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

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ABSTRACT

The U.S. Environmental Protection Agency is recommending 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. 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 Cache Valley, Cache County, Utah. Interpretation of existing data was used to produce pesticide sensitivity and vulnerability maps through the application of an attribute-ranking system specifically tailored to the western United States using Geographic Information System analysis methods.

Ground-water sensitivity to pesticides is an assessment of natural factors favorable or unfavorable to the degradation of ground water by any pesticides applied to or spilled on the land surface. We selected 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 as the five factors primarily determining ground-water sensitivity to pesticides. Areas of high sensitivity are generally located along the margins of Cache Valley where soils typically have relatively high hydraulic conductivity, and ground water is either shallow with no overlying confining layers or insufficient data are available to determine depth to shallow ground water.

Ground-water vulnerability to pesticides is an assessment of how ground-water sensitivity is modified by the activities of humans. We selected ground-water sensitivity to pesticides, the presence of applied water (irrigation), and crop type as the three factors generally determining ground-water vulnerability to pesticides. Areas of high vulnerability are primarily located along valley margins where ground water occurs at depths of less than 3 feet (1 m) or the depth to shallow ground water is unknown. Of particular concern are areas where influent (losing) streams originating in mountainous areas cross the valley margin; streams in these areas are the most important source of recharge to the basin-fill aquifer, and efforts to preserve water quality in streams at these points would help to preserve ground-water quality in the entire 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, it is unlikely that pesticides applied to crops and fields in Cache Valley represent a serious threat to ground-water quality. To verify this conclusion, future ground-water sampling by the Utah Department of Agriculture and Food in Cache Valley should be concentrated in areas of moderate and high sensitivity or vulnerability, typically along valley margins. Sampling in the central area of the valley characterized by low sensitivity and vulnerability should continue, but at a lower density than in the areas of higher sensitivity and vulnerability.

INTRODUCTION

Background

The U.S. Environmental Protection Agency (EPA) recommends 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 the state of Utah - ground water is the primary source of drinking and irrigation water.

The state of Utah is committed to preserving the quality of its ground-water resources. This report and accompanying maps provide federal, state, and local government agencies and agricultural pesticide users with a base of information concerning vulnerability of ground water to agricultural pesticides in Cache Valley, Cache County, Utah (figure 1). This study, conducted jointly by the Plant Industry Division of the Utah Department of Agriculture and Food (UDAF) and the Utah Geological Survey (UGS), provides needed information on ground-water sensitivity and vulnerability to pesticides in the unconsolidated basin-fill aquifer of Cache Valley. Geographic variation in sensitivity and vulnerability, together with hydrologic and soil conditions that cause these variations, are described herein; plates 1 and 2 show the sen-

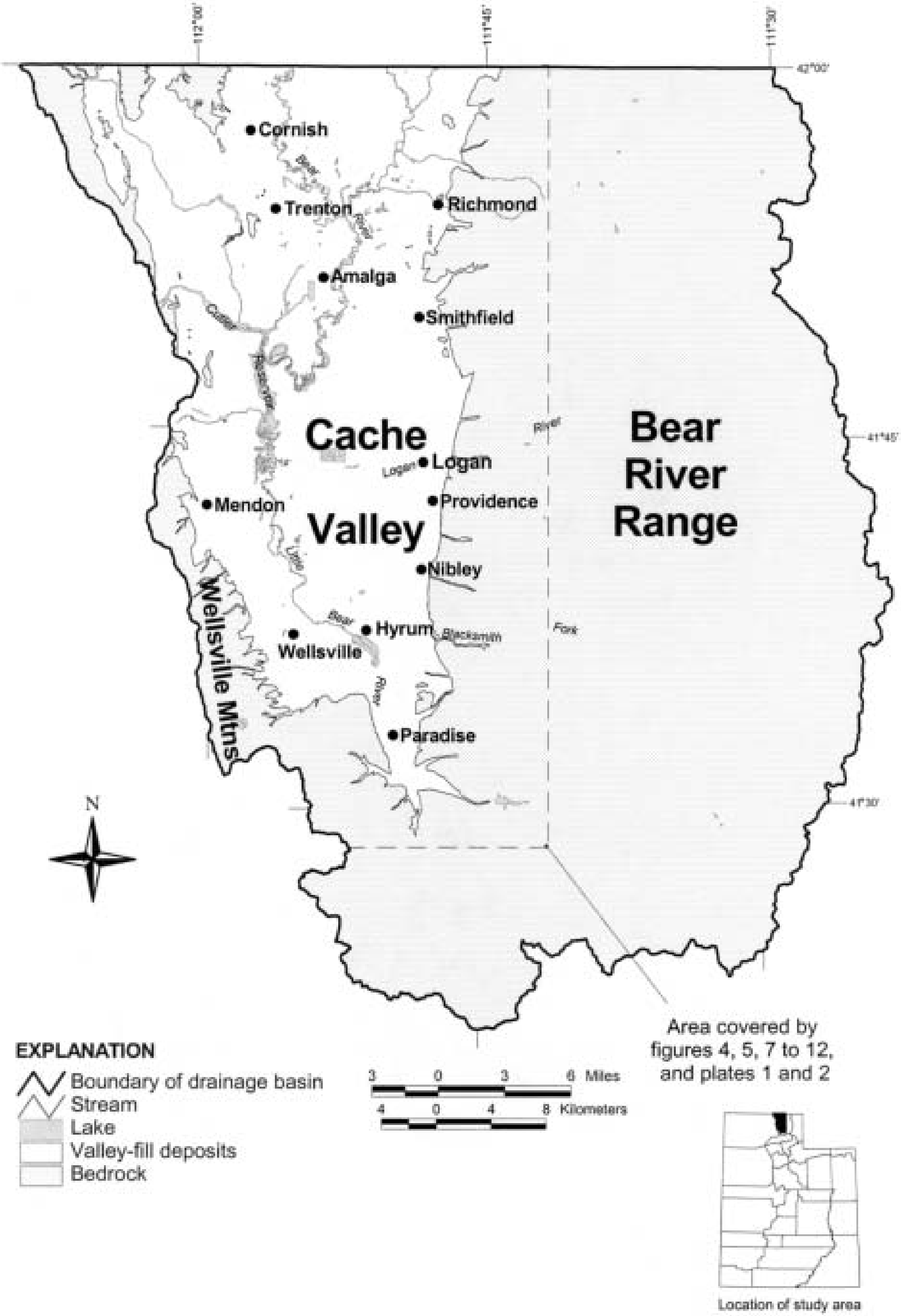

Figure 1. Cache Valley, Utah, location map.

sitivity and vulnerability of the unconsolidated basin-fill aquifer in Cache Valley, Utah, to agricultural pesticides.

Sensitivity to pesticides is determined by assessing natural factors favorable or unfavorable to the degradation of ground water by pesticides, whereas vulnerability to pesticides is determined by assessing human-induced factors and their response to natural factors. 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 soils' hydraulic conductivity, bulk density, organic content, and field capacity. Sensitivity also includes the influence of pesticide properties such as the capacity of molecules to adsorb to organic carbon in soil and the half-life of a pesticide under typical soil conditions. Vulnerability includes human-controlled factors such as whether agricultural lands are irrigated, crop type, and amount and type of pesticide applied.

Purpose and Scope

The purpose of this project is to investigate sensitivity and vulnerability of the ground-water resources in Cache 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 UDAF.

The project scope is limited to the use and interpretation of existing data to produce pesticide sensitivity and vulnerability maps through the application of Geographic Information System (GIS) analysis methods. No new field work was conducted or data collected as part of this project.

GENERAL DISCUSSION OF PESTICIDE ISSUE

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, to a significant extent, 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. Since 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 the dilemma faced by pesticide regulators. DDT was removed from widespread use in the United States in the 1970s because of its deleterious effects on bald eagles, ospreys, and peregrine falcons. Populations of these once-endangered species have recovered to a significant extent 25 years later (Environmental Defense Fund, 1997). An ongoing effort to extend the DDT ban worldwide is being hotly contested by advocates of its judicious use as a critical and inexpensive insecticide needed in developing countries to control mosquitoes that transmit the malaria parasite. It is further argued that, given the current regulatory apparatus, were the use of DDT to be re-evaluated today under rigorous scientific and regulatory criteria, it would be restricted to specific uses rather than prohibited (Okosoni and Bate, 2001).

The EPA has developed guidelines and provided funding for programs to address the problem of pesticide contamination of ground water, including a generic PMP to be developed by state regulatory agencies having responsibility for pesticides. Utah's generic plan was approved by the EPA in 1997 (Utah Department of Agriculture and Food, 1997). Its implementation involves, among other things, establishment of 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 development of a set of maps showing varying sensitivity and vulnerability of ground water to contamination by pesticides.

Since its inception in 1994, the UDAF sampling program has revealed no occurrences of pesticide contamination in any aquifer in over 1,500 samples tested statewide (Quilter, 2001). Under the generic PMP, should an instance of pesticide contamination be found and verified, a chain of events to monitor and evaluate the contamination is begun that may 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. 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 settings (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, with the beginning letter of key words in these parameters forming the acronym DRASTIC. Eventually, it became apparent 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 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 vulnerable, 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. For example, depth to the water table should be logarithmic rather than linear because the potential for impacting ground water decreases much more rapidly with depth than is represented by the linear decrease in numerical scoring used in the method (Siegel, 2000).

Rao and others (1985) developed indices for ranking the potential for pesticide contamination of ground water. 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 sensitive to pesticide contamination of ground water.

Ground-Water Quality Standards

Maximum contaminant levels (MCLs) for pesticides in drinking water are established in R309-103-2.1, Utah Administrative Code, and also in 40 CFR 141.61. MCLs are given in table 1. 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, a process is set into motion 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 hydrogeological 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 quantity and types of pesticides being applied are critical factors. 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 areas 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 Cache Valley where ground water is unconfined, degradation of the basin-fill aquifer 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, sorghum, or soybeans are grown - because the types of pesticides evaluated in this study are commonly applied to those crops. Withdrawal of water from the basin-fill aquifer via water wells could cause changes in vertical head gradient that may increase the potential for water-quality degradation. Also, the wells themselves, if not properly constructed, could provide pathways for pesticides to reach the basin-fill aquifer.

SUMMARY OF PESTICIDE DETECTION IN CACHE VALLEY

The UGS detected small amounts of pesticide in two different wells in Cache Valley during their sampling during fall 1997 and winter/spring 1998 (Lowe and Wallace, 1999; Wallace and Lowe, 1999). Both detections are in the vicinity of Wellsville in the southwestern portion of the valley. A detection of DDT at a concentration of 0.14 parts per billion (ppb), was from a well 136 feet (41 m) deep. Other nearby wells showed no detection. The other detection was atrazine at a concentration of 0.23 ppb from a well 155 feet (47 m) deep. This well, on a dairy farm, also showed a relatively high nitrate concentration at 20 milligrams per liter (mg/L). No pesticides have been detected in the Cache Valley area by the UDAF ground-water sampling program (Quilter, 2001).

PREVIOUS STUDIES

Detailed geologic investigations in the Cache Valley area began with Bailey's (1927) studies of the geology of the Bear River Range and the Bear River Range fault. Williams (1948) studied Paleozoic rocks in the area, and included a measured section of the Swan Peak Formation in Green Canyon. Ross (1951) included a description of the Garden City and Swan Peak Formations in Green Canyon. Haynie (1957) examined the Worm Creek Quartzite Member of the St. Charles Formation in Green Canyon. Williams (1958) reported on further studies of stratigraphy and geologic history in Cache County. Galloway (1970) studied the structural geology of the eastern portion of the Smithfield quadrangle. Taylor and Palmer (1981) and Taylor and others (1981) studied Cambrian and Ordovician stratigraphy and paleontology in the Bear River Range and measured a section in Green Canyon.

Many investigators have studied the Salt Lake Formation in Cache Valley (Williams, 1948, 1964; Smith, 1953; Adamson 1955; and Adamson and others, 1955). Galloway (1970) redesignated the Salt Lake Group as the Salt Lake Formation. Williams (1962) studied Bonneville lake cycle deposits in Cache Valley.

Mullen and Izett (1963), Oviatt (1986a,b), Brummer and McCalpin (1990), Evans and others (1991), Lowe and Galloway (1993), Barker and Barker (1993), and Biek and others (2001) produced 7.5′ geologic quadrangle maps of the Cache Valley area. Dover (1985) mapped geology of the Logan 30′ x 60′ quadrangle. Degraff (1976) mapped Quaternary geomorphic features in the Bear River Range. Lowe (1987) mapped the surficial geology of the Smithfield 7.5′ quadrangle.

Woodward-Lundgren and Associates (Cluff and others, 1974) conducted a reconnaissance study of the East Cache fault zone and provided recommendations for reducing risk from earthquakes. Green (1977) studied geologic hazards in Cache Valley. Rogers (1978) investigated proposed development sites on the Logan east bench. Liquefaction potential maps for this area were prepared by Hill (1979) and Bay (1987). An assessment of low-temperature geothermal potential in Cache Valley was made by deVries (1982). Swan and others (1983) studied earthquake recurrence intervals on the East Cache fault zone and trenched an area just south of Green Canyon. Christenson (1983) studied engineering geology for land-use planning in the vicinity of Smithfield. McCalpin (1986, 1989, 1994) studied surface-fault-rupture recurrence and mapped surficial geology along the East Cache fault zone. Solomon (1999) mapped the surficial geology and Black and others (2000) studied surface-fault-rupture recurrence along the West Cache fault zone.

A detailed Cache Valley ground-water study was made by Bjorklund and McGreevy (1971). Kariya and others (1994) produced a ground-water flow model for the basin-fill aquifer. Lowe and Wallace (1999; Wallace and Lowe, 1999) delineated ground-water quality of the basin-fill aquifer. Erickson and Mortensen (1974) mapped soils in the Cache Valley area.

SETTING

Physiography

Cache Valley (figure 1) is a north-south-trending valley with an area of about 660 square miles (1,710 km^2) in northeastern Utah and southeastern Idaho. About 365 square miles (945 km^2) of the valley is in Utah. Cache Valley is in the Cache Valley section of the Middle Rocky Mountains physiographic province (Stokes, 1977). In Utah, Cache Valley is bordered by the Bear River Range to the east, the Wellsville Mountains to the southwest, and Clarkston Mountain to the northwest. The Bear River, the largest tributary to Great Salt Lake, flows through Cache Valley, entering Utah from the north and exiting Cache Valley between Clarkston Mountain and the Wellsville Mountains. Several large tributaries to the Bear River, including the Logan River, Blacksmith Fork, and Little Bear River, originate in the mountains surrounding Cache Valley in Utah.

Structurally, Cache Valley is bounded by north-striking, high-angle normal faults (the East Cache and West Cache fault zones) and forms the southernmost end of a series of half-grabens within an extensional corridor between the Wasatch and Teton normal fault systems (Evans and Oaks, 1996). Both the East Cache and West Cache fault zones have been subdivided into three segments and show evidence of recurrent Quaternary movement, including Holocene events (McCalpin, 1994; Black and others, 1999).

The mountains surrounding Cache Valley consist primarily of Precambrian to Permian sedimentary and metamorphic rocks, predominantly limestone, dolomite, and quartzite (Williams, 1958; Bjorklund and McGreevy, 1971). The Tertiary Salt Lake Formation, primarily conglomerate and tuffaceous sandstone, is exposed in an almost continuous belt in the foothills surrounding the valley and underlies Quaternary deposits within Cache Valley (Williams, 1962; Evans and Oaks, 1996).

The valley floor in Cache Valley ranges in elevation from about 4,400 to 5,400 feet (1,340-1,650 m) and is underlain by unconsolidated basin fill of varying thickness. The basin fill consists mostly of fluvial and lacustrine deposits that interfinger with alluvial-fan and, to a lesser extent, deltaic and landslide deposits along the valley margins (Lowe, 1987; Lowe and Galloway, 1993). Much of the Cache Valley floor is covered with offshore lacustrine silt and clay deposited during the Bonneville lake cycle between about 12 and 26 ka (Oviatt and others, 1992, figure 3). At least one other thick (up to 80 feet [24 m]), correlatable unit of offshore lacustrine silt and clay is present within the basin-fill deposits in Cache Valley; Lowe (1987) tentatively interprets these fine-grained sediments as having been deposited during the Little Valley lake cycle sometime between 90,000 and 150,000 years ago (Scott and others, 1983).

Climate

As is typical of the "back valleys" east of the Wasatch Range, Cache Valley is characterized by large daily and seasonal temperature ranges (Utah Division of Water Resources, 1992). Normal climatic information (1961-1990 period) is available from four weather stations in Cache Valley: Logan Radio KVNU, Logan Utah State University, Richmond, and Trenton/Lewiston; average climatic information is available from the Logan Utah State Experiment Station and the College Ward Utah State University Experiment Farm (Ashcroft and others, 1992). Because the normal climatic information represents a more complete data set, those values are discussed herein. Temperatures reach a normal maximum of 90.0°F (32.2°C) (Richmond station) and a normal minimum of 10.2°F (-12.1°C) (Trenton/Lewiston station); the normal mean temperature ranges from 44.8 to 48.5°F (7.1-9.2°C) (Ashcroft and others, 1992). Normal mean precipitation ranges from 16.6 to 19.5 inches (42.1-49.5 cm); normal mean evapotranspiration ranges from 40.9 to 45.3 inches (103.9-115.0 cm) (Ashcroft and others, 1992). The average number of frost-free days ranges from 112 at Trenton/Lewiston to 158 at Logan Utah State University (Ashcroft and others, 1992).

Population and Land Use

Available population and land-use statistics are for Cache County as a whole; most people in the county live in Cache Valley. From 1990 to 2000, the average annual population increase in Cache County was 2.7 percent (Demographic and Economic Analysis Section, 2001). The current population of Cache County is estimated at 91,391 with a projected population of 113,128 by 2010 (Demographic and Economic Analysis Section, 1998a,b, 2001).

The following information is from the Cache County countywide comprehensive plan (Cache County Planning Department, 1998). Land-use surveys were conducted in Cache County in 1960, 1979, and 1990. Table 2 summarizes all three survey studies on land use in Cache County.

Existing land uses of Cache County were classified under the following general categories in the countywide comprehensive plan (Cache County Planning Department, 1998):

> Urban - These are lands used for community growth and development within incorporated areas of the county.
>
> Irrigated Pasture and Cropland - These are irrigated lands primarily used for production of alfalfa, grain, or grasses more than 50 percent of the time.
>
> Non-Irrigated Pasture and Cropland - These are lands used for pasture for domestic livestock or to produce crops from natural precipitation.
>
> Range & Forested Woodland - These are lands used for several purposes including grazing, forestry, recreation, and seasonal dwellings. These lands consist primarily of state and federally managed areas outside of Cache Valley; however, there are also areas of privately owned land in this category.
>
> Wetlands/Marsh Land Areas - These are lands and areas of critical importance to the hydrology of Cache County, and for waterfowl population and habitat. They are formally defined as wetlands and are subject to flooding.
>
> Water - These areas include reservoirs, natural lakes, and other extended areas of surface water.

Cache County has 751,360 total acres (1,174 mi^2; 3,041 km^2) within its jurisdictional boundary. Table 2 gives an estimate

Table 2. *Cache County generalized land use (acres).*

Land Use Categories	1960	%	1980	%	1990	%
Urban	13,387	1.8	19,174	2.6	17,286	2.4
Irrigated Pasture & Cropland	167,954	22.4	119,974	15.9	110,821	14.8
Non-irrigated Pasture & Cropland	--	--	60,365	8.1	60,407	8.0
Range & Forested Woodland	544,670	72.5	543,693	72.4	540,600	71.9
Wetlands/Marsh Land Areas	22,757	3.0	5,562	0.7	19,654	2.6
Water	2,592	0.3	2,592	0.3	2,592	0.3
Total	751,360	100.0	751,360	100.0	751,360	100.0

of the range of land-use types and their distribution throughout Cache County.

GROUND-WATER CONDITIONS

Basin-Fill Aquifer

Ground water in Cache Valley occurs under perched, confined, and unconfined conditions (Bjorklund and McGreevy, 1971). The basin fill is more than several hundred feet thick at many locations in the valley center (Kariya and others, 1994). In the area between Smithfield and Newton, unconsolidated sediments are up to about 1,340 feet (410 m) thick (Bjorklund and McGreevy, 1971). Because the basin fill is unconsolidated sediment consisting of multiple, discontinuous layers of silt, sand, and gravel (deposited in fluvial, alluvial-fan, landslide, and nearshore lacustrine environments) separated by layers of silt and clay (primarily deposited in offshore lacustrine environments) (Bjorklund and McGreevy, 1971; Lowe, 1987, plate 2; Lowe and Galloway, 1993, plate 2), the principal aquifer consists of a complex multiple-aquifer system under both unconfined and confined conditions (Bjorklund and McGreevy, 1971; Kariya and others, 1994) (figure 2). Ground water in the principal aquifer is mostly under unconfined conditions along the margins of Cache Valley (Bjorklund and McGreevy, 1971), but is under leaky confined conditions in the center of the valley where many flowing wells exist (Kariya and others, 1994). The leaky confined conditions were attributed by Kariya and others (1994) to the discontinuous nature of clay and silt confining layers (figure 2). The boundary between unconfined and confined conditions is gradational near the margins of the basin. The confined portion of the principal aquifer is typically overlain by a shallow unconfined aquifer (Bjorklund and McGreevy, 1971) (figure 2).

Depth to ground water in Cache Valley ranges from at or near the ground surface in the central portion of the valley to more than 300 feet (90 m) along the valley margins (Bjorklund and McGreevy, 1971). Long-term water levels in Cache Valley's principal aquifer were relatively constant between 1945 and 1982 (Kariya and others, 1994), but declined as much as 13 feet (4 m) between 1970 and 2000 (Burden and others, 2000) (figure 3). Seasonal water-level changes range

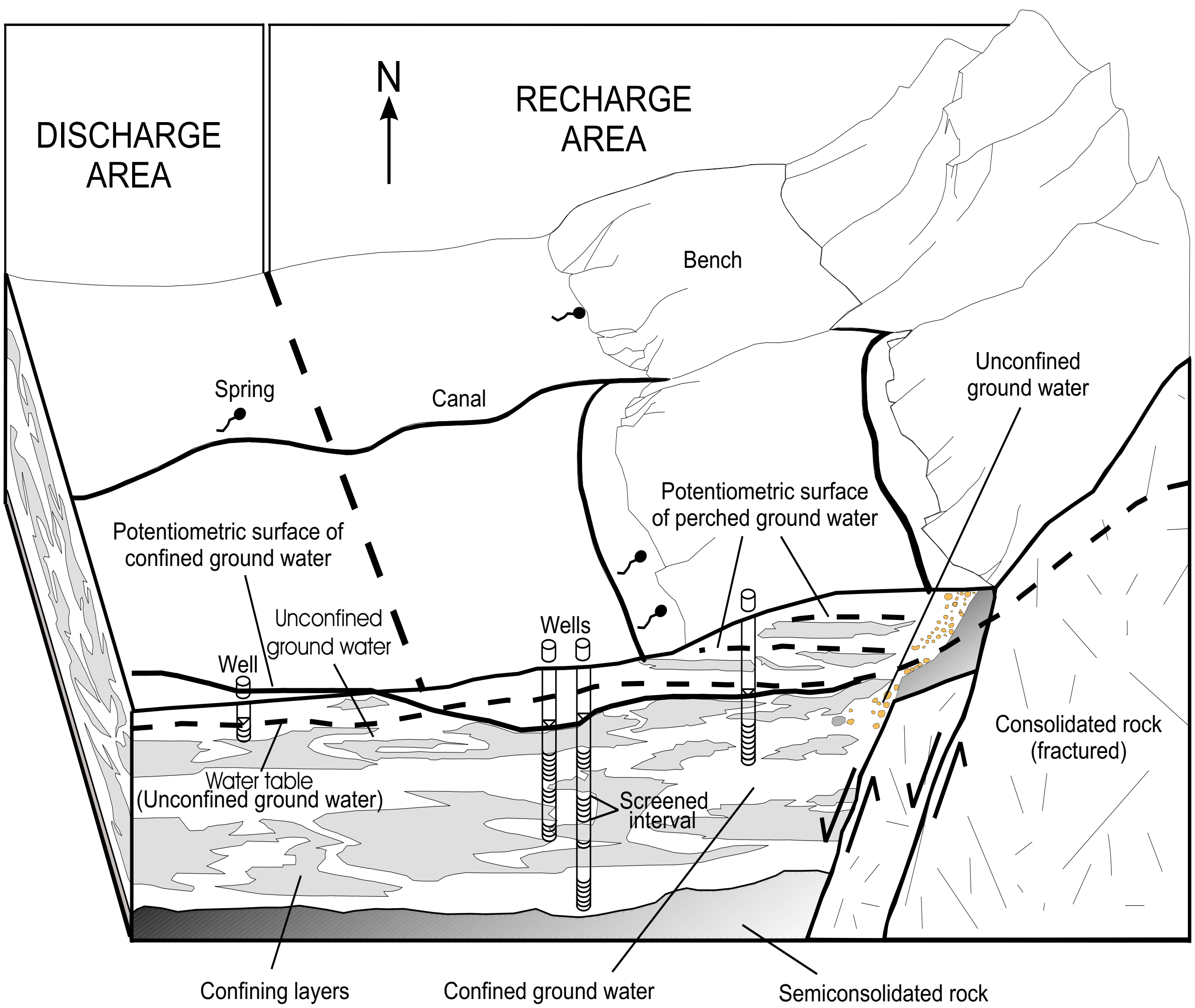

Figure 2. *Schematic block diagram showing ground-water conditions in Cache Valley, Utah (from Kariya and others, 1994).*

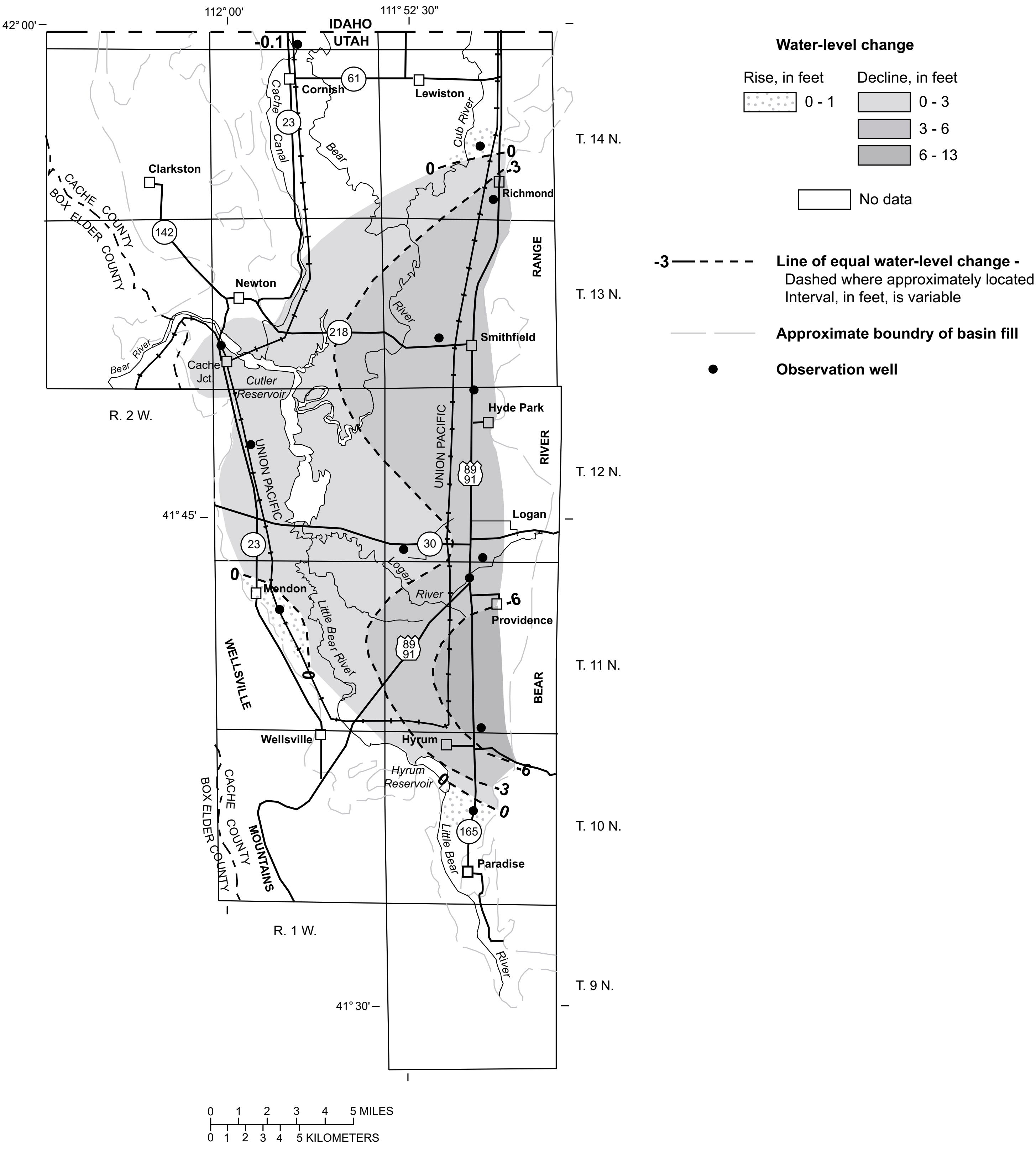

Figure 3. *Change of ground water level in Cache Valley from March 1979 to March 2000.*

from a few feet (less than 1 m) to about 20 feet (6 m) (Kariya and others, 1994, figure 12). Water levels are generally highest in the summer in northern Cache Valley, lowest in the summer in southeastern Cache Valley, and show no consistent seasonal pattern of water-level fluctuations in southwestern Cache Valley (Kariya and others, 1994).

Ground-water flow in Cache Valley's principal aquifer is north-northwest in southern Cache Valley, but in most of the valley, ground-water flow is typically from adjacent topographic highlands toward the valley center, generally toward the Bear River (Bjorklund and McGreevy, 1971, plate 4). Horizontal hydraulic gradients range from up to about 400 feet per mile (76 m/km) near the valley margins on the east side of the valley (Kariya and others, 1994) to less than 4 feet per mile (1 m/km) near the western margin of the city of Logan (Beer, 1967).

Recharge to the basin-fill aquifer system is from infiltration of precipitation, streams, canals, ditches, and irrigated fields, and by subsurface inflow from consolidated rock along the margins of the valley (Kariya and others, 1994) (table 3). Most recharge takes place along the valley margins where unconsolidated materials have the greatest permeability (Bjorklund and McGreevy, 1971). Discharge from the basin-fill aquifer system includes evapotranspiration, well-water withdrawal, and seepage to springs and Cutler Reservoir (Kariya and others, 1994) (table 3). Of the major streams in Cache Valley, the Bear River, including Cutler Reservoir, receives the largest amount of ground-water discharge as seepage to streams (Kariya and others, 1994).

Table 3. *1990 Hydrologic budget for Cache Valley (from Kariya and others, 1994).*

Recharge type	**Amount (cubic feet per second)**
Infiltration	57
Canal seepage	140
Stream seepage	3
Other	96
TOTAL	296
Discharge type	**Amount (cubic feet per second)**
Springs	138
Evapotranspiration	87
Water wells	52
Seepage to streams	180
TOTAL	457

Ground-Water Quality

Ground-water quality in Cache Valley's principal aquifer is generally very good. Calcium, magnesium, and bicarbonate are the major dissolved constituents and Bjorklund and McGreevy (1971) found total-dissolved-solids (TDS) concentrations to be mostly below 800 mg/L. However, warm saline ground water having TDS concentrations in excess of 1,600 mg/L has been documented near Newton and may be associated with fault zones (Bjorklund and McGreevy, 1971).

Lowe and Wallace (1999), as part of a ground-water-quality classification project for Cache Valley, selected 165 wells and one spring for sampling from four depth categories: (1) 38 of the wells are shallow wells (less than 100 feet [30 m] deep) completed in the principal aquifer, (2) 75 of the wells are of medium depth (100-200 feet [30-60 m]) completed in the principal aquifer, (3) 47 of the wells are deep wells (greater than 200 feet [60 m] deep) completed in the principal aquifer, and (4) one well and the spring are in and associated with the shallow unconfined aquifer. Depth is not known for five of the sampled wells presumed to be completed in the principal aquifer. These wells and the spring were sampled by the Utah Division of Water Quality during fall 1997 and winter/spring 1998 and the water was analyzed for general chemistry and nutrient content by the Utah Division of Epidemiology and Laboratory Services. Water from 46 of the wells was analyzed for organics and pesticides, and water from 13 was analyzed for radionuclides.

Figure 4 shows the distribution of TDS in Cache Valley's principal aquifer based on Lowe and Wallace's (1999) data. Total-dissolved-solids concentrations range from 178 to 1,758 mg/L, and average background TDS is 381 mg/L (Wallace and Lowe, 1999). Most of the ground water in the principal aquifer has TDS concentrations generally less than 500 mg/L (figure 4). However, for ground water in the northwestern part of Cache Valley, TDS concentrations are generally between 500 and 750 mg/L, and for ground water southwest of Amalga TDS concentrations range between 750 and 1,000 mg/L (figure 4). Three wells yielded ground-water samples that exceeded TDS concentrations of 1,000 mg/L. Two wells (1,468 and 1,758 mg/L TDS) of unknown depth are west-northwest of Lewiston. One sample from a 24-foot-deep (7 m) well completed in the shallow unconfined aquifer at a mink ranch west of Nibley yielded ground water with a TDS concentration of 1,236 mg/L (not shown on figure 4). Average TDS is 453 mg/L for water from deep wells, 331 mg/L for water from medium-depth wells, and 414 mg/L for water from shallow wells completed in the principal aquifer. Average TDS for water from the wells for which Lowe and Wallace (1999) had no depth information, typically older wells drilled or dug before well logs were required, is 843 mg/L. The spring (not shown on figure 4, but located west of Providence) yielded water with a TDS concentration of 368 mg/L.

Nitrate-plus-nitrite concentrations in Cache Valley's principal aquifer (figure 5) range from less than 0.02 to 35.77 mg/L, with an average (background) nitrate concentration of 1.9 mg/L. A total of seven wells, one northwest of Lewiston, two near Cornish, three southwest of Hyrum, and the mink ranch well with high TDS (not shown on figure 5), yielded water samples that exceed the ground-water-quality (health) standard for nitrate of 10 mg/L. High nitrate levels may be attributed to contamination from septic-tank systems, feed lots, and/or fertilizer. Average nitrate concentration is 1.21 mg/L for water from deep wells, 1.98 mg/L for water from medium-depth wells, and 4.47 mg/L for water from shallow wells completed in the principal aquifer. Average nitrate concentration for water from the wells for which Lowe and Wallace (1999) had no depth information is 6.06 mg/L. The spring (not shown on figure 5) yielded water with a nitrate concentration of 3.91 mg/L.

A water sample from one well near the confluence of the Little Bear River and the Bear River yielded an arsenic value

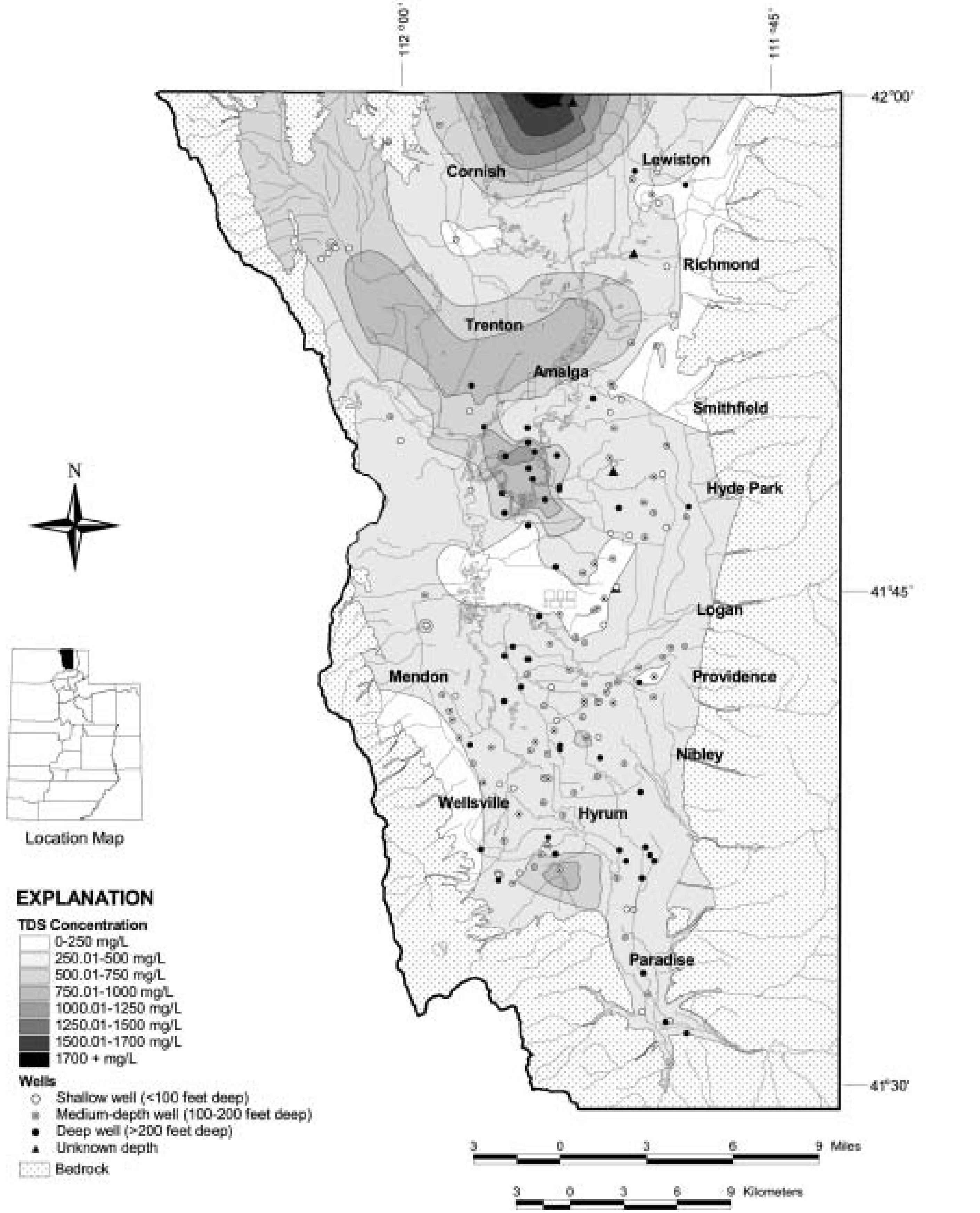

Figure 4. *Total-dissolved-solids concentrations in Cache Valley, Utah (after Lowe and Wallace, 1999).*

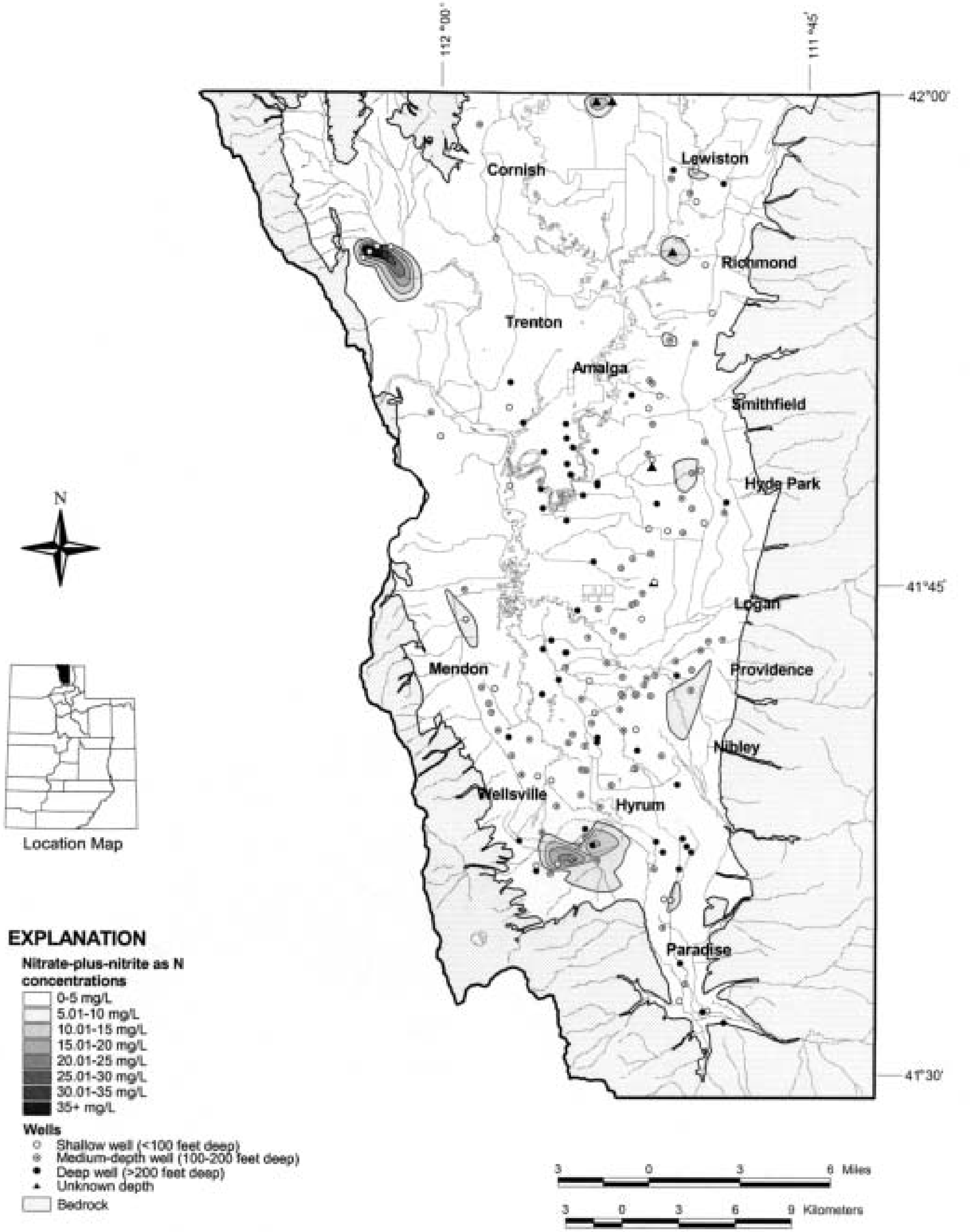

Figure 5. *Nitrate-plus-nitrite concentrations in Cache Valley, Utah (from Lowe and Wallace, 1999).*

of 100 µg/L, twice the ground-water-quality standard of 50 µg/L. A number of wells throughout the valley contain water with elevated iron concentrations that exceed the secondary ground-water-quality standard of 300 µg/L, but are not considered harmful to human health. Gross alpha is below 5 pCi/L for all ground-water samples, so samples were not analyzed subsequently for specific radionuclides. Of water wells tested for pesticides, one well yielded water with a value above the detection limit for atrazine, and another well yielded water with a value above the detection limit for DDT, but neither value exceeded ground-water-quality standards.

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. No new field work was conducted or data collected as part of this project.

Ground-Water Sensitivity to Pesticide Pollution

Ground-water sensitivity to pesticides is an assessment of natural factors favorable or unfavorable to the degradation of ground water by any pesticides applied to or spilled on the land surface. We selected five factors that are most important in determining ground-water sensitivity to pesticides: 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.

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. Primary recharge areas, commonly the uplands and coarse-grained unconsolidated deposits along basin margins, do not contain thick, continuous, fine-grained layers and have a downward ground-water gradient (figure 6). Secondary recharge areas, commonly mountain-front benches, have fine-grained layers thicker than 20 feet (6 m) and a downward ground-water gradient (figure 6). 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 (Snyder and Lowe, 1998) (figure 6). Discharge areas for confined aquifers occur where the ground-water gradient is upward and water is discharging to a shallow unconfined aquifer above the upper confining bed, or to a spring (figure 6). 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.

Anderson and others (1994) used drillers' logs of water wells in Cache Valley to delineate primary or secondary recharge areas and discharge areas, based on the presence of confining layers and relative water levels in the principal and shallow unconfined aquifers. Although this technique is useful for gaining a general idea of where recharge and discharge 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 often not recorded and because water levels were measured during different seasons and years.

Confining layers are any fine-grained (clay and/or silt) layer thicker than 20 feet (6 m) (Anderson and others, 1994). Some drillers' logs show both clay and sand in the same interval, with no information for relative percentages; these are not classified as confining layers (Anderson and others, 1994). If both clay and silt are checked on the log and the word "sandy" is written in the remarks column, then the layer is assumed to be a predominantly clay confining layer (Anderson and others, 1994). Some drillers' logs show both clay and gravel, cobbles, or boulders; these also are not classified as confining layers although in some areas in Cache Valley, layers of clay containing gravel, cobbles, or boulders act as confining layers.

The primary recharge area for the principal aquifer system in Cache Valley consists of the uplands surrounding the basin, and basin fill not containing confining layers, generally along mountain fronts (figures 2 and 6). Ground-water flow in primary recharge areas has a downward component. Secondary recharge areas, if present, are locations where there are confining layers, but ground-water flow still has a downward component. Secondary recharge areas generally extend toward the center of the basin to the point where ground-water flow is upward (figures 2 and 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 occur where the potentiometric surface in the principal aquifer system is below the ground surface.

Ground-water discharge areas, if present, generally occur at lower elevations than recharge areas. In discharge areas, the water in confined aquifers discharges to the land surface or to a shallow unconfined aquifer (figures 2 and 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 will exceed 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′ 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. It is necessary to understand the topography, surficial geology, and ground-water hydrology before

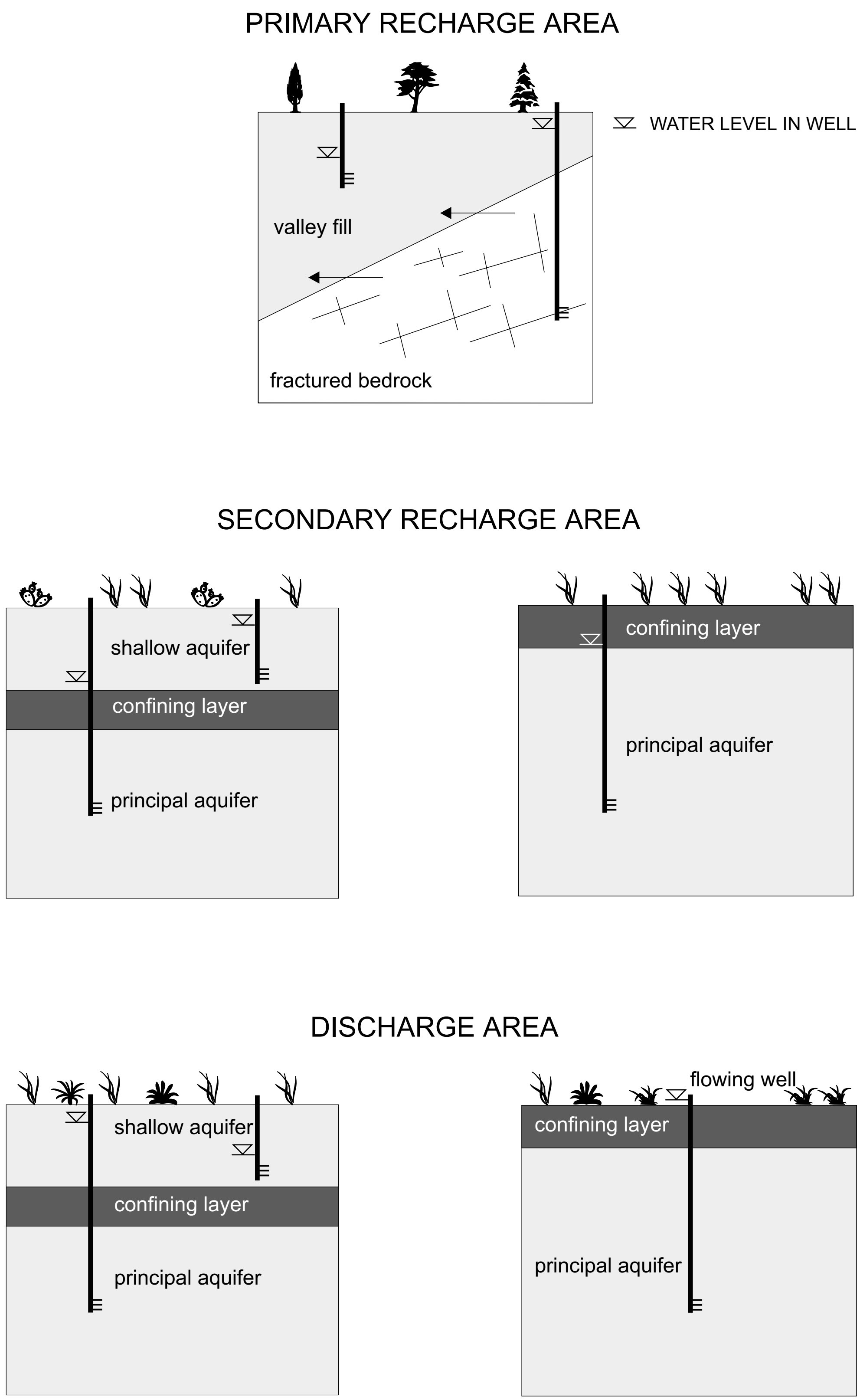

Figure 6. *Relative water levels in wells in recharge and discharge areas (from Snyder and Lowe, 1998).*

using these wetlands to indicate discharge from the principal aquifer system.

Hydraulic Conductivity of Soils

Hydraulic conductivity is a measure of the rate at which soils can transmit water. Even though fine-grained soils may have low transmissivities, water is nevertheless eventually transmitted. 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 Natural Resources Conservation Service (formerly Soil Conservation Service; Erickson and Mortensen, 1974). For our GIS analysis, we divided soil units into two hydraulic conductivity ranges: greater than, and less than or equal to 2 inches (5 cm) per minute. We categorized these by following criteria applied by the Utah Department of Environmental Quality's Division of Water Quality in permitting or not permitting septic tanks. For areas with insufficient hydraulic conductivity data, we applied the greater than 2 inches (5 cm) per minute GIS attribute ranking, described below, to be protective of ground-water quality.

Pesticide Retardation

Retardation (Rao and others, 1985) is a measure of the differential between movement of water and the movement of pesticide in the vadose zone. Since pesticides are adsorbed to organic carbon in soil they move more slowly through the soil than water, depending 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 speed as pore water in the vadose zone. The retardation factor (R_F) is a function of bulk density, organic carbon fraction, and field capacity of the soil and the organic carbon sorption distribution coefficient of the specific pesticide. Rao and others (1985) present the following equation:

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

where:

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

For this study we used data from the Soil Survey Geographic (SSURGO) database, which provides digitized data for some soil areas of the state of Utah, including Cache Valley, at a scale of 1:24,000. Data include derived values for bulk density, organic carbon fraction, and field capacity (table 4).

Table 4. *Hydrologic Soil Groups and rankings for retention capacity, bulk density of soils, and fraction of organic content generalized for Utah soils. Soil description and organic content from National Soil Survey Center (1994). Field capacity calculated from specific-retention data based on sediment grain size (from Bear, 1972). Bulk density from Marshall and Holmes (1988).*

Soil Group	Soil Description	Grain Size (mm) (field capacity)	Bulk Density Range (kg/liter)	Organic Content, Fraction (Foc)
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 (5-6%)	1.6 – 2	2.44
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 (6-7%)	1.3 - 1.61	3.31
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 (7-7.5%)	1.3 - 1.9	3.99
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 (6-15%)	1.12	3.35

We set variables in equation 1 at values that represent conditions likely to be encountered in the natural environment to establish a rationale for dividing high and low pesticide retardation for our GIS analysis. We used the organic carbon sorption distribution coefficient (table 5) for atrazine at a pH of 7, the pesticide among the four having the least tendency to adsorb to organic carbon in the soil (Weber, 1994). Applying a bulk density of 2.0 kilograms per liter (kg/L) and a field capacity of 5 percent, which represent the naturally occurring extremes that would result in the greatest sensitivity to ground-water contamination, retardation of pesticides relative to vertical ground-water movement ranges from a factor of 1 to 201 percent, depending on soil organic carbon content. Average organic content in soils in Cache Valley is shown in figure 7; note that in the lowest category organic content in soils ranges from 0 to 2.4 percent. Next, we standardized organic carbon content at a value of 0.1 percent - a value representing a reasonable minimum found in the natural environment at which ground-water quality would still be protected. At this level of organic carbon content, equation 1 results in a retardation factor of 5 percent, meaning that pesticides would travel 5 percent slower through soils in the vadose zone than water. Pesticides under these circumstances traveling downward in the vadose zone would reach the water table at a depth of 3 feet (1 m) within one year if ground-water recharge amounted to 6 inches (5 cm) or greater during the year. Greater proportions of the pesticide reach ground water at that depth with greater annual quantities of ground-water recharge. When ground-water recharge is less than 6 inches (15 cm), no pesticides reach a depth of 3 feet (1 m) in a one-year period (see attenuation discussion below). A natural division between low and high retardation exists at a value of 5 percent. Accordingly, values lower than 5 percent are designated as low retardation and are assigned a ranking value of 1. Values equal to or higher than 5 percent are designated as high retardation and are assigned a ranking value of 0.

Pesticide Attenuation

Attenuation (Rao and others, 1985) is a measure of the rate at which a pesticide degrades under the same conditions as characterized above under retardation. The rate of attenuation indirectly controls the depth to which a pesticide may reasonably be expected to migrate, given the specific conditions. The attenuation factor (A_F) is a function of depth (vertically) or length (horizontally) of the soil layer through which the pesticide is traveling, net annual ground-water recharge, half-life of the specific pesticide considered, and field capacity of the soil. Rao and others (1985) present the following equation:

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

where:

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

We set variables in equation 2 at values that represent conditions likely to be encountered in the natural environment, similar to what was done to establish high and low pesticide retardation, to establish a rationale for dividing high and low pesticide attenuation for our GIS analysis. We used a retardation factor of 5 percent, calculated as described above; the half-life for simazine (table 5), the pesticide among the four with the longest half-life (Weber, 1994); a field capacity of 5.0 percent, together with the bulk density value of 2.0 used in the retardation factor calculation described above, which represent the naturally occurring extremes that would result in the greatest sensitivity to ground-water contamination. For a net annual ground-water recharge value of 6 inches (15 cm), equation 2 results in an attenuation factor of 0.02. This means that, at the above-described values for variables in the equation, two percent of the pesticide originally introduced into the system at the ground surface would be detected at a depth of 3 feet (1 m) and would enter the ground water. For rates of annual ground-water recharge greater than 6 inches (15 cm), the calculated attenuation factor increases proportionally such that 50 percent of the original volume of pesticide would still be present at a depth of 3 feet (1 m) and would enter the ground water when the annual ground-water recharge rate is 3 feet (1 m). Accordingly, an attenuation factor of 0 is considered low, whereas 0.02 (2 percent) and above is considered high.

For this study, net annual recharge was calculated (using GIS analysis) by subtracting mapped normal annual evapotranspiration (Jensen and Dansereau, 2001) for the 30-year period from 1971 to 2000 from mapped normal annual precipitation (Utah Climate Center, 1991) for the 30-year period from 1961-1990. Data from two different 30-year periods were used because normal annual precipitation GIS data are not currently available for the 1971 to 2000 period and normal annual evapotranspiration GIS data are not available for the 1961 to 1990 period. This analysis revealed that all of the

Table 5. *Pesticide organic carbon sorption distribution coefficients (Koc) and half-lives ($T^{1}/_{2}$) for typical soil pHs (Weber, 1994).*

	Koc (mg/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

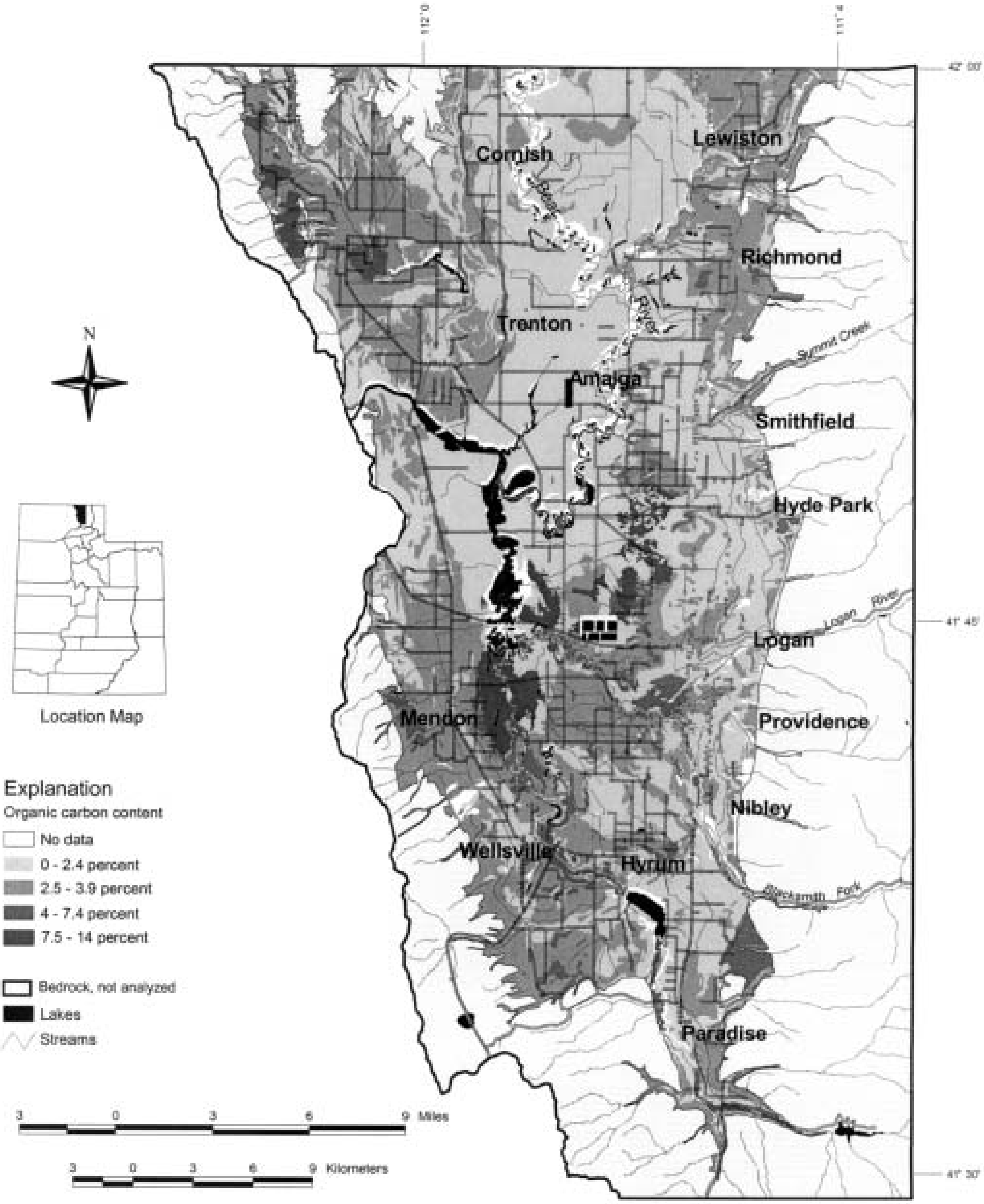

Figure 7. *Average organic carbon content in soils in Cache Valley, Cache County, Utah (data from National Soil Survey Center, 1994).*

moisture produced by precipitation is consumed by evapotranspiration in most parts of the state, including Cache Valley. Therefore, ground-water recharge from precipitation is relatively low in many areas of Utah, including Cache Valley. The only localities in which evapotranspiration is lower than precipitation are high-elevation forested areas. These are typically the source areas for surface streams which flow to valleys at lower elevations where they infiltrate the valley-fill sediment, accounting for a large part of ground-water recharge. Irrigation is another component of ground-water recharge, but it is not easily measured.

To evaluate the relationship between ground-water recharge and pesticide attenuation, we used the same array of values for variables in the attenuation equation of Rao and others (1985) (equation 2) that we applied to the retardation equation (equation 1), described above. We used the organic carbon sorption distribution coefficient for atrazine (table 5) at a pH of 7 - the pesticide among the four having the least tendency to adsorb to organic carbon in the soil - and the half-life for simazine (table 5), the pesticide among the four with the longest half-life (Weber, 1994). Applying a bulk density of 2.0 kg/L (the maximum anticipated value to be encountered in soil types represented in Cache Valley), a retention capacity of 5.0 percent (the minimum anticipated value), and an organic carbon content of 0.1 percent (the minimum value expected in these soils), 100 percent of pesticides would be attenuated before reaching a soil depth of 3 feet (1 m) until ground-water recharge reached a rate of 6 inches (15 cm) per year. In Cache Valley, ground-water recharge would be derived mainly from irrigation. At higher values for organic carbon content, both the retardation factor and the attenuation factor increase dramatically. With greater proportions of organic carbon in the soil, calculations show no amount of pesticide reaching ground water even at hypothetical levels of ground-water recharge as high as 3 feet (1 m) per year.

The exercise of calculating values for retardation and attenuation factors according to hypothetical values for the equation variables enabled us to calibrate assigned rankings of pesticide sensitivity meaningfully according to naturally occurring conditions, thus overcoming one of the major objections to the DRASTIC method. Further, the exercise illustrates that organic soil content exerts a major control on the complex interplay of conditions that increase or decrease the likelihood that pesticides will find their way into the ground water. We found that even with a moderate organic carbon content in the soil, it is unlikely that pesticides will impact the ground water.

Although quantities of pesticides applied to the ground surface empirically would seem to have a direct bearing on the amount of pesticide impacting ground water, the equations of Rao and others (1985) 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 are 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 6) are provided by the manufacturers of the four herbicides evaluated as part of this study. Pre-emergent herbicides are typically applied once per year, either in the fall after post-season tillage or in early spring before weeds begin to germinate.

Depth to Ground Water

The closer that ground water is to the land surface the more sensitive it is to being degraded by pesticides. Based on soil mottling, water encountered in test pits, or other information, soils with shallow ground water seasonally less than 3 feet (1 m) deep is one attribute of soil units mapped by the U.S. Department of Agriculture's Natural Resources Conservation Service (formerly Soil Conservation Service; Erickson and Mortensen, 1974). Three feet (1 m) was selected as the depth-to-ground-water attribute used to evaluate sensitivity of geographic areas to pesticides. For areas where depth-to-ground-water data were 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 divided pesticide sensitivity into "low," "moderate," and "high" categories using hydrogeologic setting, soil hydraulic conductivity, soil retardation of pesticides, soil attenuation of pesticides, and depth to shallowest ground-water attributes as shown on table 7. Numerical ranking for each attribute category is arbitrary, but reflects the level of importance we believe 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

Table 6. *Maximum recommended application rates* of 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.

Table 7. *Pesticide sensitivity and attribute rankings used to assign it for Cache Valley, Cache County, Utah.*

Pesticide Retardation		Pesticide Attenuation		Hydrogeologic Setting		Soil Hydraulic Conductivity		Depth to Ground Water		Sensitivity	
Attribute	Ranking	Attribute	Ranking	Attribute	Ranking	Attribute	Ranking	Attribute	Ranking	Attribute	Ranking
High	0	High	0	Discharge Area	-4	Less than 2 inches/minute	1	Greater than 6 feet	1	Low	-2 to 0
				Secondary Recharge Area	-1					Moderate	1 to 4
Low	1	Low	1	Primary Recharge Area	2	Greater than 2 Inches/minute	2	Less than 6 feet	2	High	5 to 8

heavily than the other attribute categories. A sensitivity attribute of low was assigned when the numerical ranking ranged from –2 to 0, a sensitivity attribute of moderate was assigned when the numerical ranking ranged from 1 to 4, and a sensitivity attribute of high was assigned when the numerical ranking ranged from 5 to 8.

Ground-Water Vulnerability to Pesticide Pollution

Ground-water vulnerability to pesticides is an assessment of how natural factors favorable or unfavorable to the degradation of ground water by any pesticides applied to or spilled on the land surface are modified by the activities of humans. We selected ground-water sensitivity to pesticides, presence of applied water (irrigation), and crop type as the three factors primarily determining ground-water vulnerability to pesticides. Our vulnerability maps are based on 1995 land-use data.

Ground-Water Sensitivity

We consider ground-water sensitivity to be the principal factor determining the vulnerability of the basin-fill aquifer in Cache Valley to degradation from agricultural pesticides. Low, moderate, and high sensitivity rankings were assigned numerical values for ranking as shown in table 7 and described above.

Irrigated Lands

Irrigated lands are mapped 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 either mapped from aerial photographs (pre-2000) or 5-meter (16 ft) resolution infra-red satellite data and then field checked (Utah Division of Water Resources metadata). The Cache Valley inventory was conducted in 1996 (Utah Division of Water Resources metadata). All polygons with standard type codes beginning with IA were selected to produce the irrigated land coverage for this study. These data do not distinguish areas of sprinkler irrigation versus areas of flood irrigation; areas of flood irrigation are likely to be more vulnerable to degradation from pesticides than areas of sprinkler irrigation.

Agriculture Types

Agricultural lands are mapped from 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 either mapped from aerial photographs (pre-2000) or 5-meter (16 ft) resolution IRS satellite data and then field checked (Utah Division of Water Resources metadata). The Cache Valley inventory was conducted in 1996 (Utah Division of Water Resources metadata). We selected all polygons with standard type codes IA2a1 (corn), IA2a2 (sorghum), and IA2b5 (sweet corn; none in this category were in the data set) to produce the crop type coverage for this study, since these are the crop types to which the pesticides addressed are applied in Utah. While the specific fields with these crops may change from year to year, the general areas and average percentages of these crop types likely do not.

GIS Analysis Methods

We divided pesticide vulnerability into "low," "moderate," and "high" categories using pesticide sensitivity, areas of irrigated lands, and crop type as shown in table 8. Once again, numerical ranking for each attribute category is arbitrary, but reflects the level of importance we believe the attribute plays in determining sensitivity of areas to application of agricultural pesticides; for instance, we believe ground-water sensitivity to pesticides is the most important attribute with respect to ground-water vulnerability to pesticides, and therefore weighted this attribute two times more heavily than the other attribute categories.

RESULTS

Ground-Water Sensitivity

In order to assess ground-water sensitivity to pesticide contamination, several attribute layers were assembled as intermediate steps. Attribute layers include pesticide retardation/attenuation, hydrogeologic setting (recharge/discharge areas), hydraulic conductivity of soils, and depth to shallow ground water. Data from these attribute layers were used to produce a ground-water sensitivity map using GIS

Table 8. *Pesticide vulnerability and attribute rankings used to assign it for Cache Valley, Cache 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

analysis methods as outlined in table 7 (plate 1), and are described and summarized in the following sections.

Retardation/Attenuation

Retardation/attenuation was ranked as high throughout Cache Valley because net annual evapotranspiration exceeds net annual precipitation. Net annual recharge from precipitation is negative (figure 8). Most recharge that does occur from precipitation in Cache Valley likely occurs during spring snowmelt, principally along the valley margins. Pesticides are generally applied after snowmelt. Up to several months may elapse between pesticide application and first irrigation, allowing attenuation to occur before downward migration of pesticides in the vadose zone commences under the influence of irrigation.

Hydrogeologic Setting

Ground-water recharge areas in Cache Valley were mapped by Anderson and others (1994) (figure 9). Their map shows that primary recharge areas, the areas most susceptible to contamination from pesticides applied to the land surface, make up only about 15 percent of the surface area of the basin-fill aquifer. Primary recharge areas form a narrow band around the outer margin of the basin-fill deposits (figure 9). Secondary recharge areas make up about 22 percent of the surface area of the basin-fill aquifer, forming in most places a narrow band between primary recharge areas and discharge areas (figure 9). A secondary recharge area also exists in north-central Cache Valley extending southward to Newton (figure 9). Most of the central, lower elevations of Cache Valley are ground-water discharge areas; there is also a discharge area in the southernmost part of the valley (figure 9). Discharge areas, which provide extensive protection to the principal aquifer from surface contamination from the application of pesticides, make up about 63 percent of the surface area of the basin-fill aquifer.

Hydraulic Conductivity of Soils

Surface application of pesticides is more likely to cause ground-water-quality problems in areas where soils have higher hydraulic conductivity than in areas where hydraulic conductivity is low. Hydraulic conductivity data are from National Soil Survey Center (1994). About 61 percent of the surface area of the basin-fill aquifer has soil units mapped as having hydraulic conductivity greater than or equal to 2 inches per minute (5 cm/min). Soils in this category are found along the basin margins, and they also cover large portions of the land surface in the southern and northern parts of the valley (figure 10). About 32 percent of the surface area of the basin-fill aquifer has soil units mapped as having hydraulic conductivity less than 2 inches per minute (5 cm/min); these soil units are primarily in the central part of the valley at lower elevations (figure 10). About 7 percent of the soil units within Cache Valley were not assigned hydraulic conductivity values; these soils are primarily along the margins of rivers (figure 10), and were lumped into the greater than or equal to 2 inches per minute 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 shallowest ground water rather than where ground water is relatively deeper. Depth to shallow ground-water data are from National Soil Survey Center (1994). About 30 percent of the area overlying the basin-fill aquifer has soil units mapped as having depths to shallow ground water less than or equal to 3 feet (1 m); these areas are primarily in the central part of the valley having lower elevation (figure 11). About 13 percent of the surface area of the basin-fill aquifer has soil units mapped as having depths to shallow ground water greater than 3 feet (1 m); these areas are principally mapped along the margins of rivers (figure 11), but are also expected (but not mapped, see below) along the margins of Cache Valley.

However, almost 86 percent of the surface area of the basin-fill aquifer is underlain by soil units for which depth to shallow ground water is unknown. Most of these areas with no data are located along the margins of Cache Valley (figure 11). Areas without assigned depths to shallow ground water were lumped into the less than or equal to 3 feet depth category for analytical purposes to be protective of water quality.

Sensitivity Map

Plate 1 shows ground-water sensitivity to pesticides for Cache Valley, obtained using GIS methods and ranking techniques described above. The area in the eastern and southern part of Cache County that is designated on plate 1 as “bedrock” and comprises mainly the Bear River Range is shallow bedrock in mountainous terrain. The area is sparse-

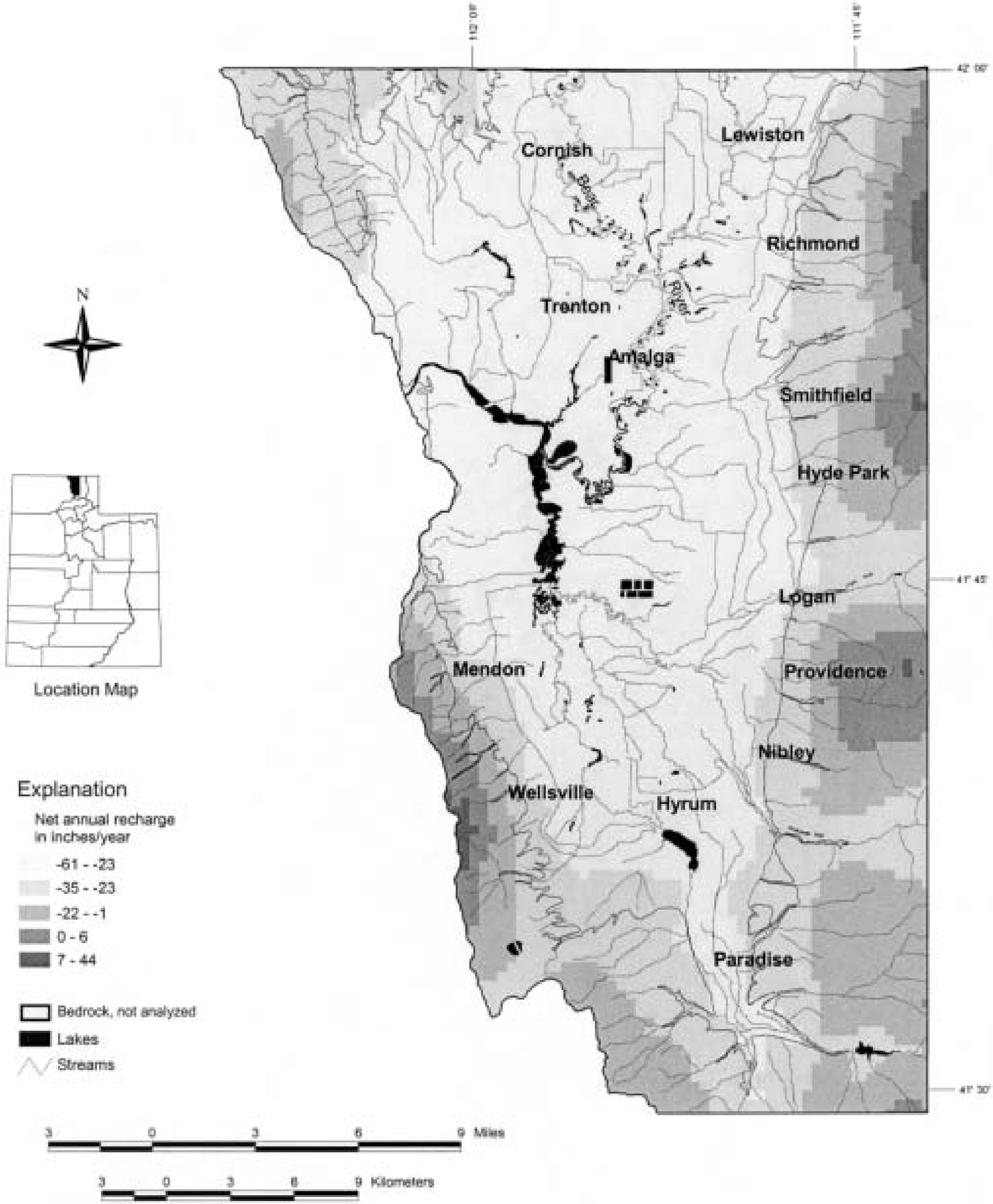

Figure 8. *Net annual recharge from precipitation for Cache Valley calculated using data from the Utah Climate Center (1991) and Jensen and Dansereau (2001). Although net annual recharge may be negative in some areas, seasonally some recharge from precipitation may occur.*

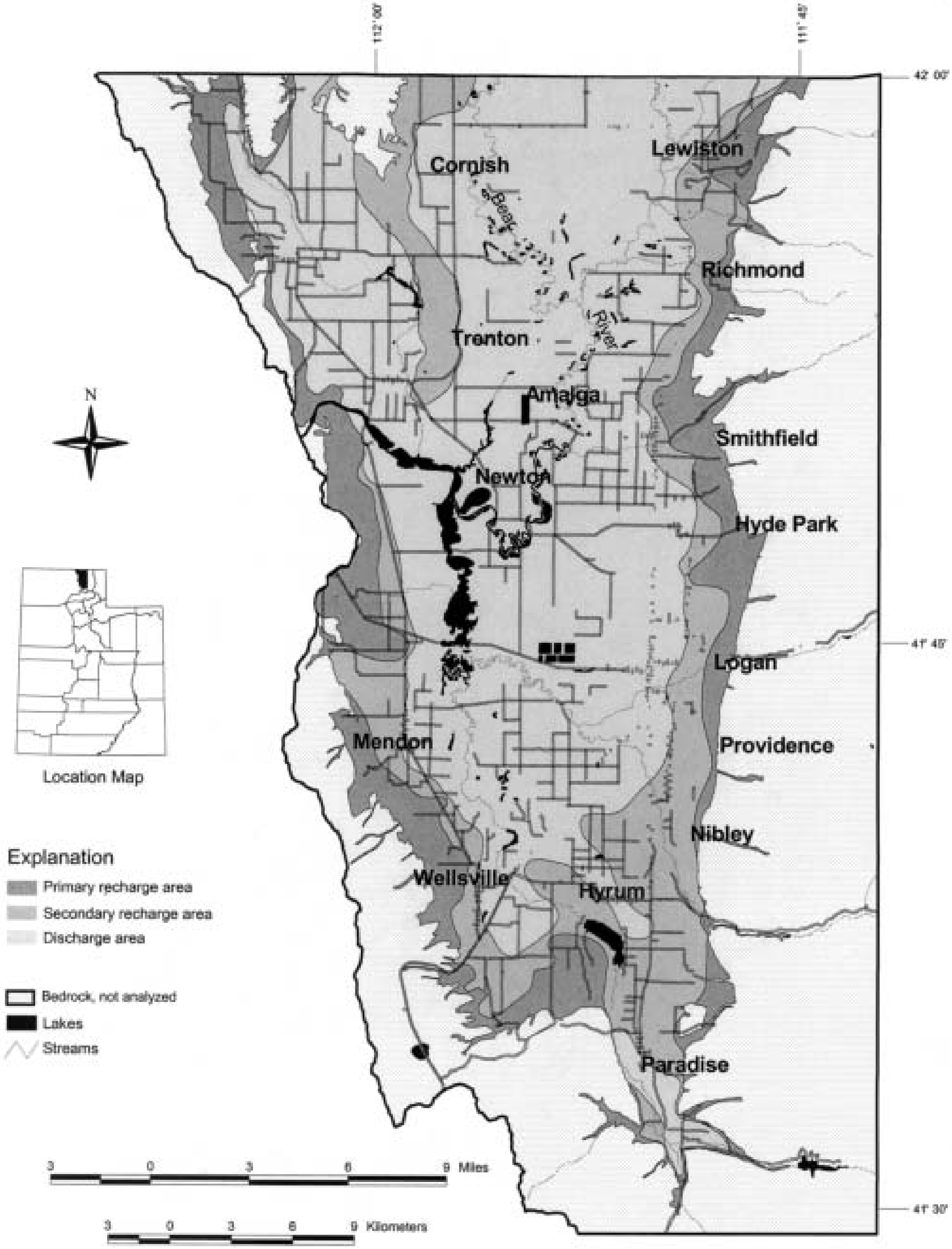

Figure 9. *Recharge and discharge areas in Cache Valley, Cache County, Utah (from Anderson and others, 1994).*

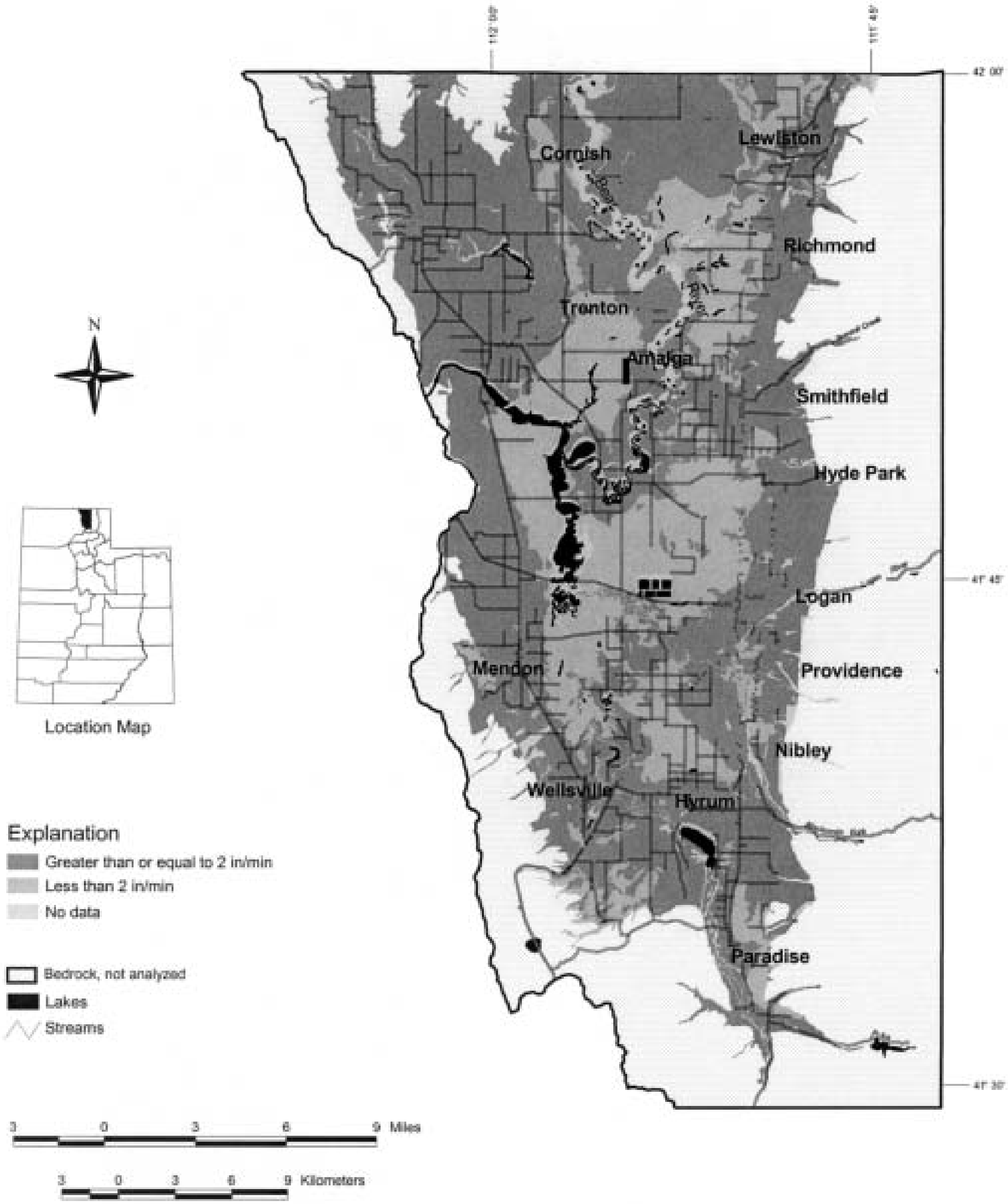

Figure 10. *Soil hydraulic conductivity in Cache Valley, Cache County, Utah (data from National Soil Survey Center, 1994).*

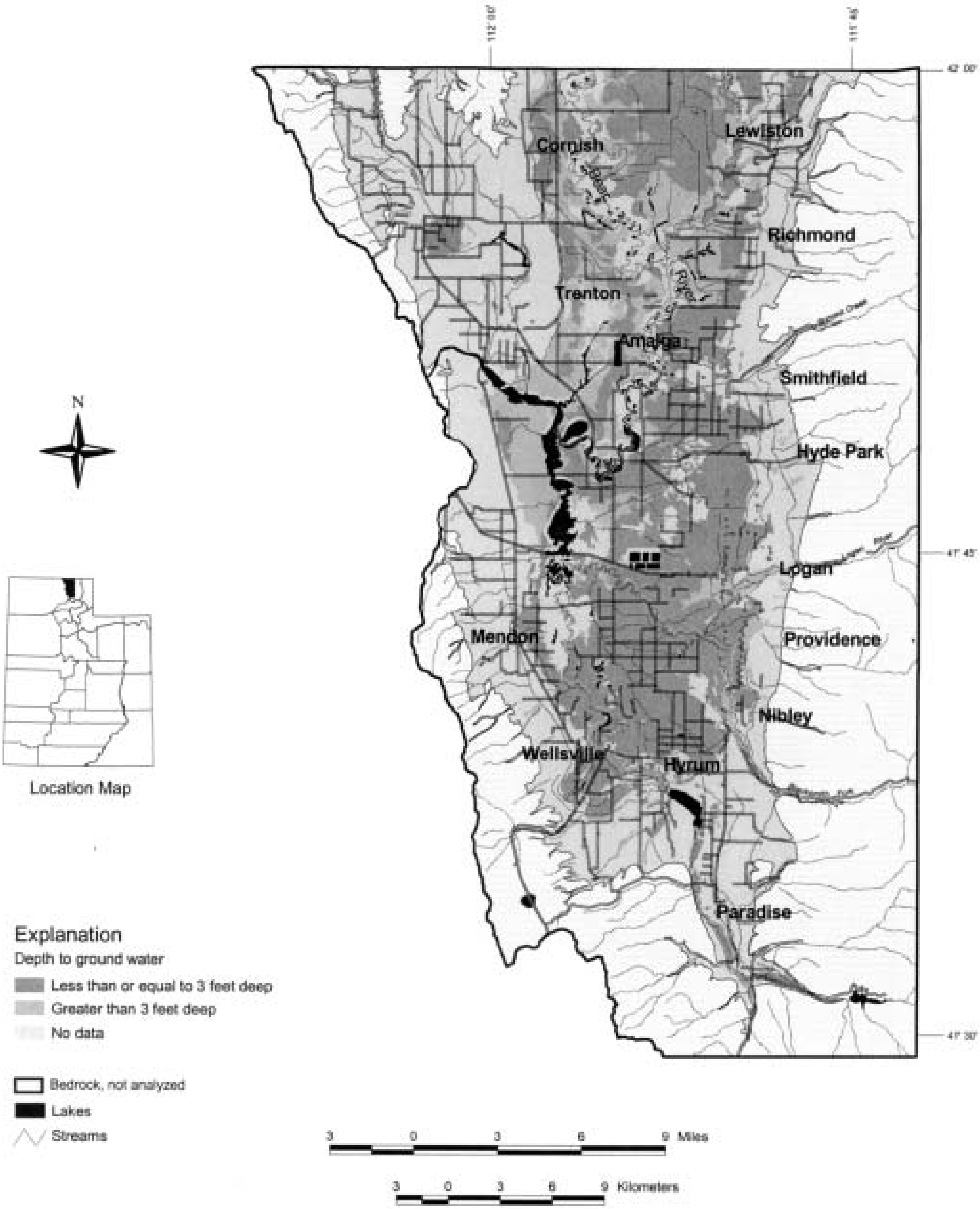

Figure 11. *Depth to ground water in Cache Valley, Cache County, Utah (data from National Soil Survey Center, 1994).*

ly populated and agricultural activity is limited to livestock range grazing. Consequently, this area was not considered in our analysis which addresses the basin-fill aquifer, the source of most ground water used in Cache Valley. However, land use may change through time.

The central part of Cache Valley is of low sensitivity (plate 1) because it is a discharge area characterized by ground-water gradients that show upward flow. Pesticides used in this area are unlikely to degrade ground water because they have little opportunity to get into the aquifer. Additionally, the soils typically have low hydraulic conductivity. In this area, pesticides spilled or misapplied have a much greater potential to contaminate surface water than ground water.

Along valley-margin benches outward from the area of low sensitivity is an area of moderate sensitivity (plate 1). This consists of primary and secondary recharge areas, in which pesticides that have been spilled or misapplied have a greater potential for impacting ground water. In areas of moderate sensitivity, the ground-water gradient has a downward component, but the aquifer is somewhat protected because it is partially confined or is at such a great depth that pesticides would undergo chemical breakdown before they migrate to such depths.

Areas of high sensitivity are located primarily along the margins of Cache Valley (plate 1). In these areas ground water is either shallow with no overlying confining layers, or insufficient data are available to make a less conservative assessment. Additionally, these areas typically have higher hydraulic conductivity. In some localities, perched water may be present above lenticular or discontinuous bodies of fine-grained sediment that form aquicludes. In some cases shallow ground water may be erroneously reported on drillers' logs. Improved data quality is required to substantiate or discount these as areas of concern. Typically, the areas of high sensitivity are bounded along mountain fronts by basin-boundary faults (plate 1) which delineate the limits of the ground-water basin.

Ground-Water Vulnerability

In order 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 attribute layers include irrigated cropland and corn- and sorghum-producing areas in Cache County, combined into one attribute-layer map (figure 12). Using GIS methods as outlined in table 8, 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 influence of human activity as a component of ground-water vulnerability cannot be ignored. Pertinent attribute layers, along with ground-water sensitivity, are described in the following sections.

Ground-Water Sensitivity

The most influential factor in ground-water vulnerability to pesticide contamination is ground-water sensitivity, described in the previous section. Sensitivity represents the sum of natural influences that facilitate the entry of pesticides into ground water. The prevailing influence of sensitivity manifests as similarity between the sensitivity and vulnerability maps (plates 1 and 2, respectively). However, a vulnerability assessment for a particular tract of land should not be made from the sensitivity map despite this similarity.

Irrigated Cropland

All of the cropland areas in Cache Valley are irrigated (figure 12), with the result that this factor does not influence configuration of the vulnerability map by itself. Irrigation is potentially significant because it is a major 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 (figure 12) are significant because the four herbicides considered in this report - alachlor, atrazine, metolachlor, and simazine - are used to control weeds in these crops. Areas of corn and sorghum crops are shown on the map of figure 12 as rectangles concentrated in the central part of Cache Valley coinciding with the area of low sensitivity shown on the map of plate 1. The effect of areas of corn and sorghum production on vulnerability is to raise vulnerability from low to moderate.

Vulnerability Map

Plate 2 shows ground-water vulnerability to pesticides for the Cache Valley basin-fill aquifer, obtained using GIS methods and ranking techniques described above. The area in the eastern and southern part of Cache County, mainly the Bear River Range, is not included in the analysis because of the predominance of shallow bedrock and mountainous terrain, and because it is not an area of significant agricultural activity.

Low-sensitivity areas and low-vulnerability areas roughly coincide, but have minor differences. Localities where corn and sorghum are raised appear as rectangle-like shapes of moderate vulnerability on plate 2 in the central part of the valley along its long axis where low vulnerability otherwise predominates.

Areas of moderate vulnerability coincide in general with those of moderate or high sensitivity. The moderate-vulnerability areas occur along valley-margin benches where ground water is at great depths or confining layers protect the deeper basin-fill aquifer. An area of high sensitivity would be categorized as having moderate vulnerability if the land is not irrigated or if corn and sorghum are not raised there. The two pesticide detections by the UGS, discussed above in the water-quality section, are in areas mapped as having moderate vulnerability to pesticides.

Areas of high vulnerability are located in primary recharge areas where ground water occurs at depths of less than 3 feet (1 m), or the depth to ground water is unknown. Of particular concern are areas where streams originating in mountainous areas cross the valley margin. Most of these localities fall within the high-vulnerability range. Recharge of ground water by such streams at these points is the most important means for recharge of aquifers in the valley fill. Therefore, efforts to preserve water quality in streams at these points would help to preserve ground-water quality in the entire basin.

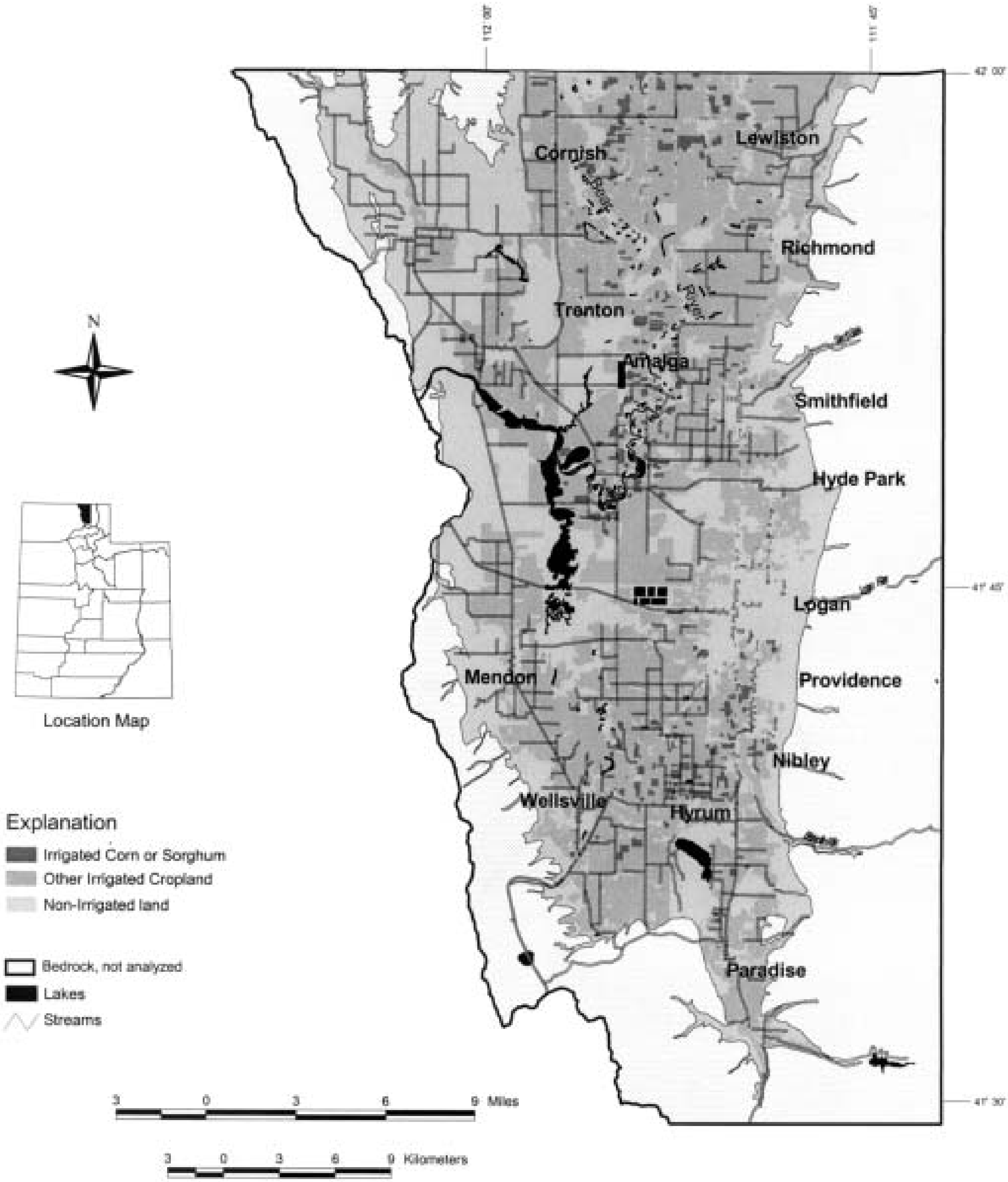

Figure 12. *Irrigated cropland in Cache Valley, Cache County, Utah (data from Utah Division of Water Resources, 1995). The pesticides being addressed in this study are mainly applied to corn and sorghum.*

CONCLUSIONS AND RECOMMENDATIONS

Precipitation is not the major source of ground-water recharge within the Cache Valley area, especially in the central part of the valley where ground-water gradients in the basin-fill aquifer are upward (ground-water discharge area). The main sources of recharge to the basin-fill aquifer are surface streams that originate in areas of higher elevation and then flow into Cache Valley in primary recharge areas. Areas where rivers and streams cross valley-bounding faults and coarse-grained alluvial fans represent the most urgent need for protection to preserve ground-water quality, based on the results of our ground-water sensitivity and vulnerability mapping. Other valley-margin areas, particularly those with unlined or poorly lined irrigation canals, also warrant measures to protect ground-water quality based on our mapping. However, 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, it is unlikely that pesticides applied to crops and fields in Cache Valley represent a serious threat to ground-water quality.

Based on these conclusions, we believe ongoing ground-water sampling in Cache Valley should be concentrated in areas of moderate and high sensitivity or vulnerability, typically along valley margins. Sampling in the central area of the valley characterized by low sensitivity and low vulnerability should continue, but at a lower density than in the areas of higher sensitivity and vulnerability. Areas where data are unavailable, particularly areas lacking shallow ground-water data, were treated conservatively (in a manner protective of ground-water quality), by assuming that the conditions most susceptible to pesticide pollution of ground water are present. This conservative treatment is particularly evident in valley-margin areas where depth to the water table is generally deep, but where GIS analysis presumed the water table to be shallow due to a lack of map data to the contrary. Therefore, our maps may show higher sensitivity and vulnerability to pesticides than what actually may be the case in those areas. Ground-water sensitivity and vulnerability to pesticides in such areas should be re-evaluated if better data become available. The maps accompanying this report were based on analyses 1:24,000 or smaller scale data and are not meant for site-specific evaluations.

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