GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES, SANPETE VALLEY, SANPETE COUNTY, 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

REPORT OF INVESTIGATION 255
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Cover Photo: View looking east of agricultural field near Mayfield, Sanpete County, Utah.

ISBN 1-55791-765-5

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2007

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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 Sanpete Valley, Sanpete County, Utah. We used existing data to produce pesticide sensitivity and vulnerability maps by applying an attribute ranking system specifically tailored to the western United States using Geographic Information System analysis methods. This is a first attempt at developing pesticide sensitivity and vulnerability maps for this area; 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 Sanpete Valley. Much of Sanpete Valley has low ground-water sensitivity to pesticides due to protective clay layers and an upward 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 Sanpete 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 Sanpete 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 Sanpete 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 should be concentrated in areas of high sensitivity or vulnerability. Sampling in the central 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 Sanpete Valley, Sanpete County, Utah (figure 1). Geographic variation in sensitivity

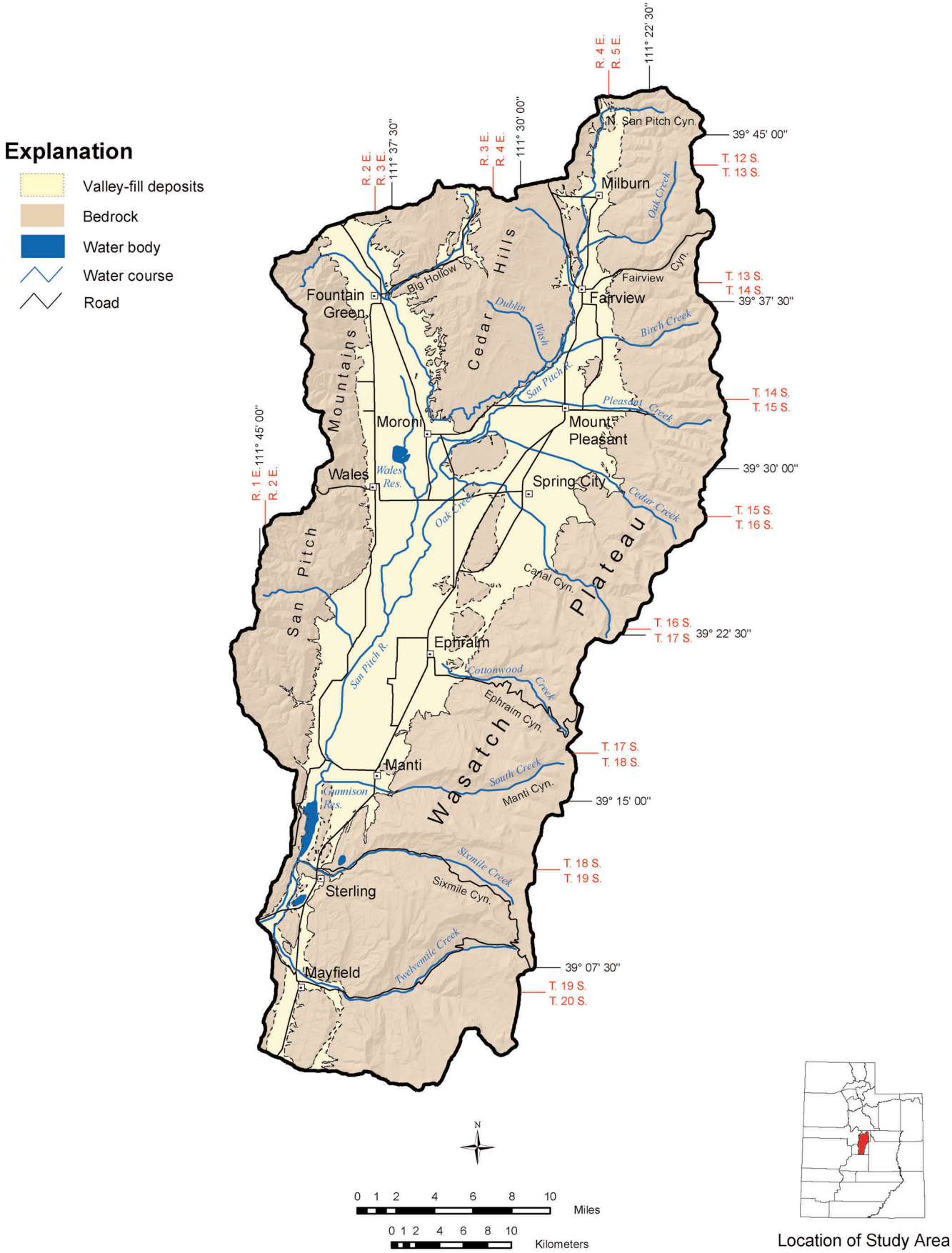

Figure 1. *Sanpete Valley, Sanpete County, Utah, study area.*

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 Sanpete Valley 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 valley-fill deposits of Sanpete 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 for this area; 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 presently 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 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 devel-

oped 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.

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 can-

not 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 Sanpete 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

Richardson (1907) performed an early reconnaissance of ground-water resources in Sanpete Valley. Robinson (1968, 1971) performed the first comprehensive assessment of ground-water resources in Sanpete Valley. Wilberg and Heilweil (1995) produced a ground-water flow model for Sanpete Valley. Horns (1995) studied nitrate contamination in the Moroni area, especially as it applied to the siting of a public water-supply well. Snyder and Lowe (1996, 1998) mapped recharge and discharge areas for the principal valley-fill aquifer in Sanpete and Arapien Valleys, and Wallace and Lowe (1997) mapped ground-water quality for this aquifer. Lowe and others (1999) evaluated the relationship of ground-water quality to ground-water recharge and discharge areas for several valley-fill aquifers in Utah, including Sanpete and Arapien Valleys. Lowe and others (2002) evaluated the water quality of the principal aquifer in Sanpete and Arapien Valleys, with emphasis on possible sources for existing nitrate in ground water. Wallace and Lowe (2005) used Lowe and others' (2002) data to petition the Utah Water Quality Board for ground-water quality classification for the principal aquifer in Sanpete and Arapien Valleys.

Swenson and others (1981) mapped soils (scale 1:24,000) in Sanpete Valley. The 1:100,000-scale geologic mapping used for this study is shown on figure 2.

SETTING

Physiography

The San Pitch River drainage basin is in the Basin and Range-Colorado Plateau transition zone (Stokes, 1977) in central Utah, which contains features characteristic of both the Basin and Range and Colorado Plateau physiographic provinces.

Stratigraphic units exposed in the Sanpete Valley area range from Jurassic to Quaternary in age. The general distribution of rock units is shown on figure 2. The San Pitch Mountains and Wasatch Plateau both consist of Jurassic to Tertiary sedimentary rocks. Tertiary limestone and mudstone cap both ranges. Cretaceous sandstones and conglomerates are steeply tilted on the east side of Sanpete Valley and unconformably underlie Tertiary rocks that are folded as a monocline in the Wasatch Plateau; these Cretaceous and Tertiary rocks form a syncline in the San Pitch Mountains. Underlying the Cretaceous units are the Jurassic Twist Gulch Formation and Arapien Shale; the Arapien Shale contains evaporite deposits. The Cedar Hills consist of the Tertiary volcaniclastic and pyroclastic Moroni Formation, mostly tuff and andesite. Consolidated rocks have a maximum combined thickness of more than 29,000 feet (9000 m). Unconsolidated valley-fill deposits are at least 500 feet (150 m) thick in Sanpete Valley along the western margin (Robinson, 1971; Lawton and others, 1997).

Sanpete Valley is bounded on the east by the Wasatch monocline, a 50-mile- (80 km) long structure along which strata dip to the west below Sanpete Valley from their near-horizontal dip atop the Wasatch Plateau, and become less steep beneath Sanpete Valley alluvium (Spieker, 1946, 1949a). The westward-facing downwarp of the Wasatch monocline is disrupted in many locations by north- and northeast-striking normal faults, which are commonly paired to form long, narrow grabens (Witkind and others, 1987). Westward-flowing consequent streams cut the tilted beds on the Wasatch monocline to form deep, sinuous canyons extending eastward into the Wasatch Plateau (Witkind and others, 1987). Along the base of the monocline is a narrow belt of Tertiary rocks that have been folded into a tilted Z-shaped sequence cut by several syngenetic faults, all likely the result of one or more thrusting events (Spieker, 1949a, 1949b).

The San Pitch Mountains, a north-south-trending, oval-shaped upland composed of sedimentary rocks that have been folded to form a southward-plunging syncline, bounds Sanpete Valley on the west (Witkind and others, 1987). The mountains include structures that are part of the Gunnison thrust system (Weiss and Sprinkel, 2000). Along the eastern margin of the San Pitch Mountains, the strata are intensely deformed into a gigantic Z-shaped structure (Gilliland, 1952). Several north-trending grabens (Witkind and others,

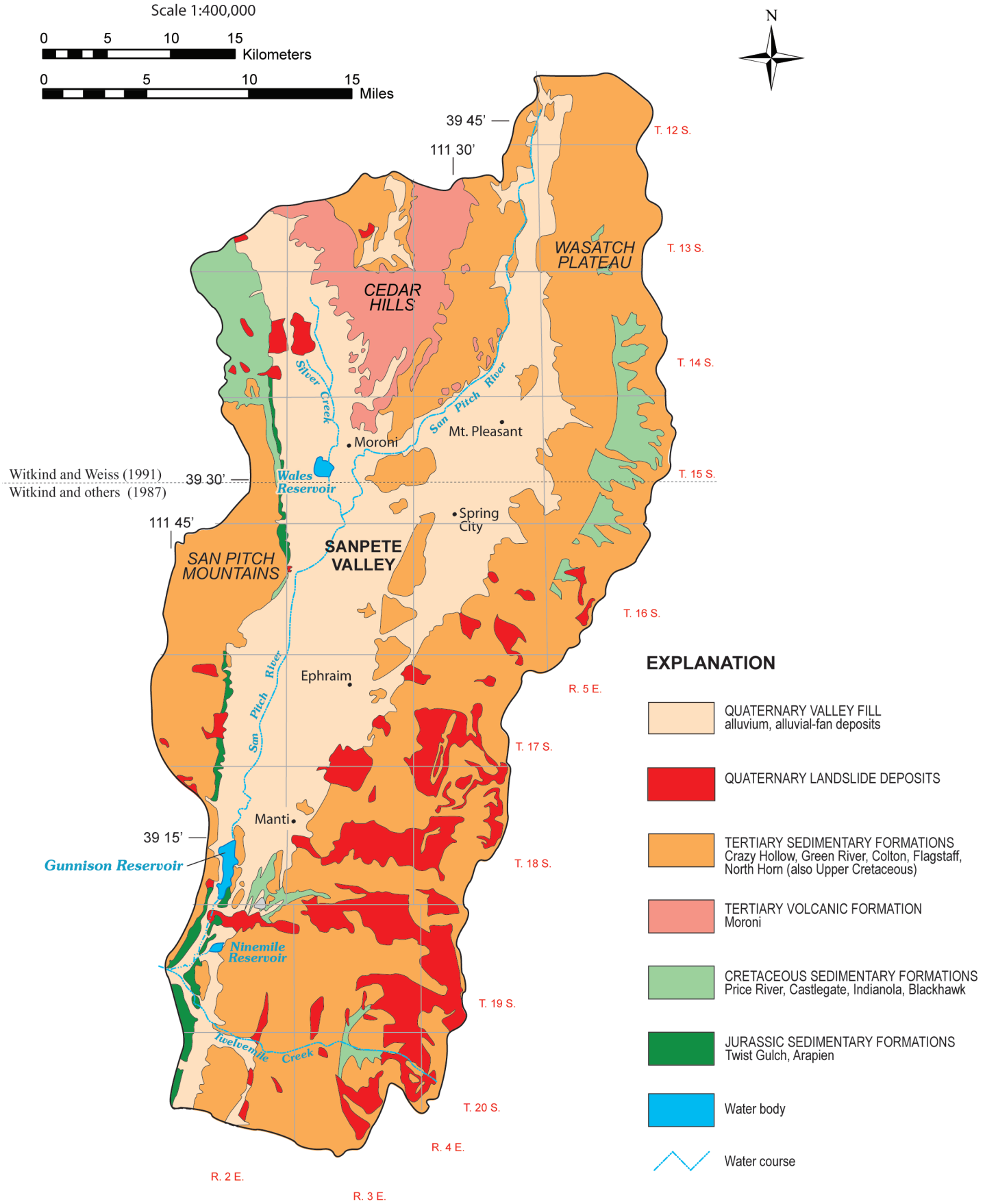

Figure 2. *Simplified geology and sources of geologic mapping for Sanpete Valley, Sanpete County, Utah.*

1987) characterize the southeastern margin of the mountains (Weiss and Sprinkel, 2000). To the north, the mountains are less faulted, and are marked by steep cliffs rising high above the adjacent valley floor (Witkind and others, 1987). Lawton (1985) and Lawton and others (1997) mapped thrust faults along the northeastern base of the San Pitch Mountains, emphasizing their most distinctive feature – a series of synorogenic, predominantly clastic deposits which record the foreland-breaking sequence of thrust deformation largely responsible for most structures in central Utah.

Sanpete Valley is also structurally complex. The Sanpete-Sevier anticline, a 65- to 70-mile- (105-113 km) long, sinuous antiform with structural relief of up to 20,000 feet (6100 m), underlies the Sanpete Valley alluvial fill (Gilliland, 1963); it is interpreted to be a large fault-propagation fold (Weiss and Sprinkel, 2000). Sanpete Valley has been downdropped along its eastern margin by the Gunnison fault (Weiss, 1982; Hecker, 1993; Black and others, 2003), which may have been active within the last 370 years (Fong, 1991). The throw on the Gunnison fault is greatest along the northern end of the San Pitch Mountains, and as much as 4400 feet (1350 m) near Wales; the magnitude of displacement on the Gunnison fault decreases to zero at the south end of the mountains (Lawton, 1985; Weiss and Sprinkel, 2000). Local diapirism has modified structures in several places in Sanpete Valley (Weiss and Sprinkel, 2000), especially in the south where the Arapien Shale is exposed along the western valley margins.

Climate

Climate in the San Pitch River drainage basin ranges from semiarid in Sanpete Valley to subhumid in the surrounding uplands (Robinson, 1971). Only three weather stations in the study area record both temperature and precipitation: Moroni, Ephraim Sorensons Field, and Manti (Ashcroft and others, 1992). The area is characterized by large seasonal and daily temperature variations, especially during the summer (Robinson, 1971). Temperatures reach a normal maximum of 89.4°F (31.9°C) and a normal minimum of 9.8°F (-12.3°C), both recorded at the Moroni station; the normal mean temperature ranges from 71.6°F (22.0°C) at Ephraim in July to 22.7°F (-5.2°C) at Moroni in January (Ashcroft and others, 1992). The average number of frost-free days in Sanpete Valley ranges from 103 at Moroni to 127 at Manti (Ashcroft and others, 1992).

Most of the precipitation in the San Pitch River drainage basin falls as snow in the mountains, particularly the Wasatch Plateau, from November to April (Robinson, 1971). The months of June through August are generally the driest, although brief, intense thunderstorms can locally produce large precipitation totals (Robinson, 1971). Normal annual precipitation in the valley ranges from 9.85 inches (25.02 cm) in Moroni to 13.74 inches (34.90 cm) in Manti (Ashcroft and others, 1992). At elevations above 8000 feet (2500 m), the Wasatch Plateau receives an average of 24 inches (61 cm) of precipitation annually (Ashcroft and others, 1992) (normal climatic information is not available).

Normal annual evapotranspiration in Sanpete Valley ranges from 48.54 inches (123.3 cm) in Moroni to 45.62 inches (115.9 cm) in Ephraim (Ashcroft and others, 1992). Robinson (1971) noted that average annual evaporation in the San Pitch River drainage basin is 3.5 times greater than average annual precipitation; the ratio of normal annual evapotranspiration to normal annual precipitation ranges from 4.9 times at Moroni to 3.3 times at Manti, with an average for the three weather stations of 4.0 times.

Population and Land Use

Sanpete Valley is a rural area experiencing moderate population growth resulting in increased residential development; much of the existing and future development uses septic tank soil-absorption systems for wastewater disposal, though some areas are connected to sewer and maintain sewage lagoons. Sanpete County had a July 2005 population estimate of 25,454 (Demographic and Economic Analysis Section, 2006). Population is projected to grow another 1% annually over the next 20 years; by 2020 the population of Sanpete County is expected to reach 28,177 (Demographic and Economic Analysis Section, 2000).

Government and non-farm proprietors (private business owners) have provided most employment in Sanpete County throughout the past decade (Utah Governor's Office of Planning and Budget, unpublished data reported in Utah Division of Water Resources, 1999). Trade replaced agriculture as the third-largest employment provider in the county between 1994 and 1997; agriculture is expected to fall below the service industry in terms of number of people employed by 2020 (Utah Governor's Office of Planning and Budget, unpublished data reported in Utah Division of Water Resources, 1999). Although employment in agriculture and the number of farms is decreasing, agricultural commodity production is expected to remain an important part of Sanpete County's economy.

GROUND WATER CONDITIONS

Valley-Fill Aquifer

Ground water in the Sanpete Valley area is obtained principally from unconsolidated deposits of the valley-fill aquifer (Wilberg and Heilweil, 1995). Ground water in the valley-fill aquifer of Sanpete Valley occurs under confined and unconfined conditions in unconsolidated deposits (figure 3) (Robinson, 1971). In areas where the principal valley-fill aquifer is under confined conditions, it is generally overlain by a shallow unconfined aquifer (figure 3).

The valley fill consists primarily of interfingered layers of clay, silt, sand, and gravel. Sediments are generally coarser grained in alluvial fans along the mountain fronts and finer grained in the central parts of the valley.

The potentiometric surface (figure 4) of ground water in the valley-fill aquifer is irregular and depends on the well depth, season, and the year water-level measurements are made (Robinson, 1971). In unconfined parts of the aquifer, the potentiometric surface corresponds to the water table; in the confined parts of the aquifer, the potentiometric surface represents the hydrostatic pressure, or head, a parameter controlling the elevation to which water will rise in wells. The potentiometric surface generally conforms to the contour of the valley floor.

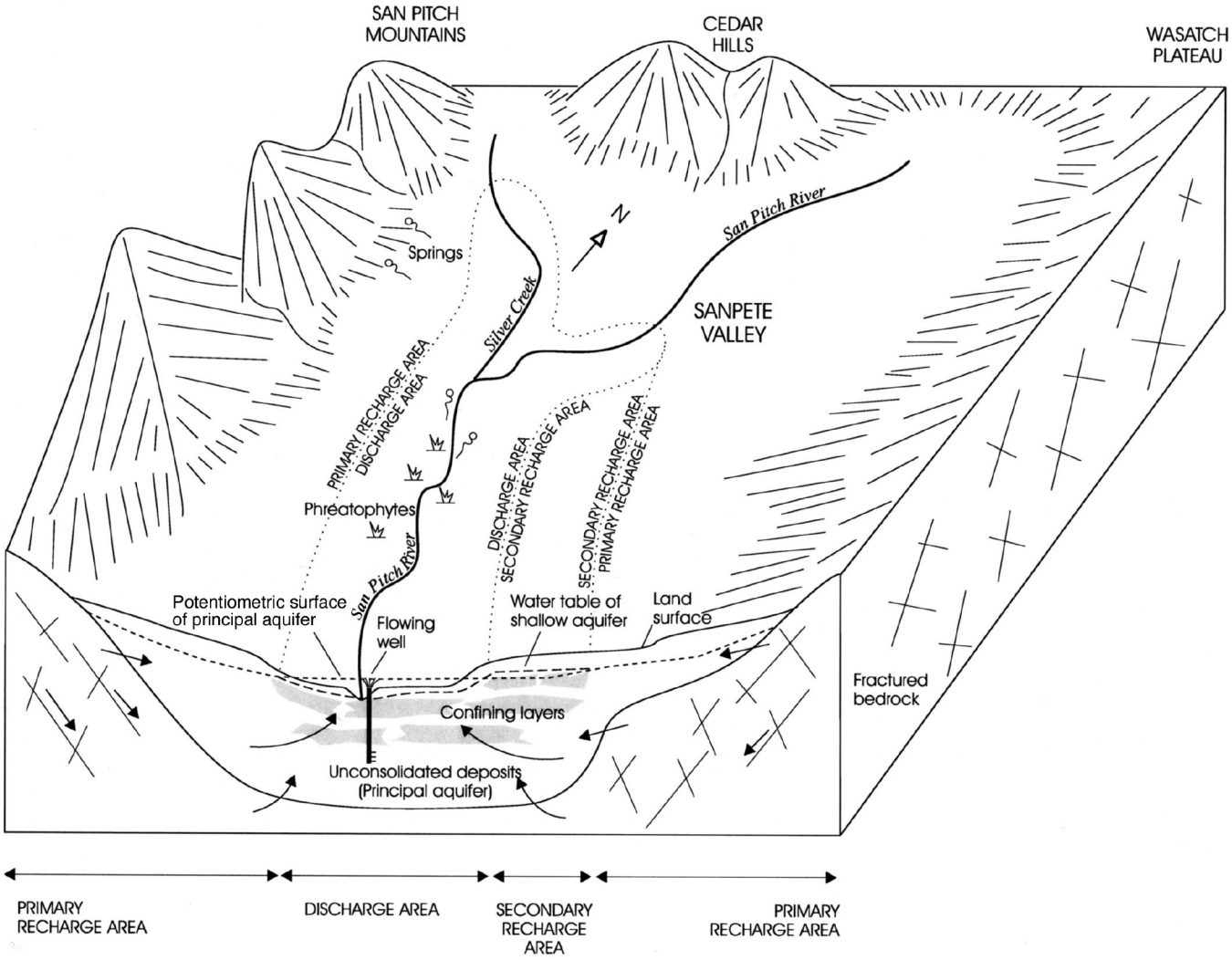

Figure 3. *Schematic block diagram showing recharge areas and direction of ground-water flow (arrows) in Sanpete Valley, Sanpete County, Utah (from Snyder and Lowe, 1998).*

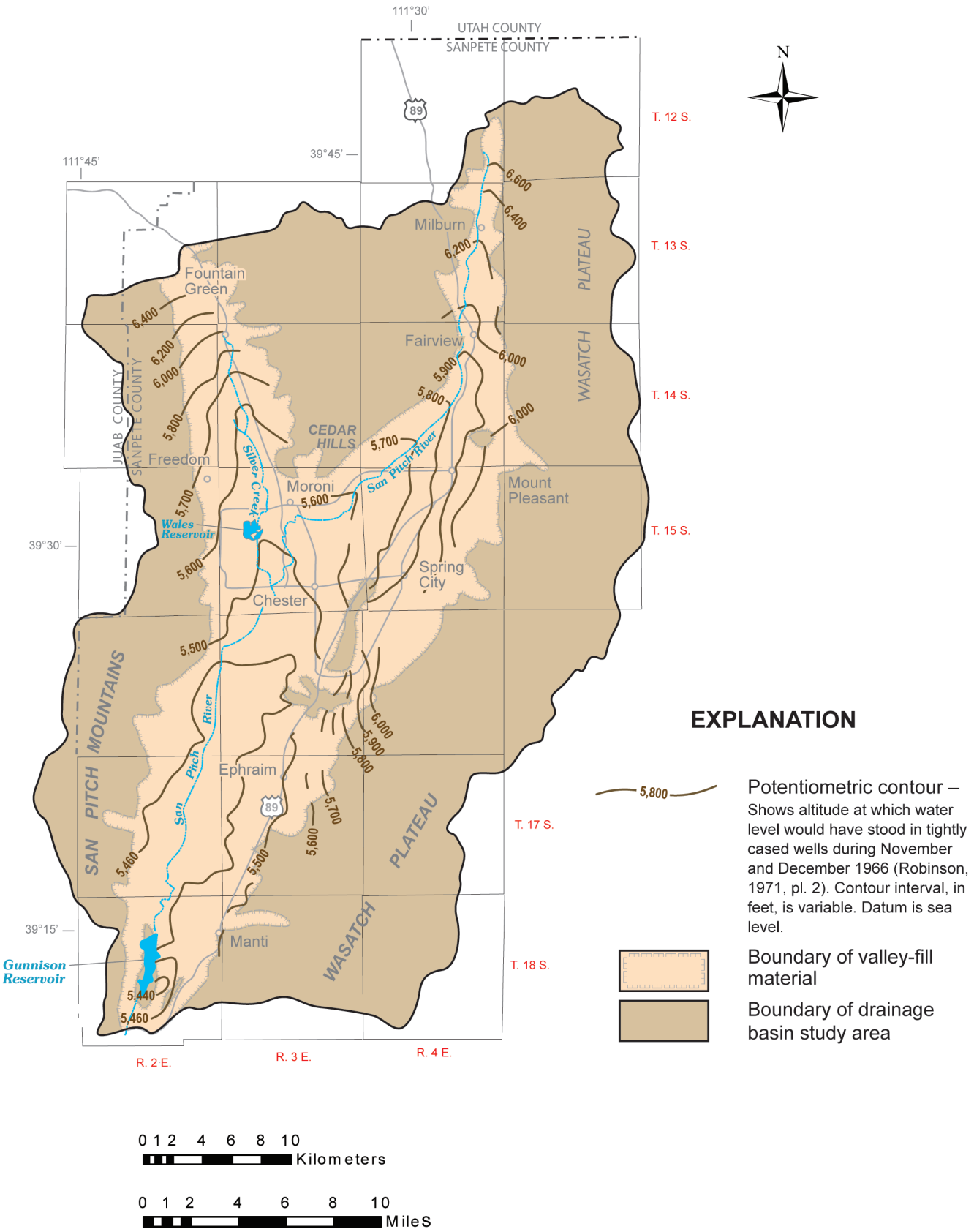

Figure 4. *Potentiometric contours of water levels for part of the valley-fill aquifer, Sanpete Valley, Utah (modified from Wilberg and Heilweil, 1995).*

Ground-water flow is generally from the higher elevation recharge areas to lower elevation discharge areas. Ground water generally flows westward from the Wasatch Plateau and eastward from the San Pitch Mountains toward the San Pitch River and Silver Creek, and then southward toward Gunnison Reservoir.

Ground-Water Quality

Ground-water quality in Sanpete Valley's principal valley-fill aquifer is generally good and suitable for most uses. Ground water in the valley-fill aquifer is generally a mixed type containing calcium, sodium, magnesium, and bicarbonate ions; however, water from many wells, especially shallow ones on the west side of the valley, is a mixed type containing magnesium, sodium, sulfate, and chloride ions (Wilberg and Heilweil, 1995).

Lowe and others (2002) collected ground-water samples from 443 wells during the summer and autumn of 1996 and spring of 1997 to evaluate total-dissolved-solids (TDS) and nitrate concentrations. Ground water from all sample locations was analyzed for the nutrients nitrate, nitrite, ammonia, and phosphate. Of the 443 wells, ground water from 118 wells was analyzed for general chemistry, 107 for dissolved metals, and 49 for organics and pesticides.

Total-dissolved-solids concentrations for wells tested for general chemistry plus 290 wells having converted specific conductance data range from 216 to 2752 mg/L (figure 5); the average measured TDS concentration is 503 mg/L (Wallace and Lowe, 2005). Elevated levels of TDS in ground water are largely attributed to proximity to outcrops of the Arapien Shale and the Green River Formation (Lowe and others, 2002).

Nitrate, typically associated with human activities, has been identified in ground water in Sanpete Valley in previous studies. The drinking water (health) standard for nitrate as nitrogen is 10 mg/L (U.S. Environmental Protection Agency, 2006). Nitrate concentration exceeding this standard was identified in a Moroni public-supply well in the 1990s (Horns, 1995); the well was replaced and taken off line. Nitrate concentrations for ground water in the principal valley-fill aquifer range from 0.02 to 40.2 mg/L, with an average concentration of 3.3 mg/L (Lowe and others, 2002). Of the water wells analyzed for nitrate, 86.5 percent yielded values less than 5 mg/L, and 3.5 percent exceeded the drinking-water standard for nitrate and are considered high-nitrate wells (Lowe and others, 2002).

Utah drinking-water standards were exceeded for lead in two wells, arsenic in two other wells, and copper in another well (Lowe and others, 2002). Of the 49 water wells tested for pesticides, seven wells yielded water having values above the detection limit, but below Utah drinking-water standards (Wallace and Lowe, 1997; Lowe and others, 2002).

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 Sanpete 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 Sanpete 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.

Snyder and Lowe (1998) used drillers' logs of water wells in Sanpete 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

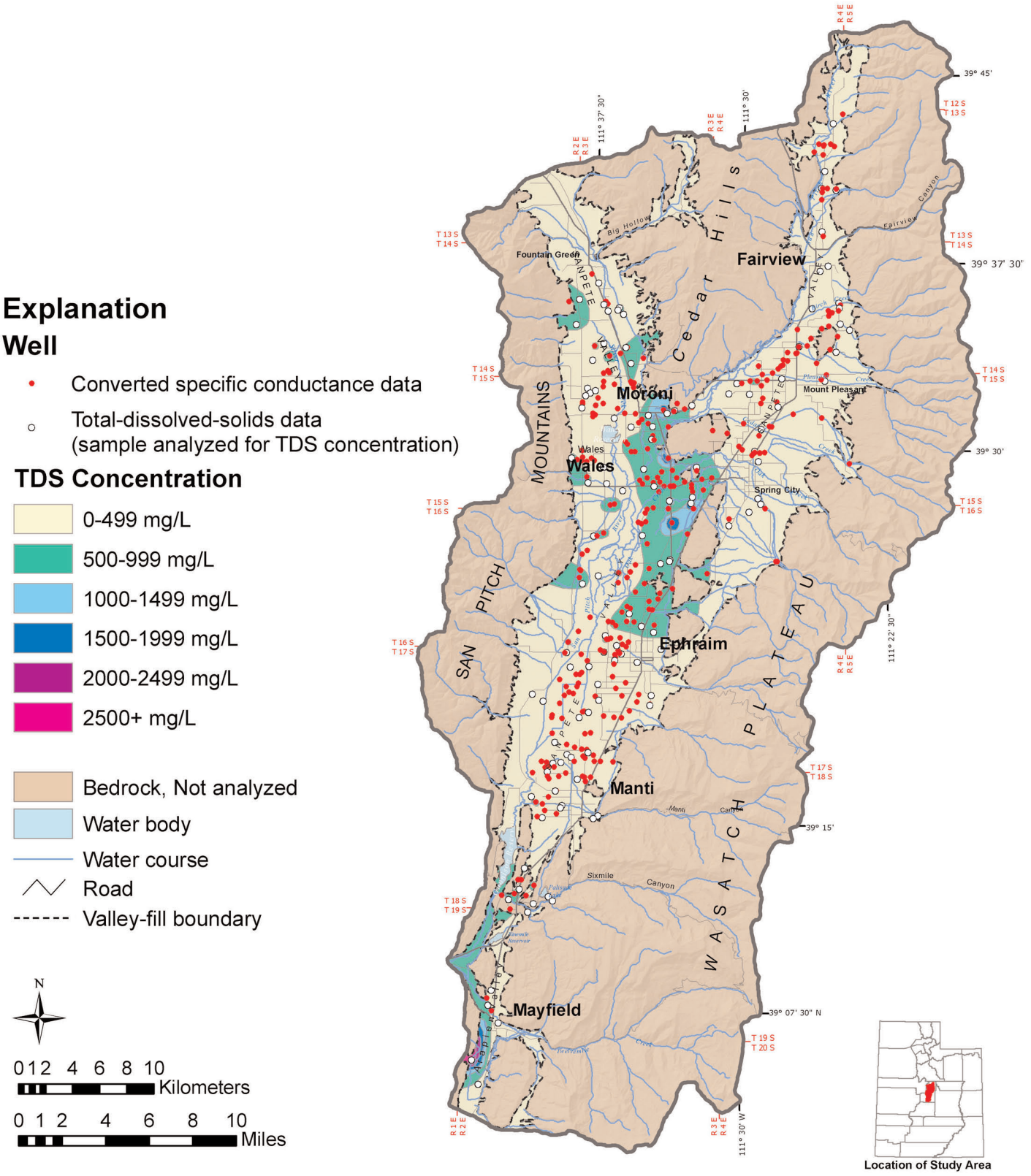

Figure 5. *Total-dissolved-solids concentration for the principal valley-fill aquifer, Sanpete Valley, Sanpete County, Utah (from Lowe and others, 2002).*

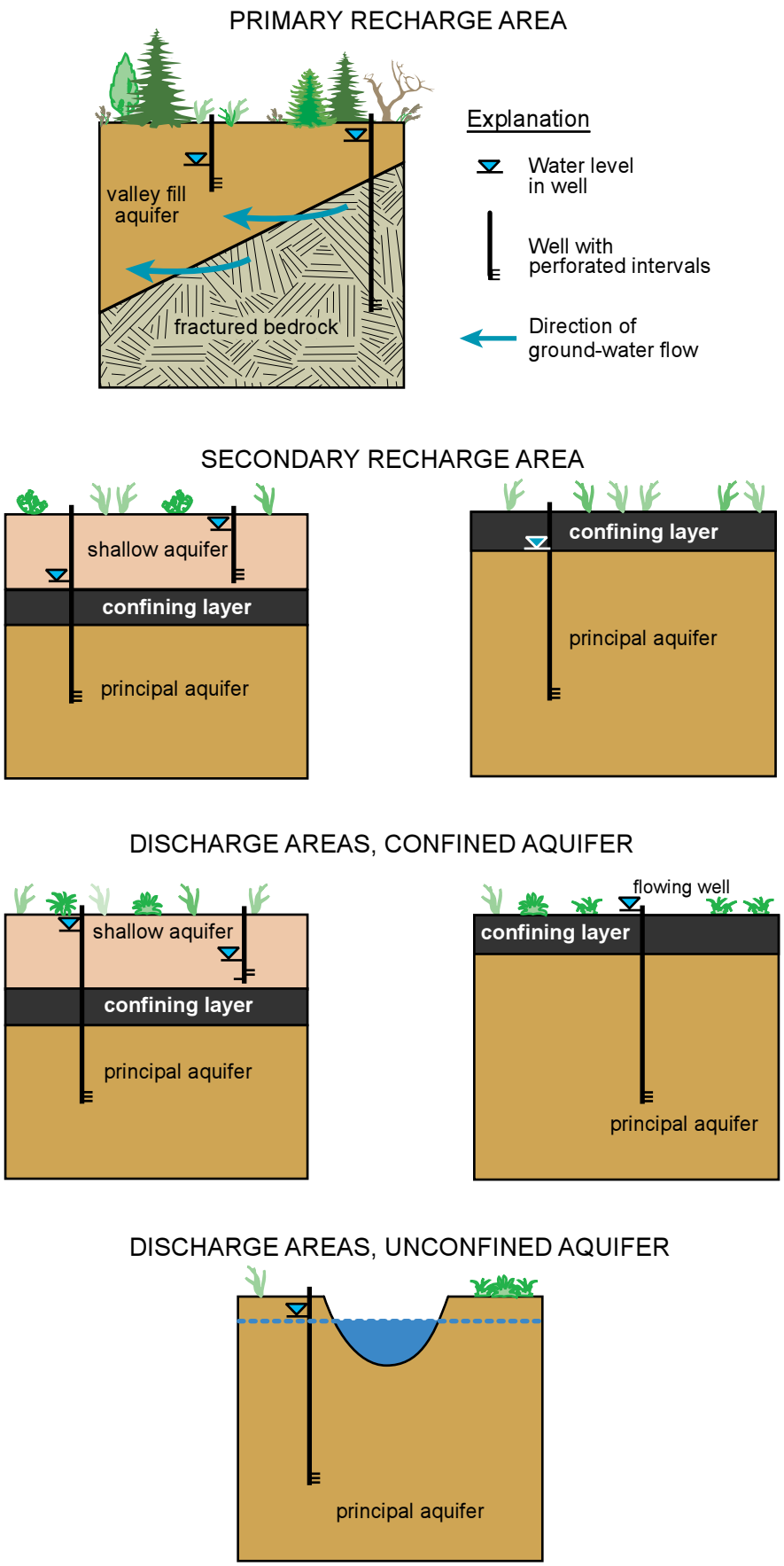

Figure 6. *Relative water levels in wells in recharge and discharge areas (modified from Snyder and Lowe, 1998).*

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 Sanpete 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. 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; Swenson and others, 1981). 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 RF 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 Sanpete Valley, at a scale of 1:24,000. Data include derived values for bulk density, organic carbon fraction, and field capacity (table 2).

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 0.145 to 5.8%
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 0.145 to 5.8%
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 0.145 to 5.8%
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 0.145 to 5.8%
G	Gravel	2.0 and greater (less than 12)	2 (2)	0.145%**

* 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.

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 Sanpete Valley, and variable soil organic carbon content using a water-table depth of 3 feet (1 m). Average organic carbon content in soils in Sanpete Valley is shown in figure 7 and ranges from 0.145 to 5.8%; 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 84. This means the

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

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

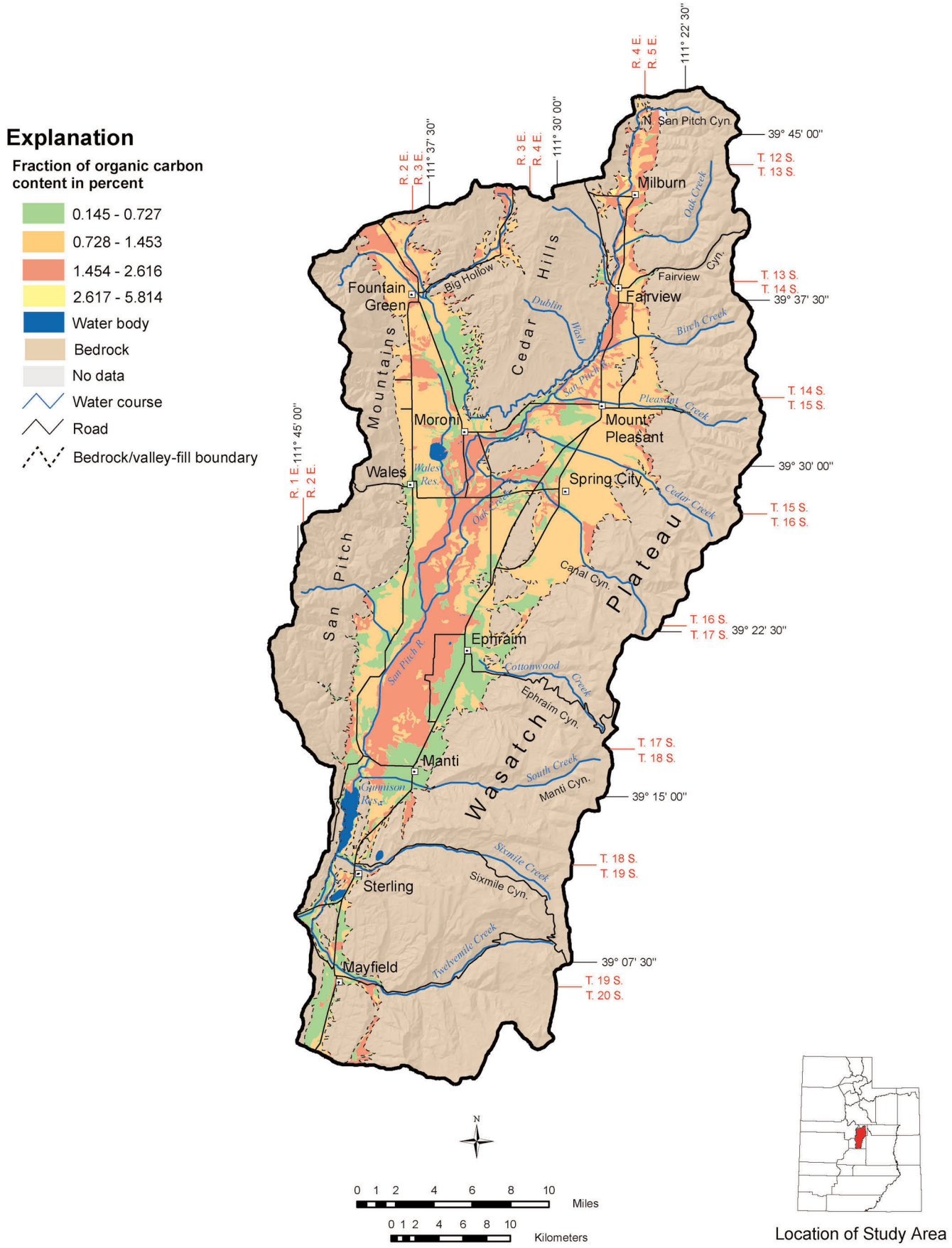

Figure 7. *Average organic carbon content in soils in Sanpete Valley, Sanpete County, Utah (data from National Soil Survey Center, 2005).*

highest relative velocity from our data is 0.7 and the lowest is 0.01; 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 Sanpete Valley, no amount of pesticide will likely reach a depth of 3 feet (1 m) in a one-year period (see attenuation discussion below). From the calculated range of R_F values, we divided pesticide retardation into two ranges for our GIS analysis: 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:

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

where:

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

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

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

Herbicide	Max. Application Rate (lbs. AI** per acre)	Time Interval
Atrazine	2.5	Calendar year
Alachlor	4.05	Pre-emergence
Metolachlor	1.9	Pre-emergence
Simazine	4.0	Pre-emergence

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

Depth to Shallow Ground Water

The closer ground water is to the land surface the more sensitive it is to being degraded by pesticides. Based on soil mottling, water encountered in test pits, or other information, soils having shallow ground water seasonally less than or equal to 3 feet (1 m) deep is one attribute of soil units mapped by the Soil Conservation Service (now Natural Resources Conservation Service; Swenson and others, 1981). We selected 3 feet (1 m) as the depth-to-ground-water attribute used to evaluate sensitivity of geographic areas to

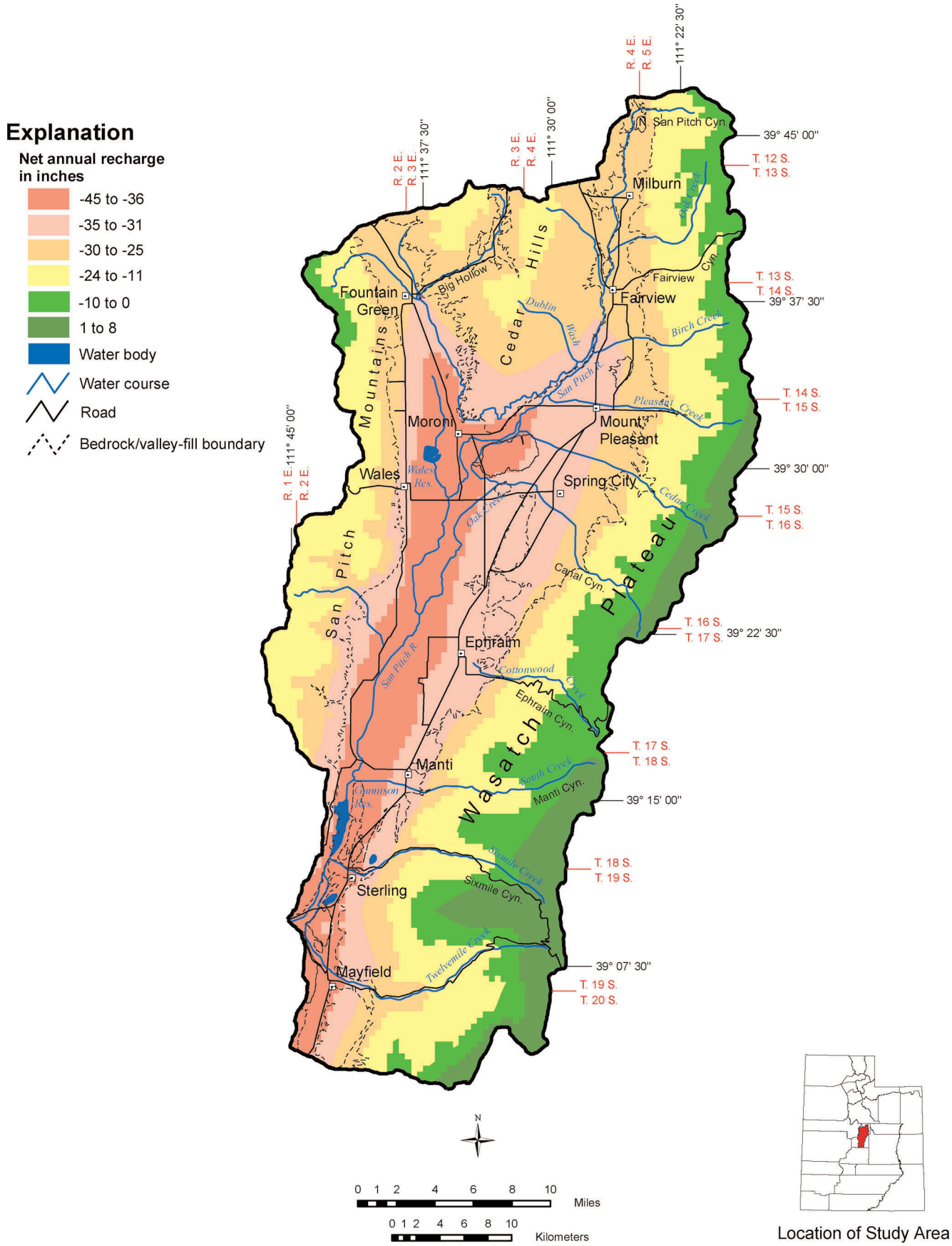

Figure 8. *Net annual ground-water recharge from precipitation in Sanpete Valley, Sanpete County, Utah. Recharge calculated using data from the Utah Climate Center (1991) and Jensen and Dansereau (2001). Although net annual recharge may be negative in some areas, seasonally some recharge from precipitation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

pesticides. For areas where depth-to-ground-water data are not available in GIS format, we applied the less-than-3-feet (1 m) GIS attribute ranking, described below, to be protective of ground-water quality.

GIS Analysis Methods

We characterize pesticide sensitivity (intrinsic susceptibility) as "low," "moderate," or "high" based on the sum of numerical values (rankings) assigned to hydrogeologic setting, soil hydraulic conductivity, soil retardation of pesticides, soil attenuation of pesticides, and depth to shallowest ground-water attributes as shown in table 5. Absolute numerical ranking for each attribute category is arbitrary, but reflects the relative level of importance the attribute plays in determining sensitivity of areas to application of agricultural pesticides; for instance, we believe hydrogeologic setting is the most important attribute with respect to ground-water sensitivity to pesticides, and therefore weighted this attribute three times more heavily than the other attribute categories. A sensitivity attribute of low is assigned when the summed ranking ranges from -2 to 0, a sensitivity attribute of moderate is assigned when the summed ranking ranges from 1 to 4, and a sensitivity attribute of high is assigned when the summed ranking ranges from 5 to 8.

Ground-Water Vulnerability to Pesticide Pollution

Ground-water vulnerability to pesticides is determined by assessing how ground-water sensitivity to pesticides is modified by human activity. In addition to ground-water sensitivity to pesticides, the presence of applied water (irrigation) and crop type are the factors primarily determining ground-water vulnerability to pesticides. Our analysis is based on 1995 Sevier 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 Sanpete 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 Sevier River basin inventory was conducted in 1995 (Utah Division of Water Resources metadata). We used all polygons having standard type codes beginning with IA to produce the irrigated land coverage for this study. These data do not distinguish areas of sprinkler irrigation versus areas of flood irrigation; areas of flood irrigation are likely to be more vulnerable to degradation from pesticides than areas of sprinkler irrigation.

Crop Type

We mapped agricultural lands using the Utah Division of Water Resources 1:24,000-scale Land Use/Water Related Use GIS data set, which includes categories of crop types. Areas of various crop-type categories were mapped from either aerial photographs (pre-2000) or 5-meter (16-ft) resolution infrared satellite data and then field checked (Utah Division of Water Resources metadata). The Sevier River basin inventory was conducted in 1995 (Utah Division of Water Resources metadata). We selected all polygons having standard type codes IA2a1 (corn), IA2a2 (sorghum), and IA2b5 (sweet corn; none in this category were in the data set) to produce the crop-type land coverage for this study, as these are the crop types to which the pesticides addressed are applied in Utah. Although the specific fields growing these crops may vary from year to year, the general areas and average percentages of these crop types likely do not.

Table 5. *Pesticide sensitivity and the attribute rankings used to assign sensitivity for Sanpete Valley, Sanpete County, Utah.*

Pesticide Retardation Factor		Pesticide Attenuation Factor		Hydrogeologic Setting		Soil Hydraulic Conductivity		Depth to Ground Water		Sensitivity	
Attribute	**Ranking**	**Attribute**	**Ranking**	**Attribute**	**Ranking**	**Attribute**	**Ranking**	**Attribute**	**Ranking**	**Attribute**	**Ranking**
High	0	Low	0	Confined Aquifer Discharge Area	-4	Less than1 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

GIS Analysis Methods

We characterize pesticide vulnerability as "low," "moderate," or "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 Sanpete 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 in basin-floor areas (figure 8). Most recharge that occurs from precipitation is principally along the basin margins and likely occurs during spring snowmelt. Pesticides are generally applied after snowmelt. Up to several months may elapse between pesticide application and first irrigation, sufficient time for attenuation to occur before downward migration of pesticides in the vadose zone commences under the influence of irrigation.

Hydrogeologic Setting

Snyder and Lowe (1998) mapped ground-water recharge areas in Sanpete 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 65% of the surface area of the valley-fill aquifer. Secondary recharge areas make up an additional 6% of the surface area of the valley-fill aquifer. Ground-water discharge areas, which provide extensive protection to the principal aquifer from surface contamination from the application of pesticides, make up 29% 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). About 42% of the surface area of the valley-fill aquifer in Sanpete Valley has soil units mapped as having hydraulic conductivity greater than or equal to 1 inch (2.5 cm) per hour (figure 10). About 57% of the surface area of the valley-fill aquifer has soil units mapped as having hydraulic conductivity less than 1 inch (2.5 cm) per hour. About 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. Depth to shallow ground-water data are from the National Soil Survey Center (2005). About 91% of the area overlying the valley-fill aquifer in Sanpete Valley has soil units mapped as having shallow ground water less than or equal to 3 feet (1 m) deep; these areas are primarily in the southern part of the study area (figure 11). Less than 8% 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. About 1% of the surface area of the valley-fill aquifer has soil units for which no SSURGO data exist. Areas without assigned depths to shal-

Table 6. *Pesticide vulnerability and the attribute rankings used to assign vulnerability for Sanpete Valley, Sanpete County, Utah.*

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

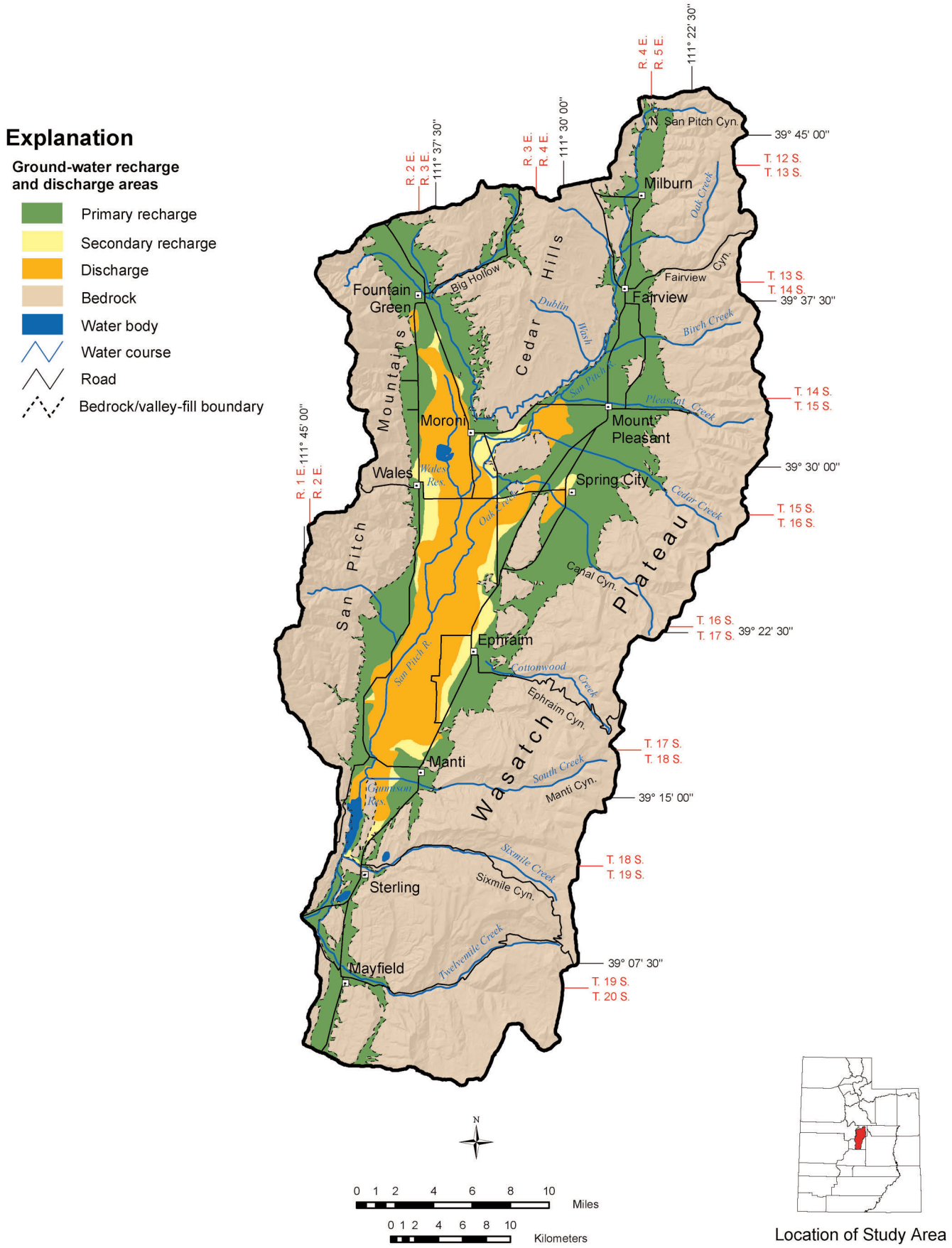

Figure 9. *Recharge and discharge areas in Sanpete Valley, Sanpete County, Utah (from Snyder and Lowe, 1998).*

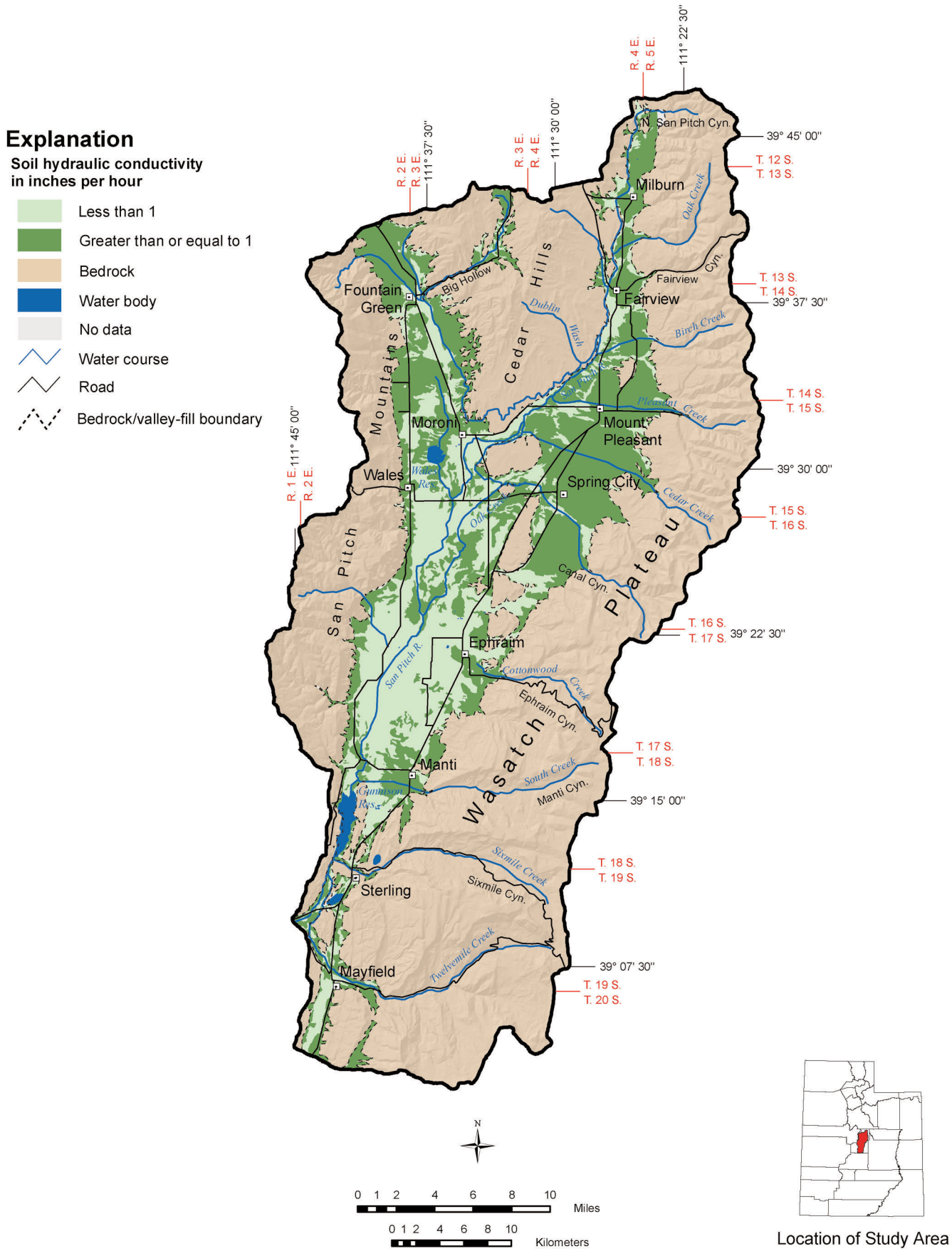

Figure 10. *Soil hydraulic conductivity in Sanpete Valley, Sanpete County, Utah (data from National Soil Survey Center, 2005).*

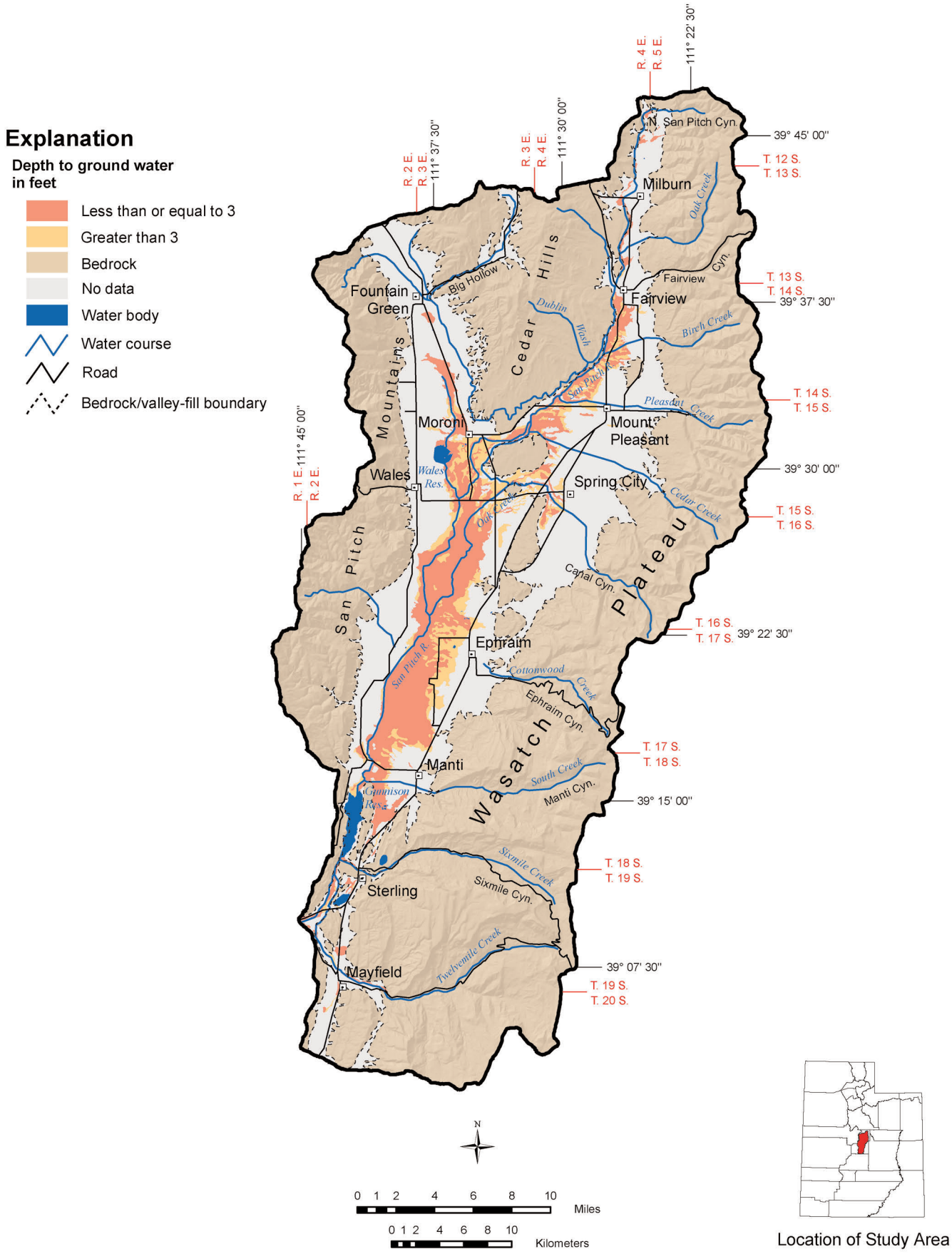

Figure 11. Depth to shallow ground water in Sanpete Valley, Sanpete County, Utah (data from National Soil Survey Center, 2005).

low ground water were grouped with the less than or equal to 3 feet (1 m) depth category for analytical purposes to be protective of water quality.

Pesticide Sensitivity Map

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

About 27% of Sanpete Valley is of low sensitivity (plate 1) because of the presence of protective clay layers and upward ground-water flow gradients (discharge area hydrogeologic setting). Pesticides used in these areas are unlikely to degrade ground water. However, pesticides spilled or misapplied have a much greater potential to contaminate surface water than ground water. Soils on much of the valley-margin alluvial-fan deposits and fluvial deposits in northernmost Sanpete Valley have relatively high hydraulic conductivities. These areas are of high sensitivity and comprise about 63% of the basin-fill aquifer area. The remaining 10% 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 Sanpete 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 Sanpete Valley. About 41% of the valley floor is irrigated cropland. Irrigation is potentially significant because it is a source of ground-water recharge to the valley-fill aquifer system.

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 southern and western parts of the valley-floor area (figure 12). The use of pesticides on corn and sorghum crops increases the vulnerability of areas where these crops are grown from low to moderate.

Pesticide Vulnerability Map

Plate 2 shows ground-water vulnerability to contamination from pesticides of the valley-fill aquifer for Sanpete 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 17% of the surface area of the valley-fill aquifer is mapped as having high vulnerability (plate 2), including areas where soil data are not available. Of particular concern are areas where ground water is shallow, as these are the areas most likely to be impacted by pesticide pollution. Areas of moderate vulnerability coincide, in general, with non-irrigated areas of moderate or high sensitivity, or irrigated areas where ground-water sensitivity to pesticides is low. About 56% of the surface area of the valley-fill aquifer is mapped as having moderate vulnerability. Low-sensitivity areas without irrigated cropland have low vulnerability to contamination associated with application or spilling of pesticides on the land surface. About 27% of the surface area of the valley-fill aquifer is mapped as having low vulnerability.

CONCLUSIONS AND RECOMMENDATIONS

In Sanpete Valley, areas of irrigated land in primary recharge areas with potential shallow depths to ground water, have the highest potential for water-quality degradation associated with surface application of pesticides. However, for the valley-fill deposits, 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.

ACKNOWLEDGMENTS

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

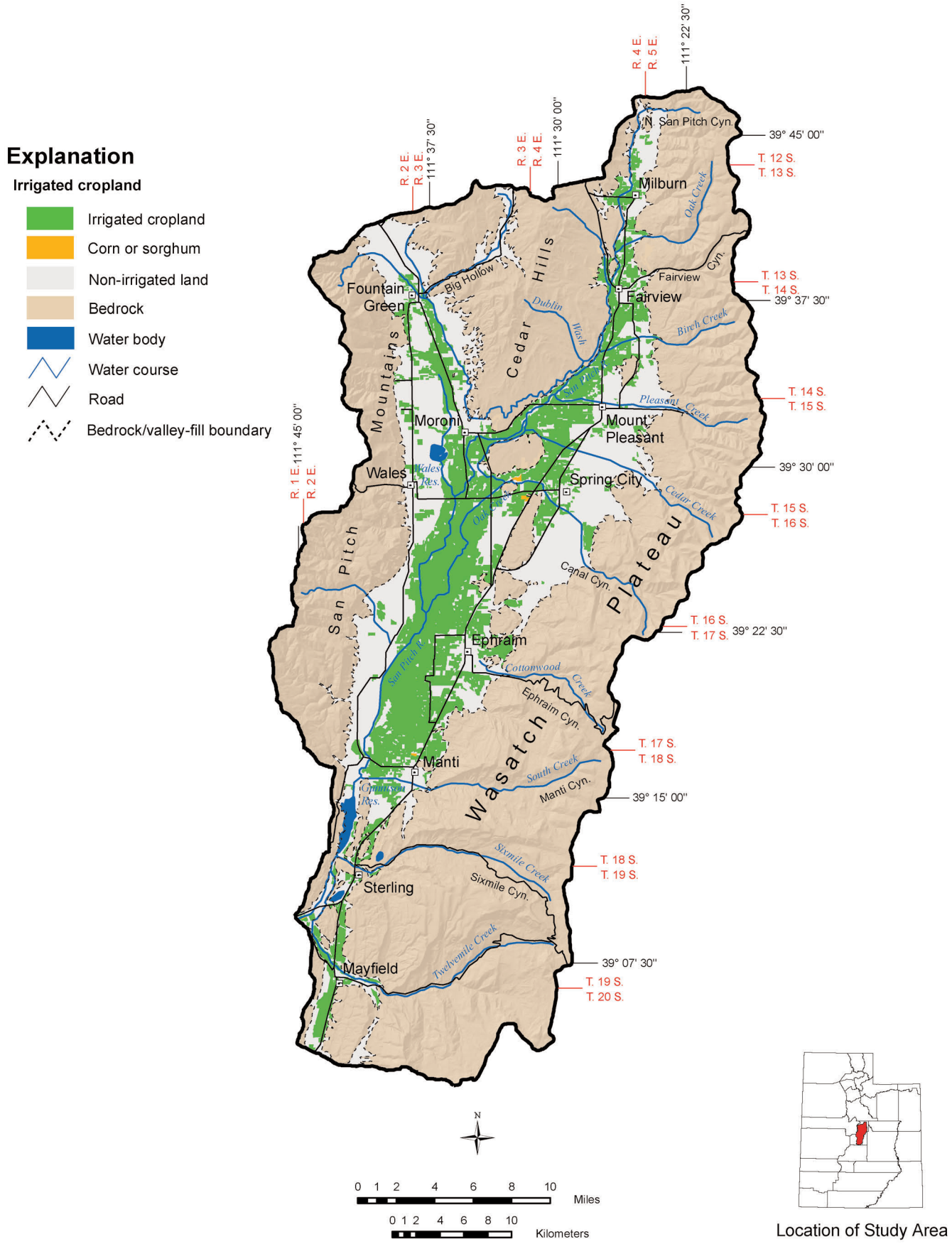

Figure 12. Irrigated and non-irrigated cropland in Sanpete Valley, Sanpete County, Utah (unpublished data from Utah Division of Water Resources).

REFERENCES

Aller, Linda, Bennett, Truman, Lehr, J.H., and Petty, R.J., 1985, DRASTIC–a standardized system for evaluating ground water pollution potential using hydrogeological settings: Ada, Oklahoma, U.S. Environmental Protection Agency, Office of Research and Development, Robert S. Kerr Environmental Research Laboratory, 163 p.

Anderson, P.B., and Susong, D.D., 1995, Hydrogeology of recharge areas of the principal aquifers along the Wasatch Front and adjacent areas, Utah, *in* Lund, W.R., editor, Environmental and engineering geology of the Wasatch Front region: Utah Geological Association Publication 24, p. 249-268.

Anderson, P.B., Susong, D.D., Wold, S.R., Heilweil, V.M., and Baskin, R.L., 1994, Hydrogeology of recharge areas and water quality of the principal aquifers along the Wasatch Front and adjacent areas, Utah: U.S. Geological Survey Water Resources Investigations Report 93 4221, 74 p.

Ashcroft, G.L, Jensen, D.T., and Brown, J.L., 1992, Utah climate: Logan, Utah Climate Center, Utah State University, 125 p.

Banton, O., and Villeneuve, J., 1989, Evaluation of groundwater vulnerability to pesticides—a comparison between the pesticide DRASTIC index and the PRAM leaching quantities: Journal of Contaminant Hydrology, v. 4, p. 285-296.

Black, B.D., Hecker, Suzanne, Hylland, M.D., Christenson, G.E., and McDonald, G.N., 2003, Quaternary fault and fold database and map of Utah: Utah Geological Survey Map 193DM, scale 1:500,000.

Cohen, S.Z., Creeger, S.M., Carsel, R.F., and Enfield, C.G., 1984, Treatment and disposal of pesticide wastes: American Chemical Society Symposium Series No. 259, p. 297-325.

Cohen, S.Z., Eiden, C., and Corber, M.N., 1986, Monitoring ground water for pesticides: American Chemical Society Symposium Series No. 315, p. 170-196.

Demographic and Economic Analysis Section, 2000, Utah data guide, summer 2000: Salt Lake City, Utah Governor's Office of Planning and Budget, 16 p.

—2006, Utah data guide, winter 2006: Salt Lake City, Utah Governor's Office of Planning and Budget, 12 p.

Environmental Defense Fund, 1997, Twenty-five years after DDT ban, bald eagles, osprey numbers soar: Press release dated June 13, 1997, 2 p.

Fong, A.W., 1991, Fountain Green South quadrangle, Juab and Sanpete Counties, Utah: Utah Geological Survey Open-File Report 204, 96 p., scale 1:24,000.

Freeze, A.R., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice Hall, Inc., 604 p.

Gilliland, W.N., 1952, Another Tertiary crustal disturbance in central Utah: American Association of Petroleum Geologists Bulletin, v. 36, p. 1461-1464.

—1963, Sanpete-Sevier Valley anticline of central Utah: Geological Society of America Bulletin, v. 74, p. 115-123.

Hecker, Suzanne, 1993, Quaternary tectonics of Utah with emphasis on earthquake-hazard characterization: Utah Geological Survey Bulletin 127, 157 p.

Horns, D.M., 1995, Nitrate contamination of the Moroni, Utah municipal water supply and hydrologic control of nitrate contamination, *in* Lund, W.R., editor, Environmental and engineering geology of the Wasatch Front region: Utah Geological Association Publication 24, p. 431-442.

Jensen, D.T., and Dansereau, D.A., 2001, Normal annual evapotranspiration 1971-2000: Logan, Utah Climate Center, Utah State University, map and data set on CD-ROM.

Lawton, T.F., 1985, Style and timing of frontal structures, thrust belt, central Utah: American Association of Petroleum Geologists Bulletin, v. 69, p. 1145-1159.

Lawton, T.F., Sprinkel, D.A., DeCelles, P.G., Mitra, Gautam, Sussman, A.J., and Weiss, M.P., 1997, Stratigraphy and structure of the Sevier thrust belt and proximal foreland-basin system in central Utah–a transect from the Sevier Desert to the Wasatch Plateau, *in* Link, P.K., and Kowallis, B.J., editors, Mesozoic to Recent geology of Utah: Brigham Young University Geology Studies, v. 42, part 2, p. 33-67.

Lowe, Mike, and Sanderson, I.D., 2003, Ground-water sensitivity and vulnerability to pesticides, the southern Sevier Desert and Pahvant Valley, Millard County, Utah: Utah Geological Survey Miscellaneous Publication 03-1, 28 p., scale 1:380,160.

Lowe, Mike, and Snyder, N.P., 1996, Protecting ground water at its source through recharge-area mapping: Utah Geological Survey, Survey Notes, v. 28, no. 1, p. 6-7.

Lowe, Mike, Wallace, Janae, and Bishop, C.E., 2002, Water-quality assessment and mapping for the principal valley-fill aquifer in Sanpete Valley, Sanpete County, Utah: Utah Geological Survey Special Study 102, 91 p., scale 1:100,000, CD-ROM.

Lowe, Mike, Wallace, Janae, Snyder, N.P., and Bishop, C.E., 1999, Recharge and discharge areas for several valley-fill aquifers in Utah, and their relation to nonpoint-source contamination [abs.]: Association of Engineering Geologists 42nd Annual Meeting Program with Abstracts, Salt Lake City, Utah, p. 75.

Marshall, T.J., and Holmes, J.W., 1988, Soil physics, second edition: New York, Cambridge University Press, 374 p.

National Soil Survey Center, 2005, Soil Survey Geographic (SSURGO) database for Sanpete Valley area, Utah, parts of Utah and Sanpete Counties: Online, http://soildatamart.nrcs.usda.gov/Metadata.aspx?Survey=UT627&UseState=UT, accessed June 7, 2006.

Okosoni, Kendra, and Bate, Roger, 2001, When politics kills–Malaria and the DDT story: Competitive Enterprise Institute, update article dated March 5, 2001, 3 p.

Quilter, M.C., 2004, 2003 State of Utah ground-water program: Salt Lake City, unpublished Utah Department of Agriculture and Food report, CD-ROM, 148 p.

Rao, P.S.C., Hornsby, A.G., and Jessup, R.E., 1985, Indices for ranking the potential for pesticide contamination of ground water: Soil and Crop Science Society of Florida Proceedings, v. 44, p. 1-8.

Richardson, G.B., 1907, Underground water in Sanpete and central Sevier Valleys, Utah: U.S. Geological Survey Water-Supply Paper 199, 63 p.

Robinson, G.B., Jr., 1968, Selected hydrologic data San Pitch River drainage basin, Utah: U.S. Geological Survey Utah Basic-Data Release No. 14, 44 p., scale 1:250,000.

—1971, Ground-water hydrology of the San Pitch River drainage basin, Sanpete County, Utah: U.S. Geological Survey Water-Supply Paper 1896, 80 p., scale 1:125,000.

Saxton, K.E., undated, Soil texture triangle hydraulic properties calculator: Online, http://wilkes-fs1.wilkes.edu/~boram/grphtext.htm, accessed February 24, 2006.

Siegel, D.I., 2000, Pesticides in groundwater–vulnerability, transport and fate: Ostrander, Ohio, Environmental Education Enterprises, Inc., short course, 259 p.

Snyder, N.P., and Lowe, Mike, 1996, Recharge and discharge areas for the principal valley-fill aquifer, Sanpete Valley, Sanpete County, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 28, p. 38.

—1998, Map of recharge areas for the principal valley-fill aquifer, Sanpete Valley, Sanpete County, Utah: Utah Geological Survey Map 174, 21 p., scale 1:125,000.

Spieker, E.M., 1946, Late Mesozoic and early Cenozoic history of central Utah: U.S. Geological Survey Professional Paper 250-D, p. 117-160.

—1949a, The transition between the Colorado Plateaus and the Great Basin in central Utah: Utah Geological Society Guidebook to the Geology of Utah, No. 4, 106 p., scale approximately 1:125,000.

—1949b, Sedimentary facies and associated diastrophism in the Upper Cretaceous of central and eastern Utah: Geological Society of America Memoir 39, p. 55-81.

Stokes, W.L., 1977, Subdivisions of the major physiographic provinces in Utah: Utah Geology, v. 4, no. 1, p. 1 17.

Swenson, J.L., Jr., Beckstrand, Delyle, Erickson, D.T., McKinley, Calvin, Shiozaki, J.J., and Tew, Ronald, 1981, Soil survey of Sanpete Valley area–parts of Utah and Sanpete Counties: U.S. Department of Agriculture Soil Conservation Service and U.S. Department of Interior Bureau of Land Management in cooperation with the Utah Agricultural Experiment Station and Utah Department of Wildlife Resources, 179 p., scale 1:24,000.

U.S. Environmental Protection Agency, 2006, Current drinking water standards: Online, http://www.epa.gov/safewater/mcl.html, accessed February 6, 2006.

Utah Climate Center, 1991, Normal annual precipitation 1961-1990: Logan, Utah Climate Center, Utah State University, scale 1:500,000.

Utah Department of Agriculture and Food, 1997, Utah ground water/pesticide state management plan: Salt Lake City, unpublished Utah Department of Agriculture and Food report, 129 p.

Utah Division of Water Resources, 1999, Utah state water plan, Sevier River basin: Salt Lake City, Utah Department of Natural Resources, variously paginated.

Waddell, K.M., Gerner, S.J., Thiros, S.A., Giddings, E.M., Basken, R.L., Cederberg, J.R., and Albano, C.M., 2004, Water quality in the Great Salt Lake basins, Utah, Idaho, and Wyoming, 1998-2001: U.S. Geological Survey Circular 1236, 36 p.

Wallace, Janae, and Lowe, Mike, 1997, Ground-water-quality mapping for the unconsolidated valley-fill aquifer, Sanpete Valley, Sanpete County, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. A-386.

—2005, Petition for ground-water quality classification, Sanpete Valley, Sanpete County, Utah: Salt Lake City, unpublished Utah Geological Survey petition to the Utah Water Quality Board, 36 p., scale 1:100,000.

Weber, J.B., 1994, Properties and behavior of pesticides in soil, *in* Honeycutt, R.C., and Shabacker, D.J., editors, Mechanisms of pesticide movement into ground water: Boca Raton, Florida, CRC Press, p. 15-41.

Weiss, M.P., 1982, Structural variety on the east front of the Gunnison Plateau, central Utah, *in* Nielson, D.L., editor, Overthrust belt of Utah: Utah Geological Association Publication 10, p. 49-63.

Weiss, M.P., and Sprinkel, D.A., 2000, Interim geologic map of the Manti 7.5′ quadrangle, Sanpete County, Utah: Utah Geological Survey Open-File Report 373, 37 p., scale 1:24,000.

Wilberg, D.E., and Heilweil, V.M., 1995, Hydrology of Sanpete Valley, Sanpete and Juab Counties, Utah, and simulation of ground-water flow in the valley-fill aquifer: Utah Division of Water Rights Technical Publication No. 113, 121 p., scale 1:100,000.

Witkind, I.J., and Weiss, M.P., 1991, Geologic map of the Nephi 30′ x 60′ quadrangle, Carbon, Emery, Juab, Sanpete, Utah, and Wasatch Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1937, 16 p., scale 1:100,000.

Witkind, I.J., Weiss, M.P., and Brown, T.L., 1987, Geologic map of the Manti 30′ x 60′ quadrangle, Carbon, Emery, Juab, Sanpete, and Sevier Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1631, scale 1:100,000.