GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES, EASTERN BOX ELDER COUNTY, UTAH

by

Mike Lowe, Janae Wallace, Neil Burk, and Matt Butler, Utah Geological Survey
and
Anne Johnson and Rich Riding, Utah Department of Agriculture and Food

MISCELLANEOUS PUBLICATION 05-1
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources
in cooperation with
Utah Department of Agriculture and Food

2005

GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES, EASTERN BOX ELDER COUNTY, UTAH

by

Mike Lowe, Janae Wallace, Neil Burk, and Matt Butler, Utah Geological Survey

and

Anne Johnson and Rich Riding, Utah Department of Agriculture and Food

Cover photo: View of farmland looking west in Collinston area, eastern Box Elder County, Utah.

ISBN 1-55791-718-3

MISCELLANEOUS PUBLICATION 05-1
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources
in cooperation with
Utah Department of Agriculture and Food

2005

UTAH GEOLOGICAL SURVEY

STATE OF UTAH
Jon Huntsman, Jr., Governor

DEPARTMENT OF NATURAL RESOURCES
Michael Styler, Executive Director

UTAH GEOLOGICAL SURVEY
Richard G. Allis, Director

PUBLICATIONS
contact
Natural Resources Map/Bookstore
1594 W. North Temple
telephone: 801-537-3320
toll-free: 1-888-UTAH MAP
website: http://mapstore.utah.gov
email: geostore@utah.gov

THE UTAH GEOLOGICAL SURVEY
contact
1594 W. North Temple, Suite 3110
Salt Lake City, UT 84116
telephone: 801-537-3300
website: http://geology.utah.gov

TABLE OF CONTENTS

FIGURES

TABLES

PLATES

GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES, EASTERN BOX ELDER COUNTY, UTAH

by

Mike Lowe, Janae Wallace, Neil Burk, and Matt Butler, Utah Geological Survey

and

Anne Johnson and Rich Riding, Utah Department of Agriculture and Food

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. 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 eastern Box Elder County, Utah. We used existing data to produce pesticide sensitivity and vulnerability maps by applying an attribute ranking system specifically tailored to the western United States using Geographic Information System analysis methods. This is a first attempt at developing pesticide sensitivity and vulnerability maps; 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 eastern Box Elder County. Much of eastern Box Elder County has low ground-water sensitivity to pesticides due to prevalent 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 eastern Box Elder County. 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 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 eastern Box Elder County.

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 eastern Box Elder County 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 eastern Box Elder County should be concentrated in areas of moderate and high sensitivity or vulnerability, typically along basin margins. Sampling in the central area of the basin 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) 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 eastern Box Elder County, Utah (figure 1). Geographic variation in sensitivity and vulnerability, together with hydrologic and soil conditions that

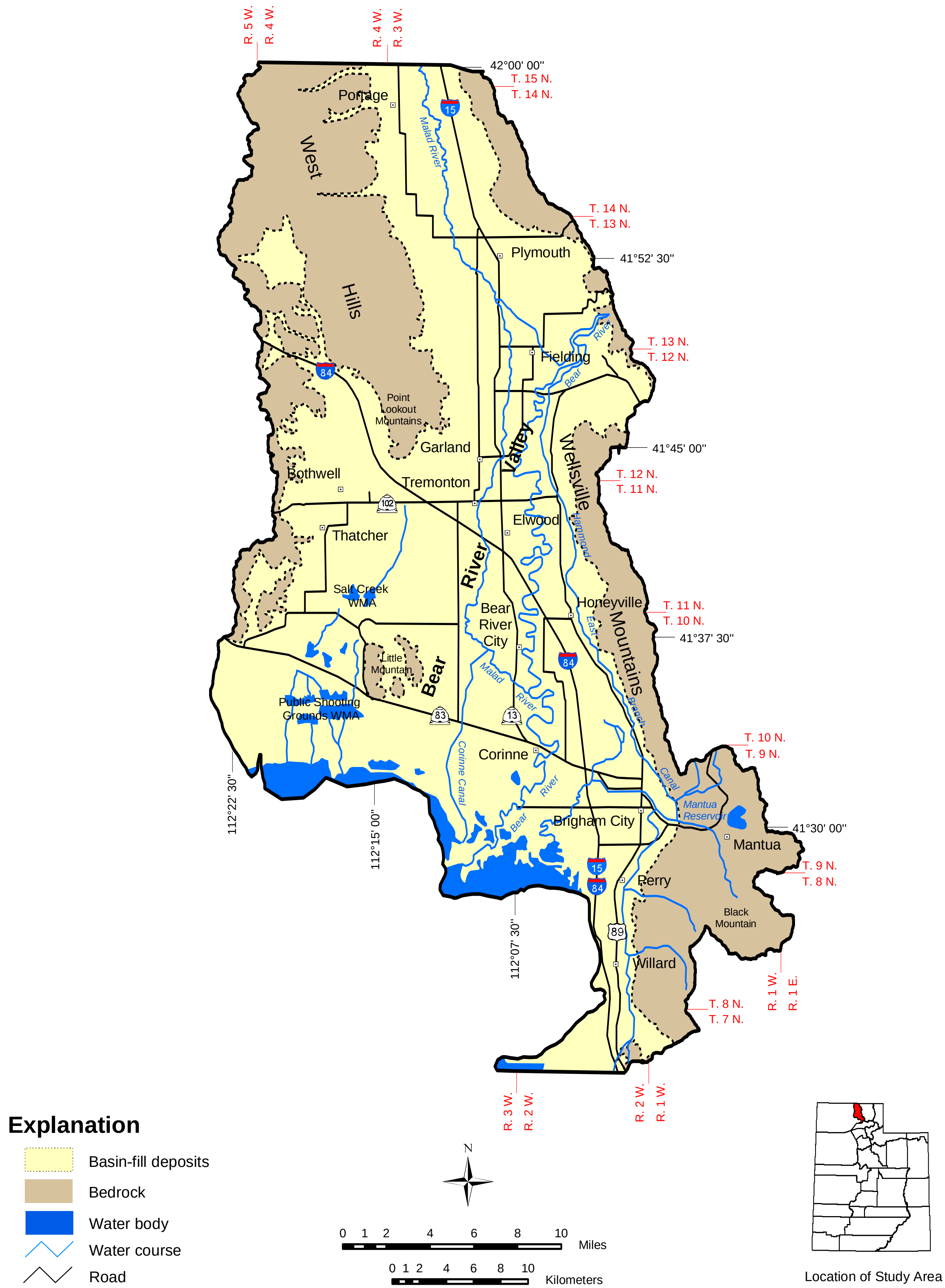


Figure 1. *Eastern Box Elder County, Utah, study area.*

cause these variations, are described herein; plates 1 and 2 show the sensitivity and vulnerability, respectively, of the unconsolidated basin-fill aquifers in eastern Box Elder County 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 amount 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 eastern Box Elder County, 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 taken directly from Lowe and Sanderson (2003).

Introduction

Ground water is the primary source of water in many rural areas for human consumption, irrigation, and animal watering. Therefore, the occurrence of agricultural pesticides in ground water represents a threat to public health and the environment. Springs and drains flowing from contaminated aquifers may present a hazard to wildlife that live in or consume the water. When we better understand the mechanisms by which pesticides migrate into ground water, we are better able to understand what geographic areas are more vulnerable – and thus deserving of more concentrated efforts to protect ground water – than other less vulnerable areas. The ability to delineate areas of greater and lesser vulnerability allows us to apply mitigating or restrictive measures to vulnerable areas without interfering with the use of pesticides in the less vulnerable areas.

The rise of the United States as the world's foremost producer of agricultural products since the end of World War II may be attributed, in part, to widespread use of pesticides. Control of insect pests that would otherwise devour the developing crop, together with control of weeds that interfere with growth and optimum crop development, permit higher quality commodities in greater abundance at lower net cost. Effective use of pesticides often means the difference between profitability and financial ruin for an agricultural enterprise.

When evidence shows pesticides are degrading the environment, harming sensitive wildlife, or posing a public health threat, two regulatory courses of action are available: (1) ban further use of the offending chemical, or (2) regulate it so that judicious use mitigates the degradation or threat. Because the four subject herbicides play an essential role in crop production and profitability, banning them outright is unnecessarily severe if the desired environmental objectives can be met by regulation and more judicious use of these herbicides.The case of DDT illustrates dilemmas faced by pesticide regulators. DDT was removed from widespread use in the United States in the 1970s because of its deleterious effects on bald eagles, ospreys, and peregrine falcons. Populations of these once-endangered species have recovered to a significant extent 25 years later (Environmental Defense Fund, 1997). An ongoing effort to extend the DDT ban worldwide is being hotly contested by advocates of its judicious use as a critical and inexpensive insecticide needed in developing countries to control mosquitoes that transmit the malaria parasite. It is further argued that, given the current regulatory apparatus, were the use of DDT to be re-evaluated today under rigorous scientific and regulatory criteria, it would be restricted to specific uses rather than prohibited (Okosoni and Bate, 2001).

The EPA has developed guidelines and provided funding for programs to address the problem of pesticide contamination of ground water, including a generic PMP to be developed by state regulatory agencies having responsibility for pesticides. Utah's generic plan was approved by the EPA in 1997 (Utah Department of Agriculture and Food, 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 R309-103-2.1, Utah Administrative Code, and also in 40 CFR 141.61. 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 eastern Box Elder County 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

The study area includes the northern part of the east shore area of Great Salt Lake in southeastern Box Elder County and the lower Bear River basin in central-eastern and northeastern Box Elder County (figure 1). Smith (1961) provided basic data on water levels and ground-water quality for the east shore area, and Smith and Gates (1963) evaluated changes in ground-water quality and water levels based on that data for the 1953-61 time period. Feth and others (1966) conducted a comprehensive study of basin-fill deposits and hydrogeologic conditions in the east shore area. Bolke and Waddell (1972) mapped ground-water quality and evaluated changes in water levels and ground-water quality in the east shore area for the 1960-69 time period. Bjorklund and McGreevy (1973, 1974) provided basic data on water levels and ground-water quality for the 1970-72 time period, and described ground-water conditions in the lower Bear River basin. Clark and others (1990) re-evaluated ground-water conditions in the east shore area and constructed a computer model for the northern Davis County and Weber County portions of the east shore aquifer to evaluate the effects of ground-water withdrawals. Anderson and others (1994; see also Anderson and Susong, 1995) mapped ground-water recharge and discharge areas for the principal aquifers along the Wasatch Front, including aquifers in the east shore area of Great Salt Lake and lower Bear River basin.

Burden and others (2000) described changes in ground-water conditions in Utah, including the northern east shore area of Great Salt Lake, from 1970 to 2000.

Chadwick and others (1975) mapped soils (scale 1:20,000) for eastern Box Elder County. Regional geologic maps covering the study area include a geologic map of Box Elder County by Doelling and others (1980), a surficial geologic map along part of the Wasatch Front by Miller (1980, scale 1:100,000), a map of the northern Wasatch Front compiled by Davis (1985, scale 1:100,000), and a map of surficial deposits along the Wasatch fault zone by Personius (1990, scale 1:50,000). Geologic quadrangle maps at 1:24,000 scale are shown on figure 2.

SETTING

Physiography

Eastern Box Elder County is in north-central Utah in the Wasatch Front Valleys subdivision of the Basin and Range physiographic province (Stokes, 1977). The study area is a 46-mile-long (74 km), north-south-trending valley that is bounded by mountains on its east and west sides (figure 1). The valley floor is 27 miles (43 km) wide at its widest point (figure 1), and the valley floor has an area of about 670 square miles (1700 km^2).

The study area is bounded on the west by the Blue Springs Hills and West Hills, and on the east by Clarkston Mountain, the Junction Hills, the Wellsville Mountains, and the Wasatch Range. The Blue Springs and West Hills are part of a dissected plateau that is about 5 to 12 miles (8-19 km) wide with crest elevations generally between 6000 and 7000 feet (1830 and 2130 m); the highest peak has an elevation of 7196 feet (2193 m). This dissected plateau is underlain by interbedded quartzite and limestone of the Pennsylvanian and Permian Oquirrh Formation (Doelling and others, 1980). The mountainous terrain on the east side of the study area consists of numerous carbonate and clastic sedimentary rock formations, ranging in age from Cambrian to Permian (Crittenden and Sorensen, 1985a). These mountains create a ridge that is about 3 to 7 miles (5-11 km) wide with crest elevations generally between 7000 and 9000 feet (2130 and 2740 m), and some peaks having elevations over 9000 feet (2740 m) (Bjorklund and McGreevy, 1974). Little Mountain is an isolated feature in the south-central part of the study area that has a peak elevation of 5607 feet (1709 m). Little Mountain consists primarily of Paleozoic carbonate and clastic sedimentary rock formations (Doelling and others, 1980).

The valley floor elevation ranges from about 4200 feet (1280 m) at the Great Salt Lake shoreline to 5200 feet (1580 m) near the benches. Most of the valley is covered by unconsolidated Quaternary Lake Bonneville deposits underlain by Tertiary Salt Lake Formation (Bjorklund and McGreevy, 1974). Maximum thickness of Cenozoic deposits is estimated to be about 8000 feet (2440 m) (Bjorklund and McGreevy, 1974). Numerous normal faults exist throughout the basin,

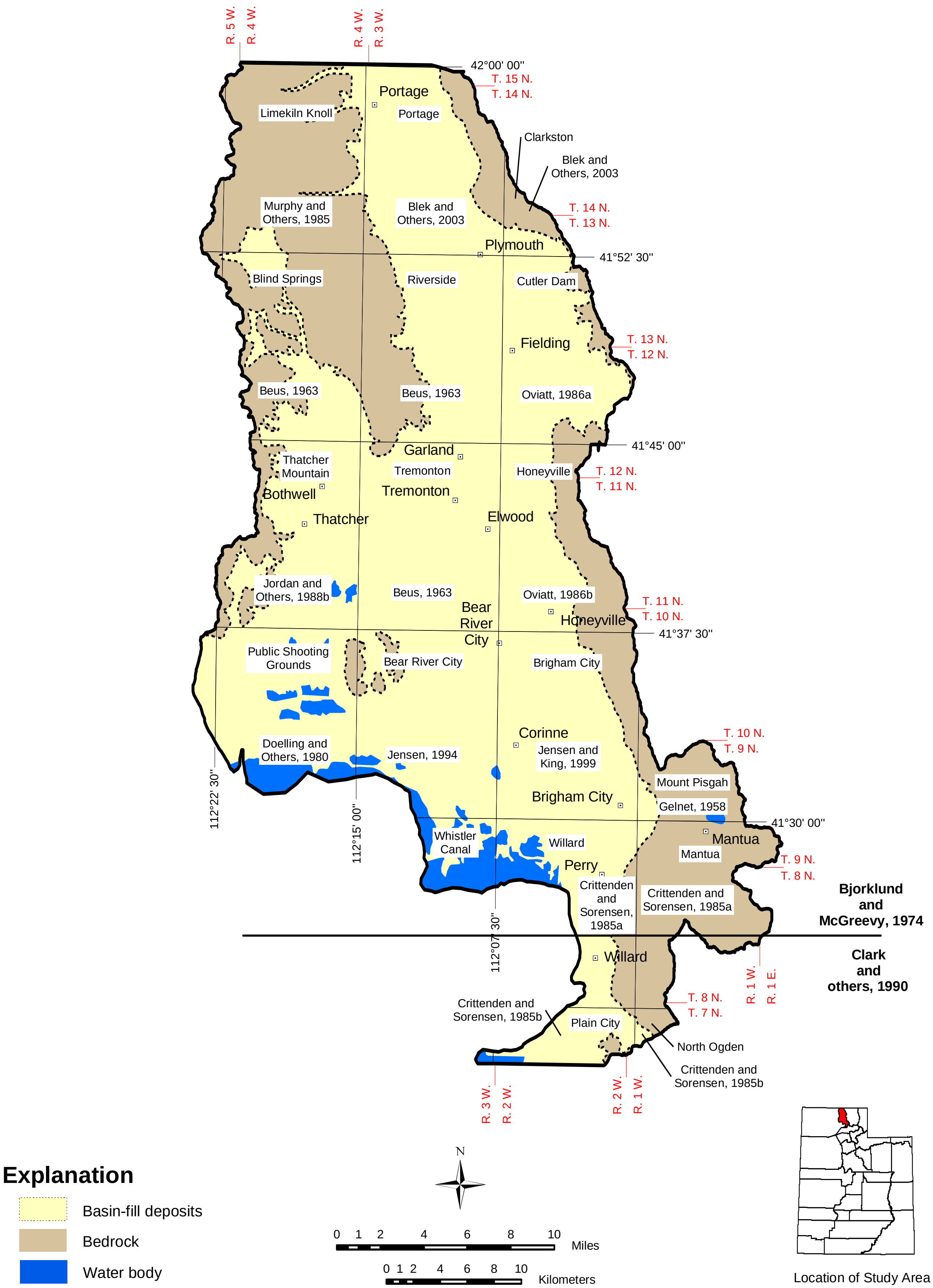


Figure 2. *Geologic quadrangle mapping and ground-water studies (in bold) used for eastern Box Elder County, Utah, study.*

including the Wasatch fault zone that runs along the base of the mountains on the eastern margin of the valley (Personius, 1990). Other geomorphic features of the valley include flood plains, alluvial fans, and terraces, bars, spits, and deltas associated with ancient Lake Bonneville.

The south-central and southwestern part of the drainage basin consists of lagoons, marshes, and mud flats associated with the Bear River and the Bear River Bay of Great Salt Lake; much of this area is part of the Bear River Migratory Bird Refuge. Major water bodies in the drainage basin include the Bear and Malad Rivers, Willard Bay, and Great Salt Lake. The Bear River enters the basin from the east and the Malad River enters from the north; the Malad then joins with the Bear River in the southern part of the basin, and drains into Great Salt Lake.

Climate

Eight weather stations are within the eastern Box Elder County study area, and all of these stations are located on the valley floor, so climate data for the mountainous areas within the drainage basin are limited. These weather stations are: the Bear River Refuge (elevation 4210 feet [1280 m]), Bothwell (elevation 4332 feet [1320 m]), Brigham City (elevation 4335 feet [1321 m]), Brigham City Waste Plant (elevation 4230 feet [1289 m]), Corinne (elevation 4220 feet [1286 m]), Cutler Dam UP&L (elevation 4291 feet [1308 m]), Plymouth (elevation 4470 feet 1362 m]), and Tremonton/Garland (elevation 4310 feet [1314 m]) (Ashcroft and others, 1992). Temperatures reach an average maximum (Brigham City station) of 92.9˚F (33.8˚C) in July and an average minimum (Cutler Dam UP&L) of 13.8˚F (-10.1˚C) in January; the normal mean ranges from 48.7 to 52.9˚F (9.3 to 11.6˚C) at Corinne and Tremonton/Garland, respectively (Ashcroft and others, 1992). Average annual precipitation ranges from 12.64 inches (32.11 cm) at the Bear River Refuge to 19.33 inches (49.09 cm) at Brigham City (Ashcroft and others, 1992). Normal annual evapotranspiration ranges from 40.63 to 47.31 inches (103.20 - 120.17 cm) at Tremonton/Garland and Corinne, respectively. The average number of frost-free days ranges from 139 to 189 at Corinne and Tremonton/Garland, respectively.

Population and Land Use

Like the rest of the Wasatch Front, eastern Box Elder County is experiencing growth. The population of Box Elder County was 44,032 in 2002 (Demographic and Economic Analysis Section, 2003), and is expected to increase to 70,755 by 2030 (Demographic and Economic Analysis Section, 2000); most Box Elder County residents live in the eastern part of the county.

The principal industry in eastern Box Elder County has traditionally been agriculture, which is largely devoted to livestock, dairy products, sugar beets, small grains, corn, alfalfa, and tomatoes (Bjorklund and McGreevy, 1974). South of Brigham City there are numerous orchards that make up the "Famous Fruitway" along highway 89, where the main agricultural products are fruits and vegetables. Most farms are irrigated with surface water from diversion canals. However, some wells also provide water for irrigation (Bjorklund and McGreevy, 1974).

The largest employer in Box Elder County is Alliant Tech - Thiokol Propulsion Group, which manufactures solid rocket motors for the space shuttle and for other military applications. It is located in Promontory, just outside the study area, but most of its employees probably reside within the study area. The second-largest employer is Autoliv ASP, which manufactures air bags and steering products, and has offices in Brigham City, Tremonton, and Promontory. The third-largest employer is Lay Z Boy, located in Tremonton (Box Elder County, 2004).

GROUND-WATER CONDITIONS

Basin-Fill Aquifers

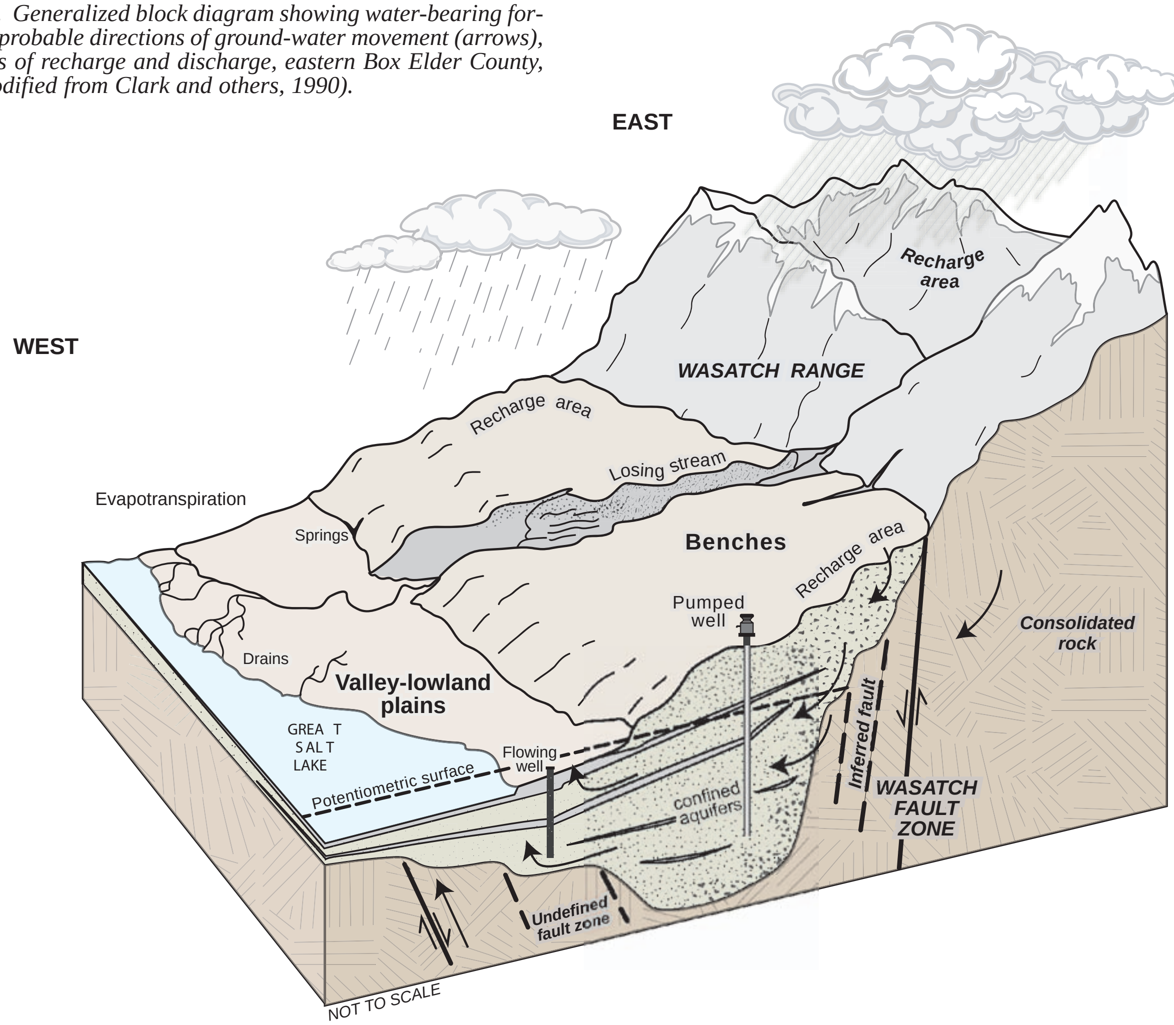
The basin-fill aquifer system in eastern Box Elder County is complex. Cold, fresh ground water in the higher elevations and upstream end of the drainage basin transitions to warm, saline ground water at the downstream end near Great Salt Lake (Bjorklund and McGreevy, 1974). As a result, a wide range of hydrologic conditions exists within the basin.

The basin-fill aquifer system can be subdivided into a principal ground-water system, a shallow unconfined system, and perched systems (figure 3) (Bjorklund and McGreevy, 1974). The principal ground-water system includes ground water under confined conditions in the lower, central parts of the basin and under unconfined conditions along the basin margins. Ground water in the shallow unconfined system occurs above the confining beds of the principal aquifer system in the central part of the basin. The perched groundwater systems occur locally along the margins of the basin above the unconfined part of the principal aquifer system (Bjorklund and McGreevy, 1974).

The basin-fill aquifer deposits include Quaternary Lake Bonneville and older deep-lake-cycle deposits, Quaternary interlacustrine deposits, and the Tertiary Salt Lake Formation; these units have a combined maximum thickness of approximately 8000 feet (2,400 m), but the thickness of the Quaternary deposits ranges from less than 100 feet (30 m) along the valley margins to more than 1000 feet (300 m) in the central part of the basin (Bjorklund and McGreevy, 1974). Quaternary sediments in the center of the basin consist primarily of lacustrine offshore and deltaic deposits and interbedded alluvium and colluvium composed mainly of silt, sand, and clay. Quaternary sediments along the basin margins consist primarily of lacustrine nearshore, alluvial-fan, and deltaic deposits composed mainly of sand, gravel, silt, and clay. The permeability of the basin-fill deposits ranges from low to high, with the basin-margin deposits having greater permeability (Bjorklund and McGreevy, 1974).

Ground-water recharge in the basin-fill aquifer of eastern Box Elder County is from precipitation, surface-water seepage, and subsurface inflow. Bjorklund and McGreevey (1974) suggested that recharge in the study area is equal to discharge, as indicated by small changes in water levels in wells, and ground-water storage is minor. Recharge from precipitation occurs mainly in and around the mountains (Bjorklund and McGreevy, 1974). Significant infiltration occurs where streams flow from canyons onto permeable alluvial deposits along basin margins. Substantial increases

Figure 3. *Generalized block diagram showing water-bearing formations, probable directions of ground-water movement (arrows), and areas of recharge and discharge, eastern Box Elder County, Utah (modified from Clark and others, 1990).*



in recharge have occurred from surface-water diversions used for irrigation; annual rises in water levels in wells average 6 feet (2 m), mostly due to seepage from irrigation canals (Bjorklund and McGreevy, 1974). Subsurface inflow of ground water likely enters the study area from the north through the Malad River valley, from the Blue Springs Hills area, and from the Wellsville Mountains (Bjorklund and McGreevy, 1974).

Ground-water discharge from the basin-fill aquifer in eastern Box Elder County is from springs, drains, wells, evapotranspiration, and subsurface outflow. The greatest discharge is by evapotranspiration from mudflats and phreatophytes in low-lying areas, and is estimated to be about 30.2 inches (76.7 cm) annually (Bjorklund and McGreevy, 1974). Springs and drains discharge both saline and fresh ground water into the basin center and into the Malad and Bear Rivers, which gain flow downstream. A small amount of ground water is discharged from wells, and a smaller amount is transported out of the drainage basin as subsurface outflow (Bjorklund and McGreevy, 1974). The direction of ground-water flow in eastern Box Elder County is from the mountains toward the basin center and then south and southwest toward Great Salt Lake (Bjorklund and McGreevy, 1974).

Transmissivity values were obtained from pumping tests for a few wells in the study area. The lowest transmissivity value is 2000 square feet per day (200 m^2/d), from a well located in Lake Bonneville deposits in the basin center. Transmissivity from wells along the basin margin ranges from 13,000 to 14,000 square feet per day (1200-1300 m^2/d) (Bjorklund and McGreevy, 1974).

Water levels in wells in eastern Box Elder County rise during the summer in irrigation areas and decline between irrigation seasons (Bjorklund and McGreevy, 1974). Water levels decline in the “Bothwell pocket” during the summer, located in the east-central part of the study area, due to pumping of irrigation wells (Bjorklund and McGreevy, 1974). Water levels in the low-lying areas of the basin decline during the summer due to evapotranspiration (Bjorklund and McGreevy, 1974). Long-term water-level measurements indicate little change in overall water levels; long-term fluctuations and changes can mostly be attributed to changes in annual precipitation (Bjorklund and McGreevy, 1974).

Ground-Water Quality

Ground-water quality in eastern Box Elder County ranges from fresh (less than 1000 mg/L dissolved solids) calcium-magnesium-bicarbonate-type water along the basin margins to saline (1000 - 35,000 mg/L dissolved solids) or briny (greater than 35,000 mg/L dissolved solids) sodiumchloride-type water in the basin center; quality also varies depending on well location and depth in basin-fill deposits (Bjorklund and McGreevy, 1974). Fresh water is derived from the mountainous areas surrounding the basin, and many of the springs located along the margins of the basin are fresh; however, numerous springs exist that are saline, especially the ones that discharge warm or hot water (Bjorklund and McGreevy, 1974). The concentration of dissolved solids generally increases with depth in the basin-fill deposits, and numerous hot and warm springs exist where hot brine rises from depth and flows through permeable rock, typically along faults. The temperature of the springs depends on how much ambient ground water mixes with the rising hot brine. Saline waters are also located in the basin center (i.e., the Bear River refuge area and along Great Salt Lake). Ground-water quality could be compromised by overpumping in some of the areas due to intrusion of salt water from depth (e.g., in the "Bothwell pocket" area), or due to recharge of saline water from the Malad River if ground-water withdrawals cause this gaining stream to become a losing stream (Bjorklund and McGreevy, 1974).

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 eastern Box Elder County. 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 eastern Box Elder County. 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 4. 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.

Anderson and others (1994) used drillers' logs of water wells in eastern Box Elder County 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 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; Anderson and Susong, 1995). Some drillers' logs show both clay and sand in the same interval, with no information describing relative percentages; these are not classified as confining layers (Anderson and others, 1994). If both silt and clay are checked on the log and the word "sandy" is written in the remarks column, then the layer is assumed to be a predominantly clay confining layer (Anderson and others, 1994). Some drillers' logs show clay together with gravel, cobbles, or boulders; these also are not classified as confining layers, although in some areas of Utah layers of clay containing gravel, cobbles, or boulders do, in fact, act as confining layers.

The primary recharge area for the principal aquifer system in eastern Box Elder County consists of the uplands along the margins of the basin, as well as basin fill not containing confining layers (figure 4), generally located along the mountain fronts. Ground-water flow in primary recharge areas has a downward component. Secondary recharge areas, if present, are locations where confining layers exist, but ground-water flow still maintains a downward component. Secondary recharge areas generally extend toward the center of the basin to the point where ground-water flow is upward (figure 4). 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

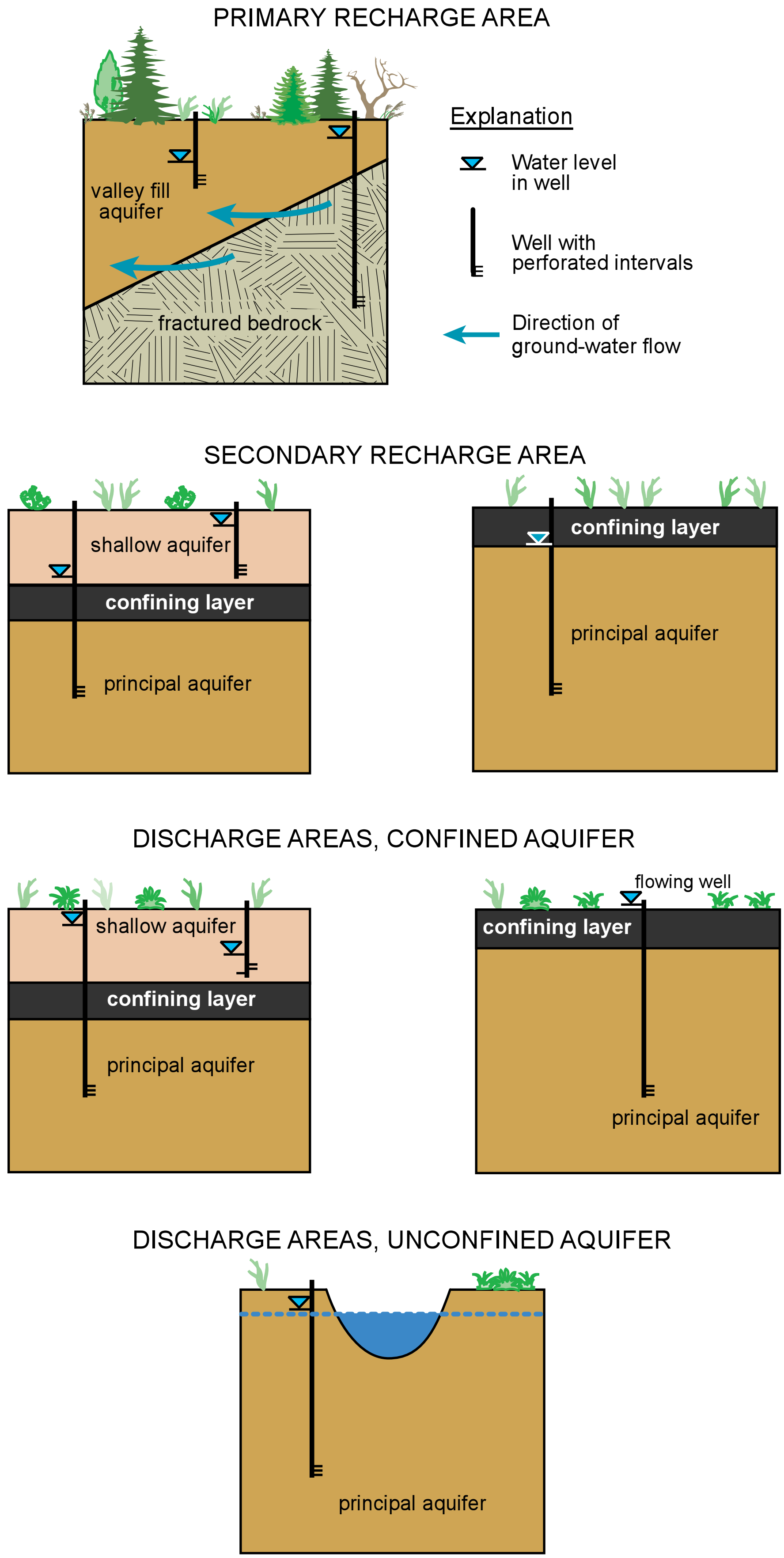


Figure 4. *Relative water levels in wells in recharge and discharge areas (modified from Snyder and Lowe, 1998).*

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.

Ground-water discharge areas, if present, generally are 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 (figure 4). 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 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's Soil Conservation Service (now Natural Resources Conservation Service; Chadwick and others, 1975). 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) present the following equation:

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

where:

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

Retardation factors typically range from (1 + 4Kd) to (1 + 10Kd) (Freeze and Cherry, 1979), where Kd is the product of the organic carbon sorption distribution coefficient (K_{oc}) and the fraction of organic carbon (F_{oc}), and based on typical unconsolidated sediment properties of dry bulk density (0.06-0.08 lb/in^3 [1.6-2.1 kg/L]) and porosity range (0.2 to 0.4). Dissolved constituents in ground water having low R_F values (around 1), such as nitrate (a relatively mobile anion), move through the subsurface at the same rate as the ground water, whereas dissolved constituents in ground water having R_F values orders of magnitude larger than one are essentially immobile (Freeze and Cherry, 1979). The relative velocity is the reciprocal of the retardation factor and describes the rate a mixture of reactive contaminant moves relative to solvent-free ground water.

For this study, we used data from the Soil Survey Geographic (SSURGO) database (National Soil Survey Center, 2002), which provides digitized data for some soil areas of the state of Utah, including eastern Box Elder County, 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 eastern Box Elder County, and variable soil organic carbon content using a water-table depth of 3 feet (1 m). Average organic carbon content in soils in eastern Box Elder County is shown in figure 5 and ranges from 0.3 to 4.4%; the mass fraction of organic carbon was computed by dividing the organic matter parameter in the SSURGO data by a conversion factor of 1.72 (Siegel, 2000). We then applied the organic carbon content end members to compute the extreme R_F values; equation 1 results in retardation factors ranging from 1.8 to 64. This means the highest relative velocity from our data is 0.56 and the lowest is 0.016; the former indicates pesticide in

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 (2002). 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 0.3 to 4.4 %
B	Silt loam or loam; moderate infiltration rate when thoroughly wetted; consists of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures.	0.015 - 0.15 (25-28)	1.3 - 1.61 (1.4)	Variable and ranges from 0.3 to 4.4 %
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 0.3 to 4.4 %
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 0.3 to 4.4 %
G	Gravel	2.0 and greater (less than 12)	2 (2)	0.1 %**

* 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).

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

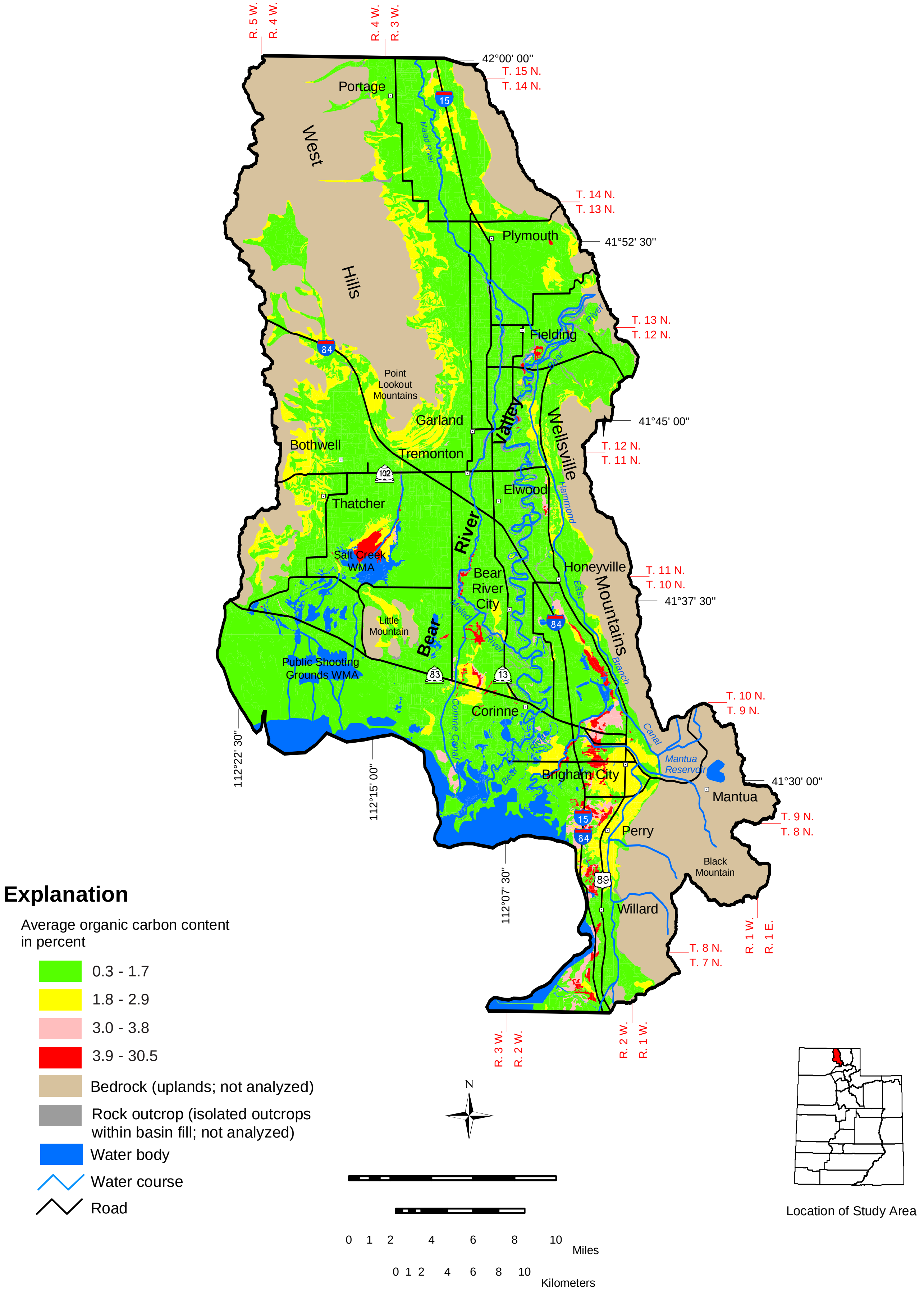


Figure 5. *Average organic carbon content in soils in eastern Box Elder County, Utah (data from National Soil Survey Center, 2002).*

ground water moves at a rate about 56% that of ground water free of pesticides, whereas the latter indicates that pesticides in ground water are essentially immobile.

A small percentage (1%) of pesticides traveling downward in vadose-zone material having an R_F of 3.6 could reach the water table at a depth of 3 feet (1 m) within one year if ground-water recharge amounted to 11.8 inches (30 cm) or greater during the year, which is the highest amount of recharge calculated for the mountains in eastern Box Elder County. When ground-water recharge is less than 9.8 inches (25 cm) per year, as is the case for the valley floor in eastern Box Elder County, 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 2.

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 (AF) 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) 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 (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 eastern Box Elder County (figure 6). 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 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, and is not evaluated in our analysis.

Using equation 2, we calculated attenuation factors for ranges of values common to soils in eastern Box Elder County, 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 2, 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 negative net annual ground-water recharge values, as are typical of the valley-floor areas of eastern Box Elder County, equation 2 results in an attenuation factor that approaches 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 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 4) are provided by the manufacturers of the four herbicides evaluated as part of this study. Pre-emergent herbicides are typically applied once per year, either in the fall after post-season tillage or in early spring before weeds begin to germinate.

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

Herbicide	Max. Application rate (lbs. AI** per acre)	Time interval
Atrazine	2.5	calendar year
Alachlor	4.05	pre-emergence
Metolachlor	1.9	pre-emergence
Simazine	4.0	pre-emergence

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

Depth to Shallow Ground Water

The closer ground water is to the land surface the more sensitive it is to being degraded by pesticides. Based on soil mottling, water encountered in test pits, or other information, soils having shallow ground water seasonally less than or equal to 3 feet (1 m) deep is one attribute of soil units mapped by the Soil Conservation Service (now Natural Resources Conservation Service; Chadwick and others, 1975). 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 1996 (lower Bear River basin) and 1999 (northern east shore area of Great Salt Lake) land-use data.

Ground-Water Sensitivity

We consider ground-water sensitivity (intrinsic susceptibility) to be the principal factor determining the vulnerability of the basin-fill aquifer in eastern Box Elder County 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 lower Bear River Basin inventory was conducted in 1996, and the east shore area of Great Salt Lake inventory was conducted in 1999 (Utah Division of Water Resources metadata). We used all polygons having standard type codes beginning with IA to produce the irrigated land coverage for this study. These data do not distinguish areas of sprinkler irrigation versus areas of flood irrigation; areas of flood irrigation are likely to be more vulnerable to degradation from pesticides than areas of sprinkler irrigation.

Table 5. *Pesticide sensitivity and the attribute rankings used to assign sensitivity for eastern Box Elder County, Utah.*

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

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 lower Bear River basin inventory was conducted in 1996, and the east shore area of Great Salt Lake inventory was conducted in 1999 (Utah Division of Water Resources metadata). We selected all polygons having standard type codes IA2a1 (corn), IA2a2 (sorghum), and IA2b5 (sweet corn; none in this category were in the data set) to produce the crop-type land coverage for this study, as these are the crop types to which the pesticides addressed are applied in Utah. Although the specific fields growing these crops may vary from year to year, the general areas and average percentages of these crop types likely do not.

GIS Analysis Methods

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

RESULTS

Ground-Water Sensitivity

To assess ground-water sensitivity (intrinsic susceptibility) to pesticide contamination, several GIS 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 (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 eastern Box Elder County; the low attenuation factors are due to net annual evapotranspiration exceeding net annual precipitation. The area is dominantly characterized by high retardation factors due to the prevalent silt/clay soil types. Net annual recharge from precipitation is negative in basin-floor areas (figure 6). Most recharge that occurs from precipitation is principally along the valley 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

Ground-water recharge areas in eastern Box Elder County (figure 7) were mapped by Anderson and others (1994). Their map shows that primary recharge areas, the areas most susceptible to contamination from pesticides applied to the land surface, comprise about 27% of the surface area of the basin-fill aquifer. Secondary recharge areas make up 20% of the surface area of the basin-fill aquifer. Ground-water discharge areas, which provide extensive protection to the principal aquifer from surface contamination from the application of pesticides, make up 53% 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 the National Soil Survey Center (2002). About 58% of the surface area of the basin-fill aquifer in eastern Box Elder County has soil units mapped as having hydraulic conductivity greater than or equal to 1 inch (2.5 cm) per hour (figure 8).

Table 6. *Pesticide vulnerability and the attribute rankings used to assign vulnerability for eastern Box Elder County, Utah.*

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

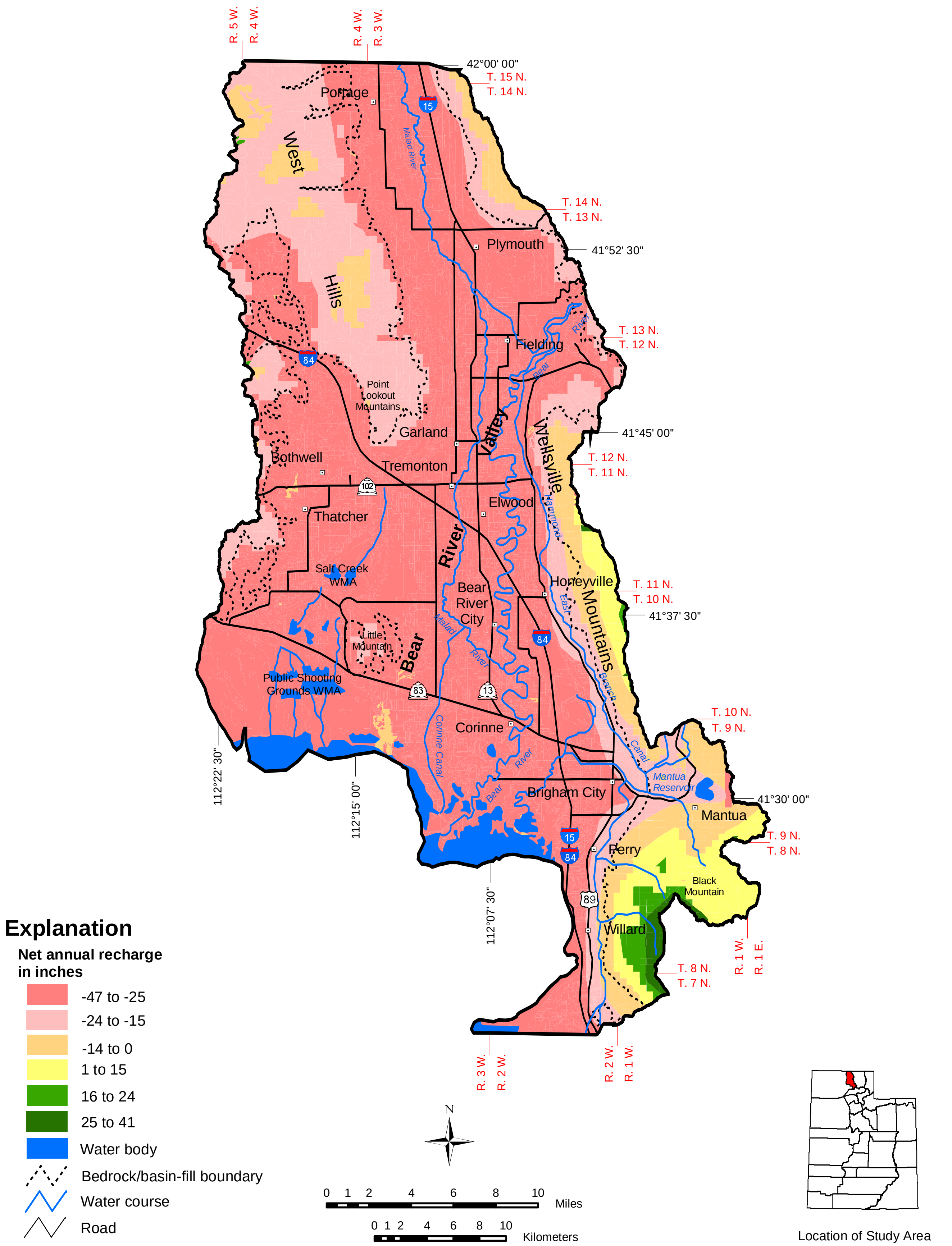


Figure 6. *Net annual ground-water recharge from precipitation in eastern Box Elder County, Utah. Recharge calculated using data from the Utah Climate Center (1991) and Jensen and Dansereau (2001). Although net annual recharge may be negative in some areas, seasonally some recharge from precipitation may occur.*

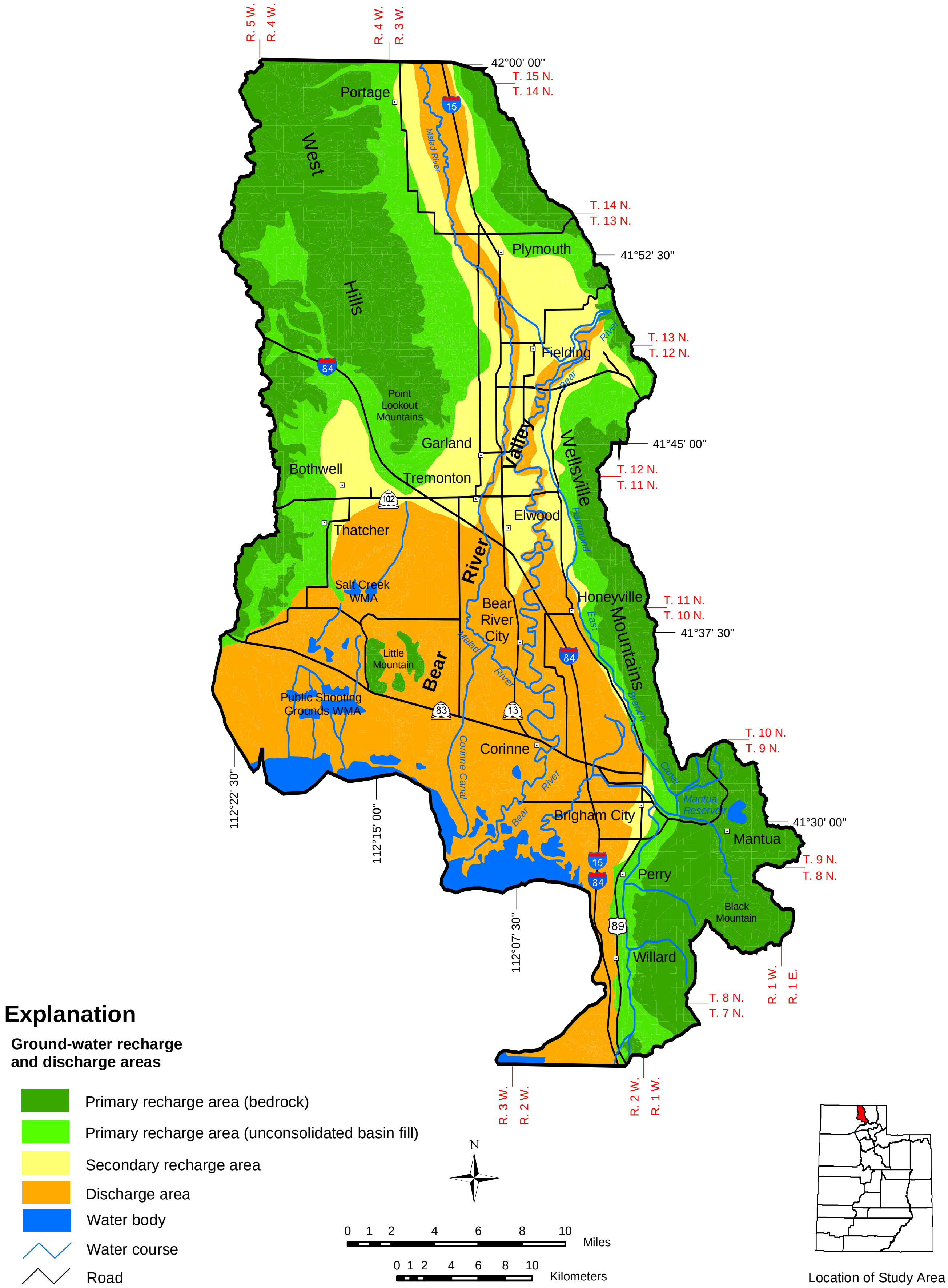


Figure 7. Recharge and discharge areas in eastern Box Elder County, Utah (from Anderson and others, 1994).

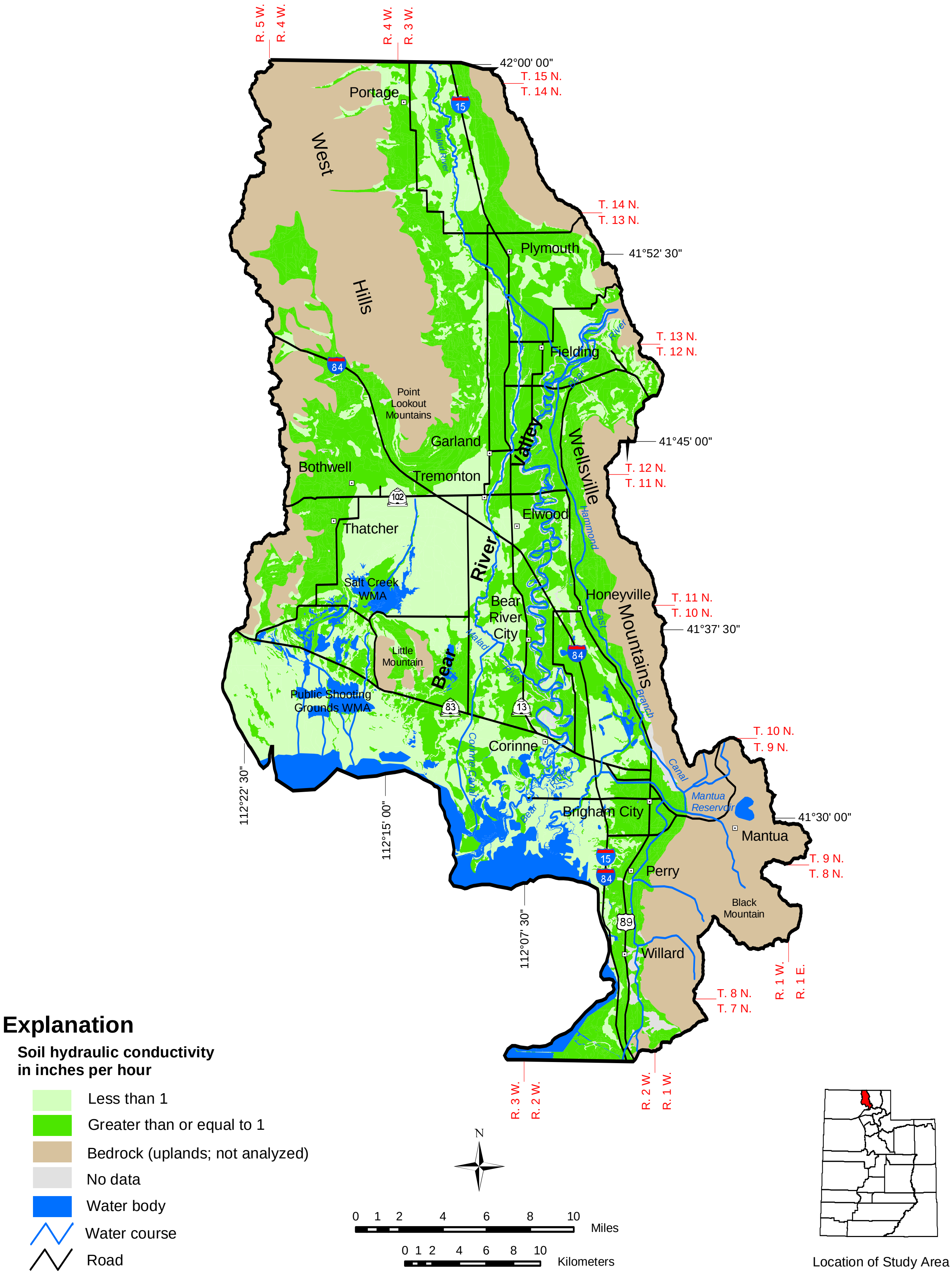


Figure 8. *Soil hydraulic conductivity in eastern Box Elder County, Utah (data from National Soil Survey Center, 2002).*

About 41% of the surface area of the basin-fill aquifer has soil units mapped as having hydraulic conductivity less than 1 inch (2.5 cm) per hour; these soil units are mainly along the shores of Great Salt Lake, and along the Malad and Bear Rivers in the northern part of the study area. About 1% of the surface area of the basin-fill aquifer has soil units for which hydraulic conductivity values have not been assigned by the National Soil Survey Center (2002); these soil polygons are scattered throughout the study area, and were grouped into the greater than or equal to 1 inch (2.5 cm) per hour category for analytical purposes to be protective of water quality.

Depth to Shallow Ground Water

Surface application of pesticides is more likely to cause ground-water quality problems in areas of shallow ground water than where ground water is relatively deep. Depth to shallow ground-water data are from the National Soil Survey Center (2002).

About 31% of the area overlying the basin-fill aquifer in eastern Box Elder County has soil units mapped as having shallow ground water less than or equal to 3 feet (1 m) deep; these areas are primarily along Great Salt Lake, and along the Malad River in the northern part of the study area (figure 9). About 25% of the surface area of the basin-fill aquifer has soil units mapped as having shallow ground water greater than 3 feet (1 m) deep. About 44% of the surface area of the basin-fill aquifer has 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 eastern Box Elder County, 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.

Most of the western part of eastern Box Elder County (53%) 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. Also, pesticides spilled or misapplied have a much greater potential to contaminate surface water than ground water. Alluvial-fan areas along the basin margins, where soils have higher hydraulic conductivities, are areas of high sensitivity (plate 1); this comprises about 27% of the basin-fill aquifer area. The remaining 20% 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 eastern Box Elder County (figure 10). 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 10 shows irrigated cropland areas in eastern Box Elder County. About 40% of the valley floor is irrigated, and about 60% is not. 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 western parts of the basin-floor area (figure 10). The use of pesticides on corn and sorghum crops increases the vulnerability of areas where these crops are grown from low to moderate.

Pesticide Vulnerability Map

Plate 2 shows ground-water vulnerability to contamination from pesticides of the basin-fill aquifer for eastern Box Elder County, 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 2% of the surface area of the basin-fill aquifer is mapped as having high vulnerability (plate 2). 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 49% of the surface area of the basin-fill aquifer is mapped as having moderate vulnerability. Low-sensitivity areas without irrigated cropland have low vulnerability to contamination associated with application or spilling of pesticides on the land surface. About 49% of the surface area of the basin-fill aquifer is mapped as having low vulnerability.

CONCLUSIONS AND RECOMMENDATIONS

In eastern Box Elder County, areas of irrigated land where the ground-water table is close to the land surface have the highest potential for water-quality degradation associated with surface application of pesticides. However, because of the relatively high attenuation (short half-lives) of pesticides in water in the soil environment, pesticides likely do not represent a serious threat to ground-water quality. We

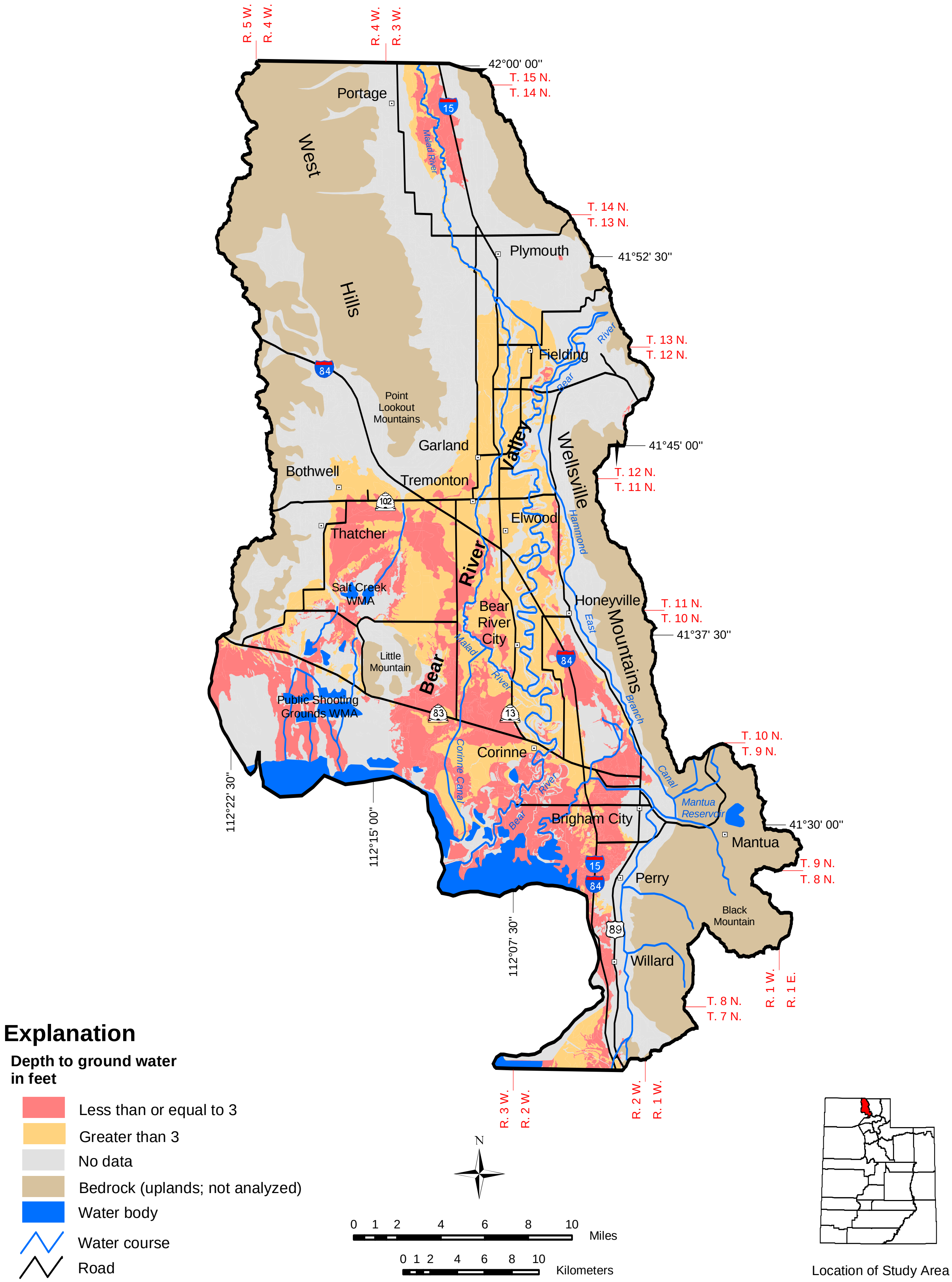


Figure 9. *Depth to shallow ground water in eastern Box Elder County, Utah (data from National Soil Survey Center, 2002).*

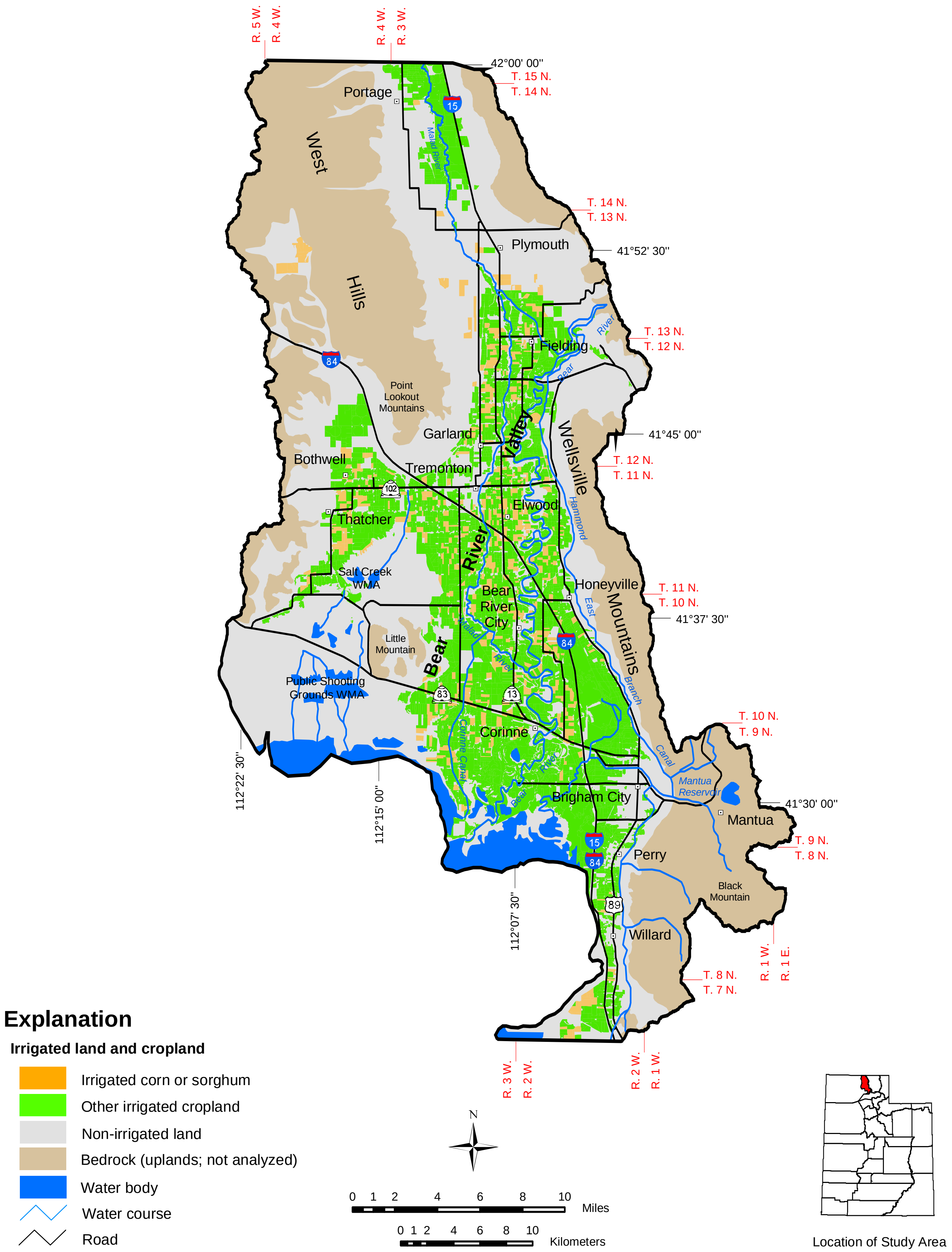


Figure 10. Irrigated and non-irrigated cropland in eastern Box Elder County, Utah, study area (data from Utah Division of Water Resources, 2003). The pesticides addressed in this study are mainly applied to corn and sorghum.

believe that 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. Sampling and testing in areas of the basin characterized by moderate sensitivity and moderate vulnerability should continue, but at a lower density than in the areas of higher sensitivity and vulnerability.

ACKNOWLEDGMENTS

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

REFERENCES

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

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

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

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

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

Beuss, S.S., 1963, Geology of the central Blue Springs Hills, Utah-Idaho: Los Angeles, University of California, Ph.D. dissertation, 233 p., scale 1:48,000.

Biek, R.F., Oaks, R.Q., Jr., Janecke, S.U., Solomon, B.J., and Barry, L.M.S., 2003, Geologic map of the Clarkston and Portage quadrangles, Box Elder and Cache Counties, Utah, and Franklin and Oneida Counties, Idaho: Utah Geological Survey Map 194, scale 1:24,000.

Bjorklund, L.J., and McGreevy, L.J., 1973, Selected hydrologic data, lower Bear River drainage basin, Box Elder County, Utah: Utah Basic-Data Release No. 23, 22 p.

Demographic and Economic Analysis Section, 2003, Utah data guide, fall 2003: Salt Lake City, Utah Governor’s Office of Planning and Budget, 12 p.

Doelling, H.H., Campbell, J.A., Gwynn, J.W., and Perry, L.I., 1980, Geology and mineral resources of Box Elder County, Utah: Utah Geological and Mineral Survey Bulletin 115, 251 p., 3 plates, scale 1:125,000.

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

Feth, J.H., Barker, D.A., Moore, L.G., Brown, R.J., and Veirs, C.E., 1966, Lake Bonneville; geology and hydrology of the Weber delta district, including Ogden, Utah: U.S. Geological Survey Professional Paper 518, 76 p.

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

Gelnett, R.H., 1958, Geology of the southern part of the Wellsville Mountain, Wasatch Range, Utah: Logan, Utah State University M.S. thesis, 72 p., scale 1:24,000.

Jensen, M.E., 1994, Geologic map of the Bear River City quadrangle, Box Elder County, Utah: Utah Geological Survey Map 151, 12 p., scale 1:24,000.

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

Jensen M.E., and King J.K., 1999, Geologic map of the Brigham City quadrangle, Box Elder and Cache Counties, Utah: Utah Geological Survey Map 173, 46 p., scale 1:24,000.

Jordan, T.E., Crittenden, M.D., Jr., Allmendinger, R.W., and Miller, D.M., 1988, Geologic map of the Thatcher Mountain quadrangle, Box Elder County, Utah: Utah Geological and Mineral Survey Map 109, 10 p., scale 1:24,000.

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

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

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

Miller, R.D., 1980, Surficial geologic map along part of the Wasatch Front, Great Salt Lake Valley, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1198, scale 1:100,000.

Murphy, B.E., Beus, S.S., and Oviatt, C.G., 1985, Provisional geologic map of the Limekiln Knoll quadrangle, Box Elder County, Utah: Utah Geological and Mineral Survey Map 79, 9 p., scale 1:24,000.

National Soil Survey Center, 2002, Soil Survey Geographic (SSURGO) data base for Box Elder County, Utah, eastern part: Online, http://www.ncgc.nrcs.usda.gov/branch/ssb/products/ssurgo/data/ut.html, accessed June 11, 2004.

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

Oviatt, C.G., 1986a, Geologic map of the Cutler Dam quadrangle, Box Elder and Cache Counties, Utah: Utah Geological and Mineral Survey Map 91, 7 p., scale 1:24,000.

—1986b, Geologic map of the Honeyville quadrangle, Box Elder and Cache Counties, Utah: Utah Geological and Mineral Survey Map 88, 13 p., scale 1:24,000.

Personius, S.F., 1990, Surficial geologic map of the Brigham City segment and adjacent parts of the Weber and Collinston segments, Wasatch fault zone, Box Elder and Weber Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1979, scale 1:50,000.

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

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

Saxton, K.E., undated, Soil texture triangle hydraulic properties calculator: Online, http://wilkes1.wilkes.edu/~boram/grph text.htm, accessed January 31, 2003.

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

Smith, R.E., 1961, Records and water-level measurements of selected wells and chemical analyses of ground water, East Shore area, Davis, Weber, and Box Elder Counties, Utah: Utah State Engineer Basic-Data Report no. 1, 35 p.

Smith, R.E., and Gates, J.S., 1963, Ground-water conditions in the southern and central parts of the East Shore area, Utah, 1953-1961: Utah Geological and Mineral Survey Water Resources Bulletin 2, 48 p.

Snyder, N.P, and Lowe, Mike, 1998, Map of recharge areas for the principal valley-fill aquifer, Ogden Valley, Weber County, Utah: Utah Geological Survey Map 176, 16 p., scale 1:75,000.

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

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

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

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

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

Plate 1

GROUND-WATER SENSITIVITY TO PESTICIDES IN EASTERN BOX ELDER COUNTY, UTAH

By Mike Lowe, Janae Wallace, Neil Burk, and Matt Butler
Utah Geological Survey
and
Anne Johnson and Rich Riding
Utah Department of Agriculture and Food

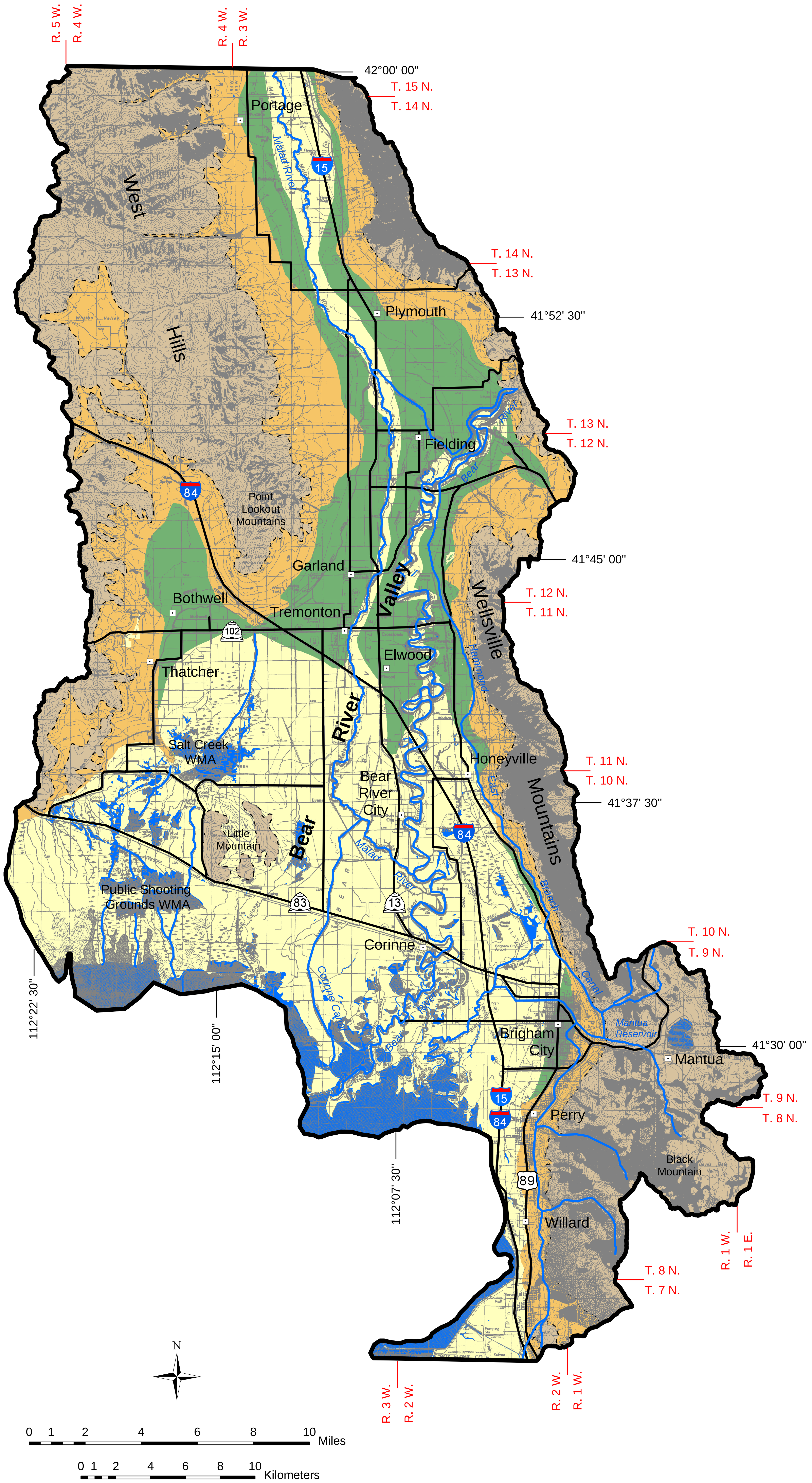
Miscellaneous Publication 05-1
2005

Explanation

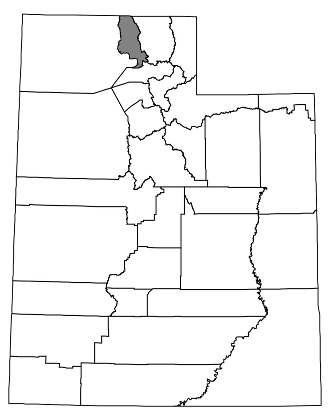
Ground-Water Sensitivity Ranking

- Low
- Moderate
- High
- Bedrock (not analyzed)

- Water body
- Water course
- Basin-fill boundary
- Road



1:120,000



Location of Study Area

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: Logan (1984), Ogden (1986), Promontory Point (1987), Tremonton (1989)

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 (2002), 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 (2003). 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.

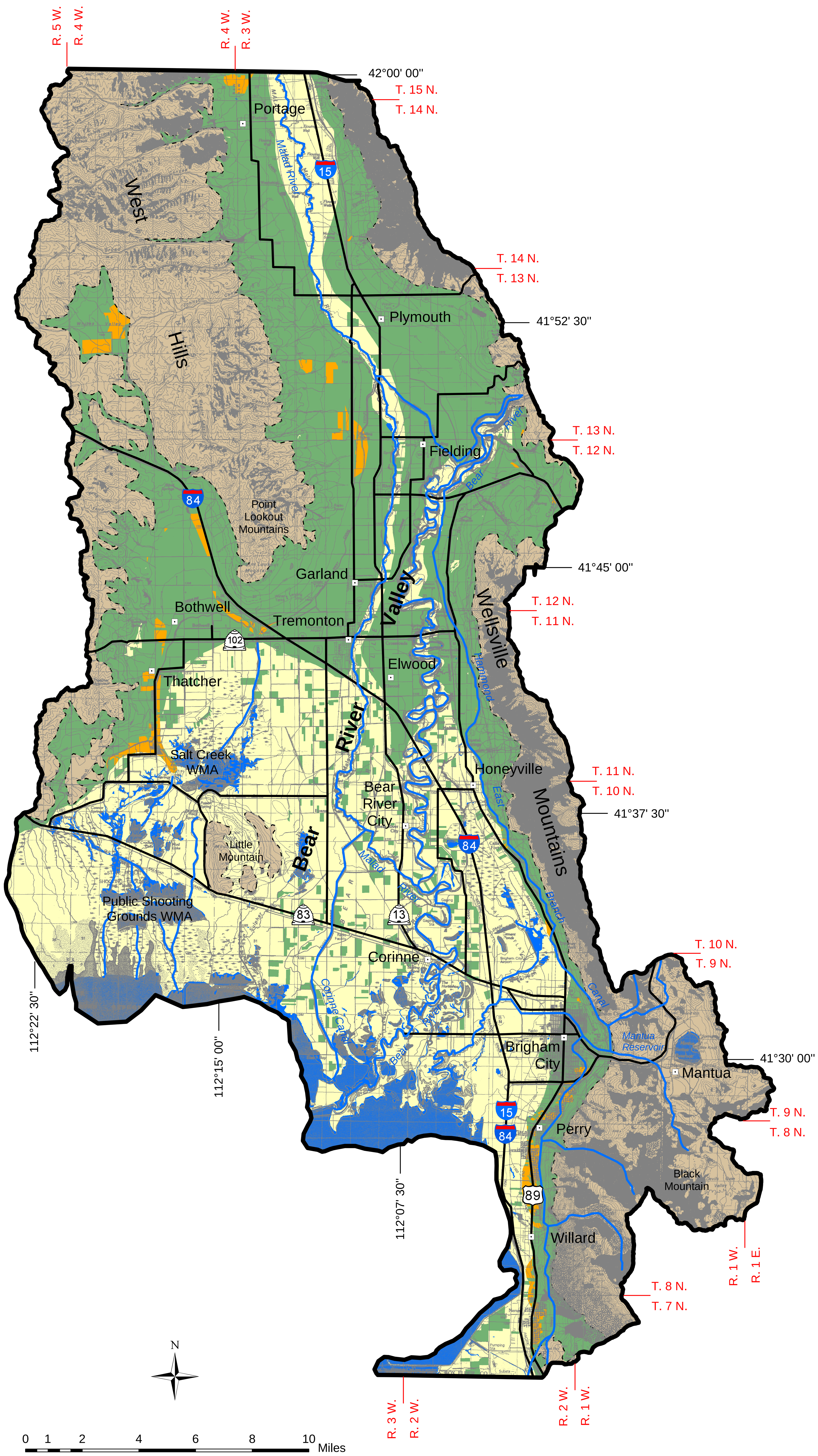
UTAH GEOLOGICAL SURVEY
UTAH GEOLOGICAL SURVEY
a division of
Department of Natural Resources

Plate 2

GROUND-WATER VULNERABILITY TO PESTICIDES IN EASTERN BOX ELDER COUNTY, UTAH

By Mike Lowe, Janae Wallace, Neil Burk, and Matt Butler
Utah Geological Survey
and
Anne Johnson and Rich Riding
Utah Department of Agriculture and Food

Miscellaneous Publication 05-1
2005

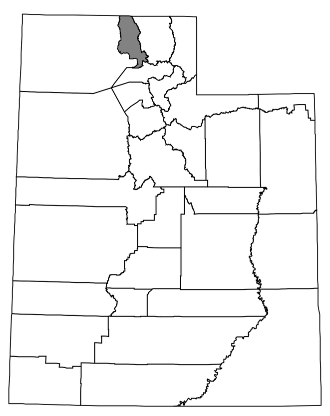


1:120,000

Explanation

Ground-Water Vulnerability Ranking

- Low
- Moderate
- High
- Bedrock (not analyzed)
- Water body
- Water course
- Basin-fill boundary
- Road



Location of Study Area

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: Logan (1984), Ogden (1986), Promontory Point (1987), Tremonton (1989)

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 (2002), 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 (2003). 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.

UTAH GEOLOGICAL SURVEY
UTAH GEOLOGICAL SURVEY a division of Department of Natural Resources