# GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES IN UTAH


by

Mike Lowe, Janae Wallace,
Hugh A. Hurlow, Ivan D. Sanderson,
and Matt Butler

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*a division of*
Utah Department of Natural Resources
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3/03

# TABLE OF CONTENTS

## FIGURES



## TABLES



## APPENDICES



## PLATES

# GROUND-WATER SENSITIVITY AND VULNERABILITY TO PESTICIDES IN UTAH

*by*

*Mike Lowe, Janae Wallace, Hugh A. Hurlow, Ivan D. Sanderson, and Matt Butler*

## 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 Utah. We used existing data to produce pesticide sensitivity and vulnerability maps by applying a combined process-based and index-based model specifically tailored to the Western United States using Geographic Information System analysis methods. This is a first cut 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 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. Hydrostratigraphy (based on primary and secondary permeability of geologic units), soil hydraulic conductivity, retardation of pesticides, attenuation of pesticides, depth to ground water, and land-surface slope are the six factors primarily determining ground-water sensitivity to pesticides in Utah. Areas of high sensitivity are associated with Quaternary unconsolidated alluvial and eolian deposits, and with a fractured-rock hydrostratigraphic unit consisting of the Navajo/Nugget, Kayenta, and Wingate/Moenave Formations.

Ground-water vulnerability to pesticides is determined by assessing how ground-water sensitivity is modified by the activities of humans. 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 Utah. Areas of high vulnerability are primarily located where corn or sorghum crops are grown on Quaternary alluvial and eolian deposits due to the typically high sensitivity to pesticides in those areas. Of particular concern are areas where influent (losing) streams originating in mountainous areas cross valley margins; streams in these areas are the most important source of recharge to basin-fill aquifers, and efforts to preserve water quality in streams at these points would help to preserve ground-water quality in the entire basin. Corn and sorghum crops are generally not grown in mountainous areas, so pesticides are not likely to impact ground water in these areas. Because of relatively high retardation (long travel times of pesticides in the vadose zone) and attenuation (short half-lives) of pesticides in the soil environment, pesticides applied to fields in the central areas of valleys and basins likely do not represent a serious threat to ground-water quality. To verify this conclusion, ground-water sampling by the Utah Department of Agriculture and Food should be concentrated in areas of moderate and high sensitivity or vulnerability, typically along valley margins. Sampling in the central areas of valleys and basins characterized by low sensitivity and vulnerability should continue, but at a lower density than in areas of higher sensitivity and vulnerability.

## INTRODUCTION

### Background

The U.S. Environmental Protection Agency (EPA) is recommending 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.

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 Utah. 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 Utah. Geographic variation in sensitivity and vulnerability, together with hydrologic and soil conditions that cause these variations, are described herein; plates 1 and 2 show the sensitivity and vulnerability, respectively, of ground water in Utah 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 the activities of humans. For this study, sensitivity incorporates: (1) hydrostratigraphy (based on primary and secondary permeability of geologic units), (2) soil properties, including hydraulic conductivity, bulk density, organic content, and field capacity, (3) 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, (4) depth to ground water, (5) average annual precipitation amounts, and (6) land-surface slope. Vulnerability includes human-controlled factors such as whether agricultural lands are irrigated, crop type, and type of pesticide applied.

### Purpose, Scope, and Limitations

The purpose of this project is to investigate sensitivity and vulnerability of ground-water resources in 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. This is a first cut 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 are not available that show the quantity of recharge to aquifers in Utah. We used a GIS coverage developed by subtracting average annual evapotranspiration from average annual precipitation as representation of average annual recharge from precipitation. While this coverage represents the largely elevation-controlled distribution of ground-water recharge, it likely does not incorporate recharge at low elevations during spring snowmelt. Additionally, the 1:500,000 digital soil maps used in this study are at a scale that indicates soils are present on rock outcrop areas. Because organic carbon in soils is one controlling factor determining the potential for pesticides to reach ground water, the higher sensitivity and vulnerability of these rock outcrop areas are not reflected in our maps. Some decisions were made to produce these maps based on our knowledge of the hydrogeology of the state and the types of data available; this includes selecting 3 feet (1 m) as the reference depth for applying pesticide retardation and attenuation equations. No new fieldwork was conducted nor 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, 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 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 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 recognized 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. 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, which we use in this study to overcome the deficiencies in the DRASTIC method. 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. This combined process-based and index-based approach provides 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 mg/L |
| Atrazine | 0.003 mg/L | 3 mg/L |
| Metolachlor | -- | -- |
| Simazine | 0.004 mg/L | 4 mg/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, 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 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 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 Utah where ground water is unconfined, degradation of 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 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 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 aquifers.

## SETTING

### Physiography

Utah includes portions of three physiographic provinces and a transition zone between two of these provinces (figure 1). Northeastern Utah is part of the Middle Rocky Mountains physiographic province (Stokes, 1977), which includes the rugged uplands of the Wasatch Range and Uinta Mountains as well as many “back-valley” basins and river valleys. Northwestern and western Utah are part of the Basin and Range Physiographic Province, which is typified by relatively short, predominantly north-trending mountain ranges bounded by normal faults and surrounded by valleys filled with alluvium and, to a lesser extent, lacustrine deposits (Stokes, 1986). Southeastern Utah is part of the Colorado Plateau Physiographic Province, which is typified by predominantly gently dipping sedimentary rocks that are locally disrupted by folds and faults forming a landscape of plateaus and mesas bounded by sloping pediments or steep linear cliffs or cut by deep canyons (Stokes, 1986). A transition zone between the Basin and Range and Colorado Plateau Physiographic Provinces extends northeastward from southwestern Utah (Stokes, 1977); the transition zone includes physiographic features typical of both of these provinces.

Hintze and others (2000) have defined eight stratigraphic type sections for different geographic areas in Utah. These stratigraphic units, their porosity and permeability types, and their permeability rank are provided in appendix A.

### Climate

Utah’s climatic conditions vary from the hot, dry deserts of the southern and western parts of the state, to the humid alpine tundra of the higher peaks in the Uinta Mountains (Greer, 1981), but its overall climate is semiarid (Utah Division of Water Resources, 2001). In addition, Utah’s climate varies dramatically with elevation and, to a lesser extent, with latitude. Utah receives an average of only 13 inches (33 cm) of precipitation annually, the second lowest average annual precipitation in the United States (Utah Division of Water Resources, 2001). Annual normal precipitation (1960-1990) for Utah ranges from less than 6 inches (15 cm) in some lowland areas to more than 50 inches (130 cm) at some mountain peaks (Ashcroft and others, 1992). Figure 2 shows the average annual precipitation by drainage basin. Temperatures range from a normal summer maximum of about 100 ˚F (38°C) in the lower elevation areas of southwestern and south-central Utah to a normal winter minimum of 0°F (-18°C) in some of the higher elevation areas of the Uinta Mountains and Bear River Range in northern Utah (Greer, 1981). Annual potential evapotranspiration ranges from less than 18 inches (46 cm) in the higher elevations of Utah to more than 36 inches (91 cm) along the Colorado River in southern Utah (Greer, 1981). The average number of frost-free days ranges from 0 to 40 in many mountainous areas of Utah to more than 200 in southwestern Utah and along the Colorado River in south-central Utah (Ashcroft and others, 1992).

## GROUND-WATER CONDITIONS

### Introduction

Ground water in Utah occurs in four different types of aquifers: sandstone and carbonate fractured-rock aquifers, and basin- and valley-fill unconsolidated aquifers. Bedrock aquifers yield water to springs and wells, but produce significantly less ground water compared to basin- and valley-fill aquifers in Utah. No single, continuous, widespread, hydraulically connected aquifer, like the Ogallala of Oklahoma/Nebraska, exists in Utah. The different types of aquifers are each most common in different physiographic provinces (figures 1 and 3) and stratigraphic type-section areas (appendix A) of Utah. For example, basin-fill aquifers are prevalent in the Basin and Range physiographic province, whereas sandstone aquifers are more common in the Colorado Plateau, and valley-fill aquifers are common in the Rocky Mountain physiographic province (Schlotthauer and others, 1981; Gates, 1985). The carbonate-bedrock aquifer, typical in far western Utah, is the least common and least well-known type of aquifer in Utah (Gates, 1985).

For all aquifer types, ground-water flow is generally from the higher elevation recharge areas to lower elevation discharge areas, or along faults and fractures in bedrock. Most recharge to aquifers comes directly or indirectly from precipitation within the drainage basins. Streams are a main

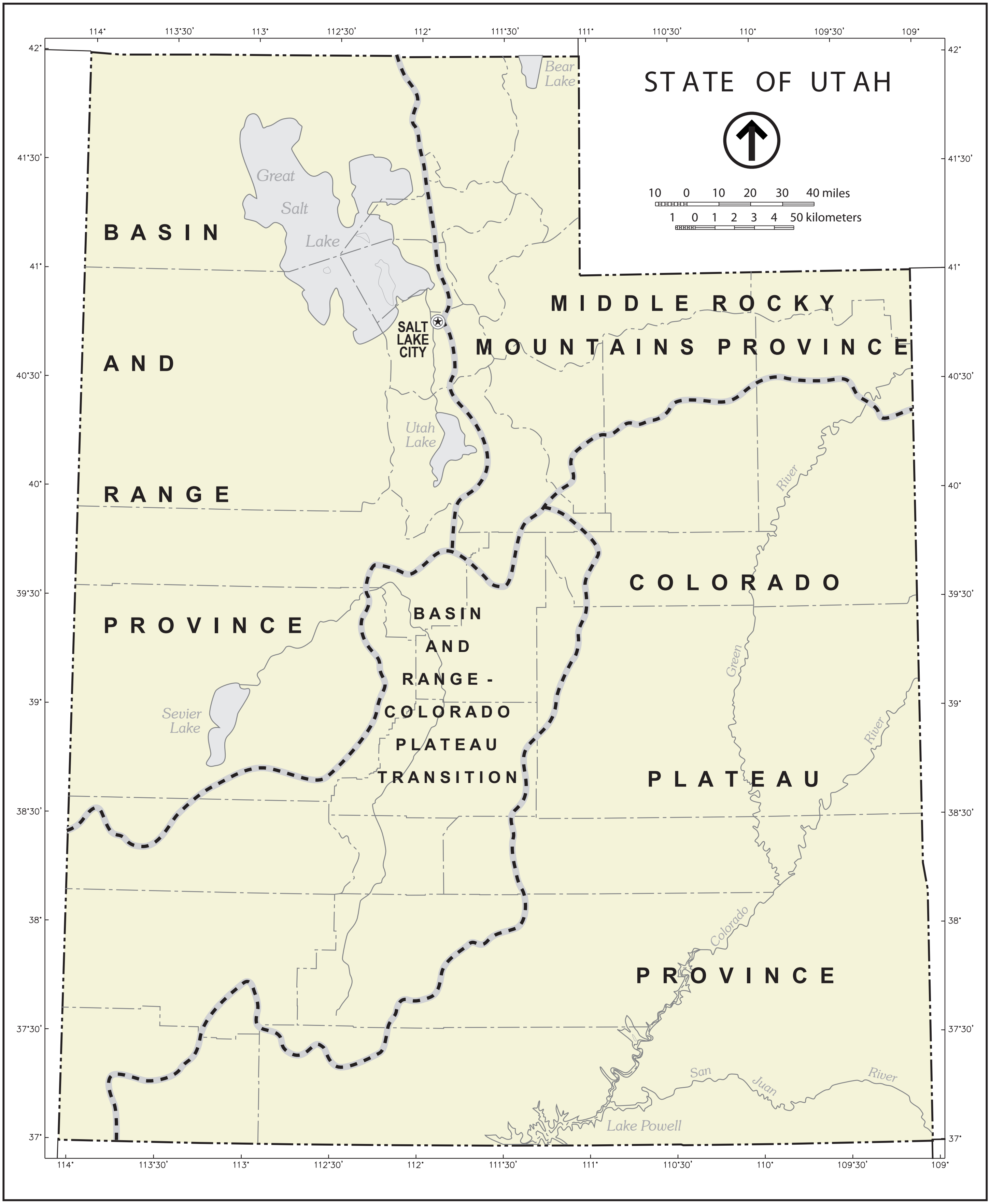



*Figure 1. Physiographic provinces in Utah (modified from Stokes, 1977).*

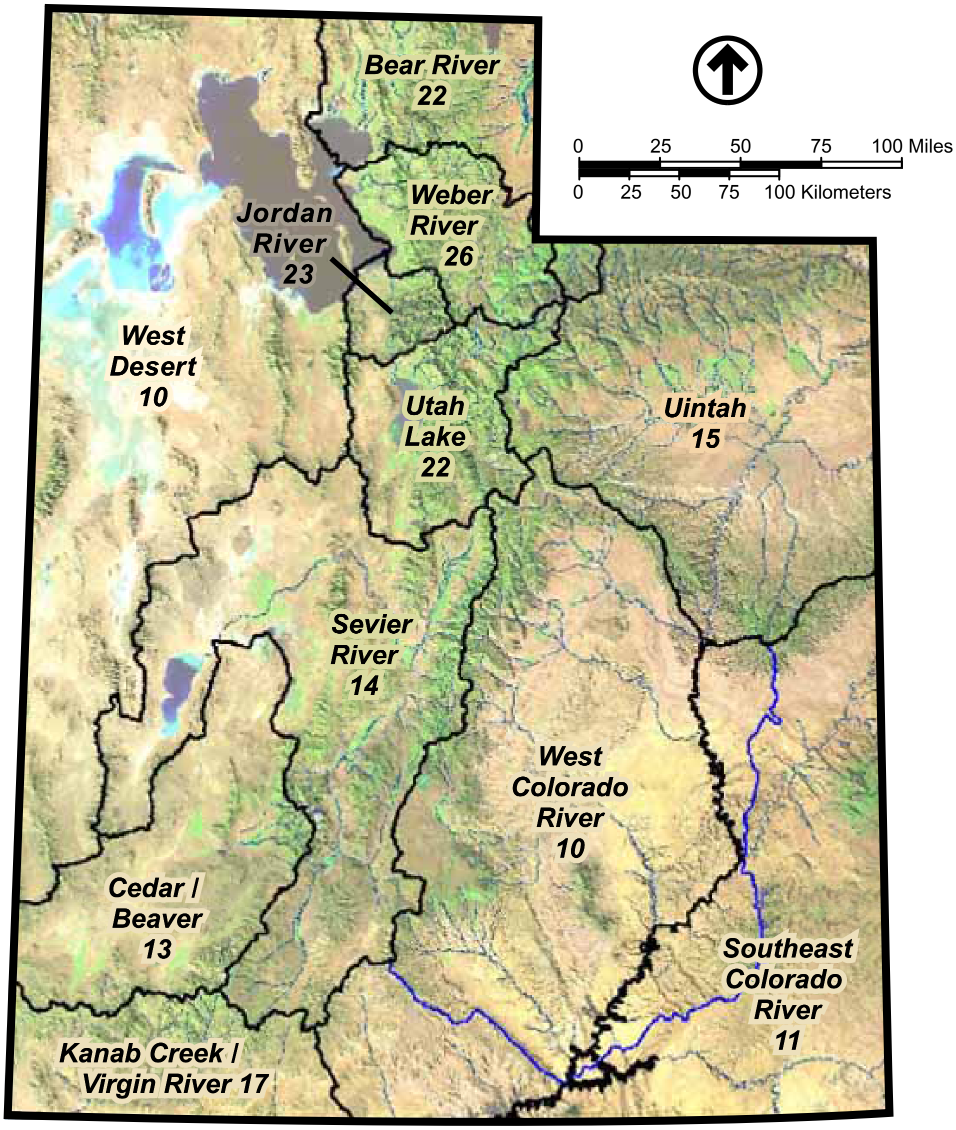



***Figure 2.*** *Average annual precipitation in inches by drainage basin in Utah (modified from Utah Division of Water Resources, 2001).*

source of recharge to aquifers. In some cases, excess irrigation water, either diverted from streams or pumped from wells, is also an important source of recharge to the aquifers. Subsurface inflow from adjacent mountain blocks may contribute a relatively small amount of recharge to aquifers. Ground water is discharged from aquifers via springs and seeps, evapotranspiration, wells, and subsurface outflow from the hydrologic basin.

## Aquifers in Unconsolidated Deposits

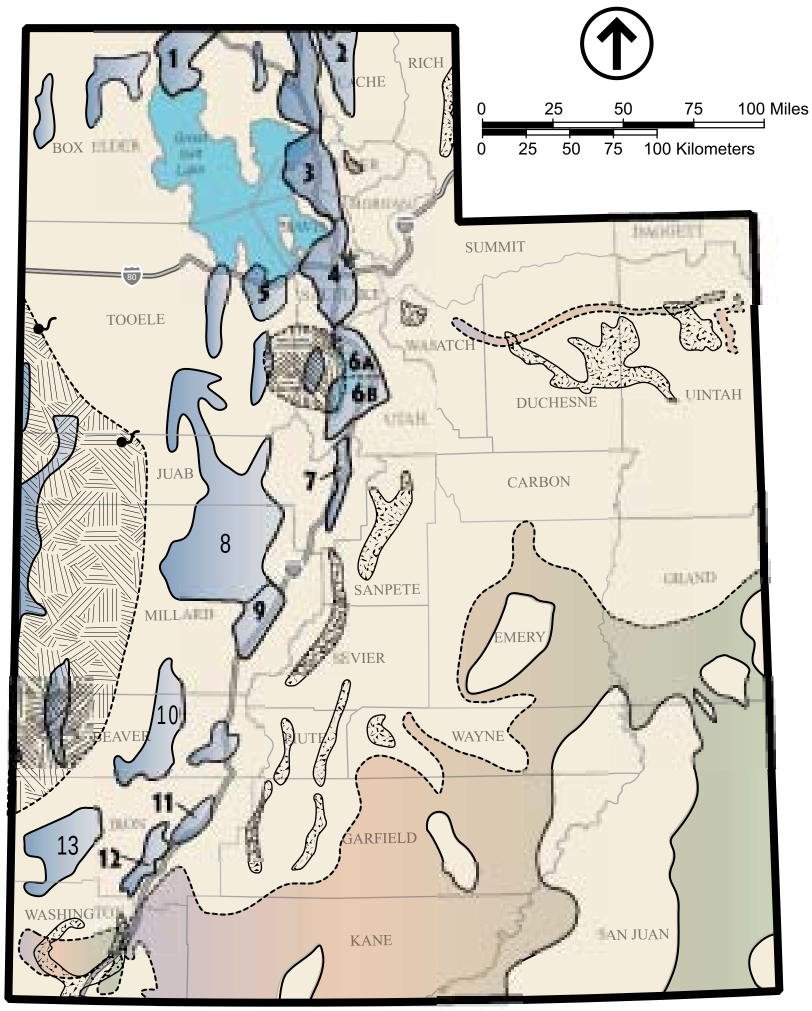
### Valley-Fill Aquifers

Valley-fill aquifers consist primarily of unconsolidated Quaternary alluvium in stream valleys (some are also structural depressions or basins) and are primarily found in the Middle Rocky Mountains and Colorado Plateau physiographic provinces (figure 3) (Gates, 1985). Valley-fill aquifers occur under confined, unconfined, and perched groundwater conditions. Wells completed in Utah's valley-fill aquifers can be over 600 feet (180 m) deep, but are commonly 50 to 200 feet (15-61 m) deep (Gates, 1985). Unconsolidated valley fill is typically composed of poorly to well-sorted bodies of sand, clay, gravel, and boulders. Valley-fill aquifers generally have unconfined conditions along the higher elevation margins where they typically consist of coarse, granular, permeable sediments deposited primarily in alluvial fans. These valley-margin deposits typically grade into finer grained fluvial (and, to a lesser extent, lacustrine) sediments in the valley centers where ground water may be under confined conditions.

Valley-fill aquifers yield water at rates averaging from 10 to 750 gallons per minute (0.6-50 L/s), and may exceed 2,000 gallons per minute (130 L/s) (Gates, 1985). The most productive aquifers consist of beds of coarse, clean, well-sorted gravel and sand that readily yield large quantities of water to wells. Avery and others (1984) estimated 1983 well-water withdrawals from Utah valley-fill aquifers at 56 million gallons (200,000 m$^3$) per day.

### Basin-Fill Aquifers

Basin-fill aquifers are found primarily in the Basin and Range Physiographic Province (figure 3), and are lithologi-




## Principal Aquifer and Subdivision

Unconsolidated Basin-fill Aquifers (1-13)

(1) Curlew Valley
(2) Cache Valley
(3) East Shore area
(4) Salt Lake Valley
(5) Tooele Valley
(6) Utah and Goshen Valleys
(6a) Northern Utah
(6b) Southern Utah-Goshen
(7) Juab Valley
(8) Sevier Desert
(9) Pahvant Valley
(10) Milford area
(11) Parowan Valley
(12) Cedar Valley
(13) Beryl-Enterprise area

Unconsolidated Valley-fill Aquifers

Sandstone Aquifers

Carbonate Rock

Not a principal aquifer

Boundary of aquifer uncertain

Spring – Discharges large volumes of water from carbonate-rock aquifer

***Figure 3.*** *Geographic distribution of principal aquifers in Utah (modified from Gates, 1985).*

cally similar to valley-fill aquifers but are typically thicker and more areally extensive (Gates, 1985). Ground water in basin-fill aquifers occurs under confined, unconfined, and perched conditions. Based on water-well and gravity data, the total thickness of typical basin-fill aquifers ranges from 0 to several thousand feet thick; these aquifers commonly contain fresh water in a zone up to 500 to 1,500 feet (150-450 m) thick (Gates, 1985). Unconsolidated basin fill typically consists of Quaternary alluvial sediments composed of poorly to well-sorted bodies of clay, silt, sand, gravel, and boulders. Basin-fill aquifers generally have unconfined conditions along the higher elevation margins where they typically consist of coarse, granular, permeable sediments deposited primarily in alluvial fans. These basin-margin deposits typically grade into finer grained lacustrine or fluvial sediments in the basin centers where ground water is generally under confined conditions.

The alluvial basin-fill deposits yield water at rates averaging from 200 to 1,000 gallons per minute (10-60 L/s) (Gates, 1985). The most productive basin-fill aquifers consist of beds of coarse, clean, well-sorted gravel and sand that readily yield large quantities of water to wells. Avery and others (1984) estimate 1983 ground-water withdrawals from Utah basin-fill aquifers at 500 million gallons (1.9 million $m^3$) per day.

## Fractured-Rock Aquifers

### Sandstone Aquifers

Ground water in sandstone aquifers occurs in fractures and pore spaces; secondary permeability due to fractures is more important than permeability related to pore spaces with respect to the ability of the sandstone aquifer to yield water to wells (Eisinger and Lowe, 1999). Sandstone aquifers are more common in the Colorado Plateau than in other areas of Utah (figure 3). Wells completed in sandstone aquifers are commonly from 100 to 1,000 feet (30-300 m) deep, but may exceed 2,000 feet (600 m) deep (Gates, 1985). Sandstone aquifers typically consist of fine- to medium-grained quartz-rich sandstone and generally have variable cementing agents. The Entrada, Navajo, and Wingate Sandstones are the most widespread and contain the most useable water in Utah, but less-extensive bedrock units locally may also be important aquifers (Schlotthauer and others, 1981; Gates, 1985).

Sandstone aquifers yield water at rates averaging from 200 to 1,000 gallons per minute (10-60 L/s) (Gates, 1985). Avery and others (1984) estimated 1983 well-water withdrawals for all sandstone aquifers in Utah at 4 million gallons (15,000 $m^3$) per day.

### Carbonate Aquifers

Ground water in carbonate aquifers, typically limestone and dolomite formations (Gates, 1985), occurs in fractures and solution cavities. Carbonate aquifers are the least common type of aquifer in Utah, and are typically found in western Utah in the Basin and Range Physiographic Province, but a less extensive carbonate aquifer is present around Utah Lake in central Utah (figure 3). The carbonate aquifers are not extensively used in Utah; therefore, little information is available about them (Waddell and Maxell, 1988). Based on unpublished U.S. Geological Survey records, Gates (1985) estimated water-well withdrawals from carbonate aquifers in Utah in 1979 at 3 million gallons (11,000 $m^3$) per day.

## Water Quality

Ground-water quality in Utah is generally good, but can vary in both unconsolidated and fractured bedrock aquifers. The type of water and quantity of dissolved solids is largely influenced by local geology.

Ground water in the basin- and valley-fill aquifers is typically fresh, calcium- and magnesium-type, and generally has dissolved-solids concentrations less than 1,000 mg/L. Ground-water having less than 250 mg/L total-dissolved-solids concentration is typically located in recharge areas along valley/basin margins and in high mountainous areas (Waddell and Maxell, 1988). Lower parts of valleys/basins can typically contain more saline water (Waddell and Maxell, 1988). Ground water with high total-dissolved-solids concentrations and high calcium and sulfate concentrations exists in some areas if rocks in the drainage basin contain abundant gypsum or salt, such as in wells downgradient from the salt-rich Arapien Shale in Sanpete Valley (Lowe and others, 2002). Ground water with high total-dissolved-solids concentrations and high sodium and chloride concentrations exists near playa areas and saline lakes, such as in wells located near the shore of Great Salt Lake (Steiger and Lowe, 1997; Lowe and Wallace, 1999). Areas where irrigation is the long-term principal use of water, and areas of ground-water withdrawal have water-quality declines over time, such as the Sevier Desert, Pahvant Valley, and the Beryl-Enterprise area (figure 4) (Waddell and Maxell, 1988).

Sandstone aquifers generally have total-dissolved-solids concentrations less than 1,000 mg/L (Gates, 1985). Negligible information is known about the quality of water in carbonate aquifers.

# 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. We combine a process-based model with an index-based model to produce sensitivity and vulnerability maps for Utah. 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 (Siegel, 2000), 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

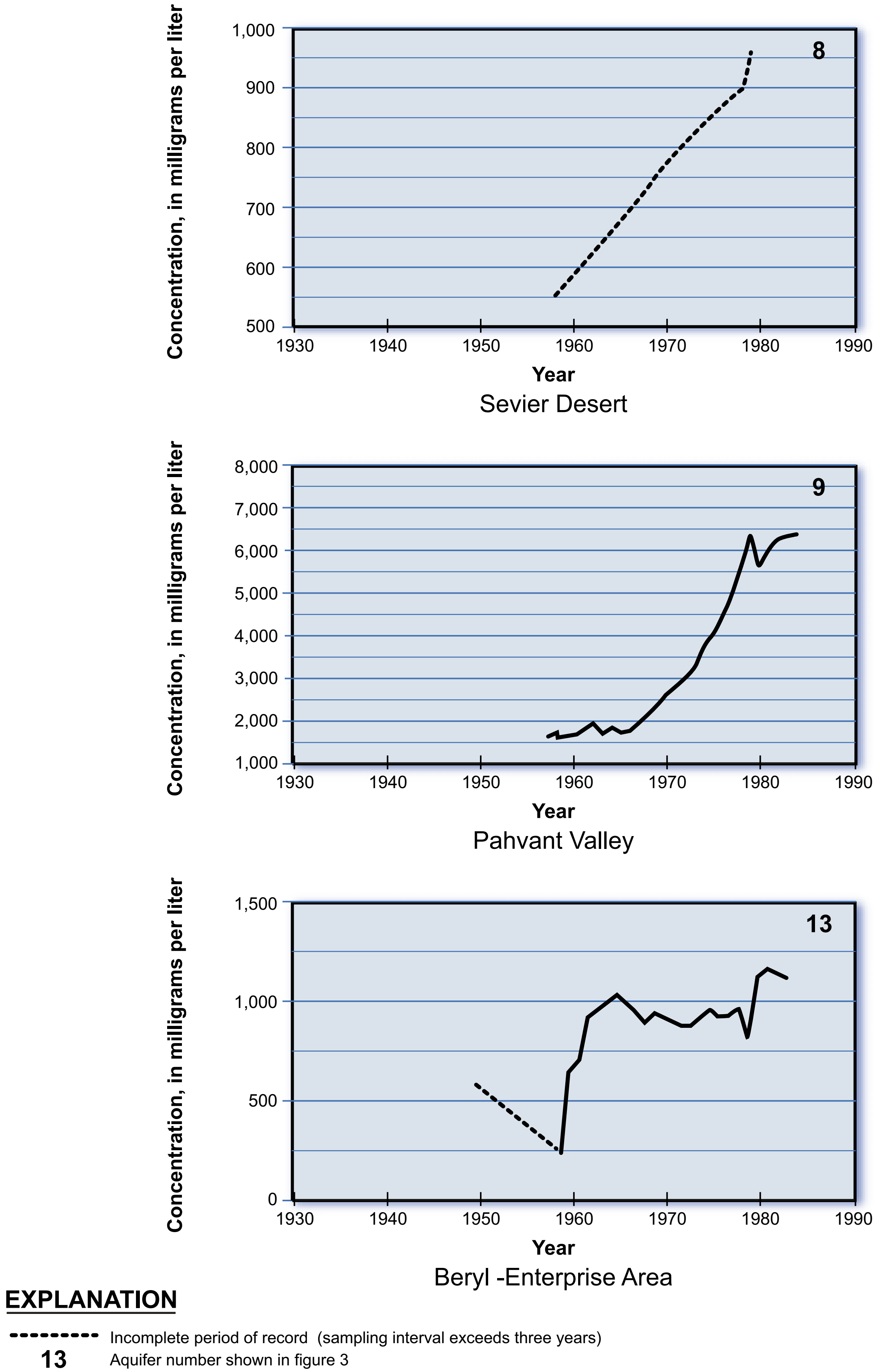



***Figure 4.*** *Long-term changes of dissolved-solids concentrations in water from selected wells in major areas of ground-water withdrawals, Utah, 1930-1985 (data modified from Waddell and Maxell, 1986).*

on the land surface. We selected six factors that are most important in determining ground-water sensitivity to pesticides: hydrostratigraphy (based on primary and secondary permeability of geologic units), soil hydraulic conductivity, retardation of pesticides, attenuation of pesticides, depth to ground water, and land-surface slope steepness.

## Hydrostratigraphy

We grouped geologic units as mapped by Hintze and others (2000) into three qualitative permeability rank categories (medium to high, heterogeneous, and low) (appendix A) for each of the eight stratigraphic type-section areas for Utah (figure A.1), based largely on information in Schlotthauer and others (1981). We also provide the principal porosity and permeability types for each of these hydrostratigraphic units (appendix A). For our GIS analysis, we characterized terrain directly underlain by hydrostratigraphic units having medium to high permeability as potentially having ground water that is more vulnerable to the surface application of pesticides, and terrain directly underlain by those units having low permeability as potentially having ground water that is less vulnerable to the surface application of pesticides; we consider terrain directly underlain by geologic units in the heterogeneous permeability rank category to be intermediate between the medium-to-high- and low-permeability rank categories in terms of vulnerability of ground water to the surface application of pesticides.

## 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 National Soil Survey Center (U.S. Department of Agriculture, 1995). For our 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 Utah Division of Water Quality's minimum allowable percolation rate for permitting septic tanks. For areas with insufficient hydraulic conductivity data, we applied the greater than or equal to 1 inch (2.5 cm) per hour GIS attribute ranking, described below, 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 more slowly through the soil than water; the relative rate of movement 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 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; a relatively low RF indicates higher sensitivity to 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;

$\rho b$ = bulk soil density (kg/L);

$F_{oc}$ = organic carbon (fraction);

$K_{oc}$ = organic carbon sorption distribution coefficient (L/kg); and

$\theta_{FC}$ = soil field capacity (volume fraction).

For this study we used data from the Soil Survey Geographic (STATSGO) database (U.S. Department of Agriculture, 1995), which includes some digitized data for soils in Utah at a scale of 1:250,000, including derived values for dry 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 for particular soil groups from STATSGO 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, 2003). 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 percent, which represent naturally occurring conditions in Utah aquifers, and variable soil organic carbon content using a water depth of 3 feet (1 m) (appendix B). Average organic carbon content in Utah soils is shown in figure 5 and ranges from 0.03 to 8.7 percent; the mass fraction of organic carbon was computed by dividing the organic matter parameter in the STATSGO 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 to 125.

A retardation factor of 1 generally corresponds to areas in the state having "0" percent organic matter based on the STATSGO database; these areas may reflect an anomaly in the data rather than actual conditions (because all soils have some organic content, however negligible). According to Freeze and Cherry (1979), retardation factors typically range from (1 + 4Kd) to (1 + 10 Kd), where Kd is the product of the organic carbon sorption distribution coefficient (Koc) and the fraction of organic carbon, and based on typical unconsolidated sediment properties of 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 cation), move through the subsurface at the same rate as the ground water, whereas dissolved constituents in ground water with $R_F$ values that are orders of magnitude larger than one are essentially immobile (Freeze and Cherry, 1979). The relative

***Table 2.*** *Hydrologic soil groups, field capacity, bulk density, and fraction of organic content generalized for Utah soils. Soil description and organic content from U.S. Department of Agriculture (1995). Field capacity based on sediment grain size calculated from a soil texture triangle hydraulic properties calculator (Saxton, 2003). Bulk density from Marshall and Holmes (1988) and Saxton (2003).*

| **Soil Group** | **Soil Description** | **Grain size (mm) (Field Capacity %)** | **Bulk Density Range (kg/L) (average)** | **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 (14-21) | 1.5 – 2 (1.75) | Variable and ranges from 0.03 to 8.7% |
| 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 ranges from 0.03 to 8.7% |
| 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 0.03 to 8.7% |
| 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 0.03 to 8.7% |

* $F_{oc}$ is calculated from STATSGO organic matter data divided by 1.72 and is unique for soil polygons.

***Table 3.*** *Pesticide organic carbon sorption distribution coefficients (Koc) and half-lives ($T^1/_2$) for typical soil pHs (modified 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 |

velocity is the reciprocal of the retardation factor and describes the rate a mixture of reactive contaminant moves relative to solute-free ground water. The highest relative velocity from our data is 0.7 and the lowest is 0.008; the former indicates pesticide in ground water moves at a rate about 70 percent that of ground water free of pesticides, while the latter indicates that pesticides in ground water are essentially immobile.

Pesticides traveling downward in vadose-zone material having an $R_F$ of 2 could reach the water table at a depth of 3 feet (1 m) within one year if ground-water recharge amounted to 9 inches (23 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. For example, at higher altitudes where recharge is as high as 44 inches per year (1.1 m/yr), about 45 percent of a solute in

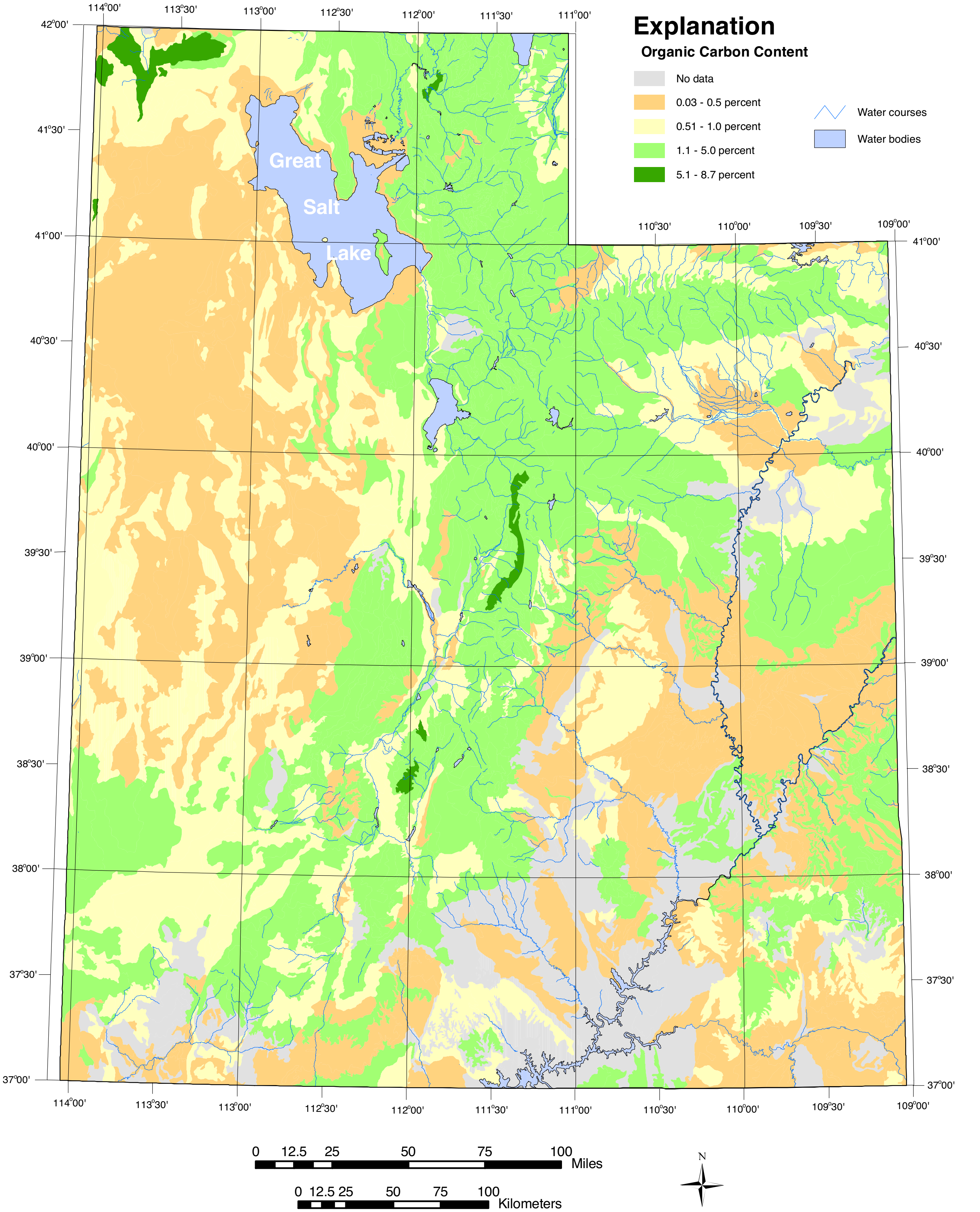



***Figure 5.*** *Average organic carbon content in soils in Utah (data from U.S. Department of Agriculture, 1995).*

ground water can reach a depth of 3 feet (1 m) in a year. When ground-water recharge is less than 6 inches (15 cm), negligible amounts of pesticide will reach a depth of 3 feet (1 m) in a one-year period (see attenuation discussion below and appendix B). A natural division between low and high retardation exists at a value of 5. For our GIS analysis, we divided pesticide retardation into two ranges: greater than, and less than or equal to 5.

## 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 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, field capacity of the soil, and retardation (from equation 1). 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 (or length);

$R_F$ = retardation factor (dimensionless);

$\theta_{FC}$ = soil field capacity (volume fraction);

$q$ = net annual ground-water recharge (precipitation minus evapotranspiration; length); and

$t_{1/2}$ = pesticide half-life (years).

For this study, net annual ground-water 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 to 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 moisture produced by precipitation is consumed by evapotranspiration in most parts of the state (95% of the state). Therefore, ground-water recharge from precipitation is relatively low in many areas of Utah (95% of the state). The only localities in which evapotranspiration is less than precipitation are high-elevation forested areas (figure 6). 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 Utah soils, similar to our approach for retardation, to delineate high and low pesticide attenuation factors for our GIS analysis. To represent naturally occurring conditions that could result in high 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 percent; and a bulk density value of 1.2 kg/L. For a net annual ground-water recharge value of 9 inches (23 cm), equation 2 results in an attenuation factor of 0.02. This means that at the above-described values for variables in the equation, 2 percent (by volume) 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 44 inches (1.1 m) (the greatest value of recharge in the STATSGO database), the calculated attenuation factor increases proportionally such that 45 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 if we input a high estimated value of an annual ground-water recharge rate of 3 feet (1 m). Accordingly, for our GIS analyses an attenuation factor of 0.02 (2 percent) or less is considered low, whereas greater than 0.02 is considered high.

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). 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 – and the half-life for simazine (table 3), the pesticide among the four with the longest half-life (Weber, 1994). Applying a bulk density of 1.2 kg/L (the minimum anticipated value to be encountered in soil types represented in Utah), a field capacity of 14 percent (the minimum anticipated value), and an organic carbon content of 0.0015 percent (a typical value for these soils), almost 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 4 inches (10 cm) per year. Based on the precipitation and evapotranspiration data, only 5 percent of the state receives more than 0 inches per year average annual ground-water recharge from direct precipitation. In many parts of the state, ground water recharges mainly from seepage from surface water (streams and lakes) and irrigation. At higher values for organic carbon content, the retardation factor increases and the attenuation factor decreases dramatically. With large amounts of organic carbon in the soil, calculations show negligible pesticide will reach ground water even at levels of ground-water recharge as high as 3 feet (1 m) per year.

The exercise of calculating retardation and attenuation factors using variable parameter values enabled us to calibrate assigned pesticide-sensitivity rankings to naturally occurring conditions, thus overcoming one of the major objections to the DRASTIC method. Further, the exercise shows 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, pesticides will likely not impact the ground water. We performed sensitivity analyses (appendix

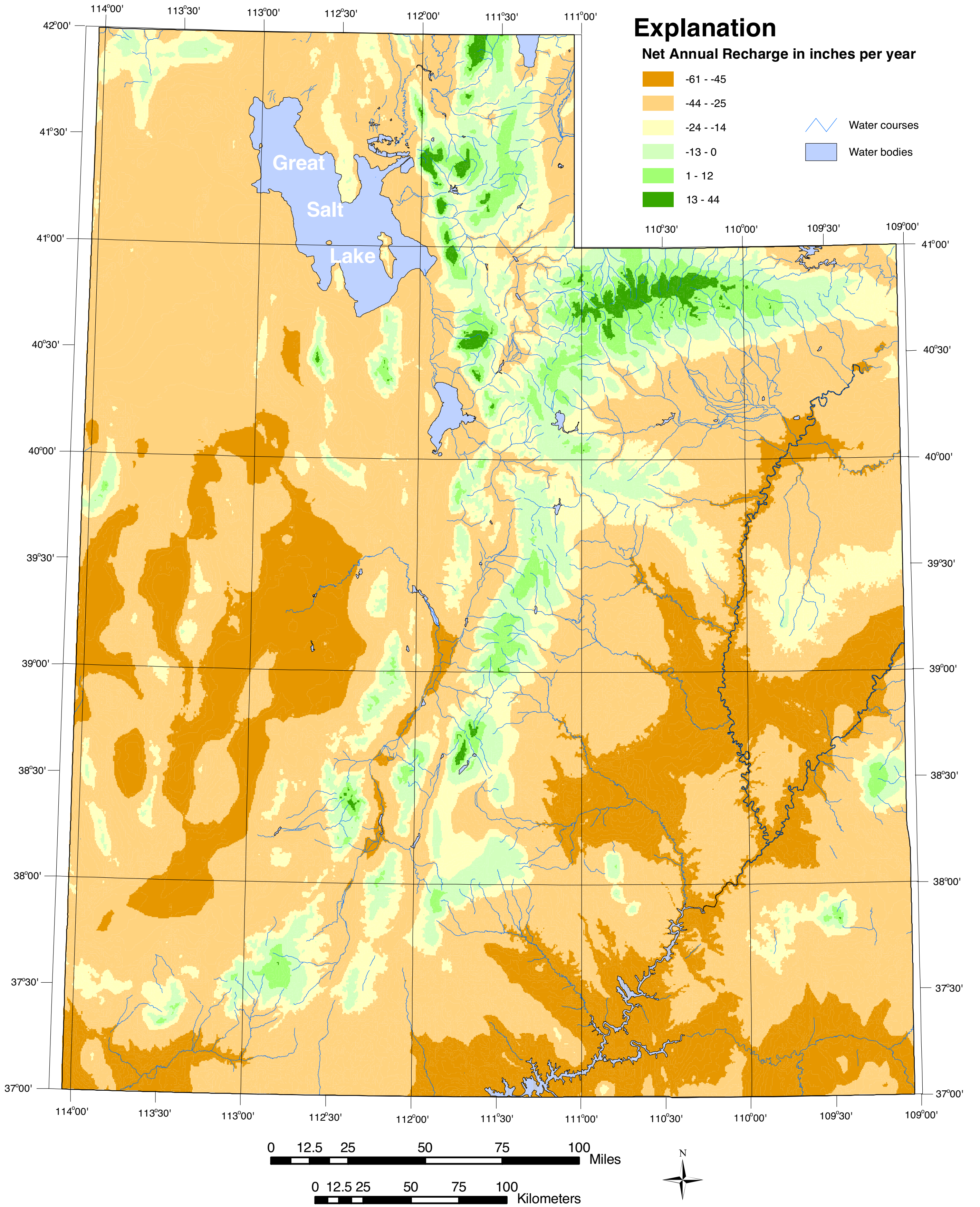



***Figure 6.** Net annual ground-water recharge from precipitation for Utah, calculated using data from the Utah Climate Center (1991) and Jensen and Dansereau (2001). Although net annual recharge may be negative in most areas, seasonally some recharge from precipitation may occur.*

B) for the retardation and attenuation factors by assigning variables for parameters representative of a variety of ground-water conditions and soil types (some of which are provided in STATSGO's database for Utah). The tables (appendix B) illustrate the variations expected for $F_{oc}$, $\theta_{FC}$, recharge, water depth, and the resultant $R_F$ values to input into equation 2. We used the resulting values that best represent statewide conditions to generate the vulnerability and sensitivity maps; the numbers we apply provide the most conservative estimate to be more protective of ground water in Utah.

Although quantities of pesticides applied to the ground surface would seem to have a direct bearing on the amount of pesticide impacting ground water, Rao and others' (1985) equations do not support this. Note that the quantity of pesticide applied to the ground surface does not enter into either equation as a variable; the half-life of the pesticide, however, is essential. The half-life of a pesticide under typical field conditions remains fairly constant. The larger the quantity of pesticide that is applied, the greater the number of bacteria that develop to decompose and consume the pesticide over the same period of time. Furthermore, the quantity of pesticide needed to control weeds is quite small (see table 4). 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 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 with shallow ground water seasonally less than or equal to 3 feet (1 m) deep is one attribute of soil units mapped by the Natural Resources Conservation Service (formerly Soil Conservation Service; U.S. Department of Agriculture, 1995). Therefore, 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-or-equal-to-3-feet (1 m) GIS attribute ranking, described below, to be protective of ground-water quality.

## Slope

The potential for infiltration of precipitation falling or melting on the ground in a particular geographic setting also depends on land-surface slope. A flatter slope allows longer residence time for standing water and increases the potential for water to percolate into the subsurface. Steeper slopes have lower potential for infiltration due to shorter residence times. We used the percent slope, calculated from digital elevation model data using GIS analysis, as a variable in our pesticide sensitivity ranking similar to an assessment of pesticide vulnerability/sensitivity in Wyoming (Arneson and others, 1998). For our sensitivity ranking we used three slope-steepness categories: gentle slopes (0 to 3 percent), moderate slopes (greater than 3 percent to 18 percent), and steep slopes (greater than 18 percent).

## GIS Analysis Methods

We divided pesticide sensitivity into "low," "moderate," and "high" categories using hydrostratigraphy, soil hydraulic conductivity, soil retardation of pesticides, soil attenuation of pesticides, depth to shallowest ground water, and slope attributes as shown on table 5. Each attribute category received an equal weighting in the analysis. A sensitivity attribute of low was assigned when the numerical ranking ranged from 0 to 2, a sensitivity attribute of moderate was assigned when the numerical ranking ranged from 3 to 5, and a sensitivity attribute of high was assigned when the added numerical ranking ranged from 6 to 7.

# Ground-Water Vulnerability to Pesticide Pollution

Ground-water vulnerability to pesticides is a measure of how natural factors favorable or unfavorable to the degradation of ground water by 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 map (plate 2) is based on 1989-99 land-use data.

## Ground-Water Sensitivity

We consider ground-water sensitivity to be the principal factor determining the vulnerability of aquifers in Utah to degradation from agricultural pesticides. Low, moderate, and high sensitivity rankings were assigned numerical values as shown in table 6 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 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 Utah inventory was conducted during 1989-99 (Utah Division of Water Resources metadata). All polygons having 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.

***Table 5.*** *Pesticide sensitivity and the attribute rankings used to assign sensitivity for Utah.*

| Hydrogeologic Setting | | Soil Hydraulic Conductivity | | Pesticide Retardation | | Pesticide Attenuation Factor | | Depth to Ground Water | | Slope | | Sensitivity | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Attribute | Ranking | Attribute | Ranking | Attribute | Ranking | Attribute | Ranking | Attribute | Ranking | Attribute | Ranking | Attribute | Ranking |
| Low permeability | -1 | Less than 1 inch/hour | 1 | High Greater than 5 | 0 | Low Less than or equal to 0.02 (2%) | 0 | Greater than 3 feet | 1 | Steep Greater than 18% | -1 | Low | 0 to 2 |
| Heterogeneous permeability | 0 | | | | | | | | | Moderate Greater than 3 to 18% | 0 | Moderate | 3 to 5 |
| Medium to high permeability | 1 | Greater than or equal to 1 inch/hour | 2 | Low Less than or equal to 5 | 1 | High Greater than 0.02 (2%) | 1 | Less than or equal to 3 feet | 2 | Gentle 0 to 3% | 1 | High | 6 to 7 |

***Table 6.*** *Pesticide vulnerability and the attribute rankings used to assign vulnerability for 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 |

## 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 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 Utah inventory was conducted during 1989-99 (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 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 divided pesticide vulnerability into "low," "moderate," and "high" categories using pesticide sensitivity, areas of irrigated lands, and crop type as shown in table 6. The numerical ranking for each attribute category is arbitrary, but reflects the relative level of importance we believe the attribute plays in determining vulnerability 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

To assess ground-water sensitivity to pesticide contamination, several GIS attribute layers were assembled as intermediate steps. Attribute layers include pesticide retardation, pesticide attenuation, hydrostratigraphy, hydraulic conductivity of soils, depth to shallow ground water, and slope. Data from these attribute layers were used to produce a ground-water sensitivity map (plate 1) using GIS analysis rankings as outlined in table 5, and are described and summarized in the following sections. Additionally, sensitivity mapped as part of valley-specific studies by Sanderson and

Lowe (2002), Sanderson and others (2002), and Lowe and Sanderson (2003) are overlain atop (given preference to) the results of the statewide analysis because they are based on better data for the basin-fill/valley-fill aquifers they addressed; the methods used in these studies are discussed in appendix C.

## Retardation

Surface application of pesticides is more likely to cause ground-water quality problems in areas where the pesticide retardation factor is low. Pesticide retardation factors are generally highest at higher elevations and lowest at lower elevations (figure 7), primarily because more plants grow, die, and contribute organic carbon to soils (figure 5) in areas of higher precipitation. About 46 percent of the surface area of Utah is mapped as having pesticide retardation factors greater than 5 (figure 7).

## Attenuation

Ground-water quality problems associated with surface application of pesticides are more likely to occur in areas where attenuation is low (the attenuation factor is high) than where attenuation is high. The attenuation factor is ranked as high (greater than 0.02 [2 percent]) in the Alta area of the central Wasatch Range and in the higher elevations of the La Sal Mountains in southeastern Utah (figure 8), based on Rao and other's (1985) equation. The attenuation factor is ranked as low over 99.96 percent of the state (figure 8). Over most of the state, annual evapotranspiration exceeds net annual precipitation (figure 6). Net annual recharge from precipitation is negative in basin floor areas (figure 6). Most recharge from precipitation likely occurs during spring snowmelt, principally in and along the margins of mountainous areas. 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 during irrigation. Therefore, pesticides are unlikely to reach ground water under conditions typical in most of Utah.

## Hydrostratigraphy

Surface application of pesticides is more likely to cause ground-water quality problems in areas where the surface-geologic units are aquifers (have medium to high permeability) than in areas where geologic units are aquitards (have low permeability). Geologic units ranked as having medium to high permeability include the Cambrian Geertsen Canyon Quartzite, Jurassic Navajo/Nugget Sandstone, and Quaternary alluvial and eolian deposits (appendix A). Geologic units ranked as having low permeability include the Mississippian Chainman, Manning Canyon, Woodman, and Doughnut Formations, the Triassic Ankareh Shale, the Jurassic Morrison Formation, and Quaternary Lake Bonneville, marsh, and mud/salt flat deposits (appendix A). All other map units of Hintze and others (2000) are considered to have intermediate permeabilities or layers of varying permeabilities (appendix A). Medium to highly permeable geologic units make up about 29 percent of the surface area of Utah, geologic units with intermediate permeabilities make up about 57 percent, and low permeability geologic units make up about 14 percent (figure 9).

## 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 U.S. Department of Agriculture's (1995) STATSGO database. About 52 percent of the surface area of Utah has soil units mapped as having hydraulic conductivity greater than or equal to 1 inch (2.5 cm) per hour, and about 41 percent has soil units mapped as having hydraulic conductivity less than 1 inch (2.5 cm) per hour (figure 10). Soil units covering about 7 percent of the surface area of Utah were not assigned hydraulic conductivity values in the STATSGO database (figure 10); these soils were lumped 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 Ground Water

Surface application of pesticides is more likely to cause ground-water quality problems in areas of shallowest ground water than where ground water is relatively deeper. Depth to ground-water data are from the U.S. Department of Agriculture's (1995) STATSGO database. Only 2 percent of the surface area of Utah has soil units mapped as having depths to ground water less than or equal to 3 feet (1 m); these areas are primarily in the central part of northern Utah valleys at lower elevations (figure 11). About 95 percent of the surface area of Utah has soil units mapped as having depths to ground water greater than 3 feet (1 m), and 3 percent is mapped as having an unknown depth to ground water (figure 11). Areas without assigned depths to ground water were lumped into the less than or equal to 3 feet depth category for analytical purposes to be protective of water quality.

## Slope

Ground-water quality problems associated with on-site surface application of pesticides are more likely to occur at sites having gentle land-surface slopes than steep land-surface slopes. Based on GIS analysis of digital elevation model data, about 41 percent of the surface area of Utah has slopes of 0 to 3 percent, 37 percent has slopes greater than 3 percent to 18 percent, and 22 percent has slopes steeper than 18 percent (figure 12). The gentle slopes are primarily in the central parts of valleys, and the steeper slopes are more common in mountainous areas.

## Sensitivity Map

Plate 1 shows Utah's ground-water sensitivity to pesticides, obtained using the GIS methods and ranking techniques described above. Utah's mountainous areas have low sensitivity because of steep slopes and the abundance of high-organic-carbon-content soils. Pesticides used in these areas are unlikely to degrade ground water because they have little opportunity to get into the aquifer. In these areas, pesticides spilled or misapplied have a much greater potential to be incorporated into runoff and contaminate surface water rather than ground water directly.

Areas of high sensitivity are located primarily along basin margins and along drainages where coarse-grained flu-

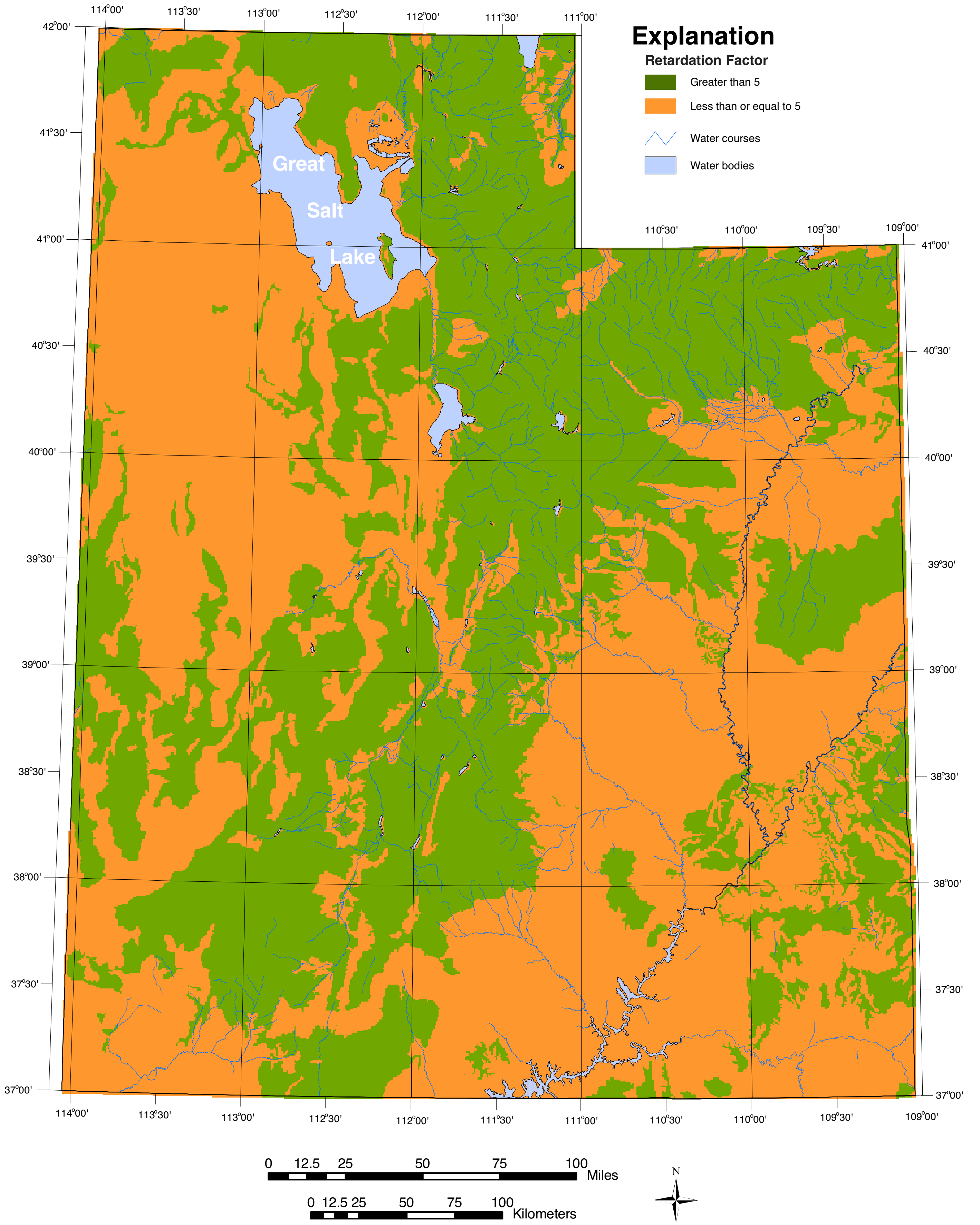



*Figure 7. Pesticide retardation in Utah (see text for further explanation).*

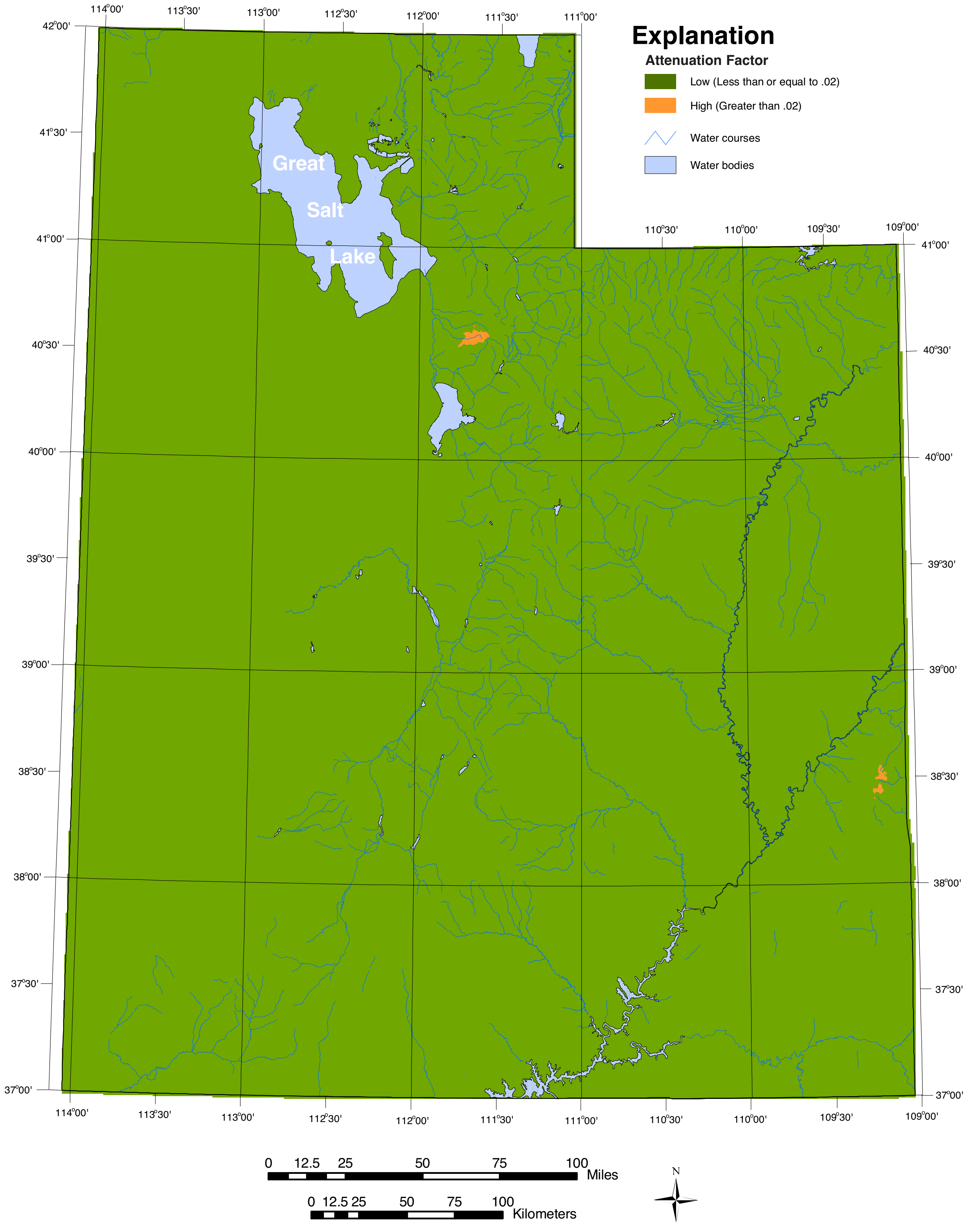



***Figure 8.*** *Pesticide attenuation in Utah (see text for further explanation).*

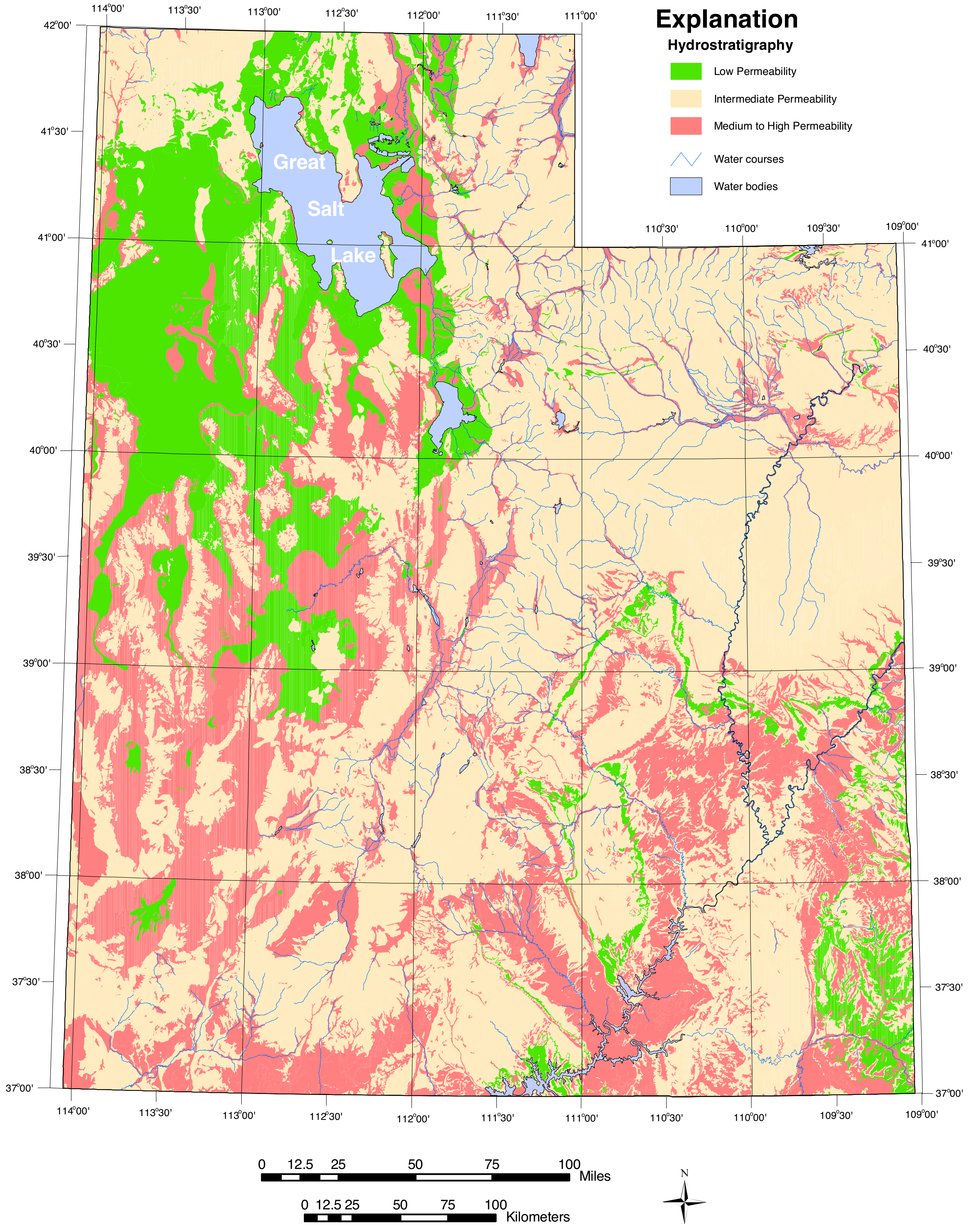



***Figure 9****. Hydrostratigraphic units in Utah.*

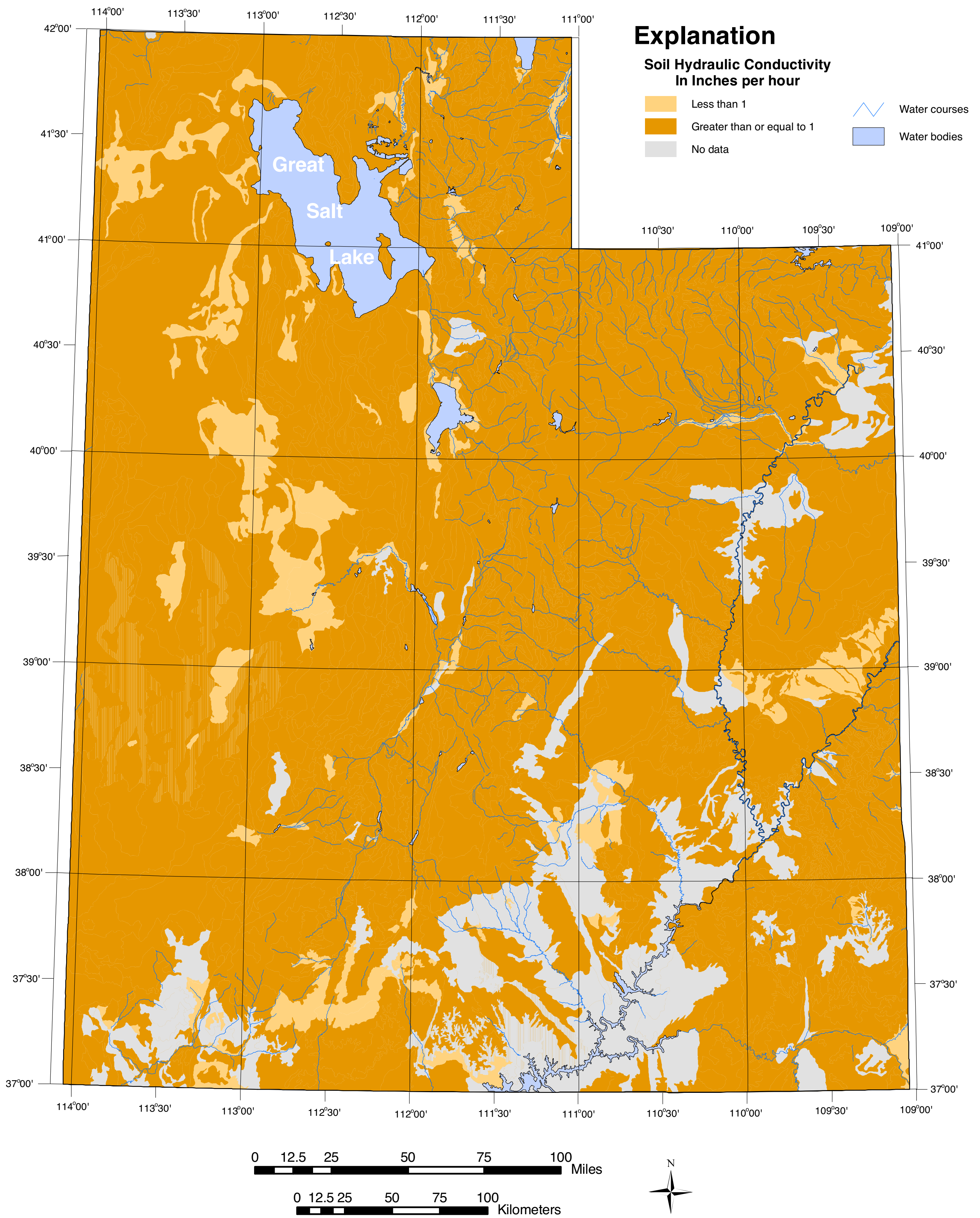



*Figure 10*. Soil hydraulic conductivity in Utah (data from U.S. Department of Agriculture, 1995).

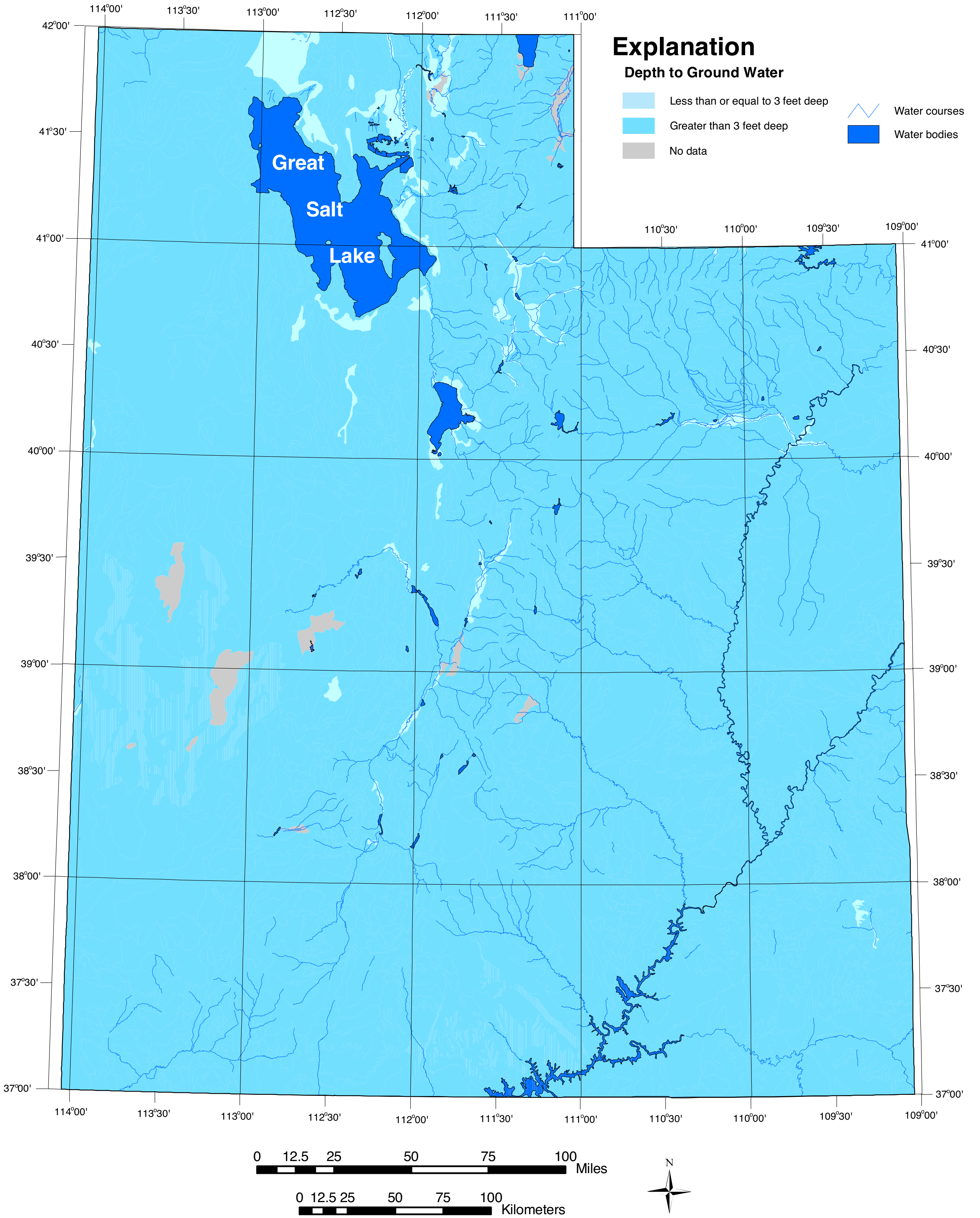



*Figure 11. Depth to ground water in Utah (data from U.S. Department of Agriculture, 1995).*

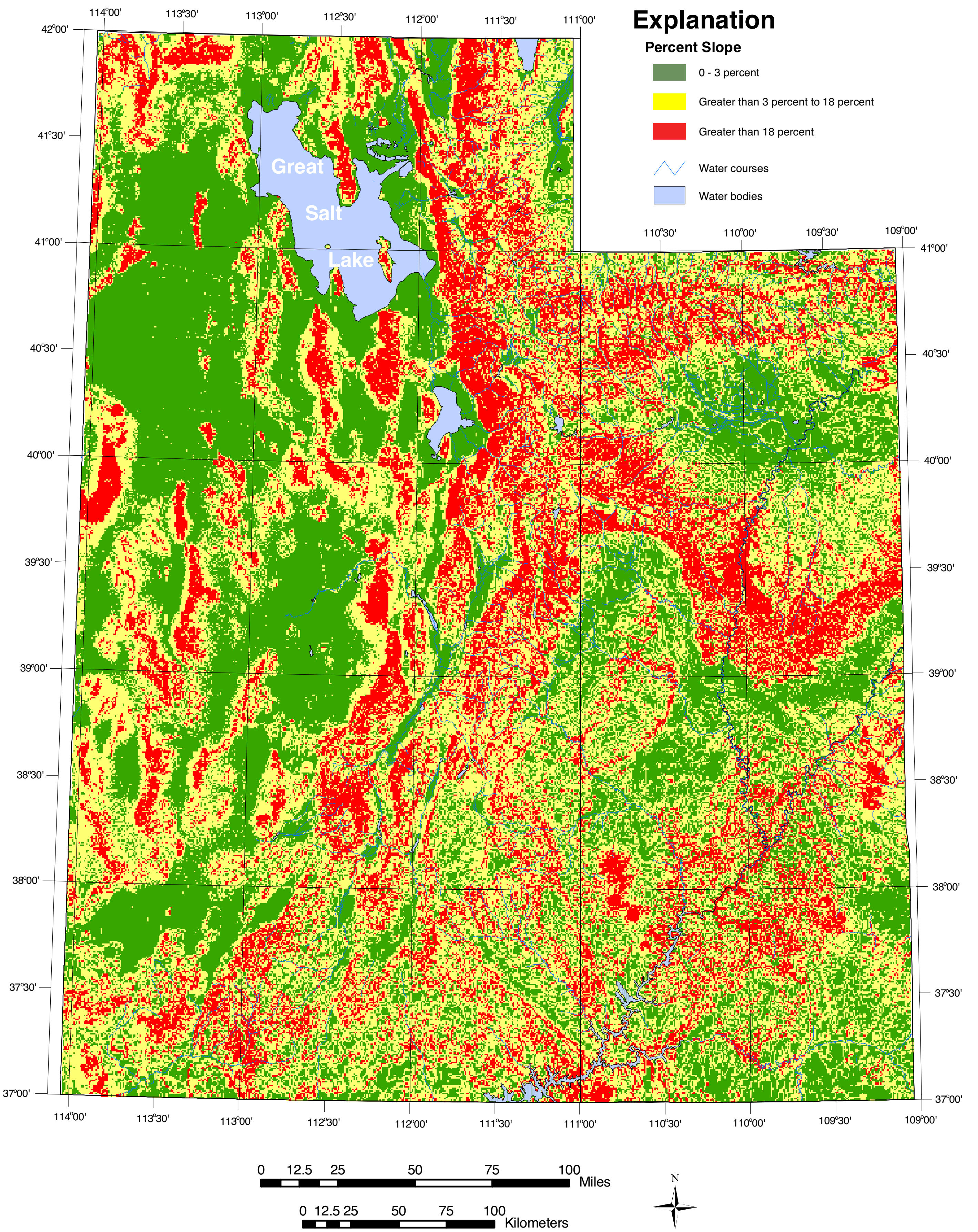



***Figure 12.*** *Land-surface slope in Utah.*

vial and alluvial deposits exist, in areas with eolian deposits, and in areas with gentle slopes underlain by a fractured-rock hydrostratigraphic unit (Jg, appendix A) consisting of the Navajo/Nugget, Kayenta, and Wingate/Moenave Formations (plate 1). Geologic units in these areas have relatively high hydraulic conductivity and lower organic carbon content.

## 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 attribute layers include irrigated cropland and corn- and sorghum-producing areas (figure 13). Using GIS methods as outlined in table 6, these pertinent attribute layers, in turn, were combined with ground-water sensitivity, discussed in the previous sections, to produce a map showing ground-water vulnerability to pesticides (plate 2). 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 previously. Sensitivity represents the sum of natural influences that facilitate the entry of pesticides into ground water. The sensitivity and vulnerability maps are therefore similar (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

Irrigated cropland areas in Utah are shown on figure 13. Irrigation is potentially significant because it is a source of ground-water recharge to aquifers.

### Corn and Sorghum Crops

From the point of view of human impact, areas where corn and sorghum are grown (figure 13) 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 northern and central Utah (figure 13). The effect of areas of corn and sorghum production on vulnerability is to raise vulnerability from low to moderate.

### Vulnerability Map

Plate 2 shows Utah's ground-water vulnerability to pesticides, obtained using GIS methods and ranking techniques described above. Low-sensitivity areas and low-vulnerability areas roughly coincide, but have minor differences. Localities where corn and sorghum are grown appear as rectangle- or circle-like shapes of moderate vulnerability on plate 2 in the central part of valleys where low vulnerability otherwise predominates; such areas are evident in the southern Sevier and Escalante Deserts. Areas of moderate vulnerability coincide, in general, with areas 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 is categorized as having moderate vulnerability if the land is not irrigated or if corn or sorghum are not grown there (see plates 1 and 2).

Areas of high vulnerability are primarily located in primary recharge areas along valley margins along the Wasatch Front where corn/sorghum crops are grown. Of particular concern are areas where streams originating in mountainous areas cross these valley margins. Some of these localities fall within the high-vulnerability range. Other areas of high vulnerability are mapped along streams in the Uinta Basin, and along the San Pitch, Sevier, and Virgin Rivers. Recharge of ground water by such streams is an important means of aquifer recharge. Therefore, efforts to preserve water quality in streams at these points would help to preserve ground-water quality in these parts of Utah.

## CONCLUSIONS AND RECOMMENDATIONS

Areas adjacent to rivers and streams, and areas where these surface-water sources cross coarse-grained alluvial fans or eolian deposits, have the highest potential for ground-water quality degradation associated with the surface application of pesticides, based on the results of our ground-water sensitivity and vulnerability mapping. Because of fine-grained soils, upward ground-water gradients (if not reversed due to pumping wells), and relatively high retardation (long travel times of pesticides in the vadose zone) and attenuation (short half-lives) of pesticides in water in the soil environment, the application of pesticides to crops and fields in the central parts of basins in northwestern Utah likely does not represent a serious threat to ground-water quality. Based on these conclusions, we believe ongoing ground-water sampling in Utah should be concentrated in areas of moderate and high sensitivity or vulnerability, typically along streams and valley margins. Sampling in areas 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 of Cache, Utah, and Pahvant Valleys 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 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.

## ACKNOWLEDGMENTS

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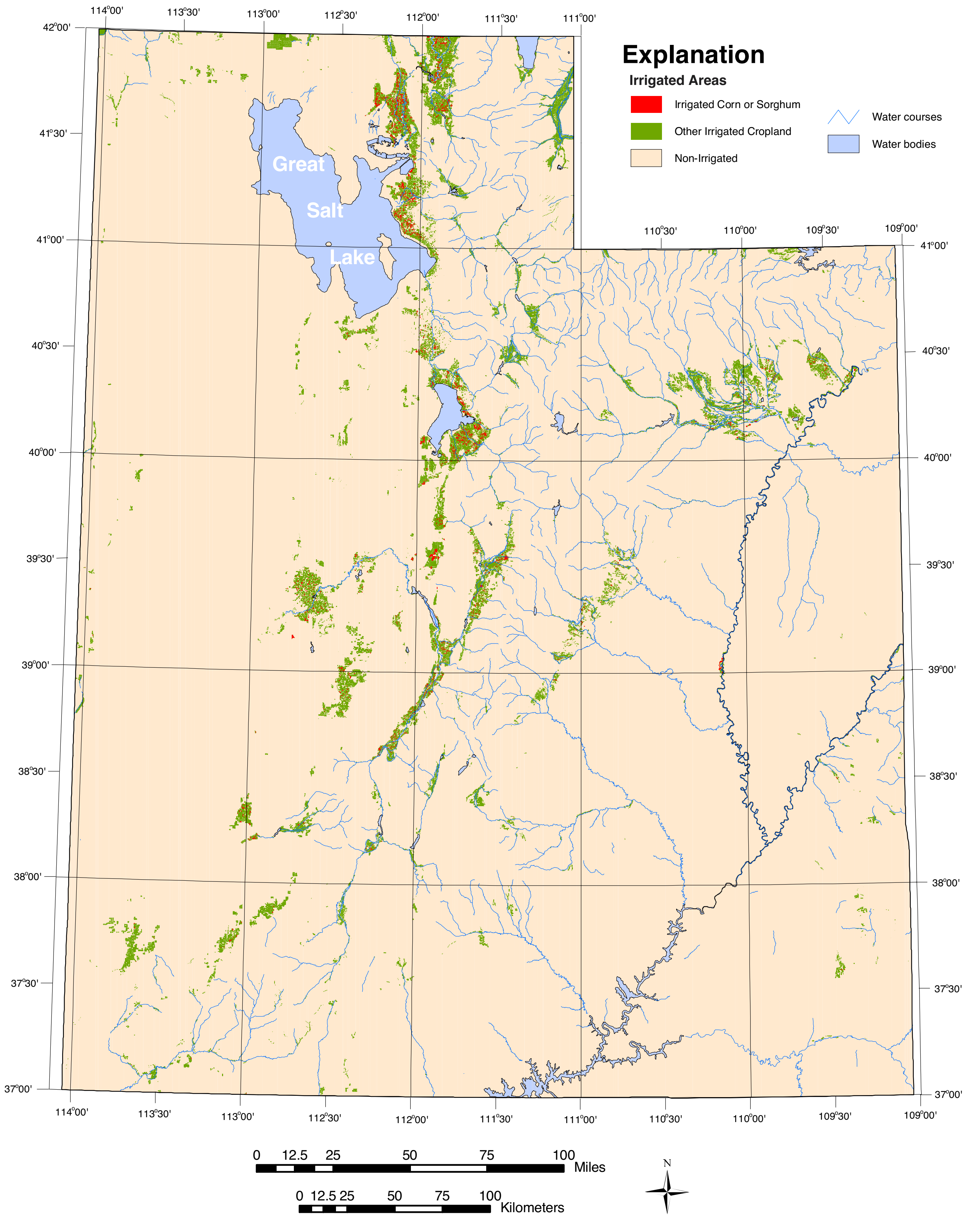



***Figure 13.*** *Irrigated cropland in Utah (data from Utah Division of Water Resources, 1995). The pesticides addressed in this study are mainly applied to corn and sorghum.*

## 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.

Arneson, C.S., Case, J.C., Frederick, K.D., Gloss, S.P., Hamerlinck, J.D., Huntoon, P.W., Munn, L.C., Needham, S., and Wireman, Michael, 1998, Wyoming ground water vulnerability assessment handbook, version 1.0, volume 1, Background, model development, and aquifer sensitivity analysis: Spatial Data and Visualization Center Publication SDVC 98-01-1, variously paginated.

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

Avery, Charles, and others, 1984, Ground-water conditions in Utah, spring of 1984: Utah Division of Water Resources Cooperative Investigations Report No. 24, 79 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.

Bear, Jacob, 1972, Dynamics of fluids in porous media: New York, Dover Publications, Inc., 764 p.

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

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

Eisinger, Chris, and Lowe, Mike, 1999, A summary of the ground-water resources and geohydrology of Grand County, Utah: Utah Geological Survey Circular 99, 28 p.,

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

Gates, J.S., 1985, Ground-water resources – Utah, in National Water Summary 1984: U.S. Geological Survey Water-Supply Paper 2275, p. 415-420.

Greer, D.C., Director, 1981, Atlas of Utah: Provo, Utah, Brigham Young University Press, 300 p.

Hintze, L.F., Willis, G.C., Laes, D.Y., Sprinkel, D.A., and Brown, K.D., 2000, Digital geologic map of Utah: Utah Geological Survey Map 179DM, CD-ROM.

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.

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 Wallace, Janae, 1999, Protecting ground-water quality through aquifer classification – examples from Cache, Ogden, and Tooele Valleys, Utah, *in* Spangler, L.E., and Allen, C.J., editors, Geology of northern Utah and vicinity: Utah Geological Association Publication 27, p. 275-312.

—2001, Evaluation of potential geologic sources of nitrate contamination in ground water, Cedar Valley, Iron County, Utah with emphasis on the Enoch area: Utah Geological Survey Special Study 100, 50 p., scale 1:48,000.

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

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

National Soil Survey, 1994, Soil Geographic (SSURGO) data base: Online, http://www.ftw.nrcs.gov/ssur_data.html, accessed March 5, 2001.

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

Quilter, M.C., 2001, State Ground-Water Program 2000: Salt Lake City, unpublished Utah Department of Agriculture and Food report, 87 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.

Sanderson, I.D., and Lowe, Mike, 2002, Ground-water sensitivity and vulnerability to pesticides, Utah and Goshen Valleys, Utah County, Utah: Utah Geological Survey Miscellaneous Publication 02-10, 26 p., scale 1:150,000.

Sanderson, I.D., Lowe, Mike, Wallace, Janae, and Kneedy, J.L., 2002, Ground-water sensitivity and vulnerability to pesticides, Cache Valley, Cache County, Utah: Utah Geological Survey Miscellaneous Publication 02-8, 28 p., scale 1:100,000.

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

Schlotthauer, W.E., Nance, B.W., and Olds, J.D., 1981, Identification and characteristics of aquifers in Utah: Salt Lake City, Utah Division of Water Rights, 240 p., 4 plates, scale 1:1,000,000.

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

Steiger, J.I., and Lowe, Mike, 1997, Recharge and discharge areas and quality of ground-water in Tooele Valley, Tooele County, Utah: U.S. Geological Survey Water Resources Investigations Report 97-4005, 2 plates, scale 1:100,000.

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

—1986, Geology of Utah: Utah Museum of Natural History Occasional Paper No. 6, 280 p.

Thomas, H.E., and Taylor, G.H., 1946, Geology and ground-water resources of Cedar City and Parowan Valleys, Iron County, Utah: U.S. Geological Survey Water-Supply Paper 993, 210 p.

U.S. Department of Agriculture, National Soil Survey Center, 1995, State Soil Survey Geographic Data Base (STATSGO): scale 1:250,000, CD-ROM.

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

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

Utah Division of Water Resources, 2001, Utah's water resources – planning for the future: Salt Lake City, Utah Division of Water Resources, 72 p.

Waddell, K.M., and Maxell, M.H., 1988, Ground-water quality – Utah, *in* Moody, D.W., Chase, E.B., and Paulson, R.W., compilers, National water summary 1986: U.S. Geological Survey Water-Supply Paper 2325, p. 493-500.

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.

# APPENDIX A.

## Hydrostratigraphic Units and Rankings

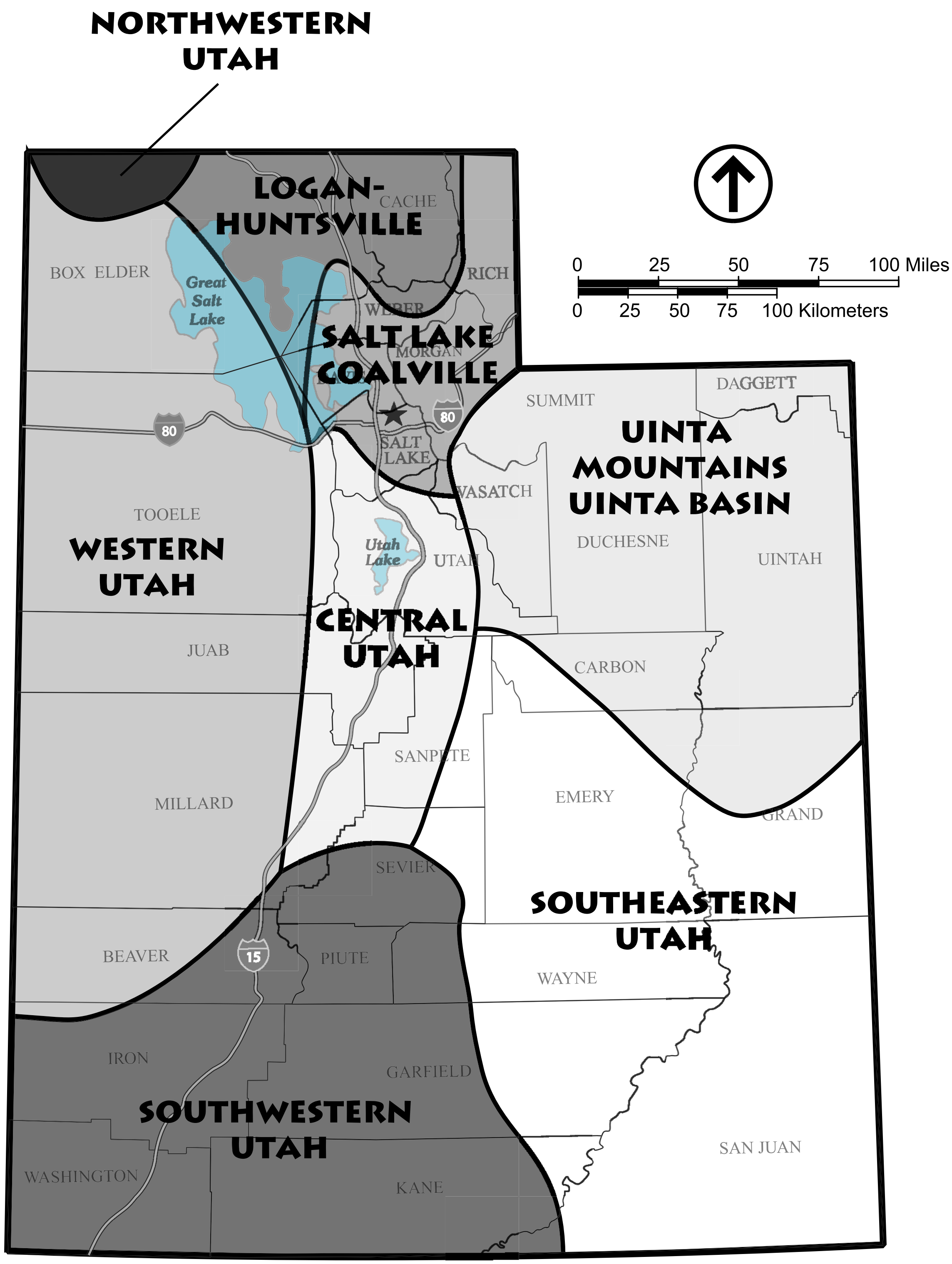



*Figure A-1. Geographic areas for stratigraphic type sections in Utah used for this study (from Hintze and others, 2000).*

***Table A1.*** *Reconnaissance hydrostratigraphic classification of pre-Quaternary geologic units in Utah. Map units from Hintze and others (2000) (see figure 2). Permeability rank based on Schlotthauer and others (1981).*

**Explanation of symbols**

Permeability rank (qualitative): 3 = medium to high, 2 = heterogeneous, 1 = low

Porosity and permeability type(s): Pf = primary framework, Pv = primary volcanic (cooling joints, vesicles, lava tubes), Sfr = secondary fractures, Sd = secondary dissolution

**A. NORTHWESTERN UTAH**

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| Tpb | Basalt | 2 | Pv |
| T4 | Salt Lake Formation(?) and other valley-filling alluvial, lacustrine, and volcanic deposits | 2 | Pf |
| Tmr | Dacitic tuff | 2 | Sfr |
| Ti | Granitic rock | 2 | Sfr |
| PP | Oquirrh Group | 2 | Sfr |
| M3 | Chainman Formation | 1 | Sfr |
| O | Fish Haven Dolomite, Eureka Quartzite, Pogonip Group | 2 | Sfr, Sd |
| C1 | Schist of Mahogany Peaks, Quartzite of Clarks Basin | 2 | Sfr |
| $PC_S$ | Schist of Stevens Spring, Quartzite of Yost, Schist of Upper Narrows, Elba Quartzite | 2 | Sfr |
| PCi, P€m | Adamellite intrusions in Green Creek Complex | 2 | Sfr |

**B. LOGAN-HUNTSVILLE ALLOCHTHON**

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| Tpb | Basalt | 2 | Pv |
| T4 | Salt Lake Formation(?) and other valley-filling alluvial, lacustrine, and volcanic deposits | 2 | Pf |
| Tmr | Rhyolite | 2 | Sfr |
| Tov | Norwood Tuff | 2 | Sfr |
| T1 | Wasatch and Evanston(?) Formations undivided | 2 | Pf, Sfr |
| TR1 | Thaynes Formation | 2 | Sfr |
| P2 | Park City, Phosphoria Formations | 2 | Sfr, Sd |
| PP | Wells Formation | 2 | Sfr |
| P | Round Valley Limestone | 2 | Sfr, Sd |
| M3 | Manning Canyon Shale | 1 | Sfr |
| M2 | Great Blue, Humbug, and Deseret Formations | 2 | Sfr, Sd |
| M1 | Lodgepole Limestone | 2 | Sfr, Sd |
| D | Leatham Formation, Beirdneau Sandstone, Hyrum Dolomite, Water Canyon Formation | 2 | Sfr, Sd |
| S | Laketown Dolomite | 2 | Sfr, Sd |
| O | Fish Haven Dolomite, Swan Peak Quartzite, Garden City Limestone | 2 | Sfr, Sd |
| C3 | St. Charles Formation, Worm Creek Quartzite, Nounan Dolomite | 2 | Sfr, Sd |
| C2 | Bloomington, Blacksmith, Ute, and Langston Formations | 2 | Sfr, Sd |
| C1 | Geertsen Canyon Quartzite | 3 | Sfr |
| $PC_S$ | Browns Hole Formation, Mutual Formation, Inkom Formation, Caddy Canyon Quartzite, Papoose Creek Formation, Kelley Canyon Formation, Maple Canyon Formation, Formation of Perry Canyon including diamictite member | 2 | Sfr |
| PCm | Metaquartzite and schist of Facer Creek | 2 | Sfr |

**C. SALT LAKE CITY-COALVILLE-RANDOLPH**

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| Tpb | Basalt | 2 | Pv |
| T4 | Salt Lake Formation and other valley-filling alluvial, lacustrine, and volcanic deposits | 2 | Pf |
| Ti | Little Cottonwood, Alta, Clayton Peak, and Pine Creek stocks | 2 | Sfr |
| Tov | Keetley Volcanics | 2 | Pf, Sfr |

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| T2 | Fowkes Formation | 2 | Pf, Sfr |
| T1 | Wasatch Formation | 2 | Pf, Sfr |
| TK | Evanston Formation | 2 | Pf, Sfr |
| K3 | Echo Canyon Conglomerate, Henefer Formation | 2 | Pf, Sfr |
| K2 | Frontier Formation, including Upton Sandstone, Judd Shale, Grass Creek, Dry Hollow, Oyster Ridge Sandstone, Allen Hollow Shale, Coalville, Chalk Creek, Spring Canyon, and Longwall Sandstone Members | 2 | Pf, Sfr |
| K1 | Aspen Shale, Kelvin Formation | 2 | Pf, Sfr |
| J2 | Morrison Formation | 1 | Pf, Sfr |
| J1 | Stump Sandstone, Preuss Sandstone, Twin Creek Limestone | 2 | Sfr |
| Jg | Nugget Sandstone | 3 | Pf, Sfr |
| TR2 | Ankareh Shale | 2 | Sfr |
| TR1 | Thaynes Formation, Woodside Shale, Dinwoody Formation | 2 | Sfr |
| P2 | Park City, Phosphoria Formations | 2 | Sfr, Sd |
| PP | Weber Quartzite | 2 | Sfr |
| P | Morgan Formation, Round Valley Limestone | 2 | Sfr |
| M3 | Doughnut Formation | 2 | Sfr |
| M2 | Humbug Formation, Deseret Limestone | 2 | Sfr, Sd |
| M1 | Gardison/Lodgepole Limestone | 2 | Sfr, Sd |
| D | Beirdneau Sandstone, Hyrum Dolomite, Water Canyon Formation | 2 | Sfr, Sd |
| S | Laketown Dolomite | 2 | Sfr, Sd |
| O | Fish Haven Dolomite, Garden City Limestone | 2 | Sfr, Sd |
| C3 | St. Charles Formation, Nounan Dolomite, Bloomington Formation | 2 | Sfr, Sd |
| C2 | Maxfield Limestone, Ophir Formation | 2 | Sfr, Sd |
| C1 | Tintic Quartzite | 2 | Sfr |
| PC$_S$ | Mutual Formation, Mineral Fork Tillite, Big Cottonwood Formation | 2 | Sfr |
| PCm | Farmington Canyon, Little Willow schist and gneiss | 2 | Sfr |

**D. WESTERN UTAH**

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| T5 | Sevier River Formation | 2 | Pf |
| Tpb | Basalt | 2 | Pv |
| T4 | Salt Lake Formation and other valley-filling alluvial, lacustrine, and volcanic deposits | 2 | Pf |
| Tmv | Quichapa Group and other volcanic rocks | 2 | Sf |
| Ti | Granitic intrusions | 2 | Sf |
| Tov | Isom, Needles Range, Escalante Desert, and Sawtooth Peak Formations, and Tunnel Spring Tuff | 2 | Sf |
| T1 | White Sage Formation | 2 | Pf |
| TK | Red conglomerate | 2 | Pf, Sfr |
| Ji | Granitic Rocks | 2 | Sfr |
| J1 | San Rafael Group | 2 | Pf, Sfr |
| Jg | Navajo Sandstone | 3 | Pf, Sfr |
| TR2 | Chinle Formation | 2 | Sfr |
| TR1 | Moenkopi Formation, Thaynes Formation | 2 | Sfr |
| P2 | Gerster Limestone, Plympton Formation, Kaibab Limestone | 2 | Pf, Sfr |
| P1 | Arcturus Formation | 2 | Sfr, Sd |
| PP | Oquirrh Group | 2 | Sfr, Sd |
| P | Ely Limestone | 2 | Sfr, Sd |
| M3 | Chainman Shale | 1 | Sfr |
| M2 | Ochre Mountain Limestone, Woodman Formation | 2 | Sfr, Sd |
| M1 | Joana Limestone | 2 | Sfr, Sd |
| D | Pilot Shale, Guilmette Formation, Simonson Dolomite, Sevy Dolomite | 2 | Sfr, Sd |
| S | Laketown Dolomite | 2 | Sfr, Sd |
| O | Pogonip Group, including Ely Springs Dolomite, Eureka Quartzite, Crystal Peak Dolomite, Watson Ranch Quartzite, Lehman Formation, Kanosh Shale, Juab Limestone, Wah Wah Limestone, Fillmore Limestone, and House Limestone | 2 | Sfr, Sd |
| C3 | Notch Peak Formation, Orr Formation, Lamb/Weeks/Wah Wah Summit Formations | 2 | Sfr, Sd |

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| C2 | Trippe Limestone, Marjum/Pierson Cove Formations, Wheeler Shale, Swasey Limestone, Whirlwind Formation, Dome Formation, Chisholm Formation, Howell Limestone, Pioche Formation | 2 | Sfr, Sd |
| C1 | Prospect Mountain Quartzite | 2 | Sfr |
| PC$_{S}$ | McCoy Creek and Sheeprock Groups | 2 | Sfr |
| PCi, PCm | Granitic intrusions at Granite Peak and metamorphic rocks | 2 | Sfr |

**E. CENTRAL UTAH**

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| T4 | Salt Lake(?) Formation and other valley-filling alluvial, lacustrine, and volcanic deposits | 2 | Pf |
| Tmv | Silver Shield Latite, Pinyon Creek Conglomerate | 2 | Pf, Sfr |
| Ti | Silver City Monzonite, Sunrise Peak Monzonite Porphyry, Swanson Quartz Monzonite | 2 | Sfr |
| Tov | Laguna Springs Latite, Tintic Mountain Group, Packard Quartz Latite, Apex Conglomerate | 2 | Sfr |
| T1 | Flagstaff Limestone | 2 | Sfr, Sd |
| TK | North Horn Formation | 2 | Pf, Sfr |
| K3 | Price River Formation | 2 | Pf, Sfr |
| K2 | Indianola Formation | 3 | Pf, Sfr |
| J2 | Morrison Formation | 2 | Pf, Sfr |
| J1 | Summerville Formation, Entrada Sandstone, Carmel Formation, Arapien Shale | 2 | Pf, Sfr |
| Jg | Navajo/Nugget Sandstone | 3 | Pf, Sfr |
| TR2 | Ankareh Shale | 1 | Sfr |
| TR1 | Thaynes Formation, Woodside Shale | 2 | Pf, Sfr |
| P2 | Park City, Phosphoria Formations | 2 | Sfr, Sd |
| P1 | Diamond Creek Sandstone, Kirkman Limestone | 2 | Pf, Sfr |
| PP | Oquirrh Group, including Bridal Veil Limestone | 2 | Sfr, Sd |
| M3 | Manning Canyon Shale | 1 | Sfr |
| M2 | Great Blue Limestone, Humbug Formation, Deseret Limestone | 2 | Sfr, Sd |
| M1 | Gardison Limestone, Fitchville Formation | 2 | Sfr, Sd |
| D | Pinyon Peak Limestone, Victoria Formation | 2 | Sfr, Sd |
| S | Bluebell Dolomite | 2 | Sfr, Sd |
| O | Fish Haven Dolomite, Opohonga Limestone | 2 | Sfr, Sd |
| C3 | Ajax Dolomite, Opex Formation | 2 | Sfr, Sd |
| C2 | Cole Canyon Dolomite, Bluebird Dolomite, Herkimer Limestone, Dagmar Dolomite, Teutonic Limestone, Ophir Formation | 2 | Sfr, Sd |
| C1 | Tintic Quartzite | 1 | Sfr |
| PC$_{S}$ | Mutual Formation, Inkom Formation, Caddy Canyon Quartzite, Papoose Creek Formation, Blackrock Canyon Limestone, Pocatello Formation | 2 | Sfr |
| PCm | Metamorphic complex of Mt. Nebo | 2 | Sfr |

**F. UINTA MOUNTAINS-UINTA BASIN**

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| T5 | Browns Park Formation | 2 | Pf |
| T4 | Bishop Conglomerate | 2 | Pf |
| T3 | Duchesne River, Uinta, and Bridger Formations | 2 | Pf, Sfr |
| T2 | Green River Formation | 2 | Pf, Sfr, Sd |
| T1 | Wasatch/Colton Formation, Flagstaff Limestone | 2 | Pf, Sd |
| TK | North Horn and Currant Creek Formations | 2 | Sfr, Sd |
| K3 | Mesaverde Group | 2 | Pf, Sfr |
| K2 | Mancos Shale, Frontier Sandstone, Mowry Shale | 2 | Pf, Sfr |
| K1 | Dakota and Cedar Mountain Formations | 2 | Pf, Sfr |
| J2 | Morrison Formation | 2 | Pf, Sfr |
| J1 | Curtis Formation, Entrada Sandstone, Carmel Formation | 2 | Pf, Sfr |
| Jg | Nugget/Navajo Sandstone | 3 | Pf, Sfr |

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| TR2 | Chinle Shale, including Gartra Grit Sandstone Member | 2 | Pf, Sfr |
| TR1 | Moenkopi, Dinwoody Formations | 2 | Pf, Sfr |
| P2 | Park City Formation | 2 | Sfr, Sd |
| PP | Weber Sandstone | 2 | Sfr |
| P | Morgan Formation, Round Valley Limestone | 2 | Sfr, Sd |
| M3 | Doughnut Shale | 1 | Sfr |
| M2 | Humbug Formation | 2 | Sfr, Sd |
| M1 | Madison Limestone | 2 | Sfr, Sd |
| C2 | Maxfield Limestone | 2 | Sfr, Sd |
| C1 | Lodore Sandstone | 2 | Sfr |
| PCs | Uinta Mountain Group | 2 | Sfr |
| PCm | Red Creek Quartzite | 2 | Sfr |

## G. SOUTHEASTERN UTAH

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| T5 | Castle Valley Conglomerate | 2 | Pf |
| Ti | Diorite porphyry intrusions | 2 | Sfr |
| T4 | Bald Knoll and Gray Gulch Formations | 2 | Pf |
| T3 | Crazy Hollow Formation | 2 | Pf |
| T2 | Green River Formation | 2 | Pf, Sfr, Sd |
| T1 | Flagstaff Formation | 2 | Sfr, Sd |
| TK | North Horn and Canaan Peak Formations | 2 | Pf, Sfr |
| K3 | Mesaverde Group, including Price River Formation, Castlegate Sandstone, Blackhawk Formation, and Star Point Sandstone | 2 | Pf, Sfr |
| K2 | Mancos Shale, including Masuk Shake, Emery Sandstone, Blue Gate Shale, Ferron Sandstone, and Tununk Shale Members | 2 | Pf, Sfr |
| K1 | Dakota Sandstone, Cedar Mountain or Burro Canyon Formations | 2 | Pf, Sfr |
| J2 | Morrison Formation, including Brushy Basin and Salt Wash Members | 1 | Pf, Sfr |
| J1 | Bluff Sandstone, Summerville Formation, Curtis Formation, Entrada Sandstone Carmel Formation | 2 | Pf, Sfr |
| Jg | Navajo Sandstone, Kayenta Formation, Wingate Sandstone | 3 | Pf, Sfr |
| TR2 | Chinle Shale, including Shinarump Conglomerate Member | 2 | Sfr |
| TR1 | Moenkopi Limestone | 2 | Pf, Sfr |
| P2 | Kaibab Limestone | 2 | Sfr, Sd |
| P1 | Cutler Group, including White Rim Sandstone, De Chelly Sandstone, Organ Rock Shale, Cedar Mesa Sandstone, Halgaito Formation, and Elephant Canyon Formation | 2 | Sfr, Sd |
| PP | Rico Formation | 2 | Sfr, Sd |
| P | Hermosa Group, including Honaker Trail, Paradox, and Pinkerton Trail Formations | 2 | Sfr, Sd |
| M1 | Molas Formation, Redwall Limestone | 2 | Sfr, Sd |
| D | Ouray Limestone, Elbert Formation, McCracken Sandstone, Aneth Formation | 2 | Sfr, Sd |
| C2 | Muav Limestone, Bright Angel Shale | 2 | Sfr, Sd |
| C1 | Tapeats/Ignacio Quartzite | 2 | Sfr |
| PCm | Schist, gneiss, granite | 2 | Sfr |

## H. SOUTHWESTERN UTAH

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| Tpb | Basalt | 2 | Pv, Sfr |
| T5 | Sevier River Formation | 2 | Pf |
| Tmb | Page Ranch and Rencher Formations, Quichapa Group in Cedar City area; Joe Lott Tuff, Mt. Belknap volcanics, Osiris Tuff, Mt. Dutton Formation in Marysvale area | 2 | Pv, Sfr |
| T4 | Muddy Creek Formation | 2 | Pf |

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| Ti | Quartz monzonite in Cedar City area, monzonite and granite in Marysvale area | 2 | Sfr |
| Tov | Isom, Needles Range Formations in Cedar City area, Bullion Canyon Volcanics in Marysvale area | 2 | Sfr |
| T1 | Claron Formation | 2 | Pf, Sfr, Sd |
| TK | Canaan Peak Formation | 2 | Pf, Sfr |
| K3 | Kaiparowits Formation; Iron Springs Formation in Cedar City area | 2 | Pf, Sfr |
| K2 | Wahweap Sandstone, Straight Cliffs Formation; Iron Springs Formation in Cedar City area | 2 | Pf, Sfr |
| K1 | Tropic Shale, Dakota Sandstone; Iron Springs Formation in Cedar City area | 2 | Pf, Sfr |
| J1 | Entrada and Carmel Formations; Arapien Shale in Marysvale area | 2 | Pf, Sfr |
| Jg | Navajo Sandstone, Kayenta and Moenave Formations | 3 | Pf, Sfr |
| TR2 | Chinle Formation, including Shinarump Conglomerate Member | 2 | Sfr |
| TR1 | Moenkopi Formation | 2 | Pf, Sfr |
| P2 | Kaibab Limestone, Toroweap Formation | 2 | Sfr, Sd |
| P1 | Coconino Sandstone, Supai Group, Pakoon Formation | 2 | Sfr, Sd |
| PP | Callville Limestone | 2 | Sfr, Sd |
| M1 | Redwall Limestone | 2 | Sfr, Sd |
| D | Temple Butte-Muddy Peak Limestone | 2 | Sfr, Sd |
| C2 | Nopah Formation, Bonanza King Formation, Muav Limestone, Pioche Shale | 2 | Sfr |
| C1 | Prospect Mountain Quartzite | 2 | Sfr |
| PCm | Vishnu Schist and granitic intrusions | 2 | Sfr |

***Table A2.*** *Reconnaissance hydrostratigraphic classification of Quaternary geologic units in Utah. Map units from Hintze and others (2000).*

**Explanation of symbols**

Permeability rank (qualitative for predominant sediment type): 3 = medium to high, 2 = heterogeneous, 1 = low
Porosity and permeability type(s): Pf = primary framework

| Map Unit | Constituent Formations | Permeability Rank | Porosity and Permeability Type(s) |
|---|---|---|---|
| Qa | Alluvium and colluvium | 3 | Pf |
| Qao | Older alluvial deposits | 2 | Pf |
| Qe | Eolian deposits | 3 | Pf |
| Qg | Glacial deposits | 2 | Pf |
| Ql | Lake Bonneville deposits | 1 | Pf |
| Qm | Marshes | 1 | Pf |
| Qs | Mud and salt flats | 1 | Pf |
| Qls | Landslides | 2 | Pf |

# APPENDIX B.

## Retardation and Attenuation Sensitivity Analyses

In our analyses described in the text for retardation ($R_F$) and attenuation factors ($A_F$), we addressed a few scenarios representing conditions that exist in Utah soils by inserting parameters in both the $R_F$ and $A_F$ equations for end-member conditions. The sensitivity analyses in this appendix show other values for $R_F$ and $A_F$ generated by adding variables of parameters that also exist in Utah. The variables include ground-water depth (m), average annual ground-water recharge from precipitation (m/yr), soil bulk density (kg/L; from STATSGO data; varies depending on soil type and unique for each soil polygon), soil field capacity ($cm^3$ water/$cm^3$ soil; derived from a soil texture triangle plot representing soils ranging from coarse sand to loam to clay), organic carbon content (from STATSGO data; unique for each soil polygon and ranging from 0.3 to 8.7 percent), organic carbon sorption distribution coefficient (L/kg; varies depending on pesticide), and pesticide half-life (yr; unique for each pesticide). The tables on the following pages represent sensitivity analyses that show some potential scenarios that could occur in Utah soils based on variations in the data input parameters using the following equations:

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

where:

$R_F$ = retardation factor;
$\rho\beta$= bulk density (kg/L);
$F_{oc}$ = organic carbon (fraction);
$K_{oc}$ = organic carbon sorption distribution coefficient (L/kg); and
$\theta_{FC}$ = field capacity (volume fraction).

And

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

where:

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

NV on the following tables indicates "no value" generated by dividing by "0".

***Table B.1.*** *Variations in Retardation Factor with variable bulk density, field capacity, organic carbon content, and organic carbon sorption distribution coefficient.*

| Retardation Factor | Bulk Density kg/L | | | |
|---|---|---|---|---|
| | 2 | | 1.2 | |
| | field | capacity | field | capacity |
| | 0.14 | 0.42 | 0.14 | 0.42 |
| **Koc**=100 | 125 | 1.14 | 75.57 | 1.09 |
| **Koc**=200 | 250 | 1.29 | 150.14 | 1.17 |
| **organic carbon** | 0.087 | 0.0003 | 0.087 | 0.0003 |

| Retardation Factor | Bulk Density kg/L | | | |
|---|---|---|---|---|
| | 1.6 | | 1.4 | |
| | field | capacity | field | capacity |
| | 0.17 | 0.37 | 0.17 | 0.37 |
| **Koc**=100 | 83 | 1.13 | 72.65 | 1.11 |
| **Koc**=200 | 165 | 1.26 | 144.29 | 1.23 |
| **organic carbon** | 0.087 | 0.0003 | 0.087 | 0.0003 |

***Table B.2.*** *Variations in Attenuation Factor with variable water depth, recharge, retardation factor, field capacity, organic carbon content, and bulk density.*

| Depth to Ground Water = 3 Feet (1 m) | | | | |
|---|---|---|---|---|
| **Attenuation Factor** | Bulk Density kg/L | | | |
| | 2 | | 1.2 | |
| Ground-water Recharge (m/yr) | field capacity | | field capacity | |
| | 0.14 | 0.42 | 0.14 | 0.42 |
| 0.00 | NV | NV | NV | NV |
| 0.01 | 0 | 2.29E-58 | 0 | 7.71E-56 |
| 0.05 | 0 | 2.96E-12 | 1.5E-255 | 9.49E-12 |
| 0.10 | 2.1E-211 | 1.72E-06 | 3.8E-128 | 3.08E-06 |
| 0.15 | 3.5E-141 | 0.000144 | 1.14E-85 | 0.000212 |
| 0.20 | 4.6E-106 | 0.001312 | 1.96E-64 | 0.001755 |
| 0.25 | 5.36E-85 | 0.004947 | 1.08E-51 | 0.006244 |
| 0.30 | 5.95E-71 | 0.011985 | 3.37E-43 | 0.014551 |
| 0.35 | 6.41E-61 | 0.022548 | 3.94E-37 | 0.026628 |
| 0.40 | 2.14E-53 | 0.036222 | 1.4E-32 | 0.041896 |
| 0.45 | 1.52E-47 | 0.052371 | 4.84E-29 | 0.059603 |
| 0.50 | 7.32E-43 | 0.070336 | 3.29E-26 | 0.079021 |
| 0.55 | 4.96E-39 | 0.089533 | 6.81E-24 | 0.099528 |
| 0.60 | 7.71E-36 | 0.109475 | 5.81E-22 | 0.120629 |
| 0.65 | 3.87E-33 | 0.129782 | 2.5E-20 | 0.141941 |
| 0.70 | 8.01E-31 | 0.150161 | 6.27E-19 | 0.163182 |
| 0.75 | 8.13E-29 | 0.170394 | 1.03E-17 | 0.184146 |
| 0.80 | 4.63E-27 | 0.190321 | 1.18E-16 | 0.204686 |
| 0.85 | 1.64E-25 | 0.209831 | 1.02E-15 | 0.224705 |
| 0.90 | 3.9E-24 | 0.228846 | 6.96E-15 | 0.244137 |
| 0.95 | 6.66E-23 | 0.247316 | 3.87E-14 | 0.262945 |
| 1.00 | 8.56E-22 | 0.26521 | 1.81E-13 | 0.281107 |
| Rf | 125 | 1.14 | 75.57 | 1.09 |

| Depth to Ground Water = 6 Feet (2m) | | | | |
|---|---|---|---|---|
| **Attenuation Factor** | Bulk Density kg/L | | | |
| | 2 | | 1.2 | |
| Ground-water Recharge (m/yr) | field capacity | | field capacity | |
| | 0.14 | 0.42 | 0.14 | 0.42 |
| 0.00 | NV | NV | NV | NV |
| 0.01 | 0 | 1.2E-172 | 0 | 2.5E-145 |
| 0.05 | 0 | 4.15E-35 | 0 | 1.2E-29 |
| 0.10 | 0 | 6.44E-18 | 1.8E-255 | 3.46E-15 |
| 0.15 | 1.3E-281 | 3.46E-12 | 1.5E-170 | 2.29E-10 |
| 0.20 | 2.1E-211 | 2.54E-09 | 4.3E-128 | 5.88E-08 |
| 0.25 | 2.9E-169 | 1.33E-07 | 1.3E-102 | 1.64E-06 |
| 0.30 | 3.5E-141 | 1.86E-06 | 1.23E-85 | 1.51E-05 |
| 0.35 | 4.1E-121 | 1.23E-05 | 1.66E-73 | 7.38E-05 |
| 0.40 | 4.6E-106 | 5.04E-05 | 2.07E-64 | 0.000243 |
| 0.45 | 2.32E-94 | 0.000151 | 2.47E-57 | 0.000612 |
| 0.50 | 5.36E-85 | 0.000365 | 1.13E-51 | 0.001282 |
| 0.55 | 2.46E-77 | 0.000749 | 4.84E-47 | 0.002348 |
| 0.60 | 5.95E-71 | 0.001364 | 3.5E-43 | 0.003889 |
| 0.65 | 1.5E-65 | 0.002266 | 6.46E-40 | 0.00596 |
| 0.70 | 6.41E-61 | 0.0035 | 4.07E-37 | 0.008593 |
| 0.75 | 6.6E-57 | 0.005103 | 1.09E-34 | 0.0118 |
| 0.80 | 2.14E-53 | 0.007097 | 1.44E-32 | 0.015574 |
| 0.85 | 2.69E-50 | 0.009495 | 1.08E-30 | 0.019894 |
| 0.90 | 1.52E-47 | 0.012299 | 4.97E-29 | 0.024731 |
| 0.95 | 4.44E-45 | 0.015503 | 1.53E-27 | 0.030048 |
| 1.00 | 7.32E-43 | 0.019093 | 3.36E-26 | 0.035803 |
| Rf | 125 | 1.14 | 75.57 | 1.09 |

***Table B.3.*** *Variations in Attenuation Factor with variable ground-water recharge, bulk density, field capacity, organic carbon content, and retardation factor.*

using a low recharge of 0.15 m/yr

| **Attenuation Factor** | Bulk Density kg/L | | | |
|---|---|---|---|---|
| | 2 | | 1.2 | |
| Ground-water depth (meters) | field capacity | | field capacity | |
| | 0.14 | 0.42 | 0.14 | 0.42 |
| 0.0001 | 0.968 | 0.999 | 0.981 | 0.999 |
| 0.0100 | 0.039 | 0.915 | 0.141 | 0.895 |
| 0.0500 | 9.494E-08 | 0.642 | 5.659E-05 | 0.574 |
| 0.1000 | 9.014E-15 | 0.413 | 3.203E-09 | 0.330 |
| 0.1500 | 8.558E-22 | 0.265 | 1.813E-13 | 0.189 |
| 0.2000 | 8.125E-29 | 0.170 | 1.026E-17 | 0.109 |
| 0.2500 | 7.714E-36 | 0.109 | 5.805E-22 | 0.062 |
| 0.3000 | 7.324E-43 | 0.070 | 3.285E-26 | 0.036 |
| 0.3500 | 6.954E-50 | 0.045 | 1.859E-30 | 0.021 |
| 0.4000 | 6.602E-57 | 0.029 | 1.052E-34 | 0.012 |
| 0.5000 | 5.951E-71 | 0.012 | 3.370E-43 | 0.004 |
| 0.6000 | 5.364E-85 | 4.947E-03 | 1.079E-51 | 1.28E-03 |
| 0.7000 | 4.835E-99 | 2.042E-03 | 3.457E-60 | 4.22E-04 |
| 0.7500 | 4.59E-106 | 1.312E-03 | 1.957E-64 | 2.43E-04 |
| 0.9000 | 3.93E-127 | 3.480E-04 | 3.547E-77 | 4.59E-05 |
| 1.0000 | 3.54E-141 | 1.436E-04 | 1.136E-85 | 1.51E-05 |
| 1.2500 | 2.73E-176 | 1.572E-05 | 6.59E-107 | 9.43E-07 |
| 1.5000 | 2.11E-211 | 1.721E-06 | 3.83E-128 | 5.88E-08 |
| 1.7500 | 1.63E-246 | 1.885E-07 | 2.22E-149 | 3.67E-09 |
| 2.0000 | 1.25E-281 | 2.063E-08 | 1.29E-170 | 2.29E-10 |
| 2.1000 | 1.13E-295 | 8.516E-09 | 4.13E-179 | 7.54E-11 |
| 2.5000 | 0.00E+00 | 2.473E-10 | 4.35E-213 | 8.90E-13 |
| Rf | 125 | 1.14 | 75.57 | 1.09 |

using a recharge of 0.55 m/yr

| **Attenuation Factor** | Bulk Density kg/L | | | |
|---|---|---|---|---|
| | 2 | | 1.2 | |
| Ground-water depth (meters) | field capacity | | field capacity | |
| | 0.14 | 0.42 | 0.14 | 0.42 |
| 0.0001 | 0.991 | 1.000 | 0.995 | 1.00 |
| 0.0100 | 0.414 | 0.965 | 0.587 | 0.98 |
| 0.0500 | 0.012 | 0.835 | 0.069 | 0.89 |
| 0.1000 | 1.477E-04 | 0.698 | 0.005 | 0.79 |
| 0.1500 | 1.796E-06 | 0.583 | 3.35E-04 | 0.71 |
| 0.2000 | 2.183E-08 | 0.487 | 2.33E-05 | 0.63 |
| 0.2500 | 2.653E-10 | 0.407 | 1.62E-06 | 0.56 |
| 0.3000 | 3.225E-12 | 0.340 | 1.12E-07 | 0.50 |
| 0.3500 | 3.920E-14 | 0.284 | 7.79E-09 | 0.45 |
| 0.4000 | 4.765E-16 | 0.237 | 5.41E-10 | 0.40 |
| 0.5000 | 7.041E-20 | 0.165 | 2.61E-12 | 0.32 |
| 0.6000 | 1.040E-23 | 0.115 | 1.26E-14 | 0.25 |
| 0.7000 | 1.537E-27 | 0.081 | 6.07E-17 | 0.20 |
| 0.7500 | 1.868E-29 | 0.067 | 4.22E-18 | 0.18 |
| 0.9000 | 3.355E-35 | 0.039 | 1.41E-21 | 0.13 |
| 1.0000 | 4.957E-39 | 0.027 | 6.81E-24 | 0.10 |
| 1.2500 | 1.315E-48 | 0.011 | 1.10E-29 | 0.056 |
| 1.5000 | 3.490E-58 | 4.53E-03 | 1.78E-35 | 0.031 |
| 1.7500 | 9.261E-68 | 1.84E-03 | 2.87E-41 | 0.018 |
| 2.0000 | 2.457E-77 | 7.49E-04 | 4.64E-47 | 0.010 |
| 2.1000 | 3.631E-81 | 5.22E-04 | 2.24E-49 | 0.008 |
| 2.5000 | 1.730E-96 | 1.24E-04 | 1.21E-58 | 0.003 |
| Rf | 125 | 1.14 | 75.57 | 1.09 |

Variables: Ground-water depth
end member bulk density = 2 and 1.2
end member field capacity = 14 and 42%
end member organic content = 0.0003 and 0.087
different recharge amount of low = 0.15 m and high=0.55 m
Rfs from table B.1 in horizontal consecutive order (125, 1.14, 75, and 1.09)

***Table B.4.*** *Variations in Attenuation Factor with variable organic carbon content, ground-water recharge, retardation factor, and pesticide half-life.*

| Depth to Ground Water = 3 Feet (1 m) | | | | |
|---|---|---|---|---|
| **Attenuation Factor** | Maximum Bulk Density = 2.0 | | | |
| | Minimum Retention Capacity = 0.14 | | | |
| Ground-water Recharge (m/yr) | Organic Carbon Content | | | |
| | 0 | 0.001 | 0.01 | 0.087 |
| 0.00 | NV | NV | NV | NV |
| 0.01 | 0.00 | 1.17E-41 | 2.4E-258 | 0 |
| 0.05 | 0.00 | 6.44E-09 | 2.67E-52 | 0 |
| 0.10 | 0.02 | 8.03E-05 | 1.63E-26 | 2.1E-211 |
| 0.15 | 0.08 | 0.002 | 6.44E-18 | 3.5E-141 |
| 0.20 | 0.14 | 0.009 | 1.28E-13 | 4.6E-106 |
| 0.25 | 0.21 | 0.023 | 4.84E-11 | 5.36E-85 |
| 0.30 | 0.27 | 0.043 | 2.54E-09 | 5.95E-71 |
| 0.35 | 0.33 | 0.068 | 4.29E-08 | 6.41E-61 |
| 0.40 | 0.38 | 0.095 | 3.58E-07 | 2.14E-53 |
| 0.45 | 0.42 | 0.123 | 1.86E-06 | 1.52E-47 |
| 0.50 | 0.46 | 0.152 | 6.96E-06 | 7.32E-43 |
| 0.55 | 0.49 | 0.180 | 2.05E-05 | 4.96E-39 |
| 0.60 | 0.52 | 0.208 | 5.04E-05 | 7.71E-36 |
| 0.65 | 0.55 | 0.234 | 0.000108 | 3.87E-33 |
| 0.70 | 0.57 | 0.260 | 0.000207 | 8.01E-31 |
| 0.75 | 0.60 | 0.284 | 0.000365 | 8.13E-29 |
| 0.80 | 0.62 | 0.308 | 0.000598 | 4.63E-27 |
| 0.85 | 0.63 | 0.330 | 0.000925 | 1.64E-25 |
| 0.90 | 0.65 | 0.351 | 0.001364 | 3.9E-24 |
| 0.95 | 0.66 | 0.371 | 0.00193 | 6.66E-23 |
| 1.00 | 0.68 | 0.389 | 0.002638 | 8.56E-22 |
| RF | 1 | 2.43 | 15.3 | 125 |

half-life (year)=0.25

| Depth to Ground Water = 3 Feet (1 m) | | | | |
|---|---|---|---|---|
| **Attenuation Factor** | Maximum Bulk Density = 2.0 | | | |
| | Minimum Retention Capacity = 0.14 | | | |
| Ground-water Recharge (m/yr) | Organic Carbon Content | | | |
| | 0 | 0.001 | 0.01 | 0.087 |
| 0.00 | NV | NV | NV | NV |
| 0.01 | 4.63E-27 | 5.51E-69 | 0.00E+00 | 0 |
| 0.05 | 5.41E-06 | 1.59E-13 | 2.61E-81 | 0 |
| 0.10 | 0.002 | 3.99E-07 | 5.11E-41 | 0 |
| 0.15 | 0.013 | 5.42E-05 | 1.38E-27 | 3.5E-220 |
| 0.20 | 0.048 | 0.000631 | 7.15E-21 | 2.6E-165 |
| 0.25 | 0.048 | 0.000631 | 7.15E-21 | 2.6E-165 |
| 0.30 | 0.132 | 0.007 | 3.71E-14 | 1.9E-110 |
| 0.35 | 0.177 | 0.015 | 3.08E-12 | 8.87E-95 |
| 0.40 | 0.220 | 0.025 | 8.45E-11 | 5.07E-83 |
| 0.45 | 0.260 | 0.038 | 1.11E-09 | 7.06E-74 |
| 0.50 | 0.297 | 0.052 | 8.74E-09 | 1.46E-66 |
| 0.55 | 0.332 | 0.069 | 4.72E-08 | 1.41E-60 |
| 0.60 | 0.364 | 0.086 | 1.93E-07 | 1.37E-55 |
| 0.65 | 0.393 | 0.104 | 6.33E-07 | 2.27E-51 |
| 0.70 | 0.421 | 0.122 | 1.75E-06 | 9.42E-48 |
| 0.75 | 0.421 | 0.122 | 1.75E-06 | 9.42E-48 |
| 0.80 | 0.469 | 0.159 | 9.19E-06 | 7.12E-42 |
| 0.85 | 0.490 | 0.177 | 1.82E-05 | 1.87E-39 |
| 0.90 | 0.510 | 0.195 | 3.34E-05 | 2.66E-37 |
| 0.95 | 0.528 | 0.212 | 5.74E-05 | 2.24E-35 |
| 1.00 | 0.545 | 0.229 | 9.35E-05 | 1.21E-33 |
| RF | 1 | 2.43 | 15.3 | 125 |

half-life (year)=0.16

# APPENDIX C.

## Methods Used to Produce Valley-Specific Maps

## METHODS USED FOR VALLEY-SPECIFIC STUDIES

For the statewide map, we included the results of site-specific valley studies that have been completed in Cache Valley, Cache County (Sanderson and Lowe, 2002), Southern Sevier Desert/Pahvant Valley, Millard County (Lowe and Sanderson, 2003), and Utah and Goshen Valleys, Utah County (Sanderson and others, 2002). Like the statewide study, the valley-specific studies were limited to the use and interpretation of existing data to produce pesticide sensitivity and vulnerability maps through GIS analyses. No new fieldwork was conducted nor data collected as part of these projects. The database used for valley-wide soils came from the same source for soil groups (table 2); we used State Soil Geographic (STATSGO) database ((National Soil Survey Center, 1994) for the statewide map and Soil Survey Geographic (SSURGO) (National Soil Survey Center, 1994) data for the localized valley maps (for net annual recharge and organic soil content). We also incorporated slope information for the statewide map obtained from a digital elevation model (DEM). We superimposed the results of these valley-wide studies on the statewide map as we believe the data representing these areas better reflects hydrogeologic conditions (ground-water flow gradient was considered). We treat hydrogeologic setting different for statewide compared to valley-specific studies; we use published recharge area maps to determine the setting for valley studies compared to a ranking system depending on rock/soil type for the statewide study, (we assign a higher permeability ranking for sediments and a lower permeability ranking for consolidated rocks). The following sections are largely summarized from Sanderson and Lowe (2002), Sanderson and others (2002), and Lowe and Sanderson (2003).

### Ground-Water Sensitivity to Pesticide Pollution

The factors that primarily determine ground-water sensitivity to pesticides in the valley-specific studies include 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. The valley-specific studies used published recharge area maps (which describe the ground-water gradient) as one sensitivity parameter, whereas for the statewide study, we used hydrostratigraphic properties of rock/sediment units (appendix A) to describe relative "permeability".

#### 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). In the valley-specific studies, hydrogeologic setting was assigned 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 (confining layers) and have a downward ground-water gradient (figure C1). Secondary recharge areas, commonly mountain-front benches, have fine-grained layers thicker than 20 feet (6 m) and a downward ground-water gradient (figure C1). Ground-water discharge areas are generally in basin lowlands. Discharge areas for unconfined aquifers occur where the water table intersects the ground surface (figure C1) 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 is discharging to a shallow unconfined aquifer above the upper confining bed, or to a spring (figure C1). 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.

#### Hydraulic Conductivity of Soils

Hydraulic conductivity data are from SSURGO (1994). The percentage of the surface area of the valley-fill aquifers varies; we selected areas having higher hydraulic conductivity where soil units are mapped as having hydraulic conductivity greater than or equal to 2 inches per minute (5 cm/min).

#### Pesticide Retardation And Attenuation

Retardation and attenuation are treated in the valley-specific studies the same as in this study, except the soil data are from the SSURGO database, which provides digitized data for some soil areas of Utah at a scale of 1:24,000, and different parameter values were applied (table C1). Organic carbon content was computed by averaging the carbon content in the SSURGO database for each type of soil polygon. For the statewide map, we used the unique value, not an average, of the organic content to more accurately reflect the organic percentage of soils, instead of assigning an organic content grouped for the particular soil category (for example, A, B, C, or D).

### Depth to Ground Water

The valley-specific studies treated depth to ground water the same as in this study, except the soil data are from the SSURGO database (National Soil Survey Center, 1994).

### GIS Analysis Methods

Sanderson and Lowe (2002), Sanderson and others (2002), and Lowe and Sanderson (2003) divided pesticide sensitivity into "low," "moderate," and "high" categories for the valley-specific studies 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 C2. Numerical ranking for each attribute category is arbitrary, but reflects the level of importance the authors believe the attribute plays in determining sensitivity of areas to application of agricultural pesticides; for instance, they 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. We employed all of these parameters in the statewide study, except for the slope parameter.

## Ground-Water Vulnerability to Pesticide Pollution

The valley-specific studies evaluate ground-water vulnerability to pesticides using the same methods applied in this study.

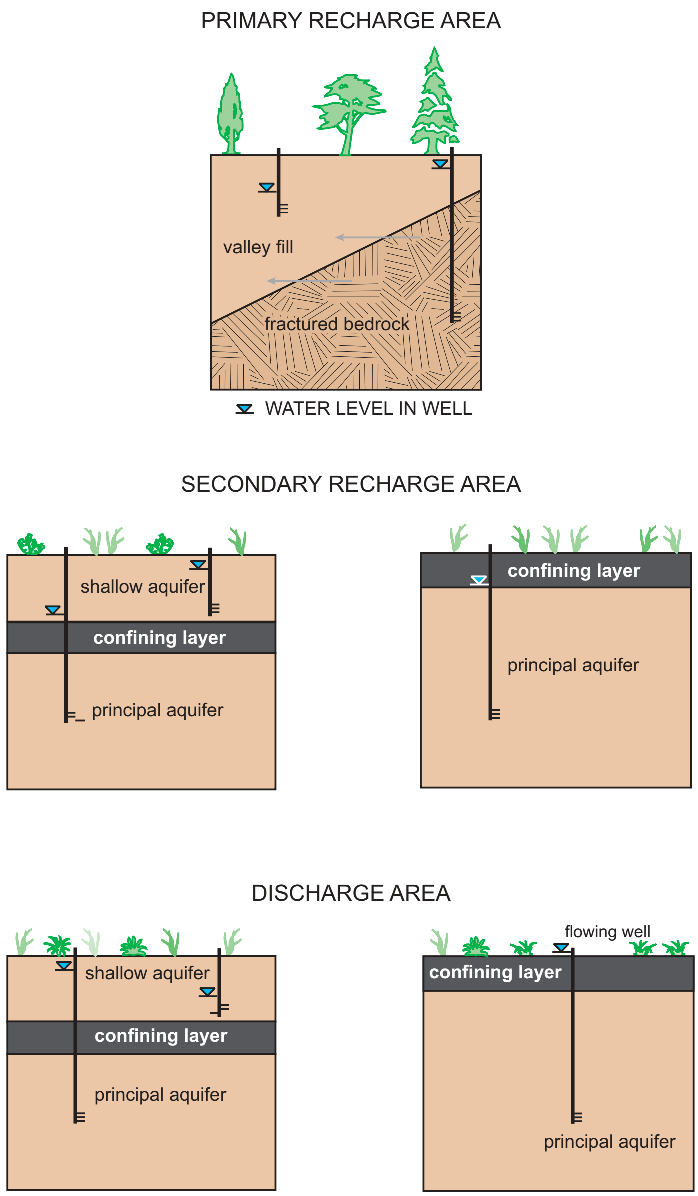



***Figure C.1.*** *Relative water levels in wells in recharge and discharge areas (Snyder and Lowe, 1998).*

***Table C.1.*** *Hydrologic Soil Groups and rankings for retention capacity, bulk density of soils, and fraction of organic content generalized for some 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 Descriptions | Grain size (mm) (Field Capacity) | Bulk Density Range (kg/L) | Organic 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<br>(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<br>(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<br>(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<br>(6-15%) | 1.12 | 3.35% |

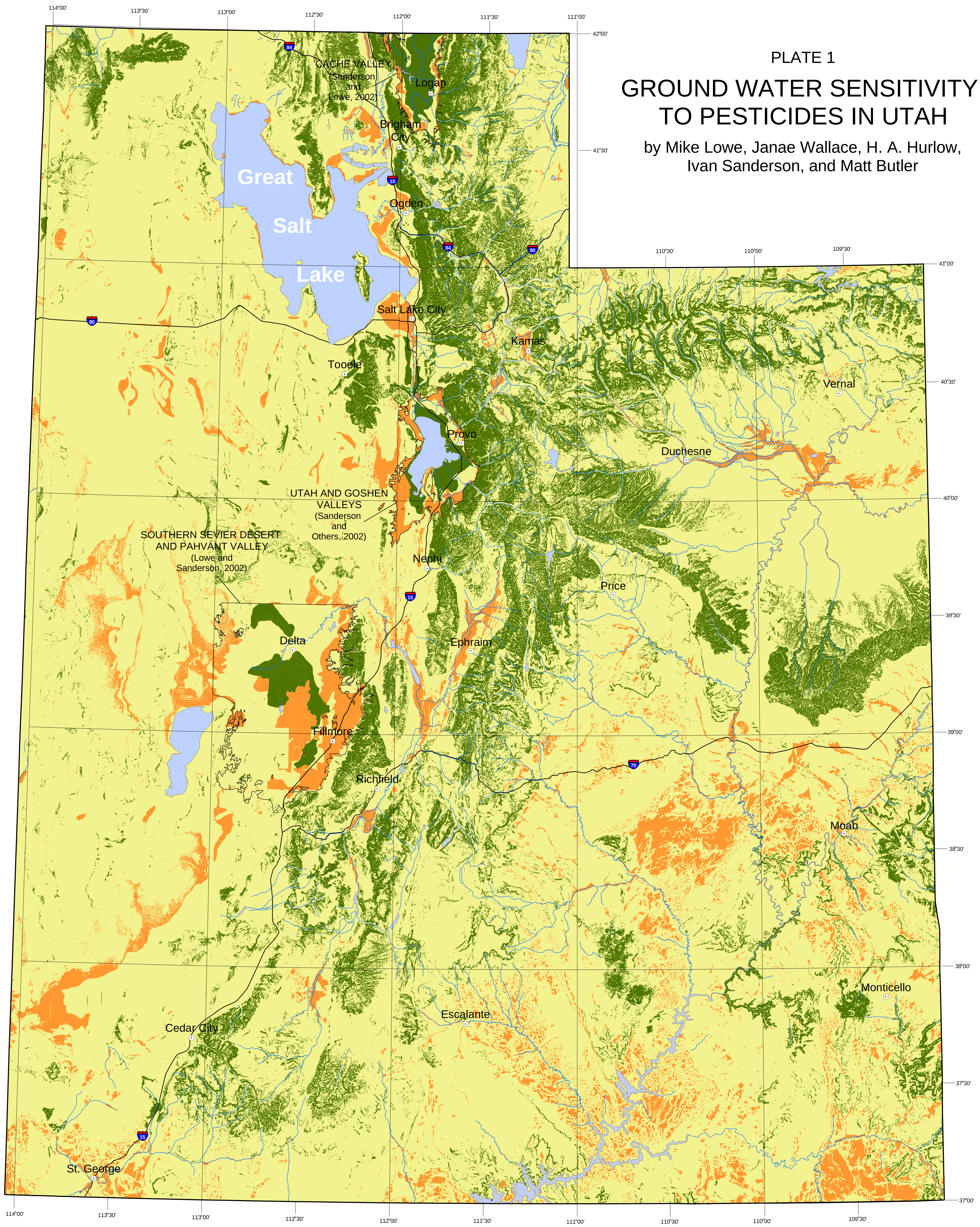
***Table C.2.*** *Pesticide sensitivity and the attribute rankings used to assign it for the valley-specific reports (from Sanderson and Lowe, 2002; Sanderson and others, 2002; and Lowe and Sanderson, 2003).*

<table>
<tr><th colspan="2">Pesticide Retardation</th><th colspan="2">Pesticide Attenuation</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="2">High</td><td rowspan="2">0</td><td rowspan="2">High</td><td rowspan="2">0</td><td>Discharge Area</td><td>-4</td><td rowspan="2">Less than 1 inch/hour</td><td rowspan="2">1</td><td rowspan="2">Greater than 3 feet</td><td rowspan="2">1</td><td>Low</td><td>-2 to 0</td></tr>
<tr><td rowspan="2">Secondary Recharge Area</td><td rowspan="2">-1</td><td rowspan="2">Moderate</td><td rowspan="2">1 to 4</td></tr>
<tr><td rowspan="2">Low</td><td rowspan="2">1</td><td rowspan="2">Low</td><td rowspan="2">1</td><td rowspan="2">Greater than 1 inch/hour</td><td rowspan="2">2</td><td rowspan="2">Less than 3 feet</td><td rowspan="2">2</td></tr>
<tr><td>Primary Recharge Area</td><td>2</td><td>High</td><td>5 to 8</td></tr>
</table>

PLATE 1

# GROUND WATER SENSITIVITY TO PESTICIDES IN UTAH

by Mike Lowe, Janae Wallace, H. A. Hurlow, Ivan Sanderson, and Matt Butler




## Explanation

- Low sensitivity
- Moderate sensitivity
- High sensitivity
- Cities
- Roads
- Water courses
- Water bodies
- Boundary of valley-specific study (see Appendix C)

N

Scale 1:750,000

0 12.5 25 50 75 100 Miles

0 12.5 25 50 75 100 Kilometers

UTAH GEOLOGICAL SURVEY

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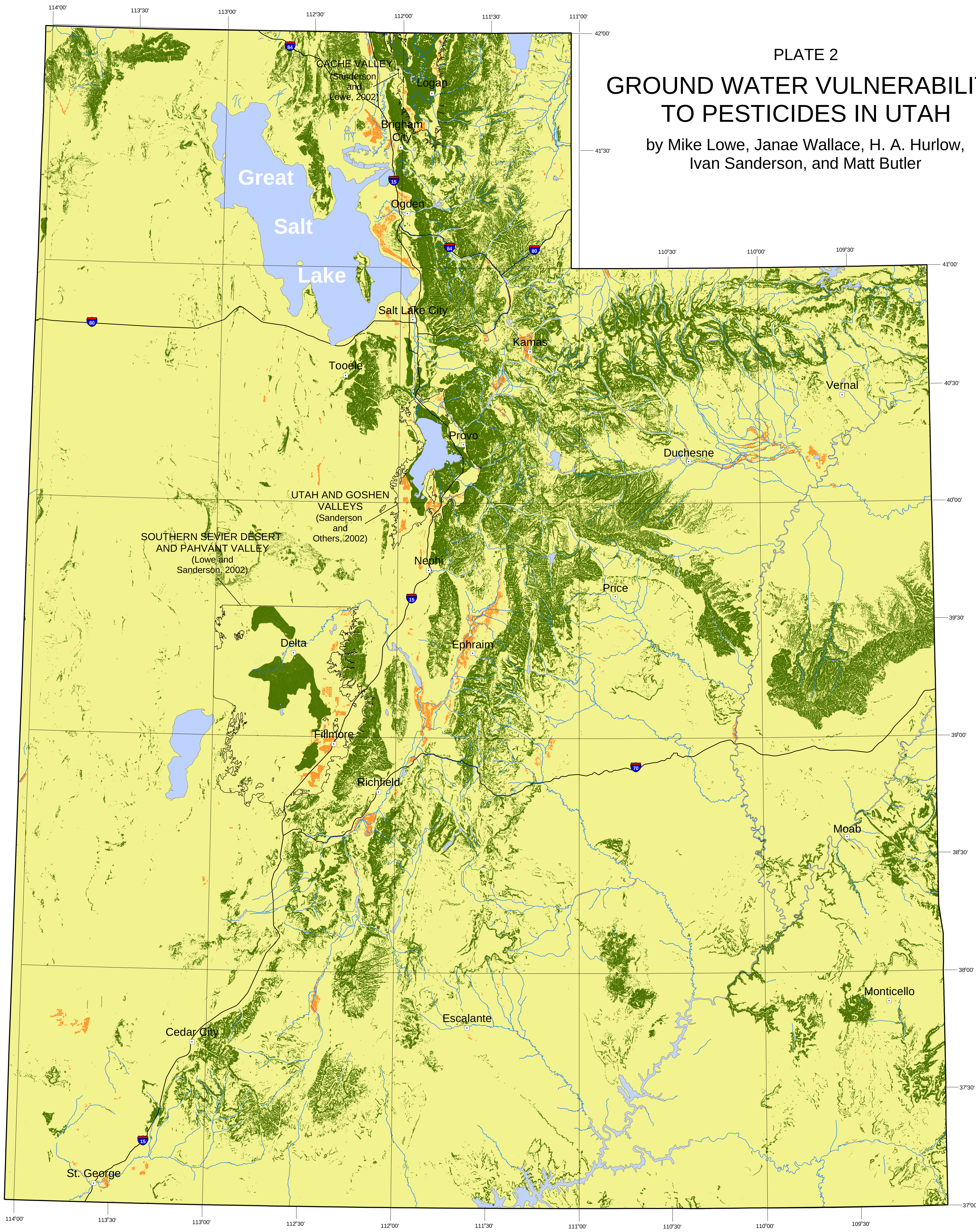
PLATE 2

# GROUND WATER VULNERABILITY TO PESTICIDES IN UTAH

by Mike Lowe, Janae Wallace, H. A. Hurlow, Ivan Sanderson, and Matt Butler




## Explanation

- Low vulnerability
- Moderate vulnerability
- High vulnerability
- Cities
- Roads
- Water courses
- Water bodies
- Boundary of valley-specific study (see Appendix C)

N

Scale 1:750,000

0 12.5 25 50 75 100 Miles

0 12.5 25 50 75 100 Kilometers

UTAH GEOLOGICAL SURVEY

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