Ground-Water Sensitivity and Vulnerability to Pesticides, Central Virgin River Basin, Washington and Iron Counties, Utah

by

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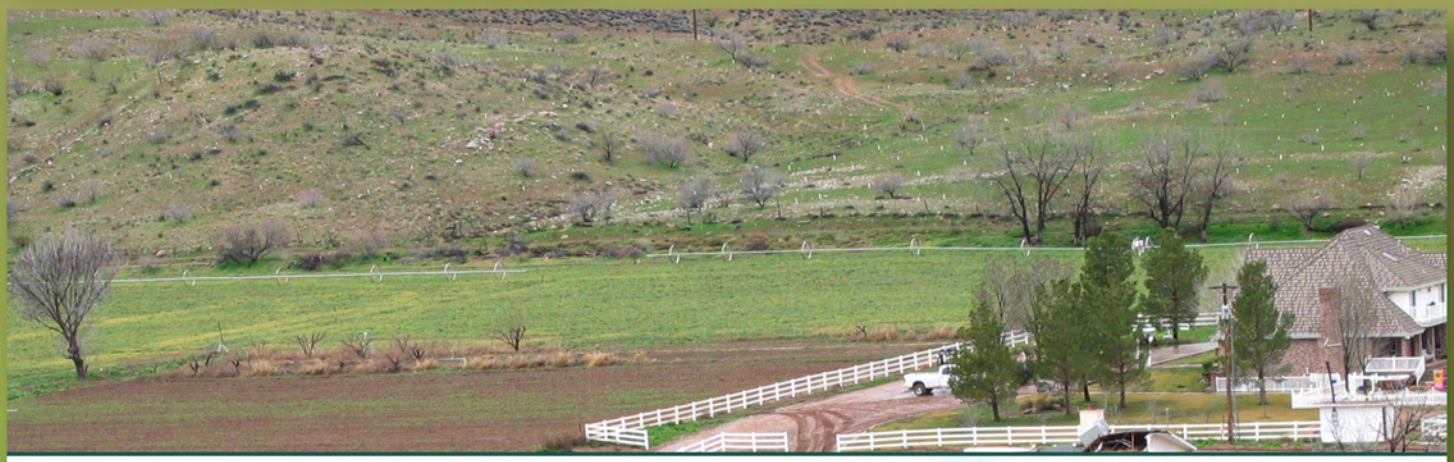

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Cover photos:

Top photo: Vineyards in Washington City, Washington County, Utah (Utah Division of Water Resources digital photograph database) and concrete-lined irrigation ditch next to alfalfa field near Washington City (photo by Ron Ollis).

Bottom photo: View of agricultural areas looking down from Santa Clara Heights (photos by Janice Hayden).

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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 the central Virgin River basin, Washington and Iron Counties, Utah. We used existing data to produce pesticide sensitivity and vulnerability maps by applying an attribute ranking system specifically tailored to the western United States using Geographic Information System analysis methods. This is a first attempt at developing pesticide sensitivity and vulnerability maps; better data and tools may become available in the future so that better maps can be produced.

Ground-water sensitivity (intrinsic susceptibility) to pesticides is determined by assessing natural factors favorable or unfavorable to the degradation of ground water by any pesticides applied to or spilled on the land surface. Hydrogeologic setting (vertical ground-water gradient and presence or absence of confining layers), soil hydraulic conductivity, retardation of pesticides, attenuation of pesticides, and depth to ground water are the factors primarily determining ground-water sensitivity to pesticides in the basin-fill deposits of the central Virgin River basin. Much of the central Virgin River basin has high ground-water sensitivity to pesticides due to a lack of protective clay layers within the basin-fill deposits.

Ground-water vulnerability to pesticides is determined by assessing how ground-water sensitivity is modified by human activity. Ground-water sensitivity to pesticides, the presence of applied water (irrigation), and crop type are the three factors generally determining ground-water vulnerability to pesticides in the basin-fill deposits of the central Virgin River basin. Areas of high vulnerability are located primarily in areas where irrigation occurs and ground-water sensitivity to pesticides is high. Of particular concern are areas where influent (losing) streams originating in mountainous areas cross the basin margins; streams in these areas are the most important source of recharge to the basin-fill aquifers, and efforts to preserve water quality in streams at these points would help to preserve ground-water quality in the central Virgin River basin.

Because of relatively high retardation (long travel times of pesticides in the vadose zone) and attenuation (short half-lives) of pesticides in the soil environment, pesticides applied to fields in the central Virgin River basin likely do not present a serious threat to ground-water quality. To verify this conclusion, future ground-water sampling by the Utah Department of Agriculture and Food in the central Virgin River basin should be concentrated in areas of high sensitivity or vulnerability. Sampling in the central area of the basin characterized by low and moderate sensitivity and vulnerability should continue, but at a lower density than in the areas of higher sensitivity and vulnerability.

INTRODUCTION

Background

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

This report and accompanying maps provide federal, state, and local government agencies and agricultural pesticide users with a base of information concerning the sensitivity and vulnerability of ground water to agricultural pesticides in the basin-fill deposits of the central Virgin River basin, Washington and Iron Counties, Utah (figure 1). Geographic variation in sensitivity and vulnerability, together with hydrologic and soil conditions that cause these variations, are described herein; plates 1 and 2 show the sensitivity and vulnerability, respectively, of the unconsolidated basin-fill aquifers in the central Virgin River basin to agricultural pesticides.

Sensitivity to pesticides is determined by assessing natural factors favorable or unfavorable to the degradation of ground water by pesticides applied or spilled on the land surface, whereas vulnerability to pesticides is determined by assessing how ground-water sensitivity is modified by human activity. For this study, sensitivity incorporates hydrogeologic setting, including vertical ground-water gradient, depth to ground water, and presence or absence of confining layers, along with the hydraulic conductivity, bulk density, organic carbon content, and field capacity of soils. Sensitivity also includes the influence of pesticide properties such as the capacity of molecules to adsorb to organic carbon in soil and the half-life of a pesticide under typical soil conditions. Vulnerability includes human-controlled factors such as whether agricultural lands are irrigated, crop type, and type of pesticide applied.

Purpose and Scope

The purpose of this project is to investigate sensitivity and vulnerability of ground-water resources in the basin-fill deposits of the central Virgin River basin, Utah, to contamination from agricultural pesticides. This information may be used by federal, state, and local government officials and pesticide users to reduce the risk of ground-water pollution from pesticides, and to focus future ground-water quality monitoring by the Utah Department of Agriculture and Food.

The project scope is limited to the use and interpretation of existing data to produce pesticide sensitivity and vulnerability maps through the application of Geographic Information System (GIS) analysis methods. No new fieldwork was conducted nor data collected as part of this project. This is a first attempt at developing pesticide sensitivity and vulnerability maps; better data and tools may become available in the future so that better maps can be produced. For example, maps that show the quantity of recharge to aquifers in Utah are not available. We used a GIS coverage developed by subtracting average annual evapotranspiration from average annual precipitation to estimate average annual recharge from precipitation. This coverage provides a rough estimate of the largely elevation-controlled distribution of ground-water recharge, but does not account for recharge at low elevations during spring snowmelt or during prolonged storm events. Additionally, the digital soil maps used in this study are too generalized to accurately depict areas of soil versus bedrock outcrop. Because organic carbon in soils is one controlling factor determining the potential for pesticides to reach ground water, the higher sensitivity and vulnerability of rock outcrop areas locally may not be reflected in our maps. To produce these maps, we needed to make some arbitrary decisions regarding the quality and types of data available based on our knowledge of the hydrogeology of the area; for example, we selected 3 feet (1 m) as the reference depth for soils for applying pesticide retardation and attenuation equations.

GENERAL DISCUSSION OF PESTICIDE ISSUE

The information presented in this section was 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

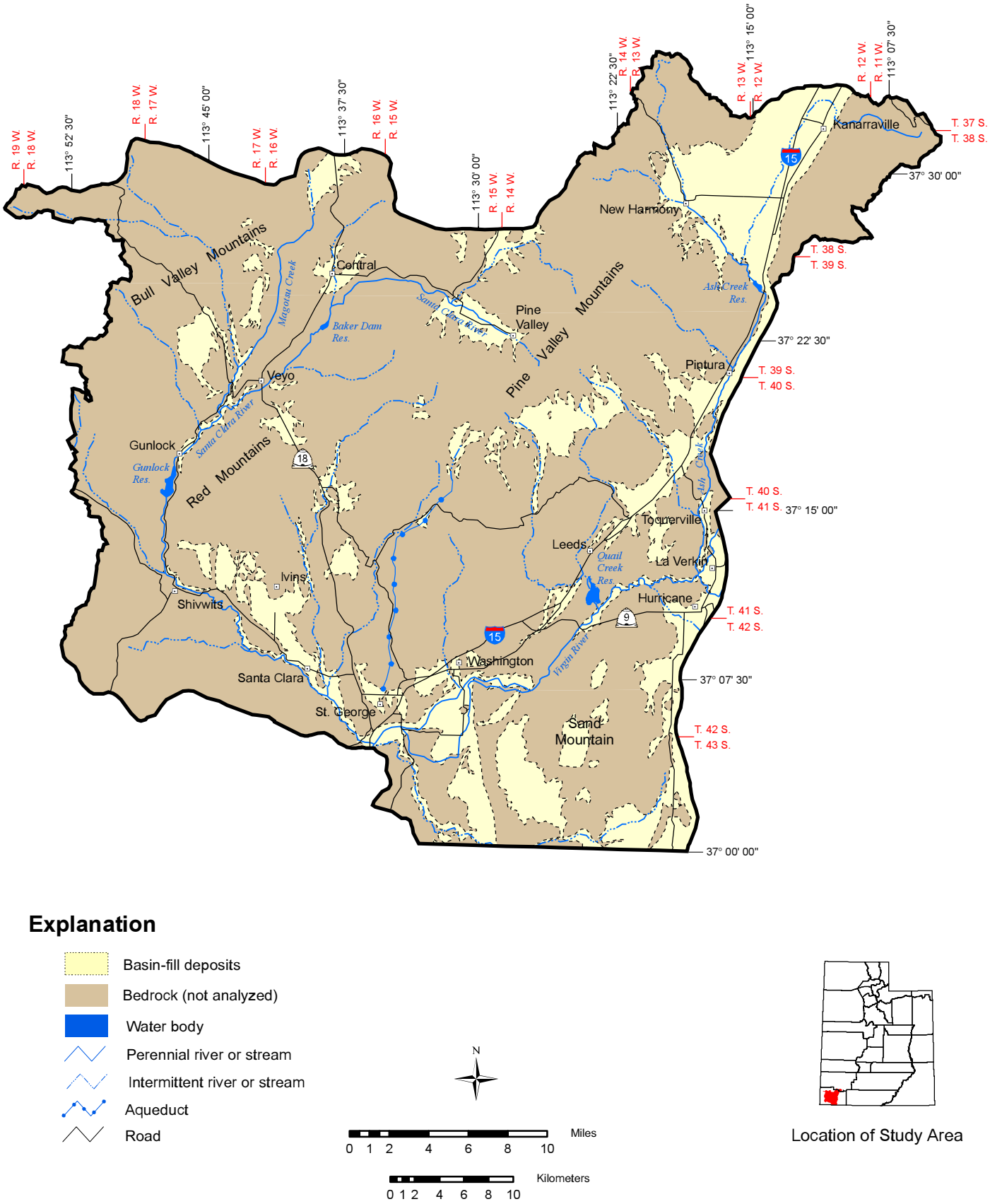

Figure 1. *Central Virgin River basin, Washington and Iron Counties, Utah, study area.*

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.

Table 1. *Maximum contaminant levels for pesticides in drinking water.*

Contaminant	Maximum Contaminant Level (MCL)	
Alachlor	0.002 mg/L	2 µg/L
Atrazine	0.003 mg/L	3 µg/L
Metolachlor	—	—
Simazine	0.004 mg/L	4 µg/L

Standards for crop irrigation and livestock watering have not been established. However, some crops would require even higher standards for herbicides than those set for human consumption to avoid crop damage.

Under Utah's PMP, if a pesticide is detected in ground water and confirmed by subsequent sampling and analysis as being greater than 25 percent of the established MCL, an administrative process begins that may eventually result in regulation or revocation of the pesticide's registration for use in the affected area as delineated in this report and the accompanying maps.

Ground-Water Contamination by Pesticides

The interplay between hydrogeologic setting, ground-water recharge, soil conditions, pesticide use, and pesticide behavior in the vadose zone determines whether ground water in a particular area is likely to become contaminated with pesticides. The type of pesticide being applied is a critical factor. Although pesticide use is highly variable and cannot be precisely monitored, the distribution of crop types and the quantities of pesticides sold to applicators may be used to obtain a general approximation. Ultimately, the only reliable method for detecting ground-water contamination by pesticides is an adequate ground-water monitoring program, with special emphasis on areas where these pesticides are being applied and where such application is most likely to impact ground water.

Vulnerability is determined on the basis of whether irrigation is used, what crops are being grown, and which pesticides are generally applied to particular crops. Areas of corn and sorghum production, in particular, would indicate areas where atrazine and similar herbicides might be used. Pesticide application should be monitored more closely in areas of corn and sorghum production than in other areas to ensure that these herbicides are not impacting ground water.

Mechanisms of Pollution

In areas of the central Virgin River basin where ground water is unconfined, degradation of the basin-fill aquifers by pesticides would occur whenever chemicals infiltrate through the vadose zone to the aquifer. In confined aquifer settings, pesticides would need to find pathways through confining layers to cause water-quality degradation. Thus, the ability of soils at the application site to retard or attenuate the downward movement of pesticides, and the hydrogeologic setting where the pesticides are applied, have a fundamental effect on the likelihood that a pesticide will travel downward to the basin-fill aquifer. Surface irrigation could cause a decrease in the retardation and attenuation of pesticides in some settings—especially in areas where corn or sorghum are grown—because the types of pesticides evaluated in this study are commonly applied to those crops. Withdrawal of water from the basin-fill aquifers via water wells could cause changes in vertical head gradient that may increase the potential for water-quality degradation. Also, the wells themselves, if not properly constructed, could provide pathways for pesticides to reach the basin-fill aquifers.

PREVIOUS STUDIES

Cordova and others (1972) studied the principal aquifers in the central Virgin River basin and included information on ground-water recharge, movement, discharge, chemical quality, and use. Cordova (1978) conducted a study that focused on the Navajo Sandstone in the central Virgin River basin, and included information from aquifer tests and a hydrologic budget. Clyde (1987) compiled a regional report for ground-water resources in the central Virgin River basin that included an evaluation for the potential development of ground-water resources. Jensen and Lowe (1992) and Jensen and others (1997) conducted a detailed evaluation of the hydrogeology of Sheep Spring. Hansen, Allen, and Luce, Inc., (1998) recommended maximum septic-tank densities to be protective of ground-water quality for Washington County. Hurlow (1998) evaluated the relation of geology to ground-water conditions in the central Virgin River basin; this study also included the Ash Creek drainage basin and much of western Washington County. Heilweil and others (2000) studied the geohydrology of and produced a numerical simulation for ground-water flow for the central Virgin River basin. Hansen, Allen, and Luce, Inc., (2005) prepared a petition to the Utah Water Quality Board on behalf of the Washington County Water Conservancy District to classify the ground-water quality of the Navajo/Kayenta and upper Ash Creek aquifers in Washington County.

Mortensen and others (1977) mapped soils (scale 1:20,000) for Washington County. Regional geologic maps covering the study area include the geologic map of the Pine Valley Mountains by Cook (1957), a geologic atlas of Washington County by Cook (1960), and geologic map of the central Virgin River basin by Hurlow (1998). Geologic quadrangle maps at 1:24,000 scale are shown on figure 2.

SETTING

Physiography

The central Virgin River basin is located in southwest Utah in the transition zone between the Basin and Range and Colorado Plateau physiographic provinces (Cook, 1960; Stokes, 1977; Anderson and Mehnert, 1979); the St. George basin in the southeast part of the study area is considered to be part of the Colorado Plateau physiographic province (Stokes, 1977). The study area is bounded on the north by Iron County (but includes the Iron County portion of New Harmony basin), on the east by the Hurricane Cliffs, on the south by Arizona, and on the west by the Beaver Dam and Bull Valley Mountains (figure 1). The principal basin-fill aquifers are found in the St. George basin, and in the New Harmony basin and Ash Creek valley in the northeast part of the study area (figure 1). Elevations range from about 10,300 feet (3100 m) in the Pine Valley Mountains to about 2400 feet (730 m) in the southwestern part of the St. George basin. The Virgin River and its tributaries, Ash Creek and the Santa Clara River, are the principal drainages in the study area (figure 1).

The mountains that surround the central Virgin River basin are composed of sedimentary and igneous rocks that range in age from Paleozoic to Tertiary. The eastern side of the Beaver Dam Mountains includes primarily Cambrian to Triassic sedimentary sedimentary rocks. The Bull and Pine Valley Mountains consists of mostly Tertiary and Cretaceous igneous and sedimentary rocks. Most of the bedrock in the central, south-central, and southeastern part of the study area includes Permian to Cretaceous sedimentary rocks, with the Navajo Sandstone, the principal aquifer in the study area, comprising about 23 percent of the surface area (Cordova, 1978).

Rock units in the study area underwent compressional deformation in the Late Cretaceous to early Eocene, resulting in a variety of structures including the Square Top thrust fault and many synclines and anticlines, including the Virgin anti-

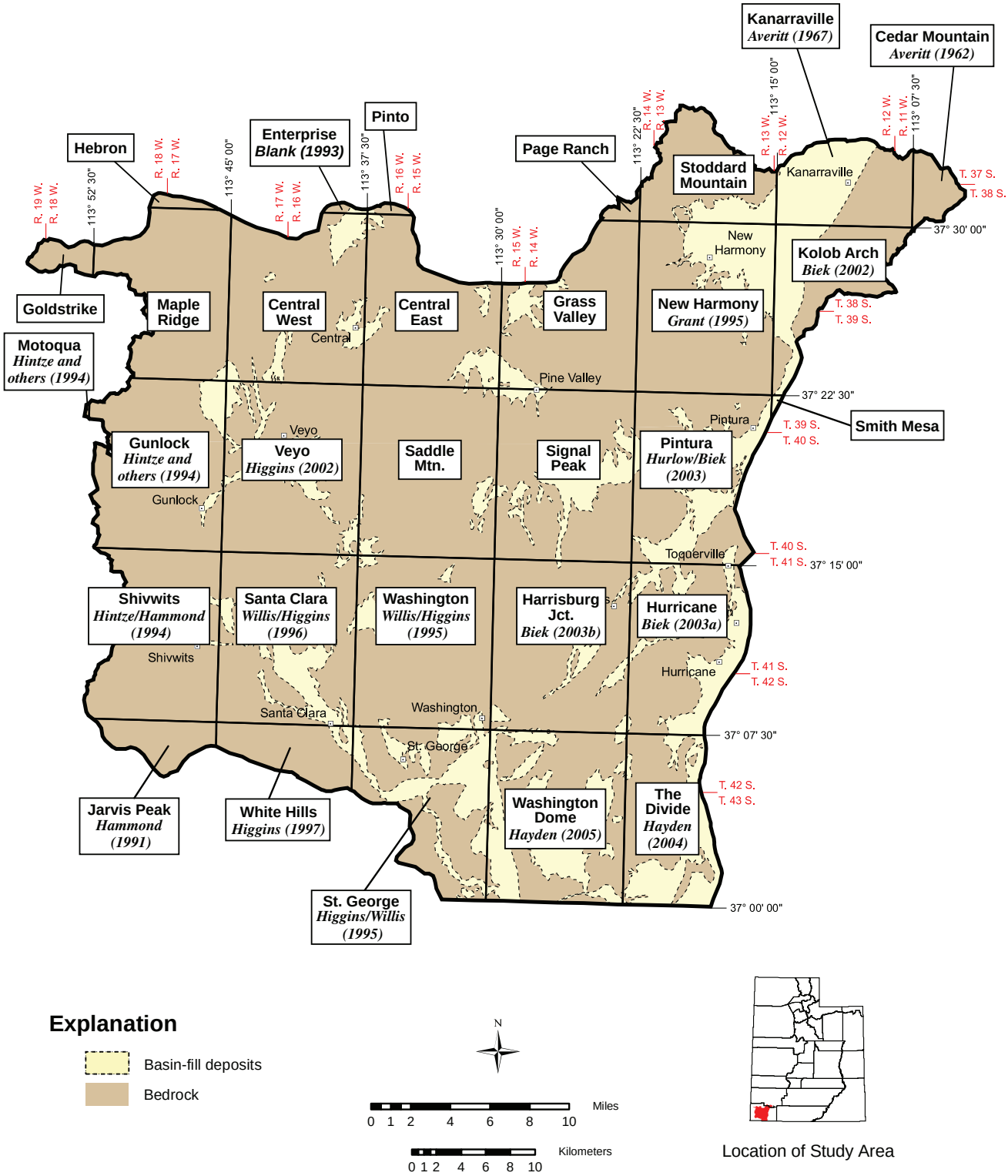

Figure 2. *Existing 1:24,000-scale geologic and topographic quadrangle maps for the cenral Virgin River basin area of Washington and Iron Counties, Utah.*

cline (Hurlow, 1998). Plutonic intrusions occurred in the study area during the Late Cretaceous to Miocene (Cook, 1960; McKee and others, 1997). During Miocene to Holocene time, extensional deformation resulted in normal faults, including the Gunlock, Washington, and Hurricane faults (Hurlow, 1998). These structures locally disrupt the mostly gently dipping Paleozoic and Mesozoic sedimentary rocks in the southern part of the study area. Volcanic deposits were extruded into the study area during Oligocene to Miocene time, and again during Pliocene to Pleistocene time (Rowley and others, 1979, McKee and others, 1997; Hurlow, 1998).

Climate

Six weather stations in the study area provide climatic data for different periods (Enterprise, 1954-92 period; New Harmony, 1948-92 period; Veyo Powerhouse, 1957-1992 period; Gunlock Powerhouse, 1948-1992 period; La Verkin, 1950-1992 period; and St. George, 1928-92 period), but only New Harmony, Veyo Powerhouse, La Verkin, and St. George provide normal climatic data for the 1961-90 period. Because the normal climatic information represents a more complete data set, those values (taken from Ashcroft and others, 1992) are discussed herein. Temperatures reach a normal minimum of 19.8°F (-6.8°C) in January at New Harmony and a normal maximum of 102.2°F (39.0°C) in July at St. George. The normal mean annual temperature ranges from 51.8°F (11.0°C) at New Harmony to 62.3°F (16.8°C) at St. George. Normal annual precipitation ranges from 8.06 inches (20.47 cm) at St. George to 18.37 inches (46.66 cm) at New Harmony. Normal annual evapotranspiration ranges from 49.56 inches (125.88 cm) at New Harmony to 62.86 (159.66 cm) at St. George. The average number of frost-free days ranges from 151 at New Harmony to 216 at St. George.

Population and Land Use

From 1990 to 2001, population in Washington County increased from 48,988 to 95,584, the highest average annual rate of population increase in Utah at 6.9 percent (Demographic and Economic Analysis Section, 2002). The projected population for Washington County by 2020 is estimated at 353,922 (Demographic and Economic Analysis Section, 2005). Most Washington County residents live in the central Virgin River basin, and residential use is the primary land use for privately owned property (Utah Reach, 2005). The dominant industries are tourism, retirement living, and golf (Utah Reach, 2005). Service and trade industries are the largest sources of employment in Washington County (Utah Reach, 2005).

GROUND-WATER CONDITIONS

Basin-Fill Aquifers

Unconsolidated basin fill covers about 20 percent of the surface area of the central Virgin River basin, and in 1970 supplied about 80 percent of the water discharged by wells (Cordova and others, 1972). By 1997, nearly all of the public-supply wells in Washington County were screened in the Navajo Sandstone (Hurlow, 1998); fractured rock aquifers are not evaluated as part of our study. Most water wells in the upper Ash Creek drainage basin (New Harmony-Kanarraville area) are screened in basin-fill deposits (Hurlow, 1998), and basin-fill deposits in the Santa Clara and Virgin River Valleys (St. George basin, figure 1) yield substantial quantities of ground water to wells, but the water is generally not of high enough quality for potable uses (Heilweil and others, 2000).

Basin-fill sediments in the central Virgin River basin consist of late Tertiary to Holocene fluvial, alluvial-fan, mass-wasting, and eolian deposits having limited extent and thickness in most areas (Hurlow, 1998). The basin-fill deposits consist of well- to poorly sorted mixtures of gravel, sand, silt, and clay, and are thickest in the New Harmony and Kanarraville basins, Ash Creek Valley, and the Santa Clara and Virgin River Valleys. Fluvial deposits, well- to poorly bedded gravel, sand, and silt, exist primarily along modern steams (Hurlow, 1998). Alluvial-fan deposits are more poorly sorted and, depending on upgradient rock types, may include abundant silt and clay. Mass-wasting deposits are found primarily at the base of the Hurricane Cliffs, and consist of poorly sorted boulder- to pebble-sized gravel, sand, and silt. Eolian deposits consist primarily of well-sorted, fine quartz sand mainly found proximal to Navajo Sandstone outcrops from which most of these deposits are derived. Hurlow (1998) concluded that alluvial deposits are the best prospective basin-fill aquifers based on their high degree of sorting and the presence of sand and gravel bars, but that alluvial-fan deposits, depending on their degree of sorting, warrant investigating near recharge sources; eolian and mass-wasting deposits are generally poorer prospective basin-fill deposits because they mostly exist above the water table (eolian deposits) or because of their poor sorting and limited extent (mass-wasting deposits). The younger, Quaternary-age deposits range from 0 to 500 feet (0-150 m) in thickness (Hurlow, 1998), and may contain fractured, broken basalt that can yield small to large amounts of water (Heilweil and others, 2000).

Recharge is mainly from infiltration of precipitation, primarily in the Pine Valley Mountains (Hurlow, 1998), which makes its way to the basin-fill aquifers through infiltration of streamflow, subsurface inflow from adjacent bedrock units, and from infiltration of unconsumed irrigation water. The overall direction of ground-water movement in the study area is toward the Virgin River and its tributaries (Cordova and others, 1972), and then downstream. Discharge occurs via seepage to streams, springs and drains; evapotranspiration by phreatophytes; water-well withdrawals; and subsurface outflow. A water budget has not been developed for the basin-fill aquifers collectively in the central Virgin River basin, so the relative contribution of each recharge or discharge category has not been defined.

Most wells and springs in basin-fill deposits yield less than 250 gallons per minute (950 L/min), but a few wells produce more ground water; a well completed in fluvial deposits along the Virgin River near Bloomington yields as high as 2700 gallons per minute (10,000 L/min) (Cordova and others, 1972). Cordova and others (1972) reported hydraulic conductivities for the basin-fill aquifers ranging from 35 to 270 feet per day (10-80 m/d). In the upper Ash Creek drainage basin, Heilweil and others (2000) reported transmissivities ranging from 2540 to 16,000 feet squared per day (240-1,500 m^2/d) for the basin-fill aquifer.

Water levels in four wells completed in the basin-fill aquifers in the central Virgin River basin declined to various extents between 1970 and 2000 (Burden and others, 2000, figure 50), with the greatest decline (73 ft; 22 m) in the southern part of the St. George basin. These declines are probably due to increased local withdrawal for irrigation (Burden and others, 2000).

Ground-Water Quality

The chemical composition of ground water in basin-fill aquifers in the central Virgin River basin varies with location, depending primarily on the source rock for the materials comprising the aquifer; shale and limestone contain more soluble material than basalt, sandstone, and igneous intrusive rocks (Cordova and others, 1972). Based on 24 ground-water samples, total-dissolved-solids concentrations in the basin-fill aquifers range from 144 to 6860 mg/L (Cordova and others, 1972). Water samples from two wells completed in basin-fill aquifers exceeded the primary ground-water quality standard for nitrate as nitrogen (10 mg/L), and water from 13 wells exceeded the secondary ground-water quality standard for sulfate (250 mg/L) (Cordova and others, 1972, table 18).

METHODS

This study is limited to the use and interpretation of existing data to produce pesticide sensitivity and vulnerability maps through the application of GIS analysis methods. As outlined in Siegel (2000), we combine a process-based model with an index-based model to produce sensitivity and vulnerability maps for the basin-fill deposits in the central Virgin River basin. The index-based model assigns ranges of attribute values and ranks the ranged attribute values as conducive or not conducive to ground-water contamination by pesticides. The process-based model incorporates physical and chemical processes through mathematical equations addressing the behavior of certain chemicals in the subsurface, in this case retardation and attenuation of pesticides, using methods developed by Rao and others (1985). No new fieldwork was conducted nor data collected as part of this project.

Ground-Water Sensitivity to Pesticide Pollution

Ground-water sensitivity to pesticides is determined by assessing natural factors favorable or unfavorable to the degradation of ground water by pesticides applied to or spilled on the land surface. Hydrogeologic setting (vertical ground-water gradient and presence or absence of confining layers), soil hydraulic conductivity, retardation of pesticides, attenuation of pesticides, and depth to ground water are the factors primarily determining ground-water sensitivity to pesticides in the central Virgin River basin. Sensitivity represents the sum of natural influences that facilitate the entry of pesticides into ground water.

Hydrogeologic Setting

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

We used drillers' logs of water wells in the central Virgin River basin to delineate primary recharge areas and discharge areas, based on the presence of confining layers and relative water levels in the principal and shallow unconfined aquifers. Although this technique is useful for acquiring a general idea of where recharge and discharge areas are likely located, it is subject to a number of limitations. The use of drillers' logs requires interpretation because of the variable quality of the logs. Correlation of geology from well logs is difficult because lithologic descriptions prepared by various drillers are generalized and commonly inconsistent. Use of water-level data from well logs is also problematic because levels in the shallow unconfined aquifer are commonly not recorded and because water levels were measured during different seasons and years.

Confining layers are any fine-grained (clay and/or silt) layer thicker than 20 feet (6 m) (Anderson and others, 1994; Anderson and Susong, 1995). Some drillers' logs show both clay and sand in the same interval, with no information describing relative percentages; these are not classified as confining layers (Anderson and others, 1994). If both silt and clay are checked on the log and the word "sandy" is written in the remarks column, then the layer is assumed to be a predominantly clay confining layer (Anderson and others, 1994). Some drillers' logs show clay together with gravel, cobbles, or boulders; these also are not classified as confining layers, although in some areas of Utah layers of clay containing gravel, cobbles, or boulders do, in fact, act as confining layers. In the central Virgin River basin, the presence or absence of confining layers is largely determined by the potential for source rocks to yield significant amounts of silts and clays as a result of erosion and weathering processes; shale and mudstone units are the most likely rock types to produce confining layers in the basin fill below or adjacent to them.

The primary recharge area for the principal aquifer system in the central River Virgin basin consists of basin fill not containing confining layers (figure 3). Ground-water flow in primary recharge areas has a downward component. Secondary recharge areas, if present, are locations where confin-

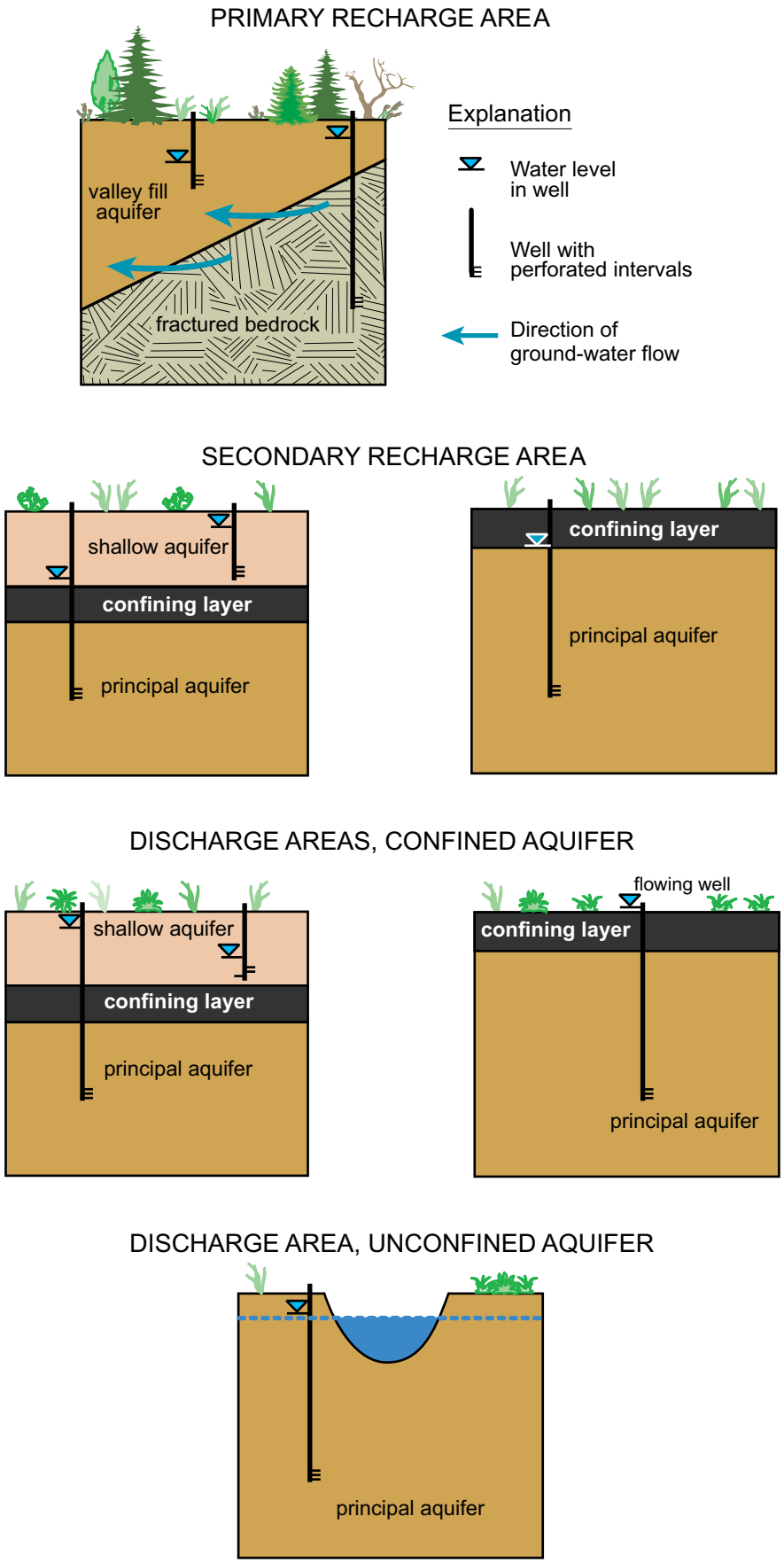

Figure 3. *Relative water levels in wells in recharge and discharge areas (modified from Snyder and Lowe, 1998).*

ing layers exist, but ground-water flow maintains a downward component (figure 3). The ground-water flow gradient, also called the hydraulic gradient, is upward when the potentiometric surface of the principal aquifer system is higher than the water table in the shallow unconfined aquifer (Anderson and others, 1994). Water-level data for the shallow unconfined aquifer are not abundant, but exist on some well logs. When the confining layer extends to the ground surface, secondary recharge areas 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 3). For this to happen, the hydraulic head in the principal aquifer system must be higher than the water table in the shallow unconfined aquifer. Otherwise, downward pressure from the shallow aquifer exceeds the upward pressure from the confined aquifer, creating a net downward gradient indicative of secondary recharge areas. Flowing (artesian) wells, indicative of discharge areas, are marked on drillers' logs and sometimes on U.S. Geological Survey 7.5-minute quadrangle maps. Wells with potentiometric surfaces above the top of the confining layer can be identified from well logs. Surface water, springs, or phreatophytic plants characteristic of wetlands can be another indicator of ground-water discharge. In some instances, however, this discharge may be from a shallow unconfined aquifer. An understanding of the topography, surficial geology, and ground-water hydrology is necessary before using 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; Mortensen and others, 1977). 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/in3 [1.6-2.1 kg/L]) and porosity range (0.2 to 0.4). Dissolved constituents in ground water having low R_F values (around 1), such as nitrate (a relatively mobile anion), move through the subsurface at the same rate as the ground water, whereas dissolved constituents in ground water having R_F values orders of magnitude larger than one are essentially immobile (Freeze and Cherry, 1979). The relative velocity is the reciprocal of the retardation factor and describes the rate a mixture of reactive contaminant moves relative to solvent-free ground water.

For this study, we used data from the Soil Survey Geographic (SSURGO) database (National Soil Survey Center, 2004), which provides digitized data for some soil areas of the state of Utah, including the central Virgin River basin, 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 the central Virgin River basin, and variable soil organic carbon content using a water-table depth of 3 feet (1 m). Average organic carbon content in soils in the central Virgin River basin is shown in figure 4 and ranges from 0.15 to 2.6%; the mass

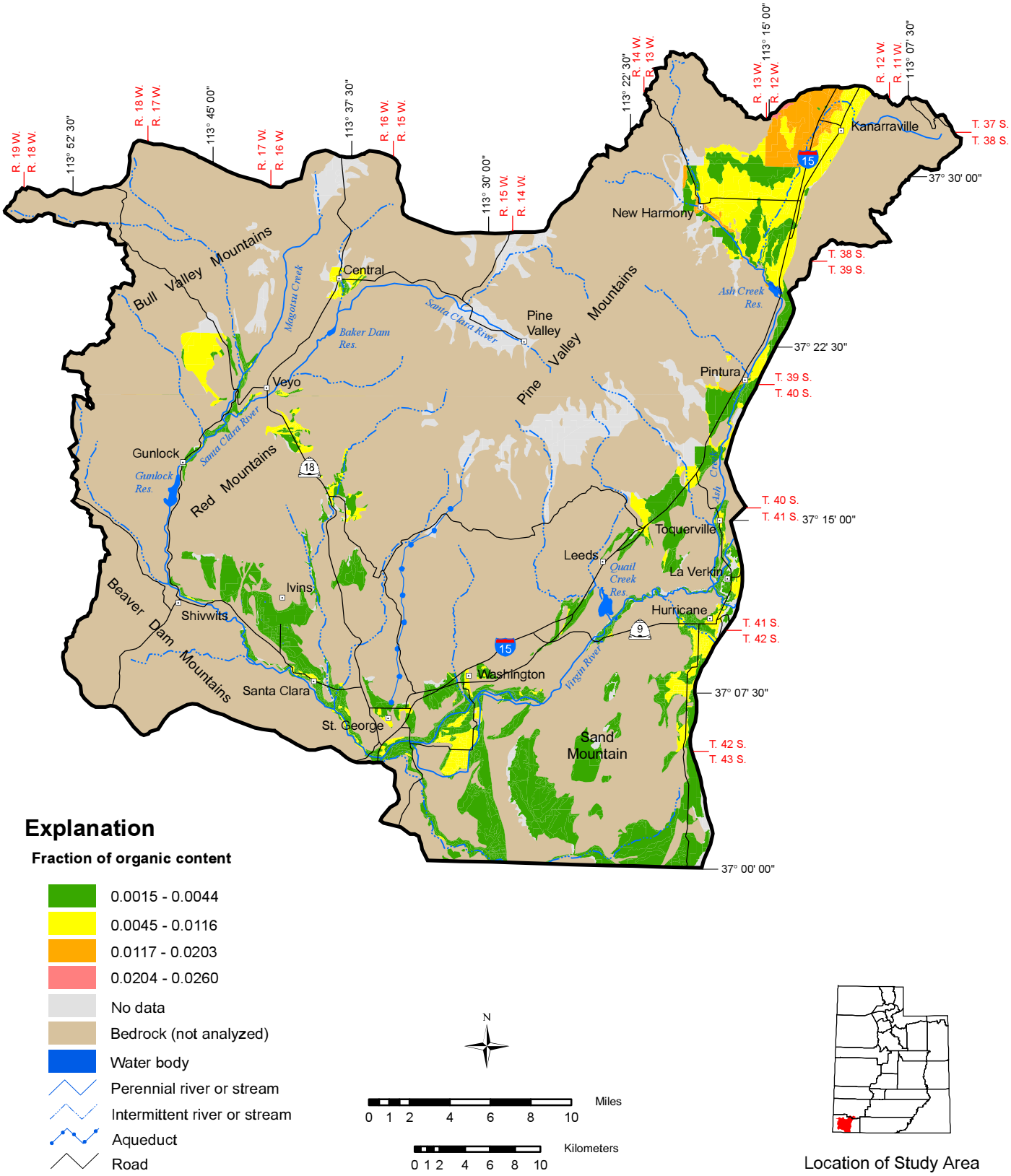

Figure 4. *Average organic carbon content in soils in the central Virgin River basin, Washington and Iron Counties, Utah (data from National Soil Survey Center, 2004).*

Table 2. *Hydrologic soil groups, field capacity, bulk density, and fraction of organic carbon content generalized for Utah soils. Soil description and organic content from National Soil Survey Center (2004). Field capacity based on sediment grain size calculated from a soil texture triangle hydraulic properties calculator (Saxton, undated). Bulk density from Marshall and Holmes (1988) and Saxton (undated).*

Soil Group	Soil Description	Grain Size (mm) (Field Capacity %)	Bulk Density Range (kg/L) (average)	Organic Carbon Content, Fraction (F_{oc})*
A	Sand, loamy sand, or sandy loam; low runoff potential and high infiltration rates even when thoroughly wetted; consists of deep, well to excessively drained sands or gravels with high rate of water transmission.	0.1 - 1 (14-21)	1.5 - 2 (1.75)	Variable and ranges from 0.15 to 2.6%
B	Silt loam or loam; moderate infiltration rate when thoroughly wetted; consists of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures.	0.015 - 0.15 (25-28)	1.3 - 1.6 (1.4)	Variable and ranges from 0.15 to 2.6%
C	Sandy clay loam; low infiltration rates when thoroughly wetted; consists of soils with layer that impedes downward movement of water; soils with moderately fine to fine structure.	0.01 - 0.15 (26)	1.3 - 1.9 (1.6)	Variable and ranges from 0.15 to 2.6%
D	Clay loam, silty clay loam, sandy clay, silty clay, and/or clay; highest runoff potential of all soil groups; low infiltration rates when thoroughly wetted; consists of clay soils with a high swelling potential, soils with a permanent high water table, soils with a hardpan or clay layer at or near the surface, and shallow soils over nearly impervious material.	0.0001 - 0.1 (32-42)	1.2-1.3 (1.25)	Variable and ranges from 0.15 to 2.6%
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 distribution coefficients (K_{oc}) and half-lives ($T_{1/2}$) for typical soil pHs (data from Weber, 1994).*

Herbicide	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

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 38. This means the highest relative velocity from our data is 0.7 and the lowest is 0.03; 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 negative net annual ground-water recharge from precipitation amounts typical of the central Virgin River basin, 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 3.

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 the central Virgin River basin (figure 5). The only localities in which evapotranspiration is less than precipitation are high-elevation forested areas. These are typically the source areas for surface streams that flow to valleys at lower elevations where they infiltrate the basin-fill sediment, accounting for a large part of ground-water recharge. Irrigation is another component of ground-water recharge, but it is not easily measured, and is not evaluated in our analysis.

Using equation 2, we calculated attenuation factors for ranges of values common to soils in the central Virgin River basin, 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 3, calculated as described above; the half-life for simazine (table 3), the pesticide among the four with the longest half-life (Weber, 1994); a field capacity of 14%; and a bulk density value of 0.04 pounds per cubic inch (1.2 kg/L). For a net annual ground-water recharge of 0 inches, as is typical of the valley-floor areas of the central Virgin River basin, 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,

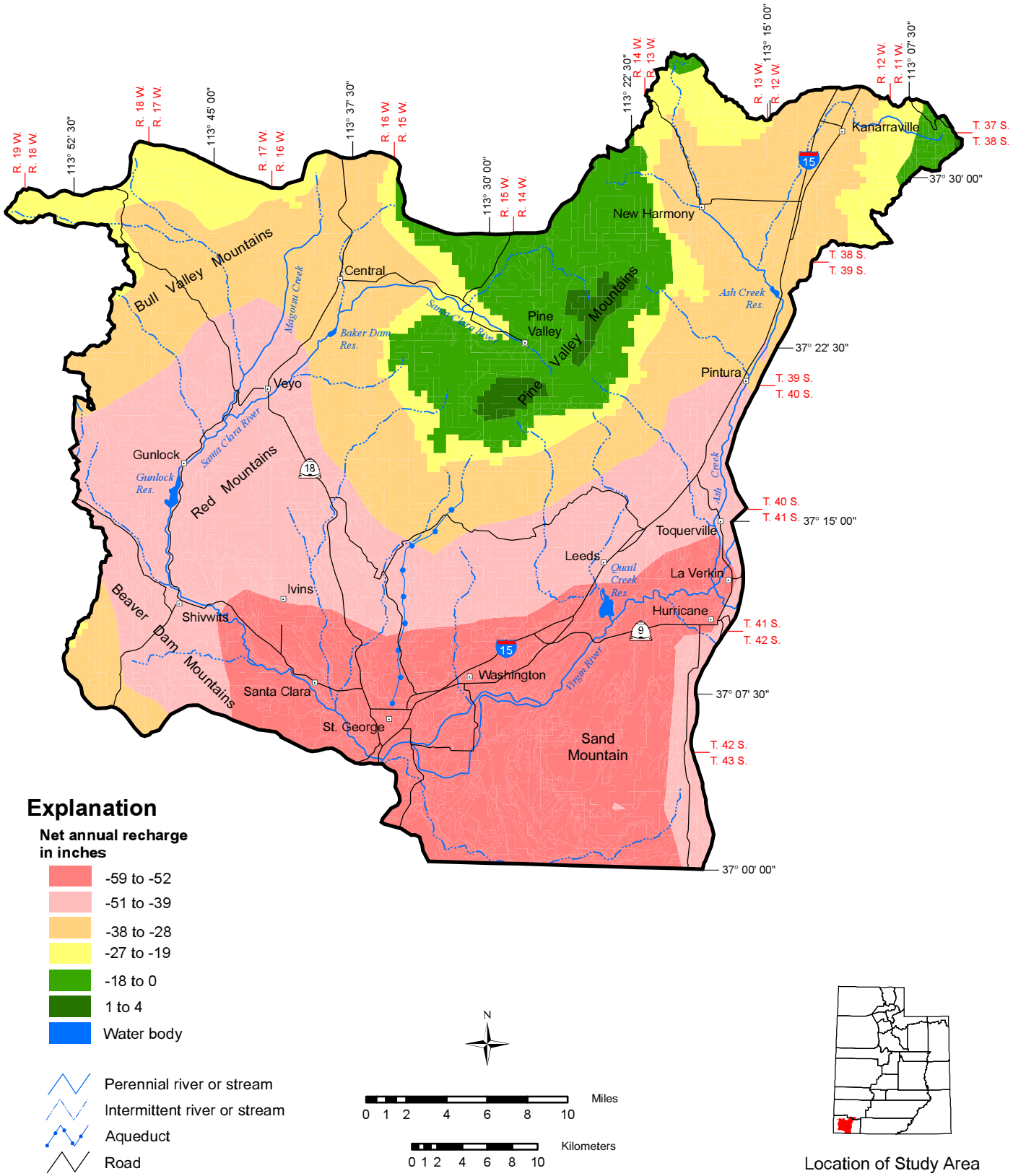

Figure 5. *Net annual ground-water recharge from precipitation for the central Virgin River basin, Washington and Iron Counties, Utah. Recharge calculated using data from the Utah Climate Center (1991) and Jensen and Dansereau (2001). Although net annual recharge may be negative in some areas, seasonally some recharge from precipitation may occur.*

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; Mortensen and others, 1977). We selected 3 feet (1 m) as the depth-to-ground-water attribute used to evaluate sensitivity of geographic areas to pesticides. For areas where depth-to-ground-water data are not available in GIS format, we applied the less-than-3-feet (1 m) GIS attribute ranking, described below, to be protective of ground-water quality.

GIS Analysis Methods

We characterize pesticide sensitivity (intrinsic susceptibility) as "low," "moderate," 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 1991 Virgin 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 the central Virgin River basin 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 Virgin River basin inventory was conducted in 1991 (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 Virgin River

Table 5. *Pesticide sensitivity and the attribute rankings used to assign sensitivity for the central Virgin River basin, Washington and Iron 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 the central Virgin River basin, Washington and Iron 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

basin inventory was conducted in 1991 (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 attribute layers were used to produce a ground-water sensitivity map (plate 1) using GIS analysis methods as outlined in table 5, and are described and summarized in the following sections.

Retardation/Attenuation

Retardation factors are variable and attenuation factors are ranked as low throughout the central Virgin River basin; 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 5). 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

We mapped ground-water recharge areas in the central Virgin River basin (figure 6). The map shows that primary recharge areas, the areas most susceptible to contamination from pesticides applied to the land surface, comprise about 83% of the surface area of the basin-fill aquifers. Secondary recharge areas make up an additional 16% of the surface area of the basin-fill aquifers. Ground-water discharge areas, which provide extensive protection to the principal aquifer from surface contamination from the application of pesticides, make up only 1% of the surface area of the basin-fill aquifers.

Hydraulic Conductivity of Soils

Surface application of pesticides is more likely to cause ground-water quality problems in areas where soils have higher hydraulic conductivity than in areas where hydraulic conductivity is low. Hydraulic conductivity data are from the National Soil Survey Center (2004). About 54% of the surface area of the basin-fill aquifers in the central Virgin River basins have soil units mapped as having hydraulic conductivity greater than or equal to 1 inch (2.5 cm) per hour (figure 7). About 16% of the surface area of the basin-fill aquifers have soil units mapped as having hydraulic conductivity less than 1 inch (2.5 cm) per hour. About 30% of the surface area of the basin-fill aquifers have 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.

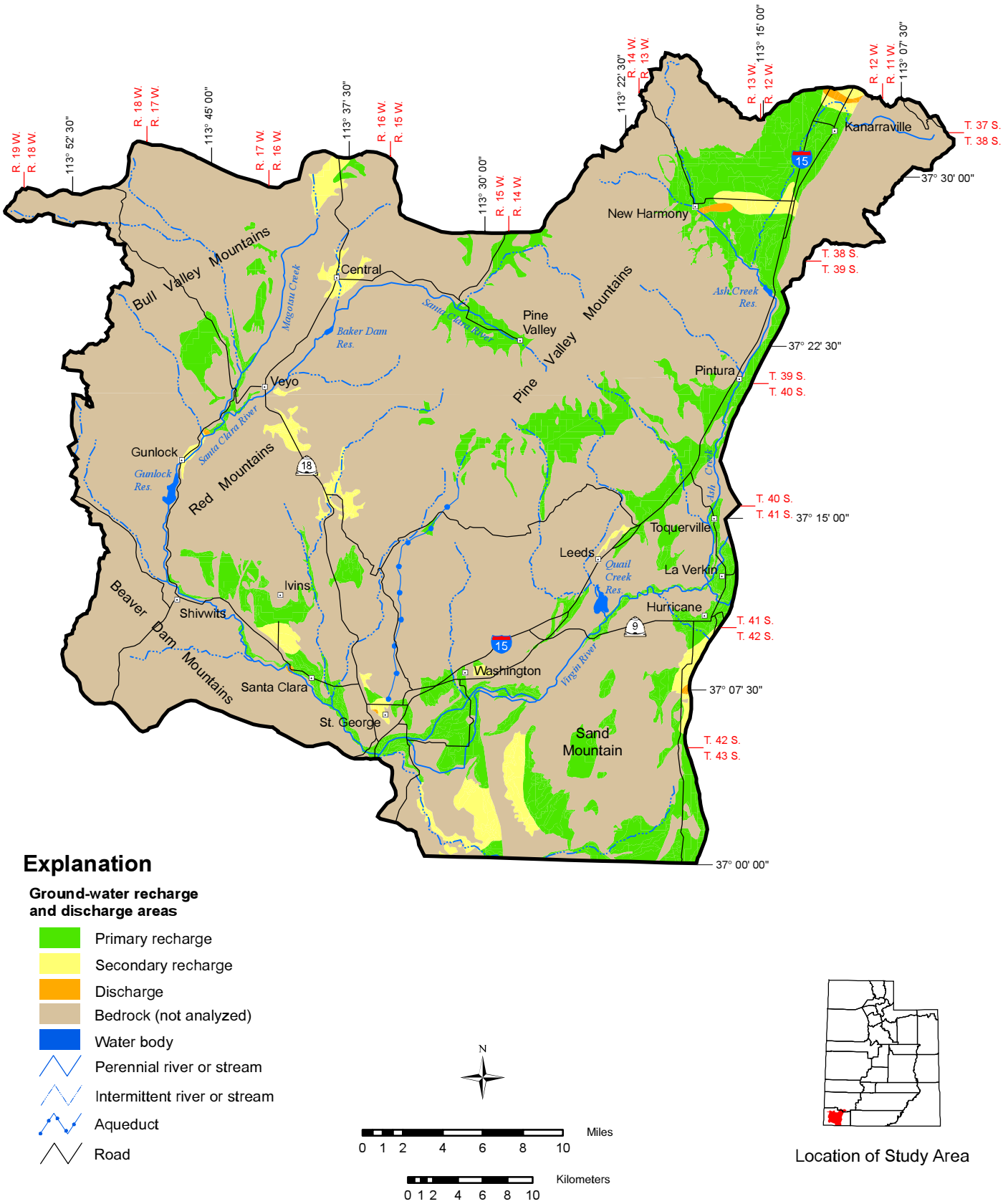

Figure 6. *Recharge and discharge areas in the central Virgin River basin, Washington and Iron Counties, Utah.*

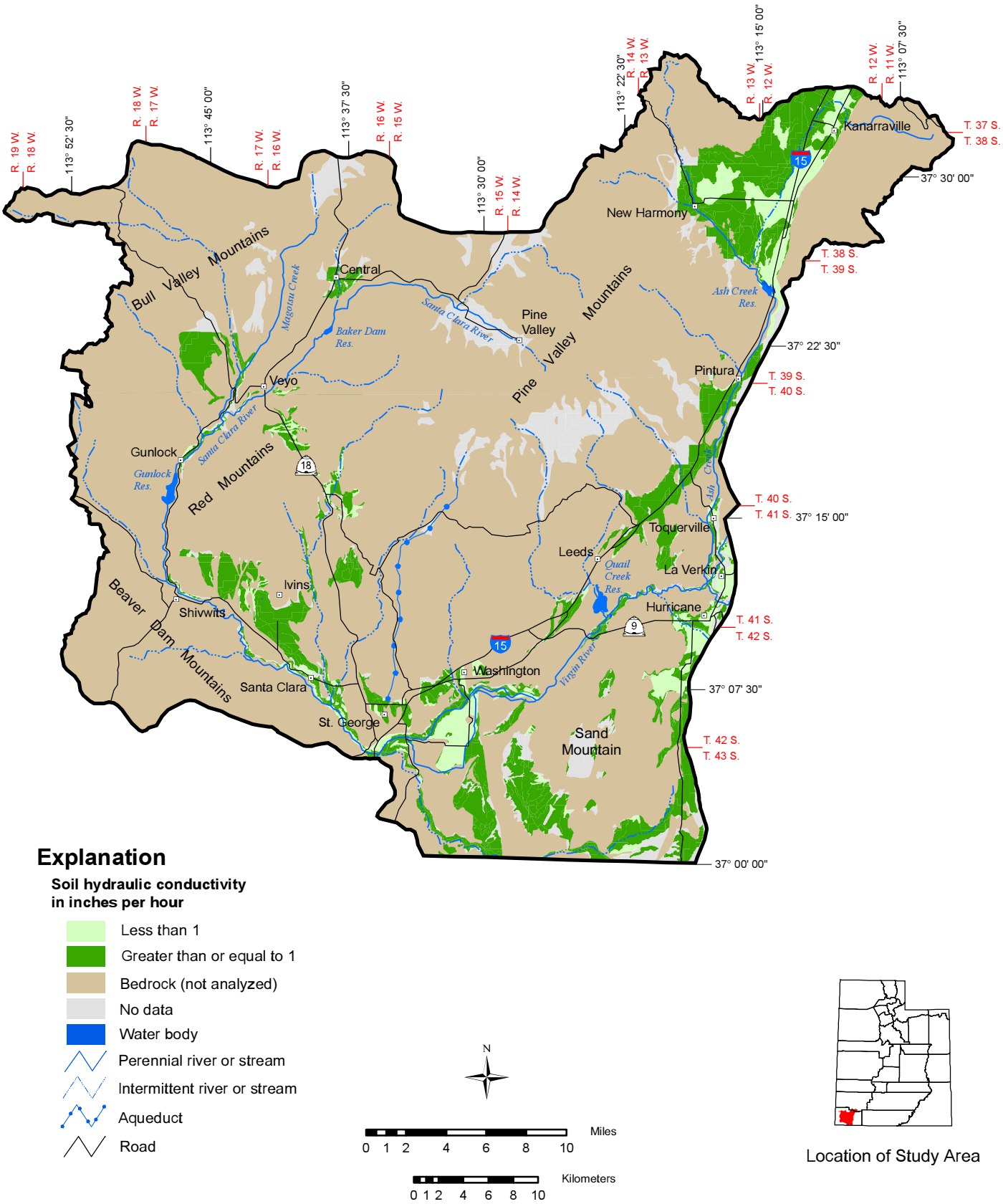

Figure 7. *Soil hydraulic conductivity in the central Virgin River basin, Washinton and Iron Counties, Utah (data from National Soil Survey Center, 2004).*

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 (2004). About 3% of the area overlying the basin-fill aquifers in the central Virgin River basins have 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 8). Less than 1% of the surface area of the basin-fill aquifers has soil units mapped as having shallow ground water greater than 3 feet (1 m) deep. About 97% of the surface area of the basin-fill aquifers have soil units for which no SSURGO data exist. Areas without assigned depths to shallow ground water were grouped with the less than or equal to 3 feet (1 m) depth category for analytical purposes to be protective of water quality.

Pesticide Sensitivity Map

Plate 1 shows ground-water sensitivity (intrinsic susceptibility) to pesticides for the central Virgin River basin, 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.

Only a small part of the central Virgin River basin (about 1%) 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 central Virgin River basin alluvial deposits have higher hydraulic conductivities than do to the prevalent sandstone formations, such as the Navajo Sandstone, they are derived from and are areas of high sensitivity (plate 1). These areas, combined with incorporated areas where soil data are not available, comprise about 83% of the basin-fill aquifer area. The remaining 16% of the study area is of moderate sensitivity.

Ground-Water Vulnerability

To assess ground-water vulnerability to pesticide contamination—the influence of human activity added to natural sensitivity—we assembled two attribute layers as intermediate steps. Pertinent statewide attribute layers include irrigated cropland and corn- and sorghum-producing areas in the central Virgin River basin (figure 9). 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 9 shows irrigated cropland areas in the central Virgin River basin. About 10% of the valley floor is irrigated cropland. Irrigation is potentially significant because it is a source of ground-water recharge in the basin-fill aquifer.

Corn and Sorghum Crops

From the point of view of human impact, areas where corn and sorghum are grown are significant because the four herbicides considered in this report—alachlor, atrazine, metolachlor, and simazine—are used to control weeds in these crops. Corn and sorghum crops are mainly grown in the southern and western parts of the basin-floor area (figure 9). Note that many areas (for instance, near Baker Dam Reservoir) corn or sorghum crops are shown as being grown on bedrock rather than on soils; this is likely due to the soil deposits being thin or of limited extent. The use of pesticides on corn and sorghum crops increases the vulnerability of areas where these crops are grown from low to moderate.

Pesticide Vulnerability Map

Plate 2 shows ground-water vulnerability to contamination from pesticides of the basin-fill aquifers for the central Virgin River basin, 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 7% of the surface area of the basin-fill aquifers 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 92% of the surface area of the basin-fill aquifers 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 1% of the surface area of the basin-fill aquifers is mapped as having low vulnerability. This vulnerability analysis is for areas underlain by basin fill; the most vulnerable areas in the central Virgin River basin are likely those areas where corn or sorghum crops are shown in bedrock areas, particularly where the underlying bedrock unit is the Navajo Sandstone, because of the thinness or limited extent of the soils the crops are grown on.

CONCLUSIONS AND RECOMMENDATIONS

In the central Virgin River basin, areas of irrigated land in primary recharge areas with potential shallow depths to ground water, along with those areas where corn or sorghum are grown on thin soils above the Navajo Sandstone, have the highest potential for water-quality degradation associated with surface application of pesticides. However, for the basin-fill deposits, we believe pesticides likely do not represent a serious threat to ground-water quality because of the

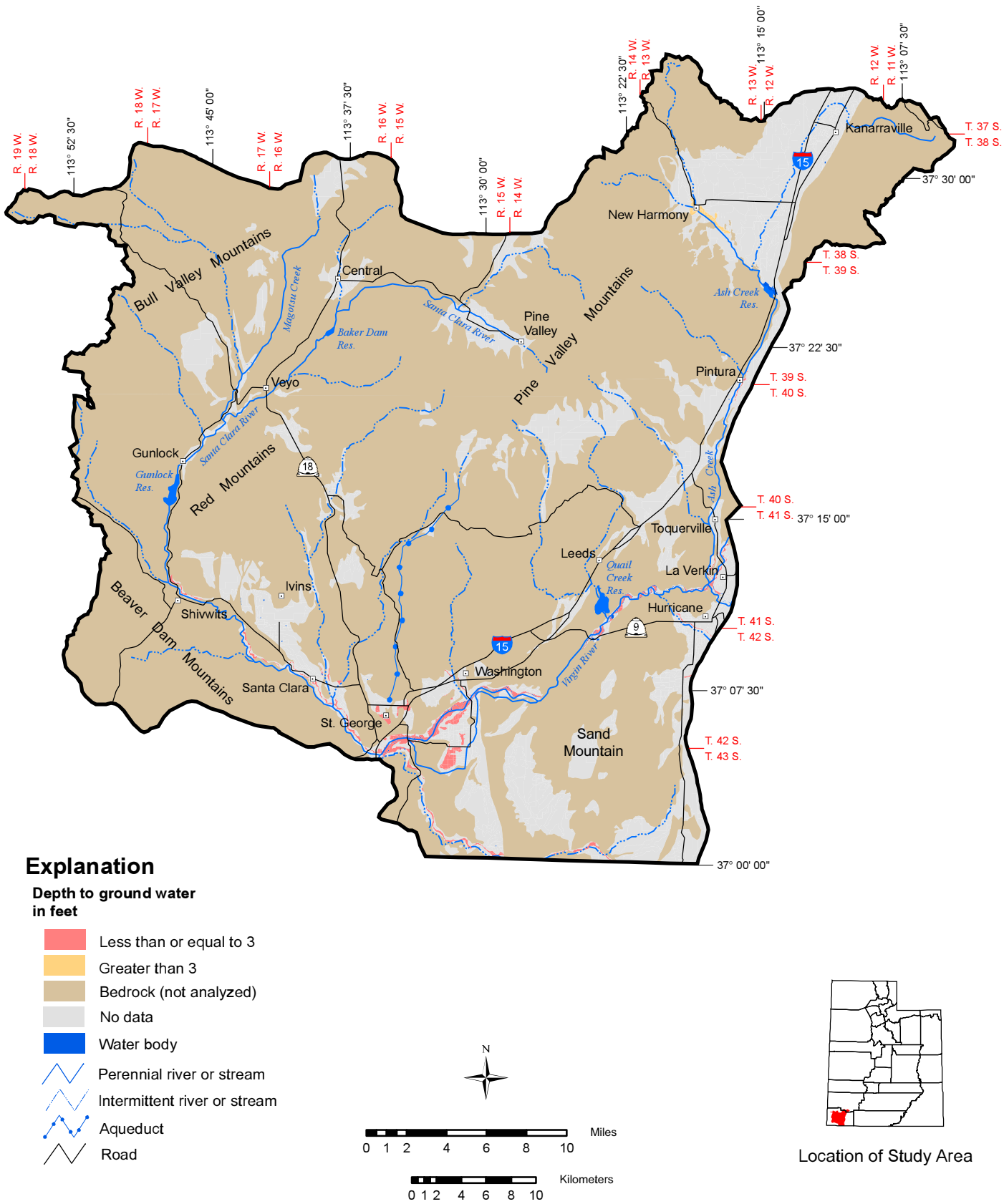

Figure 8. Depth to shallow ground water in the central Virgin River basin, Wahsington and Iron Counties, Utah (data from National Soil Survey Center, 2004).

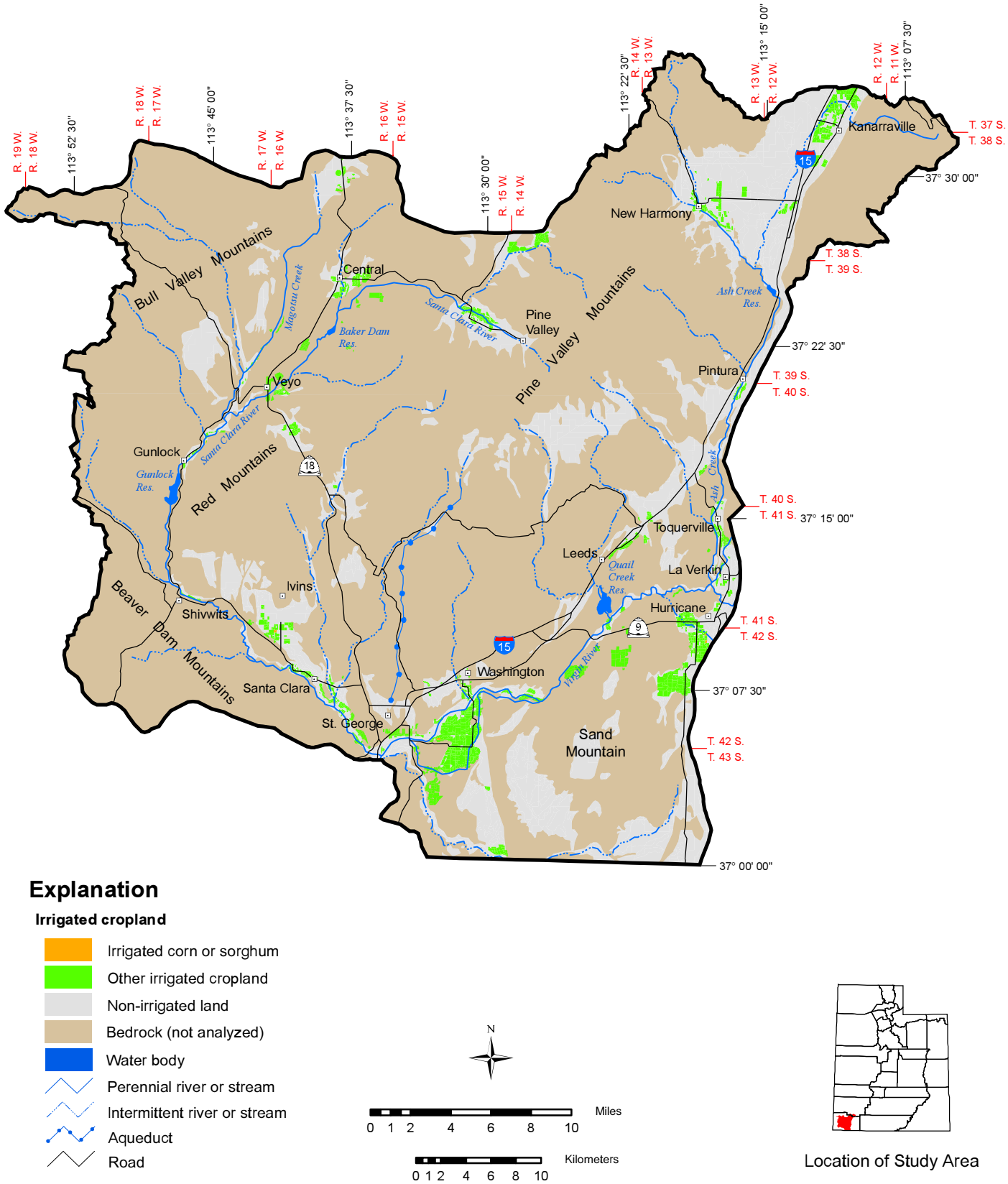

Figure 9. *Irrigated and non-irrigated cropland in the central Virgin River basin, Washington and Iron Counties, Utah, study area (unpublished data from Utah Division of Water Resources). The pesticides addressed in this study are mainly applied to corn and sorghum.*

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, particularly in areas where corn or sorghum are grown over the Navajo Sandstone. 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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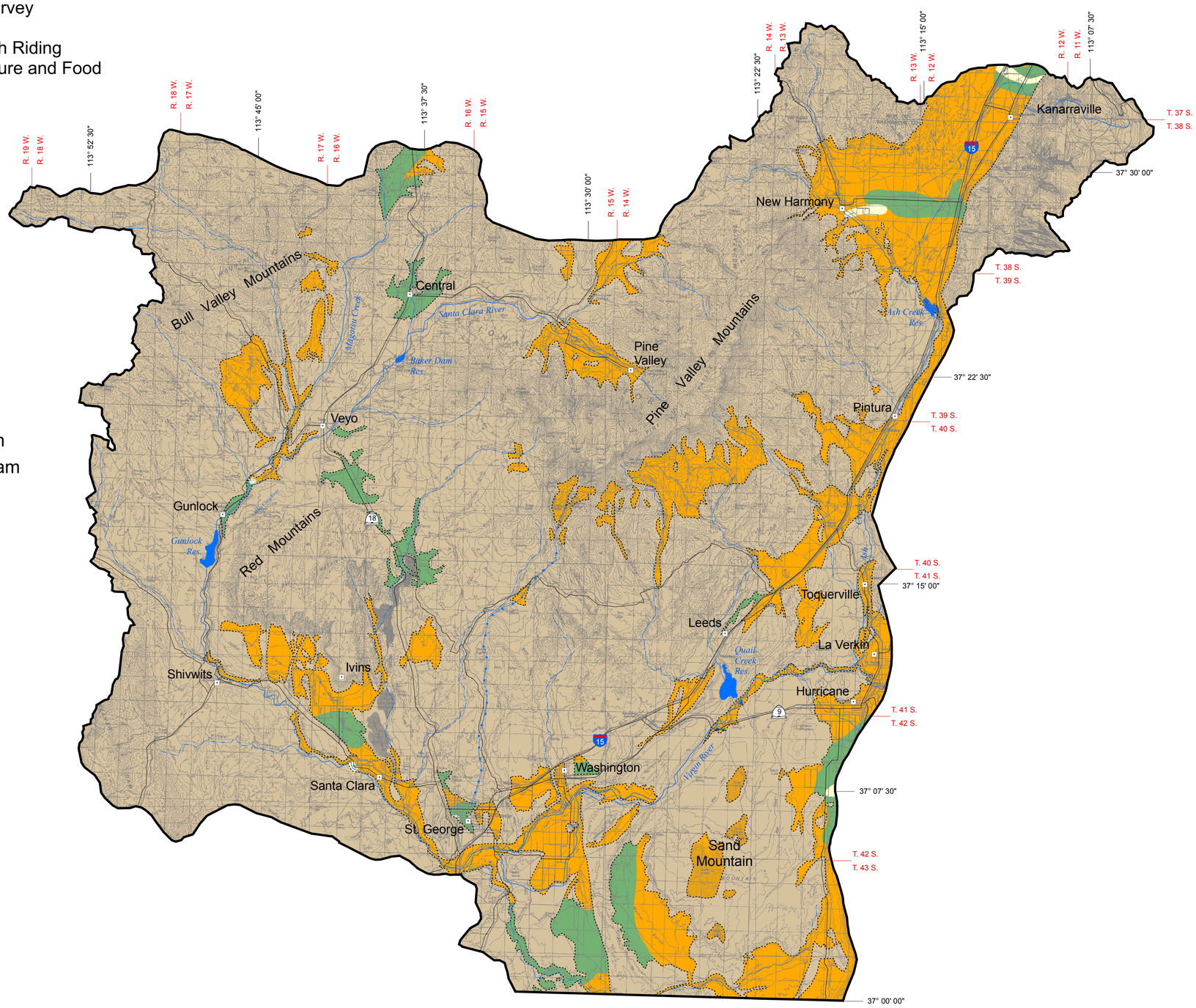
Plate 1

GROUND-WATER SENSITIVITY TO PESTICIDES IN THE CENTRAL VIRGIN RIVER BASIN, WASHINGTON AND IRON COUNTIES, UTAH

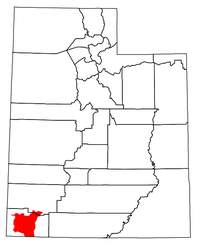
By Mike Lowe, Janae Wallace, and Justin Johnson
Utah Geological Survey
and
Anne Johnson and Rich Riding
Utah Department of Agriculture and Food



Explanation

Ground-Water Sensitivity Ranking

- Low
- Moderate
- High
- Bedrock (not analyzed)
- Water body
- Perennial river or stream
- Intermittent river or stream
- Aqueduct
- Basin-fill boundary
- Road



Location of Study Area

N
W E
S

0 1 2 4 6 8 10 Miles

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1:150,000

This map is a GIS product derived from a recharge/discharge area map by Anderson and others (1994), soil data from the National Soil Survey Center (2004), precipitation data from the Utah Climate Center (1991), evapotranspiration data from Jensen and Dansereau (2001), and land-use data from the Utah Division of Water Resources (unpublished). No additional fieldwork was performed or data collected.

This map is based on 1:24,000 or smaller scale data and should not be used for site-specific evaluations.

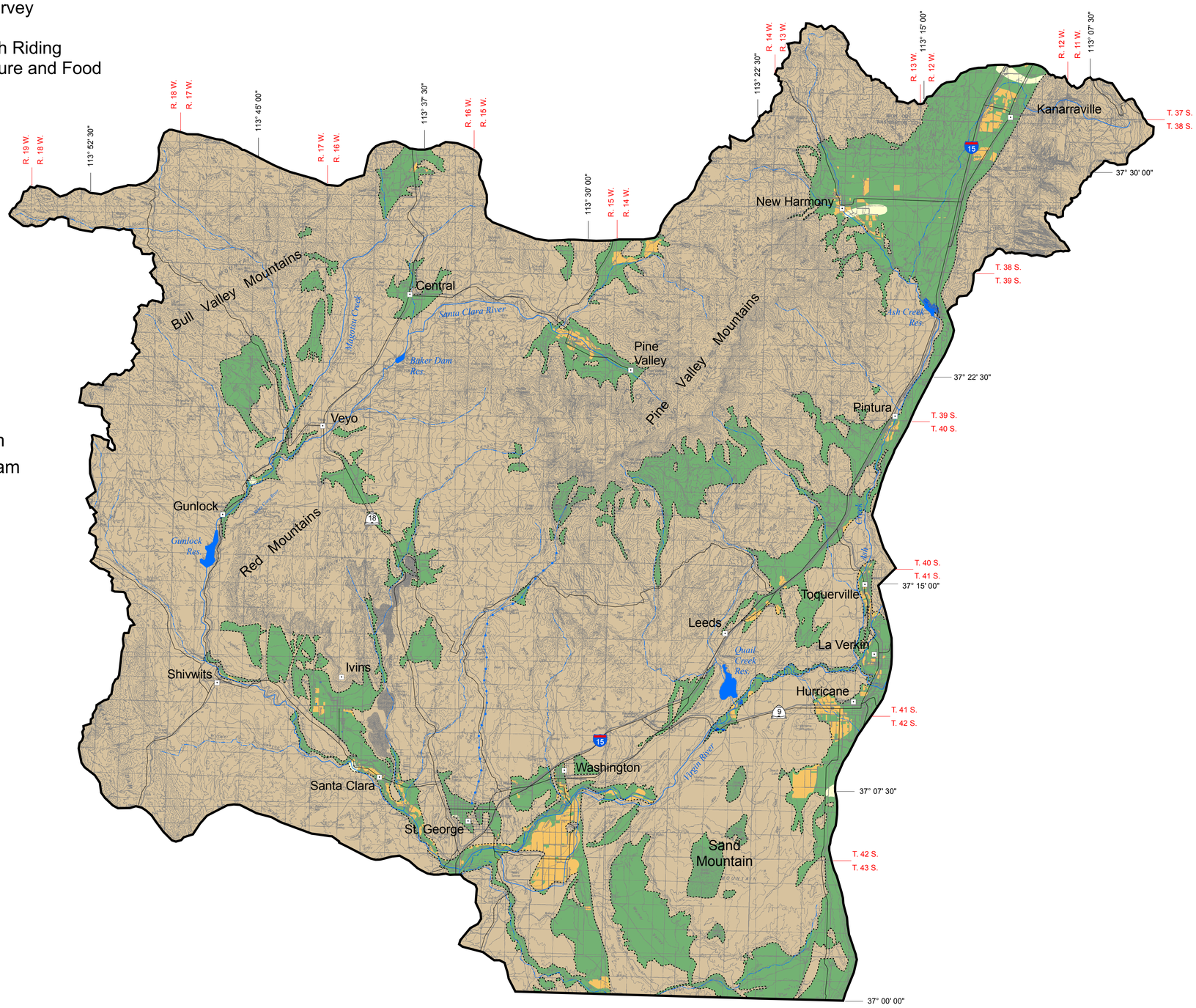
Projection: UTM
Zone: 12
Units: Meters
Datum: NAD 83
Spheroid: GRS 1980

Topographic base map from U.S. Geological Survey
1:100,000-scale digital images: Cedar City (1982), St. George (1980)

Plate 2

GROUND-WATER VULNERABILITY TO PESTICIDES IN THE CENTRAL VIRGIN RIVER BASIN, WASHINGTON AND IRON COUNTIES, UTAH

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



Explanation

Ground-Water Vulnerability Ranking

- Low
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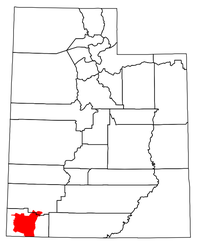

Location of Study Area

N
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0 1 2 4 6 8 10 Miles

0 1 2 4 6 8 10 Kilometers

1:150,000

Projection: UTM
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