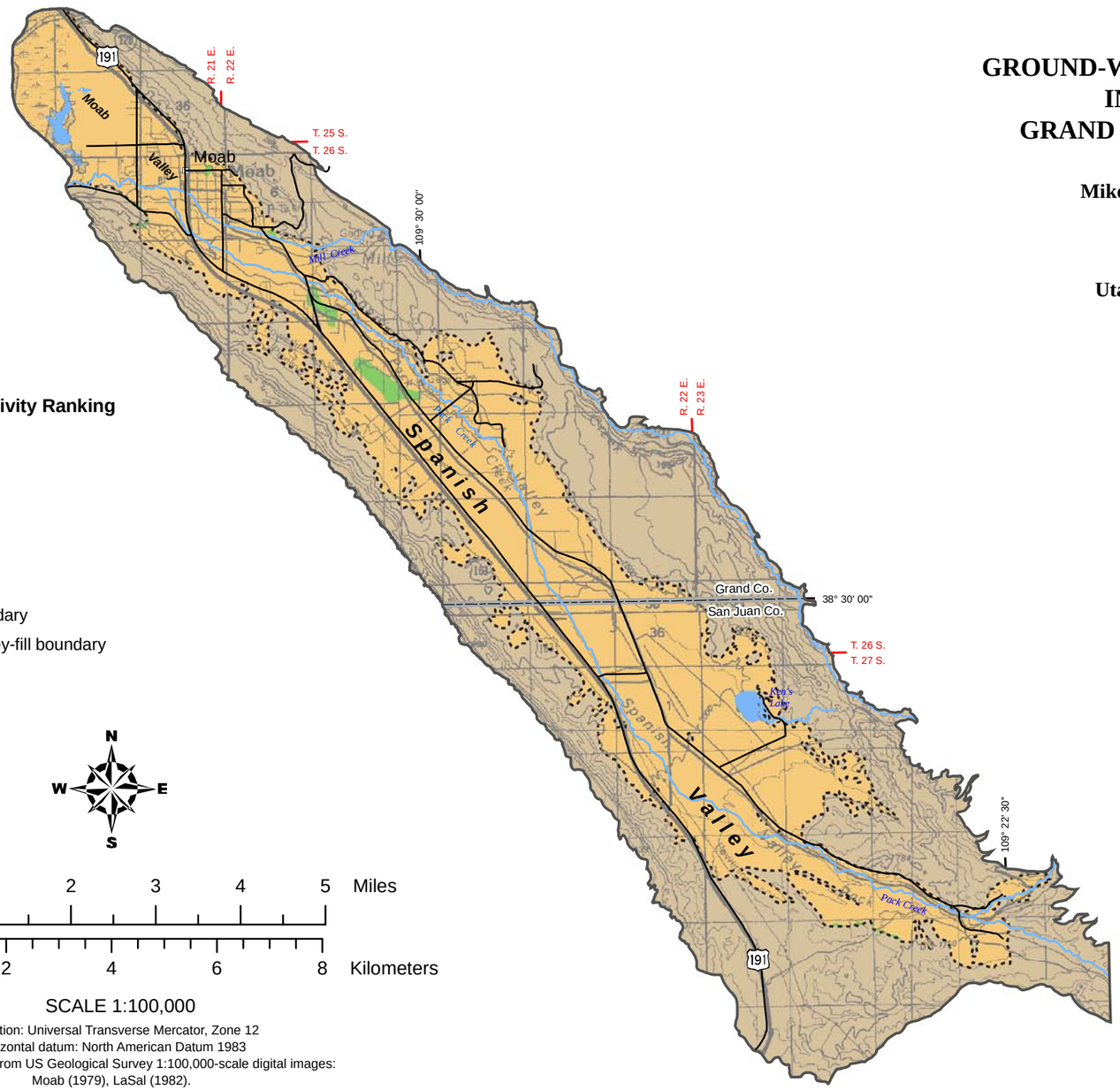
Utah Department of Agriculture and Food

Plate 1
GROUND-WATER SENSITIVITY TO PESTICIDES IN MOAB-SPANISH VALLEY, GRAND AND SAN JUAN COUNTIES, UTAH

By
Mike Lowe, Janae Wallace, and J. Scott Horn
Utah Geological Survey
and
Anne Johnson and Rich Riding
Utah Department of Agriculture and Food
2008



Explanation

Ground-Water Sensitivity Ranking

- Moderate
- High
- Bedrock
- Water body
- Water course
- Road
- County boundary
- Bedrock/valley-fill boundary

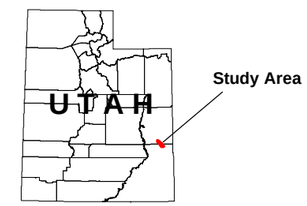
N
W E
S

0 1 2 3 4 5 Miles

0 1 2 4 6 8 Kilometers

SCALE 1:100,000

Projection: Universal Transverse Mercator, Zone 12
Horizontal datum: North American Datum 1983
Base map derived from US Geological Survey 1:100,000-scale digital images: Moab (1979), LaSal (1982).



This map is a GIS product derived from a recharge/discharge area map by Lowe and Others (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 unpublished land-use data from the Utah Division of Water Resources. 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.

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Plate 2
GROUND-WATER VULNERABILITY TO PESTICIDES IN MOAB-SPANISH VALLEY, GRAND AND SAN JUAN COUNTIES, UTAH

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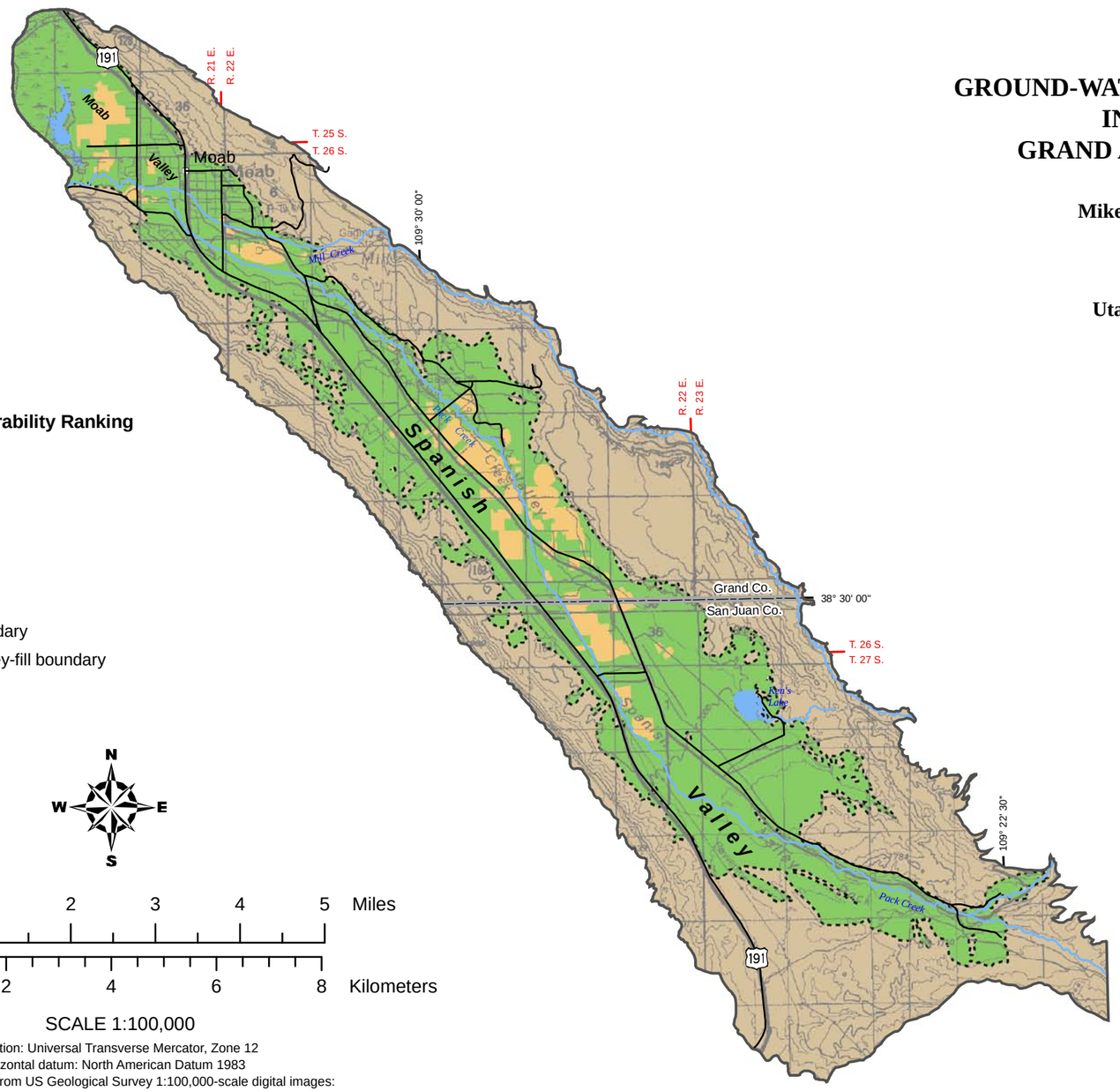

Explanation

Ground-Water Vulnerability Ranking

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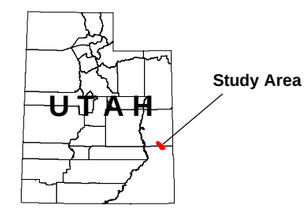

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