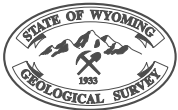


Wyoming Ground Water Vulnerability Assessment Handbook



*Volume 1:
Background,
Model Development,
and Aquifer Sensitivity
Analysis*

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CHAPTER I: INTRODUCTION

This chapter serves as an outline and guide to using this manual. Look here for the reasons for the Wyoming Ground Water Vulnerability Mapping Project's inception, what this handbook's volumes include, and what to find in each of them.

WYOMING'S GROUND WATER PROTECTION NEEDS

Ground water is one of this nation's most precious and potentially most vulnerable resources. Fifty percent of the public water supplies in the United States depend on ground water as a source of drinking water (USGS 1990). Given the extremely high cost of remediating ground water contamination and the value of ground water to society, it is clear that protecting ground water quality makes far more sense than trying to clean it up. For example, currently in the United States, between 300,000 and 400,000 sites contain contaminated soil and/or ground water. Estimates for clean up at these sites range from \$250 billion to \$1 trillion in 1993 dollars spent over the next 20 to 30 years (NRC 1994). Thus, protecting ground water is the resource manager's most viable management option given the financial and technical challenges involved in cleaning up contaminated ground water. This

Two terms are key to this project

In everyday conversation, people often confuse the terms "vulnerability" and "sensitivity." But one of the keys to understanding this project lies in being able to distinguish between "ground water vulnerability" and "aquifer sensitivity."

Aquifer sensitivity is defined here as the relative ease with which contaminants can move from the surface through various substrates to pollute ground water. The term hinges entirely on the geology that lies between the surface and the aquifer and of the aquifer itself.

Ground-water vulnerability incorporates aquifer sensitivity and the potential for a contaminant to be spilled on the surface. In other words, ground-water vulnerability hinges on the activities of people on the surface that could contaminate ground water.

The Wyoming model (explained in Chapter IV) is essentially a two-step process, in which aquifer sensitivity is first assessed as a function of geology, depth to water, soils, and recharge. Sensitivity is then combined with ratings of land use practices and pesticide use to determine relative ground water vulnerability to pesticides across the state.

realization has led to a variety of protection strategies and management policies in various stages of development around the United States. Many have been implemented under guidelines set forth by recent amendments to major federal legislation such as the Clean Water Act and Safe Drinking Water Act (Danielson and Patte 1991; Arneson, Gloss, and Hamerlinck 1997). Central to such efforts is the concept of assessing the relative sensitivity and vulnerability of ground water to pollution to prioritize which areas suggest the most immediate attention to prevent contamination.

The threat of ground water contamination is a significant concern of Wyoming citizens, as well as county, state, and federal government officials. In general, the public is aware that using, storing, and disposing of certain industrial and agricultural chemicals, petroleum products, and waste potentially puts ground water resources at risk. Local, state, and federal entities have begun addressing the public's concerns for preserving the quality of ground water in Wyoming. The State of Wyoming, in meeting its obligations under the 1987 amendments to the Clean Water Act, recently completed a statewide management plan (SMP) for pesticides (GPSC 1997). Fundamental to the development of the SMP was the assumption that current contamination of ground water from pesticide use in the state was minimal, if not altogether absent, as determined from historic ground water monitoring information. The SMP thus focuses on protection of ground water resources through prevention mechanisms to maintain ground-water quality for its existing and future beneficial use (GPSC 1997).

The Wyoming Ground Water Vulnerability Mapping Project was undertaken in order to provide the public ground water management agencies with a better understanding of the state's ground water resources and the vulnerability of important aquifers to contamination. Relative to implementation of the SMP, the project and resulting map delineations address the requirement that the SMP for pesticides include a means to identify geographic areas where ground water is susceptible (i.e., vulnerable) to effects from pesticides applied at or near the surface. Identification of these vulnerable areas will also assist state agencies and their local partners in identifying and prioritizing areas

for ground water monitoring and will help to minimize the potential for over-protection in areas of low ground water vulnerability or conversely, under-protection of highly vulnerable ground water.

The project was initiated in 1992 by the Wyoming Department of Environmental Quality's Water Quality Division (WDEQ/WQD), in cooperation with the University of Wyoming's Wyoming Water Resources Center (WWRC), the Wyoming State Geological Survey (WSGS), the Wyoming Department of Agriculture (WDA), and the U.S. Environmental Protection Agency, Region VIII (EPA).

With guidance from WDEQ and EPA, the project team approached the ground water sensitivity/vulnerability assessment project in a multi-disciplinary fashion, being careful to account for the complex nature of Wyoming's ground-water systems and the physical and chemical processes involved in contaminant transport and distribution. Led by the WWRC, significant contributors have included the Hazards Section of the WSGS and the University of Wyoming's Departments of Civil and Architectural Engineering, Geography and Recreation, Geology and Geophysics, Plant, Soil, and Insect Science (now Renewable Resources), and Statistics. In July 1998, the Spatial Data and Visualization Center (SDVC) at the University of Wyoming assumed lead responsibility for ongoing project activities. The names and affiliations of past and current project team members are listed in Appendix A.

GOALS AND OBJECTIVES OF THE GROUND WATER VULNERABILITY MAPPING PROJECT

The initial purpose of the Wyoming Ground Water Vulnerability Mapping Project was to develop a digital mapping product to comprehensively assess the relative sensitivity and vulnerability of the state's ground water resources to potential contamination. The ultimate goal of the project was to deliver a dynamic, geographic information system (GIS)-based tool to aid in planning, decision-making, and public education relative to the management of ground water resources and maintenance of ground water quality in Wyoming. Specific objectives addressed included:



Figure I-1 : Wyoming index map

- Completion of a pilot aquifer sensitivity/ground water vulnerability assessment effort for Goshen County in southeastern Wyoming. This included determination of model input parameters, data needs assessment, data acquisition, automation and/or manipulation, GIS-based analysis, and digital cartographic production;
- Application and refinement of pilot study methodologies in development of a statewide sensitivity/vulnerability mapping model;
- Data needs assessment and associated data acquisition for entire state;
- Mapping prioritization for agricultural and non-agricultural areas in each county;
 - Digital sensitivity/vulnerability analysis and map product generation on a prioritized, county-by-county basis for the entire state of Wyoming; and
 - Development of public education workshop materials and resource management application exercises associated with use of the sensitivity/vulnerability GIS data layers and desktop GIS tools.

Several related ground water resource management agency goals have also been addressed over the lifetime of the project. These include increased GIS technology utilization in water resource management applications (including, but not limited to, digital data layer develop-

ment), and secondary, management uses for the digital mapping products.

PROJECT SCOPE AND TIMELINE

To date, the Wyoming Ground Water Vulnerability Mapping Project, in addressing the goals and objectives outlined above, has progressed through three major phases. Phase one consisted of a pilot study mapping effort in Goshen County at a 1:100,000-scale level. Phase two included mapping the entire state at a 1:500,000-scale level. Phase Three was designed to map aquifer sensitivity and ground water vulnerability to pesticides in individual counties at a 1:100,000-scale level.

Phase One: Pilot Study - Goshen County

Ground water vulnerability assessment in Wyoming was initially carried out as a 1:100,000-scale pilot study in Goshen County in the southeastern portion of the state. The objective in the pilot study approach was to develop and refine an assessment/mapping methodology that could then be applied across the state. Goshen County was chosen partly because of the relative intensity of pesticide use and knowledge of vulnerable conditions as demonstrated by nitrate ground water contamination problems in the Torrington area (Parks 1991). Given the local importance of ground water for municipal and private drinking water supply and irrigation, the region had also been the subject of numerous research studies which provided a critical foundation of tabular and mapped information related to local ground water resources.

The Goshen County pilot study contributed to the statewide assessment efforts in a number of ways. Specifically, the pilot study assisted in:

- refining required model input parameters;
- identifying available data sources and needs;
- determining cost-effective procedures for generating data;
- estimating the cost of compiling the necessary information to carry out statewide sensitivity/vulnerability mapping;
- determining appropriate methods for generating final sensitivity/vulnerability maps including GIS-based spatial data manipulation procedures; and

- developing a Wyoming-specific procedure to assign ratings to individual data layers describing aquifer sensitivity.

Phase Two: Small-Scale Statewide Analysis

Completion of the Phase One pilot study resulted in a standard assessment methodology for application in the remainder of the state. However, due to funding constraints, complete county-by-county assessment at a 1:100,000-scale level was not feasible. To address this issue, the project team elected to initially assess aquifer sensitivity for the entire state at a less detailed 1:500,000-scale level, and follow it with more detailed, prioritized 1:100,000-scale assessment of individual counties under a phased-in funding approach. The 1:500,000-scale assessment included all of Wyoming with the exception of Yellowstone National Park, where availability of required data were

Table I-1: County rankings and indices

<i>Rank</i>	<i>County</i>	<i>Index</i>	<i>Rank</i>	<i>County</i>	<i>Index</i>
1	Washakie	590.45	13	Natrona	14.27
2	Park	200.17	14	Teton	*4.58
3	Goshen	176.37	15	Sweetwater	*7.74
4	Fremont	146.11	16	Uinta	22.53
5	Lincoln	74.31	17	Albany	21.17
6	Laramie	63.47	18	Converse	19.31
7	Big Horn	62.34	19	Hot Springs	16.46
8	Sheridan	58.44	20	Carbon	15.07
9	Platte	47.23	21	Campbell	12.43
10	Johnson	31.75	22	Sublette	9.26
11	Crook	28.36	23	Niobrara	3.39
12	Weston	*12.84			

* Weston, Natrona, Teton, and Sweetwater were elevated in ranking by WDEQ/WQD based upon knowledge of the existence of pesticides in ground water.

very limited. The resulting statewide sensitivity map served the dual purpose of providing a regional assessment of areas where detailed assessment was not initially possible and to help determine an appropriate categorization of sensitivity rating values that could be utilized consistently for all counties in the state.

Phase Three: Intermediate-Scale Analysis by County

The third phase of the project included assessment of each county in the state at a 1:100,000-scale. The resultant maps include additional detail with all analyses conducted using a lattice resolution of 100 meters, compared to the 500-meter resolution cells used for the 1:500,000-scale statewide analysis.

Counties were prioritized for mapping based on land use, data availability, and potential aquifer sensitivity (Appendix B). The county prioritization results are shown in Table I-1 on the previous page.

ONGOING MAPPING ACTIVITIES

Additional ground water vulnerability mapping activities are either currently underway or are planned. These include assessing vulnerability of ground water to contamination from shallow, Class V Underground Injection Control (UIC) Program wells as defined by EPA (UICP 1990). Also, a validation study is underway to examine the relationship between the final sensitivity and vulnerability maps produced by this project and actual ground water sampling data (Arneson 1999). Future work on ground water vulnerability to other potential contaminant sources is anticipated.

HOW THIS HANDBOOK IS ORGANIZED

Volume I of the handbook, entitled *Background, Model Development, and Sensitivity Assessment*, outlines the purpose of the mapping project, model background, data development, sensitivity results, and appropriate uses of the results and products. This volume includes 23 appendices detailing the individual aquifer sensitivity results and maps for each Wyoming county.

Volume II, entitled *Assessing Ground Water Vulnerability to Pesticides*,

focuses on pesticide application as a potential contaminant source. This volume and the additional 23 county appendices associated with it provide additional data development, vulnerability results, appropriate uses, and map results.

Volume III will assess ground water vulnerability to shallow UIC injection wells. Additional volumes will be added to the handbook as other sources of ground water contamination are addressed.

References

- Arneson, C.S. 1999. Correlation Between a Modified DRASTIC Ground Water Vulnerability Model and Agricultural Contaminant Occurrences in Monitoring Wells in Wyoming. M.A. Thesis, University of Wyoming.
- Arneson, C.S., Hamerlinck, J.D., and S.P. Gloss. 1997. "Groundwater Protection Issues." *Proceedings of the Wyoming Water Law Conference* November 20-21, 1997. Cheyenne, Wyo.: CLE International.
- Danielson, LE., and D.E.M. Patte. 1991. "Federal Policies and Programs to Protect Groundwater Quality," *Groundwater and Public Policy Series: Issue 12*. Groundwater Policy Education Project.
- Ground Water and Pesticides Strategy Committee (GPSC). 1997. "Generic State Management Plan for Pesticides in Ground Water for the State of Wyoming" (Draft). Cheyenne, Wyo.
- National Research Council (NRC). 1994. *Alternatives for Ground Water Cleanup*. Washington, D.C.: National Academy Press.
- Parks, G.D. 1991. *Numerical simulation of groundwater flow and contaminant transport in an alluvial aquifer*. M.S. Thesis, University of Wyoming.
- U.S. Geological Survey (USGS). 1990. *National Water Summary 1987: Hydrologic Events and Water Supply and Use*. U.S. Geological Survey Water-Supply Paper 2350.
- Underground Injection Practices Council (UIPC). 1990. *An Introduction to the Underground Injection Control Program*. Oklahoma City, Okla. Underground Injection Practices Council.

CHAPTER II: WYOMING'S GROUND WATER RESOURCES

Aquifer sensitivity ratings mean little without an understanding of the hydrogeologic setting in which they occur. This chapter briefly summarizes the geology and hydrology of the major aquifers and aquifer systems in Wyoming, as well as how ground water obtained from these sources is used. The narrative was adopted from two primary sources—Anctil (1994) and Wireman, Anctil and Frederick (1994). A more in-depth overview of the state's ground water resources may be found in Whitehead (1996). For a detailed description of the influence of Wyoming's geohydrologic environment on development of the Wyoming ground water vulnerability mapping methodology, please refer to Chapter IV of this volume.

GEOLOGY AND HYDROGEOLOGY

Five ground water regions occur within Wyoming: the western mountain ranges, the Wyoming basins, the High Plains, the nonglaciaded central, and alluvial valley regions (Figure II-1). The nature and extent of the primary aquifers and their hydrologic relationship to other parts of the ground water flow system(s) are the main criteria for delineating ground water regions. Ground water regions

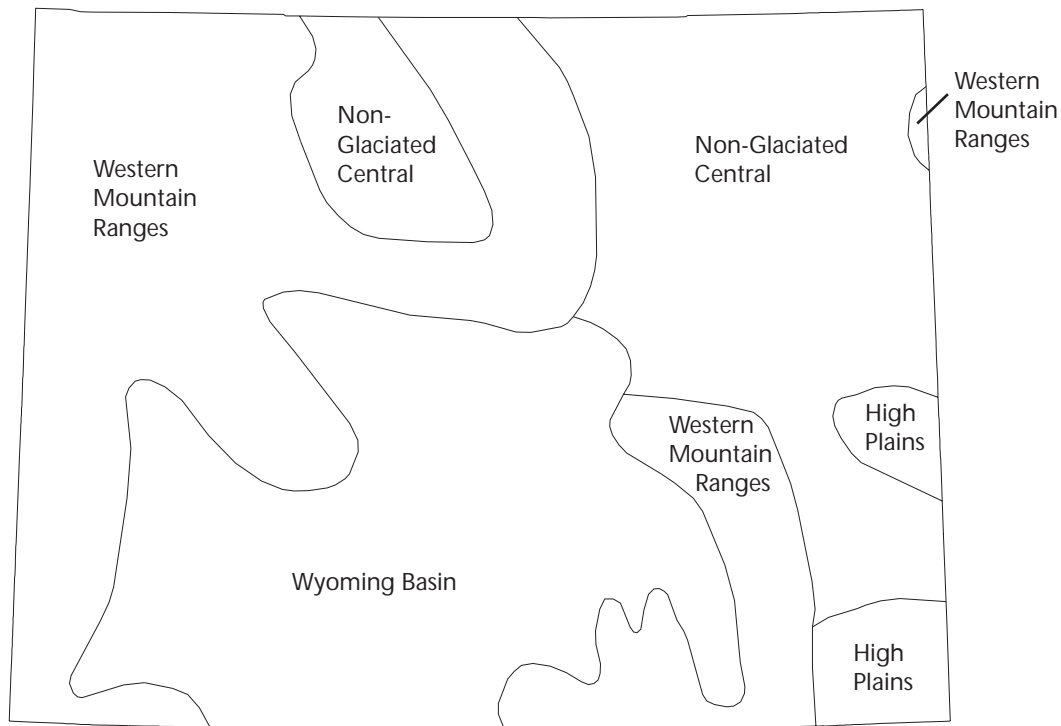


Figure II-1: Ground water regions of Wyoming

So... What's an aquifer?

An aquifer is a geologic formation that contains sufficient saturated, permeable material to yield significant quantities of water to wells or springs. An aquifer system is a combination of materials of varying permeabilities that function regionally as a water-yielding unit. Known as stacked or serial aquifers, these materials have similar hydraulic and geologic properties and are hydraulically connected. Water-bearing formations within the system are of reasonably large areal extent, and are sealed from each other by regionally extensive impermeable layers. The rocks forming these layers include formations defined as confining layers. An aquitard is a type of confining layer which slows but does not prevent the flow of water to or from an adjacent aquifer.

are also related to physiographic regions because the occurrence and availability of ground water depend on composition, arrangement, and structure of rock units. Within each region, the occurrence and availability of ground water is similar with respect to the nature of the porosity of the primary aquifer(s), the solubility characteristics of the rock matrix of the primary aquifer(s), the hydraulic characteristics of the primary

aquifer(s), and the nature and location of recharge and discharge areas (Heath 1982; 1984).

More than 100 aquifers and aquifer systems have been identified in the state, but many are limited in extent and yield only small amounts of water to wells. For this discussion, the geologic units in the state are divided into four principal aquifer systems: unconsolidated alluvial deposits, principally found along or adjacent to major drainages; semi-consolidated to locally consolidated sedimentary rocks in the High Plains (i.e., Tertiary) aquifer system; consolidated sedimentary rocks (including carbonates) found within or flanking eight different structural basins, including the Overthrust Belt of western Wyoming; and the crystalline and metamorphic rocks forming the core of the state's mountain uplifts. Principal recharge of deeper aquifers is from basin margin outcrop areas, whereas more shallow aquifers receive recharge from infiltration into outcrops, and vertical leakage between adjacent water-bearing units.

Ground water occurs in unconfined aquifers, confined aquifers, and fracture-flow aquifers, all of which have differing characteristics and requirements for evaluation, management, and development.

Within Wyoming, unconfined aquifers consist of flood plain (alluvial) and terrace deposits of Quaternary age. Locally, glacial outwash deposits can also represent important, unconfined, water-bearing units. Some sedimentary bedrock deposits (such as the Ogallala Formation) can be several hundreds of feet deep but may still be considered unconfined. Generally, unconfined aquifers are relatively shallow units that are composed of sand, silt, and gravel lying on a bedrock surface of variable topographic expression. These are typically the most sensitive of all aquifers because ground water is usually shallow and the aquifer materials are highly permeable. Confined aquifers occur within bedrock formations of relatively high permeability, such as sandstone, and are bound by less permeable strata such as shale. Because the water in confined aquifers is under pressure greater than that of the atmosphere, water levels often rise above the top of the aquifer, potentially creating a free-flowing artesian system when intercepted by a well or spring. Ground water from a confined aquifer may discharge as a spring or from a flowing well. These aquifers are often less vulnerable to human activities because they are protected to some extent from local intrusions by the less permeable strata that confines the aquifer, and because vertical ground water movement in a confined aquifer is generally upward. Fractured bedrock or solution-enhanced karst systems (both confined and unconfined) constitute some of the most productive aquifers in Wyoming. Ground water time of travel can be rapid and may be several orders of magnitude greater than ground water circulation in other aquifers. Under certain conditions, potential contaminants can readily reach the ground water through fractures and solution cavities, thus greatly increasing the sensitivity of these aquifers to contamination.

MAJOR AQUIFERS AND AQUIFER SYSTEMS

Alluvial Aquifers

The valley-fill aquifers of Wyoming consist primarily of alluvial (in some places glaciofluvial) floodplain and terrace deposits that border the major rivers in the state. The most significant valley-fill aquifers are located along the North Platte, the Upper Snake, the Salt, the Bear, and

the Greybull Rivers (Figure II-2). At least five other rivers have mapped alluvial aquifers, but these aquifers are local in extent and use.

The North Platte River forms in northern Colorado and flows north into Wyoming to the city of Casper before looping south-eastward, crossing the Nebraska state line near Torrington, Wyo. North Platte valley-fill deposits comprise the most significant valley-fill aquifer in the state in terms of areal extent, water storage, and availability for agricultural, municipal (i.e., culinary), and industrial uses (Wireman, Anctil and Frederick, 1994). It is composed in large part of unconsolidated, coarse-grained, glaciofluvial sands and gravels. The Upper Snake River originates in Yellowstone National Park and flows south through Grand Teton National Park and Jackson Hole before turning westward into Idaho. The Snake River Valley contains several hundred feet of glaciofluvial sediments that underlie the floodplain and terraces. South of Jackson, the valley fill is primarily gravel and coarse sand, and supplies large quantities of water to wells. To the south, Quaternary alluvium and colluvium deposits along the Salt River support both

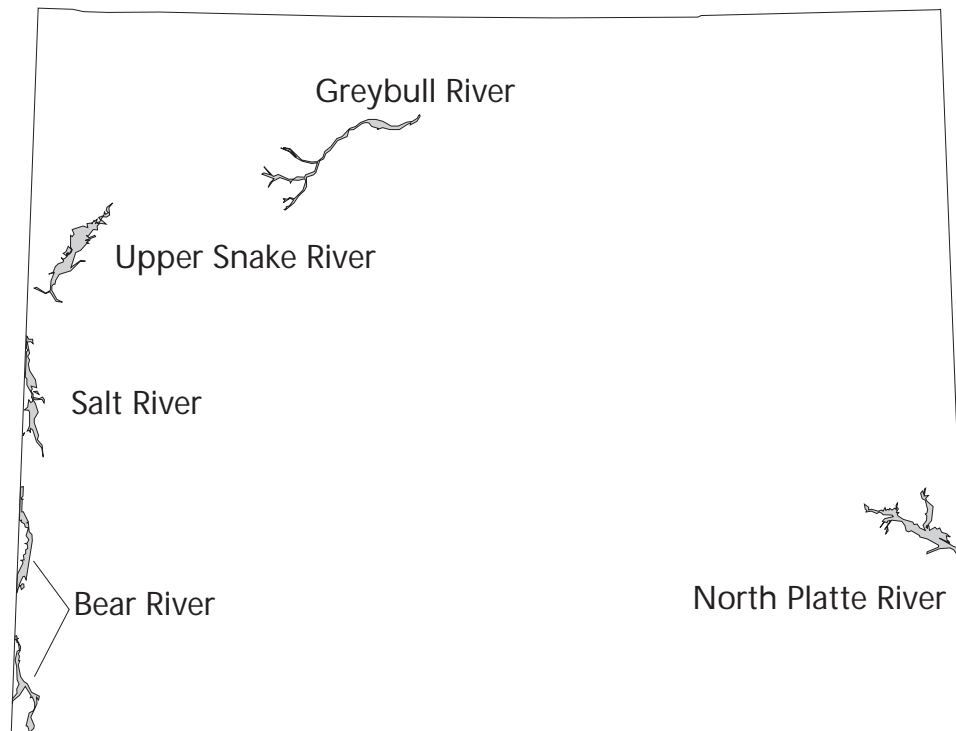


Figure II-2: Major alluvial aquifers of Wyoming

domestic and irrigation wells in both Upper and Lower Star Valley. The Bear River begins in the Uinta Mountains of Utah, flows northward through the southwestern corner of Wyoming, and continues into Idaho near Cokeville, Wyo. The Greybull River forms in the Absaroka Range, travels northeastward and enters the Bighorn River near the town of Greybull.

Well yields in the alluvial aquifers generally range from 50 to 100 gallons per minute (gpm) and can exceed 3,000 gpm. Transmissivity and hydraulic conductivity values are generally high, particularly where glacio-fluvial deposition has occurred. Reported transmissivities range from 1,000 to 65,000 gallons per day per foot (gpd/ft). In areas of significant glaciofluvial deposition, values have exceeded 750,000 gpd/ft (Wireman, Anctil, and Frederick 1994).

Water quality in the valley-fill sediments is generally suitable for most purposes. Concentrations of total dissolved solids (TDS) typically range from 200 to 1,200 milligrams per liter (mg/l), averaging approximately 500 mg/l. Prior to irrigation, many Quaternary terraces were dry or had relatively little saturated thickness. The advent of irrigation practices increased saturated thicknesses, which also increased the leaching of soluble minerals within the terrace and floodplain deposits and TDS concentrations downstream. These formations typically yield hardness values of 100 to 1,000 mg/l of calcium carbonate. In some agricultural areas, nitrate concentrations in the valley-fill deposits exceed the federal maximum contaminant level (MCL) of 10 mg/l (Parks 1991). In non-agricultural areas, nitrate concentrations are typically less than 1 mg/l (Wireman, Anctil, and Frederick 1994).

High Plains Aquifer System

The High Plains aquifer system underlies portions of eight states, however, in Wyoming it occurs only in the southeast quarter of the state. There it consists primarily of Tertiary and Quaternary sediments that are weakly consolidated with varying degrees of confinement by lower permeability strata. In general, the water-bearing strata in the upper portions of the aquifer are poorly consolidated and unconfined; the deeper, water-bearing strata are typically more consolidated and

semi-confined to confined by less permeable overlying materials.

Most ground water in the High Plains aquifer system is found in the Ogallala Formation and the underlying Arikaree Formation. The Ogallala is generally unconsolidated and consists of poorly sorted silt, sand, and gravel with minor clay, becoming coarser and less cemented in the lower parts of the formation. The Arikaree rocks are predominantly massive, fine-grained sandstone with localized beds of other fine-grained to amorphous sediments. The aquifer can exceed 1,000 feet in thickness in some places. Locally, the Oligocene Brule Formation is considered a part of the High Plains aquifer where it contains sandstones of secondary porosity in the form of fractures.

The High Plains aquifer system is the most developed aquifer in Wyoming, accounting for approximately 50 percent of the ground water developed in the state (Stockdale 1993). Uses include irrigation, and municipal and industrial water supplies. Laramie County draws on the Ogallala portion of the system, whereas the remainder of the region depends on the deeper Arikaree.

Well yields of several hundred gallons per minute are common from the High Plains aquifer system, with yields of 1,000 gpm being common locally. Transmissivity values range from 1,600-700,000 gpd/ft for the Ogallala, and 110-77,000 gpd/ft for the Arikaree. Hydraulic conductivity ranges from 160 to 4,000 gpd/ft² for the Ogallala, and 1.3 to 375 gpd/ft² for the Arikaree. Specific capacity values for both formations range from 0.2 to 230 gpm/ft (Libra et al. 1981; Wireman, Anctil, and Frederick 1994).

The High Plains aquifer typically provides very good water quality suitable for all beneficial uses, but is very vulnerable in areas to contamination from overlying land uses (Wireman, Anctil, and Frederick 1994). Concentrations of total dissolved solids (TDS) are typically less than 500 mg/l. Ground water from the High Plains is typically moderately hard to hard, with concentrations averaging less than 200 mg/l of calcium carbonate. In localized areas nitrate concentrations exceed 10 mg/l, but are typically less than 2 mg/l (Wireman, Anctil, and Frederick 1994).

Structural Basins

Wyoming's asymmetrical structural sedimentary basins are hydrogeologically somewhat similar to one another. These basins include the Powder River, Bighorn, Wind River, Green River (and Overthrust Belt), Great Divide/Washakie, Laramie, Shirley, Hanna, and Denver/Julesberg basins (Figure II-3). These basins contain 12,000 feet (Denver/Julesberg) to 43,000 feet (Green River) of Phanerozoic sedimentary rocks. Mesozoic rocks (mainly Cretaceous) typically comprise the bedrock with the greatest thickness of the basins (11,000 to 15,000 feet); Cenozoic formations average 8,000 to 9,000 feet in thickness, while the Paleozoic rocks range from 3,000 to 4,000 feet thick.

Within each basin, three major hydrologic units have been defined. The hydrologic units are regional, stratigraphically adjacent formations with similar hydraulic properties and recharge/discharge characteristics. They can function as regional aquifer systems or regional aquitards.

Regional aquifer systems include stratigraphically adjacent formations consisting of permeable sandstones, limestones, and siltstones, or sedimentary formations with significant secondary fracturing. Ground water can be found under both confined and unconfined conditions within a regional aquifer system. Ground water flows from one formation to another under a variety of hydrologic conditions, and withdrawal of ground water from one formation can affect the pressure head in adjacent formations. Formations that comprise aquifers can also behave locally as individual aquifers with minimal hydraulic connection.

Although they may be used locally as a limited water source, thick sections of shales and siltstones typically retard the flow of ground water and form boundaries for the regional aquifer systems. If thick enough, these formations may function as aquitards. If they are not thick enough, they will typically function as leaky confining units.

Within these regional aquifer systems are local aquifers made up of permeable formations of limited extent or permeable members of

otherwise low-permeability formations. These aquifers tend to be discontinuous and are often interbedded with low-permeability sedimentary rocks.

In each of Wyoming's sedimentary basins, the upper hydrologic unit is composed of Upper Cretaceous and Tertiary rocks functioning as a regional aquifer system. Below this, a thick section of Cretaceous marine rocks comprise a regional aquitard. This isolates the upper regional aquifer system from the underlying Lower Cretaceous and Paleozoic aquifer system. The Paleozoic consists primarily of limestones and sandstones of Cambrian to Pennsylvanian age (depending on the basin) and is considered a separate hydrologic unit.

A brief description of each hydrologic unit follows which emphasizes the upper regional aquifer system. For an overview of each system, presented in a basin-by-basin format, please see Anctil (1994).

Upper Hydrologic Unit

The base of the upper hydrologic unit is typically formed by the Lance (siltstone/sandstone) and Fox Hills (sandstone) formations of late

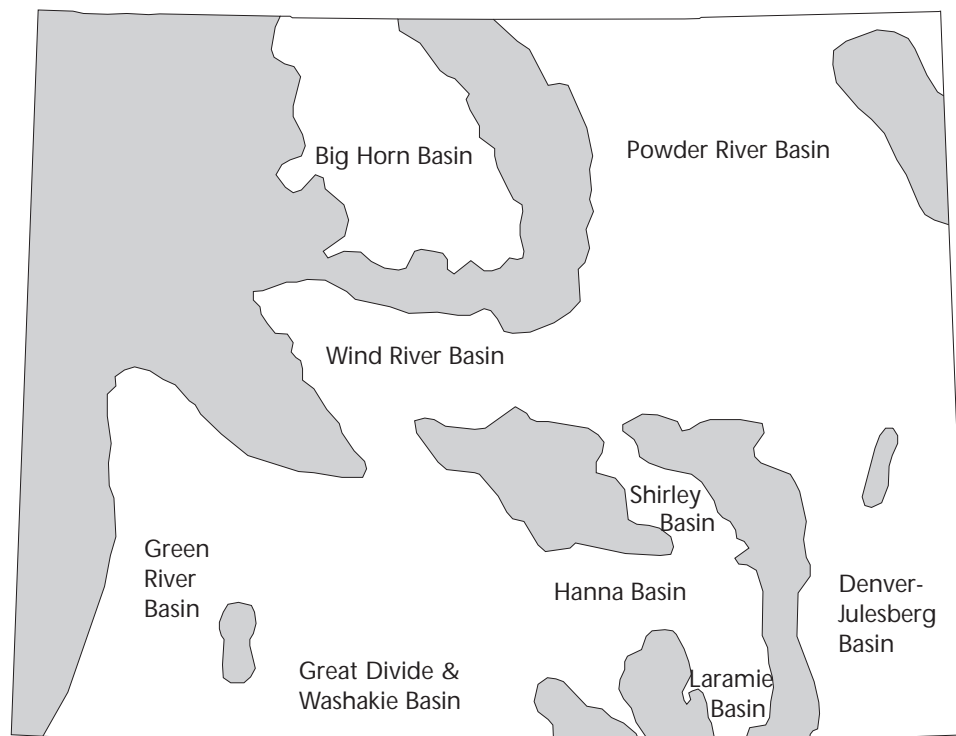


Figure II-3: Structural basins of Wyoming

Cretaceous age. The Paleocene Fort Union Formation overlies the Lance Formation in all of the basins except the Denver/Julesberg, where the Lance is overlain by the Oligocene White River Group. The Fort Union Formation is overlain by the Wasatch Formation in the Green River, Great Divide, and Powder River basins; both are composed of interbedded sandstones, siltstones, and coals. In the Wind River basin, the Fort Union is overlain by the Wind River Formation, a stratigraphic equivalent to the Wasatch Formation. The upper Tertiary Ogallala and Arikaree Formations form the top of the upper hydrologic unit in the Denver/Julesberg, Powder River, and Wind River basins. In the Green River and Great Divide basins, the upper Tertiary Browns Park, North Park, and South Pass Formations, composed of semi-consolidated to consolidated coarse-grained clastic rocks, form the top of the upper hydrologic unit.

Locally, the upper hydrologic unit may be divided into three aquifer systems: the Lance-Fox Hills, the Wasatch-Fort Union, and the Ogallala-Arikaree or North Park-Browns Park-South Pass aquifer systems. These systems are typically separated by leaky confining units of various thicknesses and extents.

Reported well yields for the formations in the upper hydrologic unit typically are less than 200 gpm, though yields of more than 1,000 gpm are possible from wells that penetrate more than 1,000 feet of the aquifer (Zimmerman 1985).

The quality of ground water contained in the upper hydrologic unit formations varies considerably. Most well water is suitable for domestic and livestock use, though in certain areas, sulfate concentrations have exceeded 500 mg/l (Zimmerman 1985). Total dissolved solids also vary greatly from a few hundred mg/l to several thousand mg/l, typically increasing with depth and distance from recharge areas.

Regional Aquitard System

In all of the structural basins in Wyoming, the upper hydrologic unit is underlain by a thick sequence of lower- and upper-Cretaceous marine shales and associated limestones. Typically 4,000 to 6,000 feet thick in the basins' centers, these marine sections function as regional

aquitards. Except for the basin margins, these low-permeability rocks effectively preclude hydraulic connection between the overlying regional aquifer system and rocks underlying the regional aquitard.

In all basins, Jurassic, Triassic, and Permian rocks comprise a series of local aquifers and leaky confining units or aquitards. These rocks consist primarily of siltstones and evaporites.

Lower Hydrologic Unit

A lower hydrologic unit also has been identified in all of Wyoming's structural basins, composed of a sequence of sandstones and carbonates of Cambrian to Pennsylvanian age, including (most notably) the Madison Limestone of Mississippian age and the Tensleep Sandstone of Pennsylvanian age (Zimmerman 1985). This carbonate and sandstone aquifer system "crops out in small areas of the state... [M]uch of the land is steep [with rocks generally dipping sharply] toward the basins and, within a few miles of the outcrops, are too deep to be economically accessible for most potential users" (Zimmerman 1985).

The formations of the lower hydrologic unit have a combined thickness of 1,000 to 3,000 feet. Reported transmissivities typically range from 1,000 to 60,000 gpd/ft. Significant karst has developed in the upper part of the Madison limestone. Wells developed in the karst areas have reported yields of 2,000 gpm. Though the formations that comprise this lower hydrologic unit are productive aquifers, they have not been developed to any great extent because of their increased depths.

Concentrations of dissolved solids in this unit are typically less than 500 mg/l. Ground water in the carbonates is typically a calcium carbonate type near the basin margins. Basinwide, the water is typically a calcium sulfate. Tensleep and Madison ground waters are typically similar in type.

Other Aquifers

In addition to Wyoming's major aquifer systems, a number of locally important aquifers provide water throughout the state, consisting primarily of igneous and metamorphic Precambrian- to Cenozoic-

age rocks and Cretaceous-age formations containing a high percentage of marine shale and fine-grained sandstone.

Well yields from igneous and metamorphic rock outcrops in the State's mountainous regions are commonly 10 to 30 gpm, depending upon the interconnectedness of fractures and joints or the thickness of the shallow weathered zone. Most water is of excellent quality and suitable for most uses (Zimmerman 1985).

Along the margins of structural basins, locally important water-bearing units are composed of shale and fine-grained sandstones. In western Wyoming, sandstone-dominated formations may produce yields exceeding 300 gpm. In eastern Wyoming, wells are typically deep, drilled more than 1,000 feet to shale-capped sandstones. Water in the shallower sandstone beds, though more accessible, is typically of poor quality with high sulfate concentrations and total dissolved solids (Zimmerman 1985).

GROUND WATER USE IN WYOMING

Each year, nearly 180 million acre-feet of water is put to use in the western United States. Of that total, approximately 59 million acre-feet, or 23%, originate from a ground water source. In Wyoming, ground water accounted for just 430,000 acre-feet (approximately five percent) of the total 8.5 million acre-feet utilized in 1990 (Solley 1997). Nevertheless, approximately 75 percent of the state's residents are dependent wholly, or in part, on ground water for their drinking water (90% for rural residents). In fact, more than 200 Public Water Supply (PWS) systems in Wyoming rely wholly, or in part, on ground water (Oakleaf and Hamerlinck, 1996).

Figure II-4 depicts the generalized hydrostratigraphy of the State, along with a partial listing of Wyoming communities tapping the principal aquifers in the State. Note the majority of ground water development in the State relies upon the alluvial aquifers situated along major drainages, the Tertiary aquifers, and the Paleozoic aquifer system. Hydrogeologic conditions vary for the PWSs across the state. Well depths range from tens to thousands of feet below the land surface. The types and thicknesses of overlying materials that may

protect the aquifer from contamination also vary.

Groundwater quality varies widely within and between aquifers in Wyoming. Dissolved-solids concentrations are high in many areas, often accompanied by correspondingly large sulfate and chloride concentrations. Despite its small population density, groundwater has

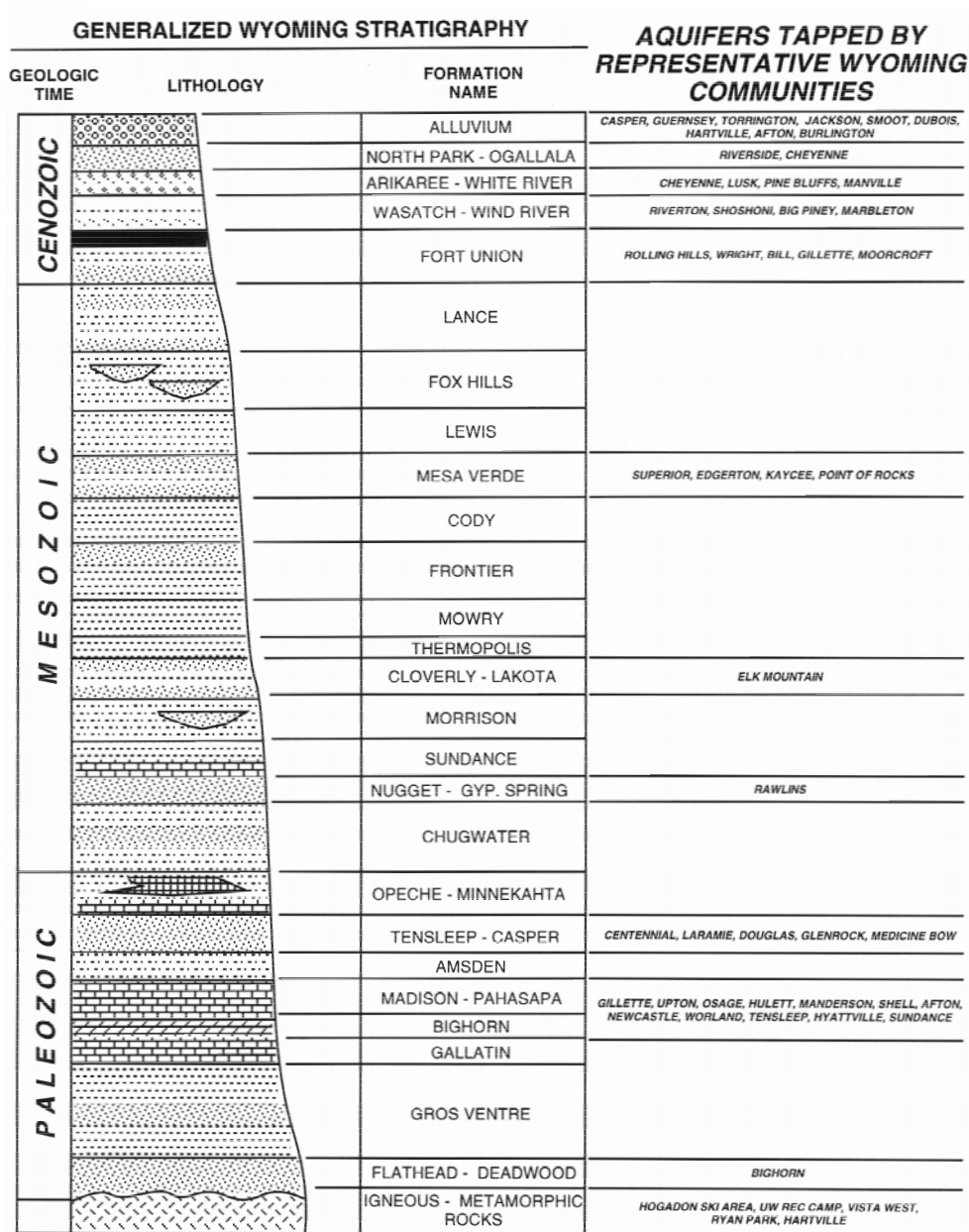


Figure II-4: Stratigraphy of Wyoming (WWPSC 1997 - Figure E-2)

been contaminated from anthropogenic sources in localized areas of the state. Common sources include leaking underground storage tanks, septic-tank leach fields, fertilizer and pesticide applications, and corrals and feedlots (Mora, Larson, and Rucker 1986). Despite these occurrences, both natural and human-related, groundwater in Wyoming continues to serve as an important water resource for a wide range of uses.

References

- Anctil, R.J. 1994. "The Aquifers and Aquifer Systems of Wyoming," unpublished manuscript.
- Freeze, R.A. and J.A. Cherry. 1979. *Groundwater*. Englewood, N.J.: Prentice-Hall.
- Heath, R.C. 1989. Basic Ground Water Hydrology. U.S. Geological Survey Water Supply Paper 2220.
- Heath, R.C. 1982. Classification of Ground-Water Systems of the United States. *Ground Water*, v. 20, no. 4, July-August 1982.
- Heath, R.C. 1984. Ground water regions of the United States: U.S. Geological Survey Water-Supply Paper 2242.
- Libra, R.D., Collentine, Michael, and K.R. Feathers. 1981. Occurrence and characteristics of ground water in the Denver-Julesburg Basin, Wyoming: Water Resources Research Institute, University of Wyoming, v. VII-A.
- Mora, K.L., Larson, L.R., and S.J. Rucker, IV. 1986. Wyoming Ground-Water Quality. National Water Summary 1986-Ground-Water Quality: U.S. Geological Survey Water-Supply Paper 2325.
- Oakleaf, J.R. and J.D. Hamerlinck. 1996. Global Positioning System-Based Mapping of Public Water System Facilities in Wyoming, WWRC-96-13. Laramie, WY: Wyoming Water Resources Center.
- Parks, G.D. 1991. Numerical simulation of groundwater flow and contaminant transport in an alluvial aquifer. M.S. Thesis, University of Wyoming.
- Solley, W.B. 1997. Estimates of Water Use in the Western United States in 1990 and Water-Use Trends, 1960-90, report to the Western Water Policy Review Advisory Commission. Reston, VA: U.S. Geological Survey.
- Stockdale, R.M. 1993. Personal communication, Wyoming State Engineer's Office.
- Whitehead, R.L. 1996. Ground Water Atlas of the United States, Segment 8: Montana, North Dakota, South Dakota, Wyoming. U.S. Geological Survey Hydrologic Investigations Atlas 730-1.
- Wireman, M., Anctil, R.J., and K. Frederick. 1994. "A Brief Overview of the Hydrogeology of the Major Aquifers and Aquifer Systems in Wyoming," unpublished manuscript.
- Wyoming Department of Environmental Quality Water Quality Division (WDEQ/WDQ). 1994. 1994 Wyoming Water Quality Assessment. Cheyenne, WY.

Wyoming Wellhead Protection Strategy Committee (WWPSC). 1997. "Wyoming State Wellhead Protection Guidance Document". Cheyenne, WY.

Zimmerman, E.A. 1985. Wyoming Ground Water Resources. National Water Summary 1984 - Hydrologic Events, Selected Water-quality Trends and Ground Water Resources: U.S. Geological Survey Water-Supply Paper 2275.

CHAPTER III: GROUND WATER VULNERABILITY ASSESSMENT CONCEPTS

This chapter guides readers through the requirements and assumptions that are necessary for completing a ground water vulnerability assessment for an area as large as Wyoming. Aquifer sensitivity and ground water vulnerability concepts are defined, followed by a discussion of the major categories of vulnerability assessment methods and the approach ultimately adopted for Wyoming.

GROUND WATER RESOURCE CHARACTERIZATION

An adequate characterization of ground water resources in a region or state is an essential first step in developing effective, long-term ground water management programs. Conducting such an assessment involves, “collecting and analyzing data on the physical ground water system, followed by a consideration of the ground water’s use, value, and vulnerability to human activity” (USEPA 1993a). The broad nature of these activities is designed to produce a foundation upon which local, state, and federal agencies as well as Wyoming citizens may conduct a wide range of ground water protection programs. The information resulting from these assessments enables managers to better understand ground water resources, identify existing and potential problems, and prioritize allocation of resources to address and mitigate the consequences.

In Wyoming, statewide ground water resource assessment activities are implemented by the Wyoming Department of Environmental Quality (WDEQ). The department oversees ground water protection and compliance in Wyoming, and coordinates development of regulations, policies, databases, and outreach documents pertaining to management, protection, and use of ground water in the state, in conjunction with the US Environmental Protection Agency (EPA), the Wyoming State Engineer’s Office and the Wyoming Department of Agriculture (WDA). Individual divisions within the department address statewide and community wellhead protection, aboveground and underground storage tanks, solid and hazardous wastes, underground injection control facilities, and public water systems.

GROUND WATER VULNERABILITY ASSESSMENT APPROACHES

A key element of many ground water resource characterization programs is an assessment of ground water vulnerability (USEPA 1993a). In general, ground water vulnerability assessments are aimed at determining the tendency or likelihood for contaminants to reach a specified position in the ground water system after introduction at

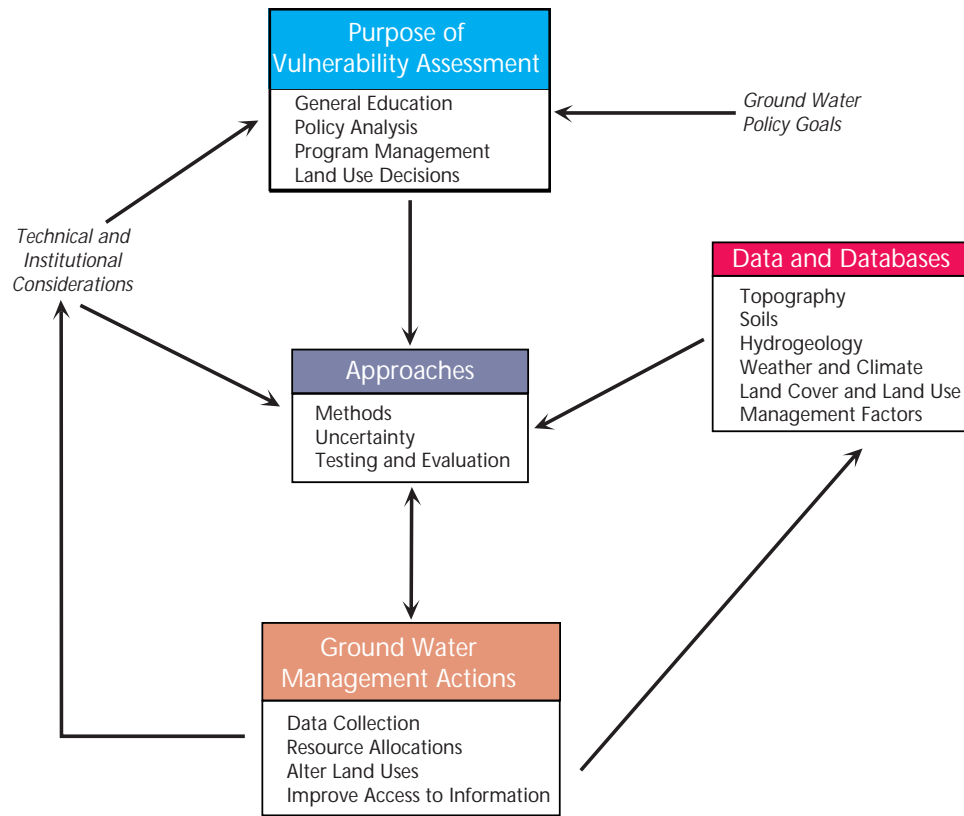


Figure III-1 : The vulnerability assessment process

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some location above the uppermost aquifer (NRC 1993). Vulnerability assessments combine the physical and chemical components of ground water (i.e., hydrogeologic setting) with indicators of the nature and extent of potential contaminant sources to determine the potential impact of these anthropogenic influences on the ground water quality.

Assessing ground water vulnerability is a dynamic and iterative process, with activities ranging from determination of policy goals to evaluation of technical and institutional factors associated with various assessment methodologies (Figure III-1). Such assessments can be useful resource management tools for guiding decisions about ground water protection, provided that methods and approaches incorporate cooperative planning between regulatory policy makers, resource managers, planners, technical experts, and land owners (NRC 1993).

Sensitivity ≠ Vulnerability

Aquifer sensitivity is the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest. It is a function of the intrinsic characteristics of the geologic material in question and the overlying saturated and unsaturated materials. Aquifer sensitivity is not dependent on land use and contaminant characteristics.

On the other hand, ground water vulnerability is the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest under a given set of land-use management practices, contaminant characteristics, and aquifer sensitivity conditions. In addition to hydrogeologic environment, ground water vulnerability assessment also addresses the 'human' factor, including contaminant properties and/or associated land use (USEPA 1993a).

AQUIFER SENSITIVITY AND GROUND WATER VULNERABILITY DEFINED

In the early 1990s, acknowledging unique differences between contamination potential factors based on the natural environment and those based on specific contaminant properties and/or human land use and surface management activities, the EPA moved to distinguish between the sensitivity of an aquifer and the overall vulnerability to contamination of an area's ground water resources. By EPA definition, aquifer sensitivity refers to the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest, based solely upon hydrogeologic factors. In contrast, ground water vulnerability combines the hydrogeologic characteristics determining sensitivity with "human" vulnerability factors, specifically addressing specific land uses, management practices, and/or contaminant properties (USEPA 1993b).

AQUIFER SENSITIVITY AND GROUND WATER VULNERABILITY METHODS

Over the last 15 years, geologists and hydrologists have developed a wide range of methods for assessing ground water vulnerability based upon an understanding of the factors that affect the transport of contaminants introduced at or near the land surface. Generally, these methods may be classified as process-based simulation model methods involving mathematical models that attempt to approximate the behavior of substances in the subsurface environment; empirical statistical methods drawing associations with areas where contamination is known to have occurred; or overlay and index methods (also called parameter-weighting) that combine specific physical characteristics affecting vulnerability (NRC 1993). (See descriptions on following page.)

Selecting the most appropriate approach and determining associated data needs requires consideration of reference location, degree of contaminant specificity, contaminant pathways considered, and spatial and temporal scales. Reference location refers to the specific position within the ground water system for which sensitivity and vulnerability are being assessed (typically the water table). Degree of contaminant specificity applies to vulnerability assessments only and is concerned with the level of detail addressed by a method with regard to contaminant characteristics. For example, specific vulnerability considers a specific contaminant (e.g., aldicarb), contaminant class (e.g., pesticides), or human activity (e.g., irrigated cropland), while intrinsic vulnerability (i.e. sensitivity) is determined without consideration of particular contaminant attributes or behavior. With regard to contaminant pathways, sensitivity and vulnerability assessments typically assume simple percolation of a contaminant from the land surface or shallow subsurface, ignoring such preferential flow paths as root holes, cracks, and joints. Spatial and temporal scales vary widely between sensitivity and vulnerability methods. The spatial scale of overlay/index map products is directly tied to the resolution or level of detail associated with the model's input data parameters. While simulation and statistical methods require very detailed data for relatively small study

areas, overlay/index approaches lend themselves better to large-area analysis, acknowledging that existing available data may vary in detail and accuracy (NRC 1993).

Of the three major classes, the overlay/index method has been the most widely adopted for assessing both aquifer sensitivity and ground water vulnerability at a regional or statewide scale. Overlay/index assessment methods involve combining maps or spatially-referenced digital data layers of various physiographic and land-use characteristics for a region by assigning a numerical index or rating to each attribute.

Overlay/index-based aquifer sensitivity mapping requires consideration of the properties and processes that influence the transport of potentially available contaminants from the ground surface into an aquifer. An aquifer sensitivity map describes the inherent capacity of the terrestrial and underground environments to transport available pollutants. Variables used in overlay/index-based aquifer sensitivity mapping typically include approximate depth-to-water table, recharge, and properties of soil and aquifer media. Overlay/index-based ground water vulnerability mapping models combine sensitivity variable ratings with attributes representing contaminant properties, land use,

Predicting ground water vulnerability

There are three common techniques for conducting an assessment of ground water vulnerability.

Process-based simulation model methods predict how long a contaminant will take to reach a given depth and/or the amount of contaminant by mathematically modeling the processes influencing contaminant fate and transport. The complexity of the models can range from simple transport model indices to multi-phase, multi-dimensional modeling of contaminant movement through saturated and unsaturated zones.

Empirical statistical methods calculate the probability of contamination by characterizing contamination potential for the specific geographic area using data from known contamination distribution in the area. This method, too, is quite complex – especially if applied over a large area.

The technique used within this project is a type of overlay/index method. These relatively simple applications assign a numerical index or rating to mapped physiographic and anthropogenic attributes of a region. The ratings are then combined to generate a composite sensitivity/vulnerability rating. The ratings can be considered equally or weighted according to the relative magnitude of their influence in the overall assessment determination. Best of all, these ratings are easy to create and apply to an area as large as the state of Wyoming (USGAO 1992; NRC 1993).

and/or management practices on the land surface in order to characterize the likelihood that potential contaminants will impact the underlying ground water. Examples of overlay/index vulnerability map variables include cropland delineations, irrigation practices, and pesticide application rates.

Originally developed as a “manual” process, these techniques have evolved greatly in use and sophistication with the growing application of geographic information systems (GIS) technology (see Chapter IV). Overlay/index models tend to be applied at intermediate or small map scales (1:100,000-1:500,000). The models’ reference location is typically the water table or “first encountered ground water.” The degree of contaminant specificity in overlay/index-based vulnerability assessment models varies but typically focuses on contaminant class or broad land use categories.

MAPPING GROUND WATER VULNERABILITY IN WYOMING

Overlay/index-based sensitivity and vulnerability mapping methods have evolved considerably since their inception in the early 1980s, particularly with regard to use of parameter-weighting schemes and utilization of GIS technology. Nevertheless, nearly all past applications of this type of technique have dealt only with determining relative indices of aquifer sensitivity (e.g., the physical environment), failing to incorporate human factors and vulnerability characterizations into the modeling process.

The Wyoming Ground Water Vulnerability Mapping Project extends traditional overlay/index sensitivity mapping approaches to take into consideration existing land use and its associated influences on both contamination availability and recharge to address how vulnerable various geohydrologic environments may be to contamination given current land use practices. The Wyoming approach (explained in Chapter IV) is essentially a two-step process, in which aquifer sensitivity is first assessed as a function of geohydrology, depth to water, soils, and recharge. Sensitivity is then combined with ratings of land use practices and pesticide use to determine relative ground water vulnerability to pesticides across the state.

References

National Research Council (NRC). 1993. *Ground Water Vulnerability Assessment: Contamination Potential Under Conditions of Uncertainty*. Washington, D.C.: National Academy Press.

U.S. Environmental Protection Agency (USEPA). 1993a. *Ground Water Resource Assessment*, EPA 813-R-93-003. U.S. Environmental Protection Agency: Washington, D.C.

U.S. Environmental Protection Agency (USEPA). 1993b. *A Review of Methods for Assessing Aquifer Sensitivity and Ground Water Vulnerability to Pesticide Contamination*, EPA 813-R-93-002. U.S. Environmental Protection Agency: Washington, D.C.

U.S. General Accounting Office (USGAO). 1991. *Groundwater Protection: Measurement of Relative Vulnerability to Pesticide Contamination*, GAO/PEMD-92-8. U.S. General Accounting Office: Washington, DC.

CHAPTER IV: WYOMING AQUIFER SENSITIVITY MAPPING METHODOLOGY

This chapter provides an in-depth overview of Wyoming's DRASTIC-based aquifer sensitivity mapping methodology, including details on DRASTIC's customization for use in the state and descriptions of all base data layers and model parameter inputs.

DRASTIC MODEL OVERVIEW

Many models have been designed to assess ground water pollution hazard, but DRASTIC and DRASTIC-like models are the most widely used for such efforts (USEPA 1993).

DRASTIC was originally designed as an easy-to-use model that would allow a user with a basic knowledge of hydrogeology to assess the relative potential for ground-water contamination. The model was neither designed nor intended to replace on-site inspections or to specifically site any type of facility or practice (Aller et al. 1987). Scientists designed the system to generalize the pollution potential for areas of 100 acres or larger. Because pollutants vary widely in their mobility and attenuation characteristics, DRASTIC developers assumed a generic pollutant with the travel properties of water. Following a Delphi consensus method, the DRASTIC development group, composed of highly qualified geohydrologists, eventually developed a broad-based model for people with little or no expertise in ground-water hydrology contaminant transport. Because it was neither practical nor feasible to obtain quantitative evaluations of the many micro-scale processes that affect contaminant transport and distribution from a regional perspective, it was necessary to look at the broader physical parameters that incorporate the many processes. When these processes are coupled with an evaluation of the hydrogeology of the area, a realistic estimation of ground water vulnerability is possible.

The DRASTIC method assesses aquifer sensitivity based on seven independent parameters that form its acronymic name:

Depth-to-ground water
 Recharge (net annual)
 Aquifer media
 Soil media
 Topography (slope)
 Impact of the vadose zone (unsaturated area below soil but above water table)
 Conductivity (saturated hydraulic).

These seven parameters constitute the pollution potential equation

$$PP = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w,$$

where PP is the pollution potential, r is the rating, and w is the weight for each factor.

Ratings for each of the parameters can range from 1 to 10, based on the relative role that the unit plays in pollution potential. Higher numbers indicate greater potential for pollution. For example, fine-textured soils such as clay are assumed to be less permeable to water than coarse soils like sand. Fine-textured soils are therefore assigned a lower rating than soils having a coarse texture because, all other things being equal, they are less likely to allow infiltration of a pollutant. Likewise, areas where depth-to-water is great are assigned lower ratings because it is assumed that, all other things being equal, pollutants are less likely to reach a deeper water table (Merchant 1994). DRASTIC weights can range from one to five and reflect the relative importance of each of the seven parameters. Users alter weights based on the particular land use in question to adjust for differences in impacts of the parameters on each use.

The index pollution potential calculated by the model is a relative indicator of the potential to contaminate ground water. The value has no real quantitative meaning other than to describe in relative terms which regions within the study area have a higher potential for contamination than others. This index value can only be applied meaningfully within its hydrogeologic setting or area of similar hydrologic characteristics (Aller et al. 1987).

DRASTIC MODEL MODIFICATIONS

The DRASTIC methodology developed for EPA by Aller et al. (1987) of the National Water Well Association has often been modified to better address local issues or better represent a local geohydrologic setting (Merchant 1994). The Wyoming sensitivity/vulnerability assessment is modified from the original DRASTIC methodology in a number of key aspects.

First, the Wyoming procedure utilizes several different mapping layers than DRASTIC. DRASTIC uses map layers for saturated hydraulic conductivity and aquifer media while the Wyoming procedure replaces these two layers with a more comprehensive geohydrologic setting mapping unit layer.

Second, the Wyoming procedure does not adhere to the DRASTIC method for assigning rating values to predefined map classes. A new rating system reflects Wyoming's unique hydrogeologic environment and landscape characteristics influencing contaminant transport.

Third, the Wyoming procedure uses equal weights for

Why this project demanded a GIS

Aquifer sensitivity assessments demand large volumes of data that are not practical to work with in a non-computerized setting. To handle the data organizational needs of this project, a geographic information system (GIS) was used. A GIS is a computerized system of hardware and software designed for geographic database building that can perform map digitizing, map scanning, database editing, and data importing and exporting as standard database development features. Simply defined, a GIS is a computer-based information technology that stores, analyzes, and displays both spatial and non-spatial data. In addition, a GIS is capable of many sophisticated analysis routines such as proximity analysis or raster surface derivation. Its primary advantage is that it integrates data layers from a multitude of sources and scales them into one system. A GIS also incorporates different types of data. For example, data layers for this project included point features (wells), line features (streams), area features (soils), and raster surfaces (precipitation). Each of these layers was derived or acquired from a different source and overlaid to produce a final composite map. These traits make GIS an excellent tool for managing the ground water modeling process, analyzing the results, and updating and archiving spatially-referenced data sets (Richards et al. 1993). While not fully implemented here, a GIS is capable of answering an entire range of "what if" questions including "If land use management practices were altered in an area, what would be the affect on ground water vulnerability?" Because of these capabilities, GISs have been applied to a wide range of modeling problems. Merchant et al. (1987) were probably the first to use GIS to implement DRASTIC (Merchant 1994), but since then, many others have followed suit.

each of the sensitivity parameter maps based on the lack of scientific evidence to support any weight assignment. DRASTIC elected to use weights for each layer to account for different land uses and emphasize some layers more than others (e.g., Depth to Ground Water weighted as a five and Slope weighted as a one, implying that depth-to-ground water is five times more important than slope for predicting sensitivity).

The potential problems with this approach are twofold. First, there is no scientific basis for defining what these weights should be. Recent literature suggests that the relationship between measurements of selected parameters and real-world sensitivity is often unclear at best. For example, it would seem intuitively obvious that there should be a strong relationship between depth-to-initial-ground water and aquifer sensitivity. But some studies have not detected significant relations between pesticide occurrence and water-table depth (Barbash and Resek 1996, 283). While it may be appropriate to assume that a relationship exists, it seems more conservative to apply equal weights until further research can better define the relationships between each of the six parameters.

In addition, DRASTIC applies a different set of weights for each application of the product. For example, a sensitivity map produced to examine agriculture would appear much different than a sensitivity map for some other purpose. Producing several different sensitivity maps for the same area seems to invite misuse (or even abuse) when the wrong map is applied in an application that is not clearly described in the map title. The Wyoming model will create only one sensitivity map and one vulnerability map for each land use in a given area.

Initially, this project took a more conservative position in regard to weights and because Wyoming's model approaches the issue of separate uses by applying different land uses (e.g., agriculture, landfills, septic systems, etc.) within the vulnerability model so that a single and comprehensive aquifer sensitivity model may be applied in multiple planning activities. Nevertheless, if at some later date, a more conclusive relationship between the characteristic layers is found, geographic information systems (GIS) technology allows for the analysis portion of

the project to be altered quickly and easily to produce a new product.

The Wyoming model also ignores situations in which a single factor overwhelms the importance of all other ground water vulnerability factors because of limited site-specific data (e.g., very shallow water table). Finally, vulnerability in the Wyoming study is accounted for by integrating a rating map of human land use with the final sensitivity map.

The final sensitivity layer is created by using a GIS to overlay the six individual parameter rating maps and sum their rating values. The ratings shown on the final sensitivity map reflect the contribution of each individual parameter map. Higher ratings depict areas where the ground water is inherently more sensitive to contamination; lower ratings highlight areas that are less sensitive.

The ground water vulnerability map was generated by combining the final sensitivity map with a map of croplands and urban areas within the state. This map represents those areas where the natural hydrogeologic system has been modified through irrigation and pesticides or where there is known intense use of agricultural chemicals. Ratings represent the impact that pesticides applied to dryland and irrigated agriculture could have on the subsurface aquifers. They are based on the capacity of irrigation water to enhance the transport of potential contaminants and the availability of pesticides at the land surface.

BASE DATA LAYERS

To complete this project several initial data layers were necessary. These layers which are referred to within this document as base layers include bedrock geology, surficial geology, ground water wells, surficial water features, elevation, and precipitation. From these initial base layers much of the other necessary parameter information was derived. Figure IV-1 outlines the relationships of these layers. For more detailed information about the GIS development specifics for each of the layers refer to Appendix C containing layer metadata. This section includes detail on the development process, accuracy, and attributes for each GIS layer.

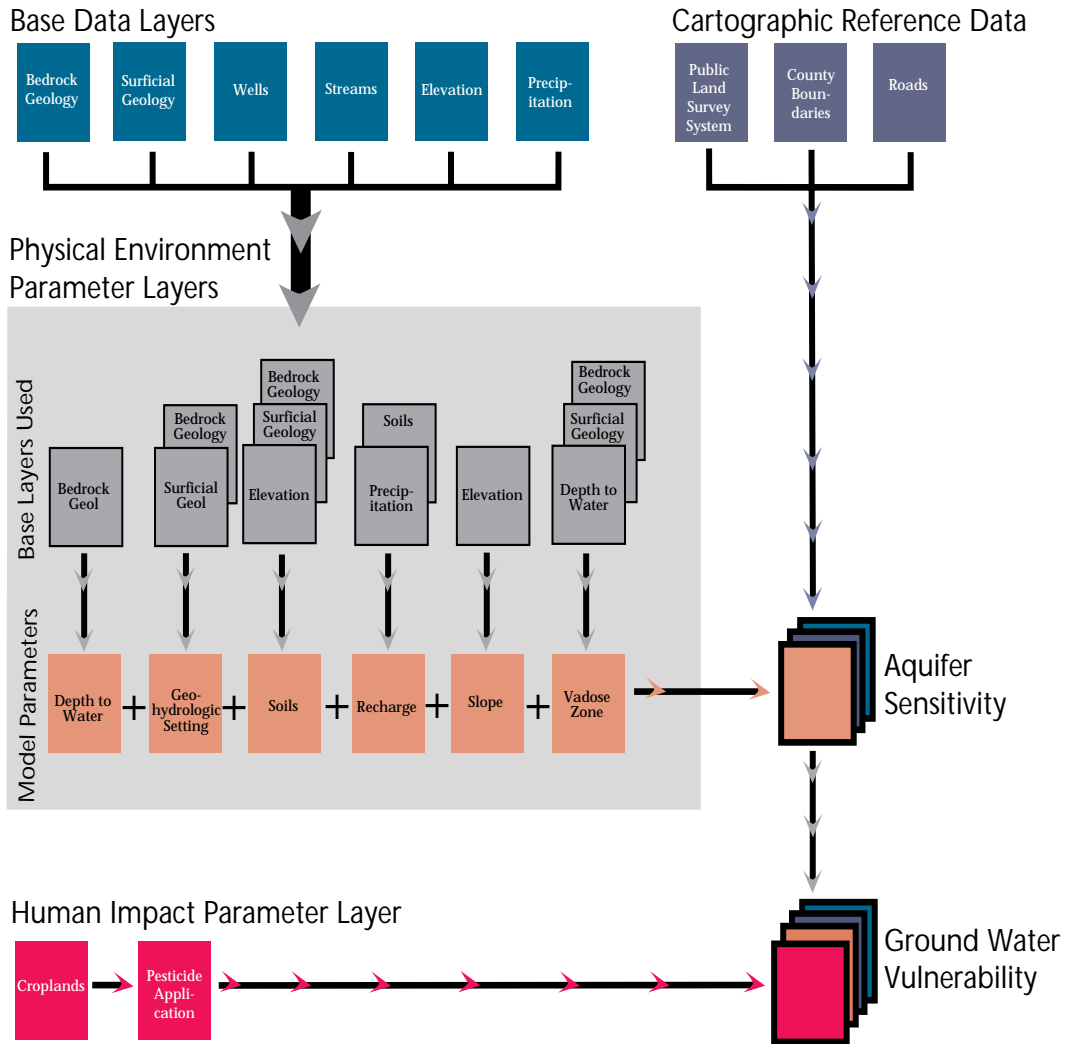


Figure IV-1 : Layer lineage within Wyoming's sensitivity and vulnerability model

Bedrock Geology

This project utilizes USGS Open-File Report 94-0425, The Digital Geologic Map of Wyoming in ARC/INFO Format (Green and Drouillard 1994), as the source of bedrock geology data. The Digital Geologic Map contains common geologic formation descriptions and linear geologic features such as faults and folds at a scale of 1:500,000. The Wyoming Water Resources Center (WWRC) cooperated with the U.S. Geological Survey (USGS), Geological Resources Division from Denver, Colorado, to create this digital layer from the original paper edition, Geologic Map of Wyoming (Love and Christiansen 1985).

Surficial Geology

The Geologic Hazards Section of the Wyoming State Geological Survey (WSGS) developed the base information for the surficial geology layer. Created specifically for this project, the surficial geology layer was developed using aerial photography interpretation techniques to map Quaternary-age deposits. The layer has been published separately as the Wyoming State Geological Survey Geologic Hazards Section Digital Map 98-1 (HSDM 98-1), Preliminary 1:500,000-Scale Surficial Geology Map of Wyoming (Case, Arneson, and Hallberg 1998). Originally drafted based on National High Altitude Program (NHAP) 1:58,200-scale color infrared photos, the map was photo-reduced to 1:500,000 scale for this project, then converted to a digital form at the WWRC.

To depict the surficial landforms and deposits in Wyoming, most of the state was newly mapped at a scale of 1:100,000 utilizing the previously cited photography to properly locate small features in the basins and in areas of low relief. The geologic maps listed in Wyoming State Geological Survey Map Series 9A-9R (De Bruin 1983, 1984, 1985; De Bruin and Greer 1986; Glass 1981; Greer and Ver Ploeg 1989; King and Ver Ploeg 1990) provided guidance for the mapping. For this project, many of the 1:100,000-scale surficial geology maps contained too much detail to be transferred directly to the 1:500,000-scale base. In such areas, mapped units were combined into slightly more general units before they were transferred to the 1:500,000-scale base. Every effort was made to combine similar or related units; however, the same mapped units were not always consistently combined. Instead, the combinations were dependent on the density of the mapped units in any area. More information can be found in HSDM 98-1 (Case, Arneson, and Hallberg 1998).

Water Wells

A digital map showing ground water levels in selected wells across the state was used to help compile the depth-to-initial-ground water layer, the vadose zone layer, and the geohydrologic setting layer. The project developed a well location data set using information from well

drilling permits and completion reports cataloged by the Wyoming State Engineer's Office (SEO). Compiled from the late 1800s through 1994, the permits include wells of varying use and status. Well permits represent data from different years and for various seasons. This project recognizes that well drilling permits will inevitably lead to misrepresentations because of the inconsistencies of dates, drilling techniques, and documentation quality, but no other adequate source of ground water level data exists for the entire state of Wyoming. Each record is an individual snapshot of the ground-water levels and well characteristics at the time of completion.

To complicate matters, well records are prepared by many different drillers who apply no standard drilling procedures or recording methods. Furthermore, no agency or organization conducts drilling record review or provides error-checking mechanisms. Within the SEO archives, some well permit records are completely filled out with careful detail, while other permits record only the minimal amount of information required. For this project, a large number of well completion reports were obtained so that the well database could be edited and still contain a sufficient number of reliable records to carry out interpolation for estimating water depth across the state. While data from 84,700 wells were initially obtained, this project recognizes that many areas in the state contain too few wells to accurately depict the true water depth. In addition, it must be recognized that within several areas of the state, water levels have changed significantly within the past several years. Using historic well permits will inevitably lead to a misrepresentation of these areas.

The SEO maintains the initial well permit information as an Advanced Revelation (AREV) database. The fields contained within this database include permit number, permit holder, location in Public Land Survey format down to the quarter-quarter section, facility name, permit status, use code, priority date, yield, well depth, static water depth, main water-bearing zone (mwbz) top, mwbz bottom, well diameter, county, and water district. These records were transferred into an INFO database at the WWRC, and an initial quality-assurance

routine was performed. A GIS point layer was then created using the FORTRAN program TR-LL (Morgan and McNellis 1965) to convert the township-range locations into latitude and longitude coordinates for point coverage generation in ARC/INFO. (The sole piece of information regarding location within the well permits is a Public Land Survey description to the nearest 40 acres or quarter-quarter section. No other spatial location is required by the SEO on the permits.) Several additional quality assurance routines were then performed to eliminate points with obvious errors, which included illogical township/range descriptions, wells that fell outside the state boundaries, and records with textual information contained within the wrong database field. After these initial routines were performed, 74,370 wells remained of the original 84,700.

Surficial Hydrography

The surficial hydrography data layer for this project was obtained from the 1992 TIGER/Line files produced by the U. S. Bureau of the Census. This data layer was originally created at a 1:100,000-scale and contains not only the linear and area hydrologic features, but the types of those features. For this project, ephemeral features were ignored. Hydrography data were separated from other non-hydrographic information but were otherwise unaltered.

Elevation

This project used USGS 90-meter resolution Digital Elevation Models (DEMs) for the entire state (USGS 1990) to represent topography. While some higher-resolution, 30-meter (1:24,000-scale) lattices exist for Wyoming, they have not been finalized for the entire state and were excluded from any analysis. The USGS DEMs were obtained as 28 separate files and imported into the ARC/INFO GRID module before being joined into one seamless lattice of elevation values. The 90-meter DEMs needed minor changes to account for missing data. In these rare situations, when cells were missing or contained erroneous data, they were assigned an average value from the surrounding cells.

Precipitation

The precipitation data layer for this project was generated using the PRISM climate model (Daly et al. 1994) which was designed to better interpolate precipitation distributions by including orographic or mountain-based effects into the model. This layer was derived from precipitation values collected from 1961 to 1990 and was acquired from the Oregon Climate Service and resampled to 500-meter and 100-meter resolution lattices for analysis within the sensitivity model. Further information on this layer can be found within the metadata appendix (Appendix C).

CARTOGRAPHIC REFERENCE DATA

Several layers were acquired for cartographic reference on the final map products. These layers included public land survey system, county boundaries, and transportation.

Public Land Survey System

This project required the Public Land Survey System (PLSS) as a base map and cartographic reference data layer. It was used to spatially locate wells within the state as well as to provide a visual reference for users of the final maps. The WWRC created this layer between 1992 and 1994, digitizing the 1:100,000-scale Land Status series of paper maps produced by the U.S. Bureau of Land Management (BLM). Fifty-six maps were digitized for Wyoming, then joined into a final, seamless coverage showing township, range, and section information. Appendix C includes full metadata detailing the data automation process, quality assessment and quality-control procedures, and data limitations.

County Boundaries

The Wyoming Gap Analysis Project provided county and state boundaries for this project (Merrill et al. 1996). This data layer was also digitized from the 1:100,000-scale Land Status series of paper maps produced by the BLM.

Transportation

The transportation data layer required as cartographic reference was obtained from the 1992 TIGER/Line data produced by the U.S.

Bureau of the Census. The 1:100,000-scale data layer was essentially unchanged.

MODEL PARAMETERS

Derived from the project base layers described above, map units on hydrogeologic parameters were assigned ratings and compiled into the final sensitivity map. Figure IV-1 outlines the relationships of these layers to the base layers.

Depth to Initial Ground Water

Depth to ground water is a significant factor controlling the ability of pollutants to reach the aquifer. The closer that ground water is to the land surface, the quicker water-transported contaminants can reach it. In addition, the shorter the travel distance through soils and unsaturated geologic materials, the less contact time there is between contaminants and chemical attenuating materials. Conversely, the greater the depth to water, the less sensitive an aquifer is to contamination.

This project utilizes a Depth to First Encountered Ground Water layer generated from the SEO well permits database as the mapped water depth. (See Base Data Layers section.) Though there may be multiple aquifers existing vertically through the geologic media, each potentially vulnerable to contamination, the first encountered water is first and most intensely impacted by contaminant leaching from the surface. Furthermore, the uppermost aquifer is utilized for many purposes, including irrigation, industry, stock, and domestic consumption.

Although the use of digital well completion records is problematic, it is the largest and best source of available information for ground water mapping. For this project, all available SEO well records were obtained so that the well database could be edited and still contain a sufficient number of reliable records to carry out interpolation for estimating water depth across the state.

Well records were divided into three distinct data layers according to geologic age of the landform in which they were drilled to isolate independent surficial aquifers from deeper and more massive bedrock

Table IV-1: Sensitivity ratings equations used for depth-to-initial-ground-water calculations

<i>Range of Depth (feet)</i>	<i>Rating</i>
0 - 5	10
5 - 30	$10.60 - 0.12(\text{depth})$
30 - 100	$23.94 - [4.98 \times \ln(\text{depth})]$
> 100	1

aquifers. These three classes of wells (Tertiary, Quaternary, and Other) were then separately spatially analyzed before they were combined in the final depth-to-ground water layer.

Editing water depth records required analyzing spatial depth patterns at several scales. Outlier wells of significantly deeper or shallower depths relative to the surrounding water depth values were both automatically and manually detected and removed. Initially, all wells that listed the depth-to-initial-ground water as either 0 feet or greater than 1,000 feet were removed for being industrial deep-water wells (which typically ignore surficial aquifers) or potential database errors. Because each well could be pinpointed no closer than the center of a 40-acre parcel, many wells of varying depths were often located in each parcel. This proved to be a formidable problem in the alluvial valleys. Routines were developed to eliminate all but the shallowest well in each location for the analysis. While this process eliminated many outliers, others in less densely drilled sections still

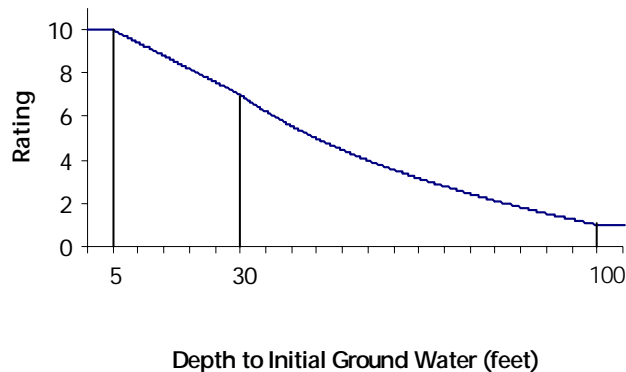


Figure IV-2 : Depth to initial ground water sensitivity rating curve

existed. By comparing each well to all other wells within two separate geographic scales, other potential outliers could be identified. Wells that were more than 50 feet deeper than the mean of a 50 square-mile zone or a 200 square-mile zone were removed from the analysis. These quality-control procedures pared the database to the 30,946 wells used to generate the water depth map.

Interpolation was conducted using the Ordinary Kriging method in ARC/INFO Version 7.1. Kriging is a spatial interpolation technique that generates a continuous surface of values from a scattered set of observational points (Burgess and Webster 1980). It is based upon the "regional variable theory," which assumes the spatial variability in observed values (i.e. water depth) is statistically homogeneous throughout the surface. Kriging is the preferred interpolation procedure because it provides "estimate values at unrecorded places without bias and with minimum and known variance" (Burgess and Webster 1980).

In Kriging, spatial variation across a set of point values is measured using the semi-variance, defined as one-half the average squared difference in point values between sample points. This semi-variance or per-observation variance between pairs represents a measure of similarity, on average, between points a given distance apart. The more alike point values are, the smaller the semi-variance and vice-versa. The semi-variance between all pairs of possible points is calculated using the following equation:

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^n [Z(x_i) - Z(x_i + h)]^2$$

where

n = number of pairs of sample points

h = distance between sample points

x = point location

Z = Z-value (water depth)

A semi-variogram is created by plotting the distances between pairs of sample points versus the resulting semi-variance values. At smaller distances between recorded point values, it can be seen that

the semi-variance is relatively low and that the semi-variance values do not vary significantly. At larger distances between points, semi-variance values and variability of semi-variance values increase. At a point along the semi-variogram curve called the semi-variogram sill, semi-variance value variability levels off and remains relatively constant. The sill represents the range of variance that can be explained based upon the spatial dependence of the observed data. Beyond the sill, variance between points can no longer be considered spatially correlated. Transferring the representation of spatial correlation contained in the semi-variograms to a mapped representation requires fitting a mathematical function to the semi-variance data in the semi-variogram. Interpolated values (depth-to-water) are calculated based on the distances between observed points. An exponential function best fit the data in the depth-to-water semi-variogram. A grid resolution of 100 meters was selected for generating the interpolated map for each county. For the purposes of this project, a depth-to-initial-water value beneath major surface water bodies including perennial rivers, streams, major irrigation canals, and lakes was assigned a value of 0 feet.

A sensitivity rating was assigned to the water depths by using a set of functions relating depth-to-first-encountered-ground water to a sensitivity rating (Table IV-1). The DRASTIC ratings as defined by Aller et al. (1987) were used as a guide for developing these equations. The relationship between sensitivity rating and depth can be seen in Figure IV-2.

GIS was used to facilitate the conversion of the depth-to-water data layer to a sensitivity-rating map by processing the mapped data through the above functions. The ground water depth map and the resulting sensitivity-rating map reside in a gridded, continuous surface format. Each data layer is a representation of a surface at a 100-meter cell resolution for the individual counties or a 500-meter resolution for the entire state.

Geohydrologic Setting

Within this project, Geohydrologic Setting represents the geohydrologic characteristics of the uppermost aquifer. This comprehensive

layer replaces both the Aquifer Media and the Saturated Hydraulic Conductivity layers that are used within the standard DRASTIC methodology.

For purposes of this project, there was no existing single comprehensive analysis on the generalized hydrologic characteristics of the geological formations present in Wyoming. There were, however, a number of studies that addressed the hydrology of specific structural sedimentary basins or regions within the state. The first step in analyzing the geohydrologic settings for all areas in Wyoming was to determine the generalized hydrologic characteristics for each geological formation in the state by summarizing the formation-specific hydrologic characteristics published in the Water Resources Research Institute (WWRI) Basin Ground Water Report Series¹. The WWRI (the precursor of the WWRC) reports provided overviews on the occurrence and characteristics of ground water in most basins in Wyoming². The USGS Hydrologic Investigations Atlases provided ground water reconnaissance for most of the state³, and selected USGS Water Supply Papers were used for information on ground water resources and geology for specific areas of the state⁴.

Guided by these references, the Wyoming State Geological Survey (WSGS) developed a classification scheme to rank all geological formations in Wyoming by generalized hydrologic characteristics. In cases where the hydrologic characteristics were not described in the litera-

¹ (Feathers, Libra, and Stephenson 1981; Libra, Doremus, and Goodwin 1981; Richter 1981; Ahern, Collentine, and Cooke 1981; Collentine and others 1981; Libra, Collentine, and Feathers 1981)

² (Susong, Smalley, and Banta 1993; Plafcan, Cassidy, and Smalley 1993; Ogle 1992; Plafcan and Ogle 1994; Lowry and others 1993; Plafcan and others 1995; Nolan and Miller 1995; Cooley and Crist 1994)

³ (Welder and McGreevy 1966; Whitcomb and Lowry 1968; Welder 1968; Hodson, Pearl, and Druse 1973; Lowry, Rucker, and Wahl 1973; Lowry, Lowham, and Lines 1976; Lines and Glass 1975; Cox 1976)

⁴ (Rapp, Warner, and Morgan 1953; Kohout 1957; Bradley 1956; Morris and others 1959; Rapp, Visher, and Littleton 1957; Swenson 1957; Berry 1960; Krieger and Jochens 1959; Morris and Babcock 1960; Berry and Littleton 1961; Robinove and Berry 1963; McGreevy, Hodson, and Rucker 1969; Robinove and Langford 1963; Robinove and Cummings 1963; Whitcomb and Morris 1964; Weeks 1964; Whitcomb 1965; Kilburn 1964; Welder and Weeks 1965; Whitcomb, Cummings, and McCullough 1966; Lowry and Cummings 1966; Walker 1965; Lowry and Crist 1967; Crist and Lowry 1972; Crist 1974)

ture, the characteristics were estimated, based upon the dominant lithology of the formation. The classification scheme is as follows:

1. Aquiclude/aquitard - low to no yield
2. Aquitard with aquifer interbeds - low yield
3. Aquitard with aquifer interbeds, secondary permeability - low to moderate yield
4. Aquifer and aquitard mixed - moderate to low yield
5. Aquifer with aquitard interbeds - moderate yield
6. Aquifer with aquitard interbeds, secondary permeability - moderate to high yield
7. Aquifer - high to moderate yield
8. High-yield aquifer - high yield

The Stratigraphic Chart Showing Phanerozoic Nomenclature for the State of Wyoming (Love, Christiansen, and Ver Ploeg 1993) was used as the basis for the classified geological formations. Geologic formations were classified within specific geographic regions of the state. Generalized hydrologic classifications assigned to the formations range from a high-yield aquifer to an aquiclude/aquitard with low to no yield. For the purposes of this study, the following definitions of yield were used:

High Yield: May provide water supply for irrigation or water supplies for large communities in Wyoming. In general, such formations yield more than 100 gallons per minute and may yield thousands of gallons per minute.

Moderate Yield: May provide water supply for small communities or for light industrial needs. In general, such formations may yield approximately 30 gallons per minute.

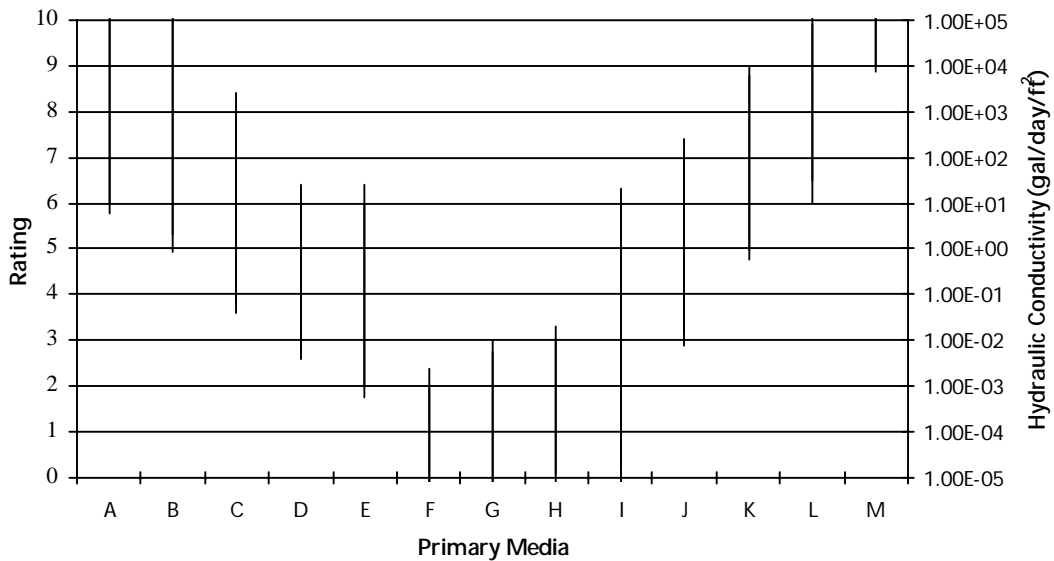
Low Yield: May provide a limited water supply for stock or domestic use. In general, such formations may yield as many as five gallons per minute.

The values for yield are approximate, and in localized areas, any geologic formation may produce significantly more or less water than indicated by the classification. The classification represents average characteristics for a formation over an entire basin.

One of the key elements of the Ground Water Vulnerability Map-

ping Project is the final aquifer sensitivity analysis, which synthesizes data from multiple sources. The project used the 1:500,000-scale Geologic Map of Wyoming (Love and Christiansen 1985) as one of the base layers for the sensitivity assessment. The aerial extent of many geologic formations is too small to be shown at a scale of 1:500,000, and some formations with similar ages but dissimilar hydrologic characteristics have been combined on the Geologic Map of Wyoming. As a result, to delineate geohydrologic settings, many of the formations individually classified by hydrologic characteristics were combined with other formations with similar geologic characteristics. The combination was then reclassified using the scheme presented above. Individual formations, however, may have different classifications based on their location in the state (Case and Arneson 1998).

DRASTIC (Aller et al. 1987) defines a sensitivity rating for saturated



- | | |
|--|-----------------------------|
| A = Karst Limestone | G = Shale |
| B = Permeable Basalt | H = Unweathered Marine Clay |
| C = Fractured Igneous and Metamorphic Rock | I = Glacial Till |
| D = Limestone and Dolomite | J = Silt, Loess |
| E = Sandstone | K = Silty Sand |
| F = Unfractured Metamorphic and Igneous Rock | L = Clean Sand |
| | M = Gravel |

Freeze/Cherry, GROUNDWATER, ©1979,p.29. Reprinted with permission of Prentice Hall, Upper Saddle River, NJ.

Figure IV-3 : Relative rankings from the eight-step aquifer characteristics model

aquifer media in large part based upon inferred hydrologic, geologic, and lithologic characteristics for various rock and material types. It ranges from one to 10, with one representing unfractured massive shale with a low pollution potential and 10 representing well-developed karst limestone with a high pollution potential. Because the Wyoming method uses a more comprehensive Geohydrologic Setting layer in place of the Aquifer Media and Hydraulic Conductivity layers, the DRASTIC classification was modified to include hydraulic conductivity values from Freeze and Cherry (1979), which are shown in Figure IV-3.

Relative rankings from the Wyoming model were compared to the relative rankings from the eight-class aquifer characteristics model, presented above. One of the limitations of the DRASTIC model is that sensitivity rankings are largely based upon rock type, lithology, and inferred hydrologic characteristics. The comparison allowed the DRASTIC ranking to be adjusted to reflect the actual hydrologic characteristics of the geologic formation or material.

Soils

A number of soil characteristics control the ability of contaminants to move into ground water and as a result, how they affect aquifer sensitivity. The thickness of the soils helps determine the length of time contaminants reside within the soil media. The longer the contact time, the more opportunity for interaction with biological, chemical, and physical processes that can potentially attenuate and degrade pollutants. The texture or size of the soil particles will influence the rate at which contaminants percolate downward through the soil profile. Coarse-textured sands and loams allow contaminants to pass more quickly through open spaces than fine-textured silts and clays. Similarly, the greater the organic content of certain soil constituents, the greater the likelihood for attenuating reactions. For instance, organic material, clays, and other minerals can react with contaminants to degrade, adsorb, or volatilize the chemicals. Finally, the type of clay in the soil will further influence contaminant flow. Certain clays having large shrink and swell capacities will crack after drying, allowing contaminants to move unhindered through parts of the profile.

Because this project mapped aquifer sensitivity at two separate scales, it was necessary to complete two individual digital soil layers. The first soil layer, the more general Wyoming State Soils Map produced at 1:500,000-scale, includes 45 individual soil mapping units across the state. The second soil layer, conducted on a county-by-

Table IV-2 : Criteria for assignment of soil sensitivity ratings

<i>Sensitivity Rating</i>	<i>Particle Size</i>	<i>Other Limiting Soil Conditions</i>
10	Any	Bedrock outcrop; bedrock at less than 50 cm; high water table (aquic moisture regime)
9	Sandy	No diagnostic B horizon; loamy, and shallow with mollic epipedon; clayey and shallow without natric horizon
8	Clayey	With natric horizon, smectitic, shallow
7	Loamy-skeletal	No argillic horizon
6	Loamy-skeletal; coarse-loamy	With argillic horizon
5	Fine-loamy; Fine-loamy over sandy or sandy-skeletal	With or without Bt horizon
4	Clayey; fine-silty	No argillic or natric horizon
3	Fine-silty	With argillic horizon and mollic epipedon
2	Fine	Smectitic, or fine-silty with mollic epipedon; ustertic intergrade
1	Fine	Mixed, with argillic horizon

county basis at a 1:100,000-scale, allows each county to contain approximately 15 separate soil mapping units that may or may not exactly match the bordering counties. *The Soils Map of Wyoming* is intended to depict process-based soil categories found in Wyoming. Representative soils in the mapping units for this map are classified at the family level of *Soil Taxonomy* (Soil Survey Staff 1975, 1996). Technical soil terminology follows the definitions in the *Glossary of Soil Science Terms* by the Soil Science Society of America (1997).

These maps provide a generalized description of soils within the state. Soils are highly variable, both on a regional basis (plains, moun-

tains, basins) and locally, with changes in topography (north versus south slopes, side slopes versus ridge crest or foot slope positions), vegetation, climate, and geology. These maps should be used for broad-scale planning and general assessment of large areas of land. They should not be used for site-specific interpretations, such as site selection for an underground fuel storage tank or the development of management plans for individual farm fields. Such site-intensive land uses require much more detailed soils information than this map provides.

The Wyoming State Soils Map and the generalized soils maps of the Wyoming counties are derived from the five soil-forming-factors model first proposed in its entirety by the Russian soil scientist Dokuchaev in the 1880s. This model, introduced broadly to American soil scientists by Hans Jenny (1941), presented the five factors of soil formation as soil parent material, climate, biota, topography, and time. As Hudson (1992) pointed out, soil survey conforms well to the theories of paradigm-based science. During detailed soil surveys, field mapping is based on the projection of soil mapping unit concepts onto landscape types, after which mapping unit composition and boundary placement are subject to immediate field-checking in the form of soil pit excavations. Generalized soils maps are often based on a process of consolidation of detailed soils maps or projection of limited data from direct observation across a broad area through soil-landscape models. In the United States, the five soil-forming-factor model is the soil-landscape model used almost universally. The maps prepared for this project were developed by tying soil surveys, maps, and reports of the Natural Resource Conservation Service, the Forest Service, and the BLM; numerous theses and scientific papers published by the Wyoming Agricultural Experiment Station; and the University of Wyoming and the current understanding of soil-landscape models.

Because the soil layers produced by this project are applicable to a vast array of other types of analyses, these layers are being published separately from this report (Munn and Arneson 1998a, 1998b). These publications include detailed information on the theory and the processes applied. For more detailed information on the methods and

unit descriptions used in these layers, please refer to those publications directly. For more detailed descriptions of the sensitivity rating values applied to each soil unit refer to the layer metadata (Appendix C).

Sensitivity ratings were assigned to soil mapping unit components based on soil texture and rock content, depth to bedrock, depth to ground water, and soil class mineralogy (Table IV-2). The comprehensive soil mapping units were assigned ratings based on the weighted averages of component ratings, which were prorated based on the relative extent of the components in the mapping unit.

Aquifer Recharge

Net aquifer recharge refers to the volume of water that infiltrates the soil and continues to percolate through the soil and unsaturated geologic material into the ground water. Recharge is expressed as an amount of water infiltrating to the water table per unit of area per unit of time (inches per year).

Recharge is a primary transport mechanism of potential contaminants from the ground surface into a shallow aquifer. At modest recharge rates, the more water available to recharge, the more susceptible the ground water is to potential contamination. Note that there is a higher recharge rate where recharge begins to dilute contaminants, resulting in an inverse relationship between recharge and potential ground-water contamination. Nevertheless, this dilution is not considered likely under natural conditions of the semi-arid Wyoming landscape (Knight 1994).

Actual recharge values are poorly documented in much of Wyoming. Recharge values for this project were based on published percolation percentages for documented soil/vegetation combinations. Using this approach, several common themes are found within the body of scientific literature on this topic:

- Recharge fraction (R/P) or percent of precipitation that reaches the uppermost aquifer for a given environment increases as the depth to the water table decreases;
- Recharge fraction increases as precipitation increases;
- Recharge fraction increases as the sand and rock content of the soil increases;
- Recharge fraction will be higher in an above-average precipita-

- Seasonal patterns and occurrence of major events like spring snowmelt alter the general effect of mean annual precipitation.

In Soil Taxonomy (USDA-NRCS 1996), five moisture regimes are recognized in the soils of Wyoming. These are aquic, udic, ustic, xeric, and aridic. The aquic regime has a high or perched water table from an isolated surficial aquifer during at least part of the growing season. The udic regime is a leaching regime, meaning precipitation exceeds evapotranspiration for a significant portion of the growing season. Soils with a udic regime commonly have a perched water table just after snowmelt. In the aridic regime, evapotranspiration exceeds precipitation, and soils are characterized by accumulations of secondary salts of varying solubility (CaCO_3 , gypsum, and more soluble salts). Recharge to the aquifer usually only occurs where the soils are very sandy, as with stabilized sand dunes in soils along the banks of perennial streams with shallow water tables. The ustic and xeric moisture regimes are intermediate between aridic and udic regimes and characterized by primarily grassland, shrub land, or dry, open woodland. The ustic regime in Wyoming typically occurs where the precipitation varies between 11.8 in. (30 cm) and 17.7 in. (45 cm) per year. The xeric regime is similar to the ustic regime except that precipitation is concentrated in the non-growing season. Soils in this regime can be as dry as aridic soils during the growing season, but water accumulations in excess of the soils' winter water storage capacity may leach them of salts.

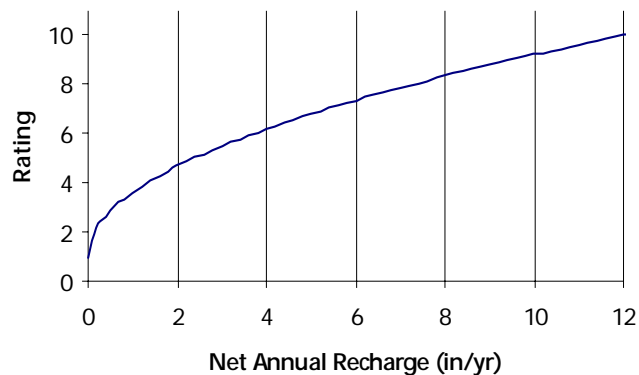


Figure IV-4 : Net annual recharge sensitivity rating curve

To generate DRASTIC-type rating values for recharge within Wyoming, researchers created a map of soil management unit (SMU) boundaries (discussed in the soils section), assigned recharge fraction values (%), combined similar units, overlaid the precipitation map, multiplied to calculate average annual recharge, and applied the rating function of:

$$Rating = (Recharge \times 6.749)^{\frac{1}{2}} + 1$$

Figure IV-4 provides the relationship between Rating and Recharge, as illustrated in the previous equation.

Land Surface Slope

Land surface slope refers to how steep the land surface is. It is normally represented as a degree or as a percentage (45 degrees = 100 percent). This project uses percent slope as a default. Land surface slope affects the amount of water and water-borne contaminants available at the surface for infiltration into the soils and (potentially) to the ground water. The flatter the slope, the longer water resides in one place on the land surface and the greater the potential for infiltration.

For this project, Wyoming was divided into raster-based grid cells. A slope for each grid cell was calculated from the USGS Digital Elevation Model (DEM) in ARC/INFO grid routines by identifying the maximum elevation change from each cell to its neighbor and assigning to the cell the maximum elevation difference. A percent slope value is then determined by dividing the elevation difference by the dimension of the grid cell and multiplying by 100. Cell sizes of 500 meters (for the small-scale statewide analysis) and 100 meters (for the intermedi-

Table IV-3 : Sensitivity ratings resulting from percent slope-ground water interaction

<i>Percent Slope</i>	<i>Rating</i>
0 - 1	10
1 - 18	5.5 + 4.5 {sin [(slope + 7) x 0.19]}
> 18	1

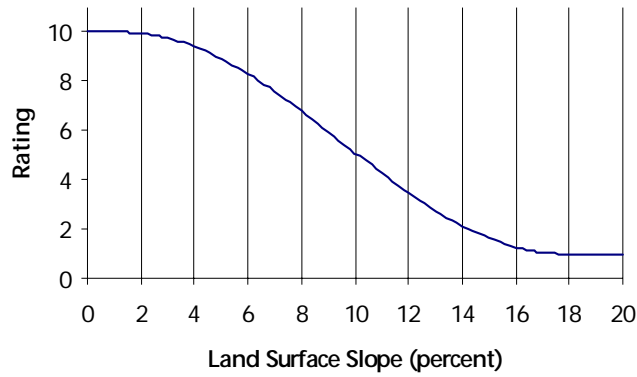


Figure IV-5 : Land surface slope sensitivity rating curve

ate-scale county analyses) were easily resampled from the 90-meter cell sizes of the original DEM.

The derived slope values for Wyoming fall between zero and 206 percent (64 degrees), with a mean slope of 6.9 percent or 3.9 degrees. Forty-four percent of the state has a slope between zero and two percent, 22 percent of the state has a two- to five-percent slope, 13 percent is in the range of five to 10 percent, and 21 percent has a slope greater than 10 percent.

Sensitivity ratings were assigned to the slope map through a set of functions shown above (Table IV-3) that describe how percent slope influences potential ground water contamination (Figure IV-5). The

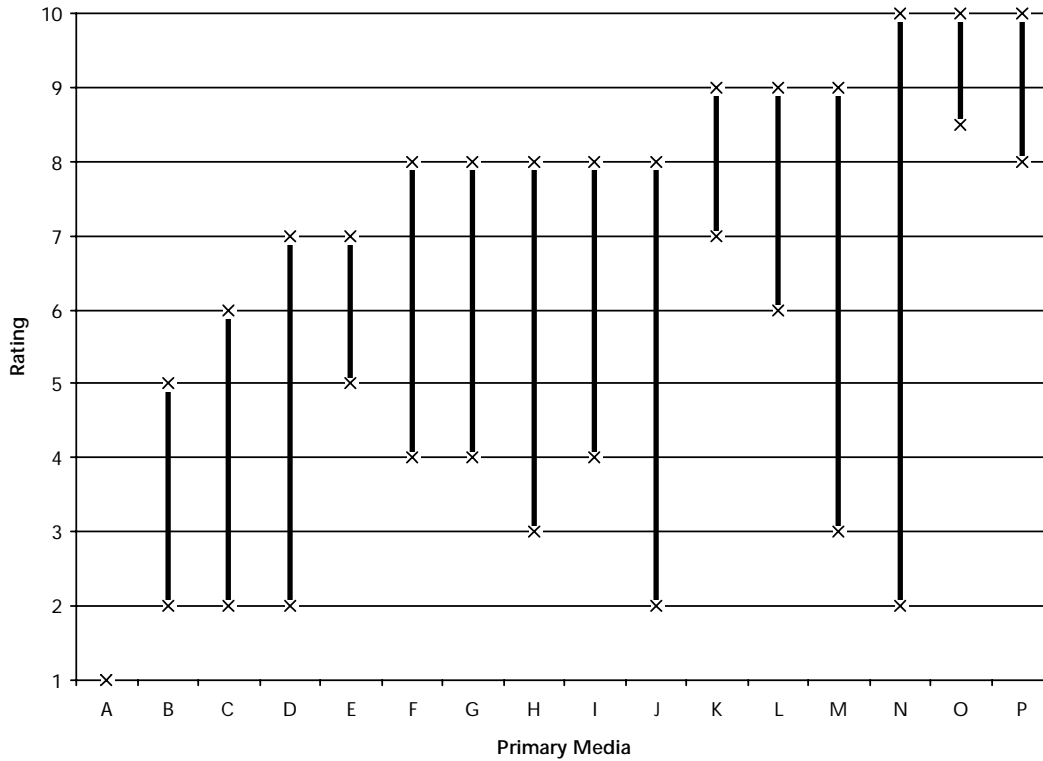
Table IV-4 : Vadose zone sensitivity rating formulas

<i>Formula Used</i>	<i>Surficial Units</i>
TV = SV	Ai, aR, ti, tre, fi, ei, gi, li, pea, ki, ai, oai, Mi, Ki, xi, Ti
TV = 10	glacier, lake
TV = BV	Ri
TV = 50%BV + 50%SV	Ai, aR, ti, tre, li, ki, bi, mi
TV = 75%BV + 25%SV	fi, pea, bdi, tdi, fdi, sci, ri, ui
TV = 25%BV + 75%SV	ei, gi

TV = Total Vadose (composite) Rank

BV = Bedrock Vadose Rank

SV = Surficial Materials Vadose Rank



- | | |
|---|--------------------------------|
| A = Confining Layer | I = Sand and Gravel |
| B = Shale | with Significant Silt and Clay |
| C = Silt/Clay | J = Metamorphic/Igneous |
| D = Limestone | K = Eolian Sand |
| E = Eolian Silt | L = Sand and Gravel |
| F = Sandstone | M = Volcaniclastics |
| G = Bedded Limestone, Sandstone,
and Shale | N = Basalt |
| H = Coal Sequences | O = Clinker |
| | P = Karst Limestone |

Figure IV-6 : Vadose zone sensitivity rating ranges

functions selected for this project approximate the slope-vulnerability curve presented in the DRASTIC documentation (Aller et al. 1987).

The GIS was used to transform the percent land surface slope map to a sensitivity rating layer by processing the mapped slope data through the above functions.

Vadose Zone

DRASTIC (Aller et al. 1987) defined a sensitivity ranking for vadose zone media (the vadose zone being the unsaturated zone above the water table and below the soil horizon). The DRASTIC ranking ranged

from one to 10, with rank one representing a confining layer with minimal potential for contaminants to migrate to the saturated zone, and rank 10 representing highly fractured and jointed basalt or karst limestone with a high potential for contaminant migration to the saturated zone.

The WSGS modified the sensitivity ranking for vadose zone media to reflect media present in Wyoming. WSGS added eolian silt (rank five to seven), coal sequences (rank three to eight), eolian sand (rank seven to nine), volcanoclastics (rank three to nine), and clinker (rank eight to 10). The modified ranking scheme is shown in Fig. IV-6.

The vadose zone in Wyoming is composed of bedrock, surficial materials, or a combination of the two. As a result, a vadose zone rating was assigned to the representative composition of each geological formation or combinations of geological formations present on the Geologic Map of Wyoming. The surficial units present on each geological formation were then defined and assigned a vadose zone rank that reflects the possible influence of the underlying bedrock on the composition and properties of the surficial unit. In many cases, the vadose zone includes bedrock and the overlying surficial materials, requiring a composite rank that reflects both the bedrock rank and the surficial materials rank. A series of formulas was developed to allow for the generation of the composite rankings. The formulas used for generating a total vadose ranking are presented in Table IV-4.

ANALYSIS METHODS

Once these model characteristic layers were developed, each had to be individually rated for the model. These ratings were designed to be completely independent of each other and to reflect the role that each layer represents in the movement of contaminants from the land surface to the upper surface of the shallowest aquifer. Ratings can range from one to 10, with 10 representing a highly sensitive area. Once all six model rating parameters were created and checked for quality, they were combined to create the final sensitivity assessment map.

In the Wyoming model, the aquifer sensitivity layer is created by adding the rating layers for each of the characteristic maps. Unlike the original DRASTIC model, equal weights were chosen for the model parameters.

Using equal weights of one, the final range of ratings on the composite aquifer sensitivity map can fall between six, if all of the parameters for an area receive a rating of one, and 60 in areas where the parameters are consistently very sensitive. Because a ground water vulnerability map employs a seventh parameter layer (land use) which also has a range of ratings from 1 to 10, the composite vulnerability layer will have a potential range from seven to 70.

References

- Ahern, J., Collentine, M., and S. Cooke. 1981. Occurrence and Characteristics of Ground Water in the Green River Basin and Overthrust Belt, Wyoming. Wyoming Water Resources Research Institute report to U.S. Environmental Protection Agency, vol. V-A.
- Aller, L., Bennett, T., Lehr, J.H., Petty, R., and G. Hackett. 1987. DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings. U.S. Environmental Protection Agency. EPA/600/S2-87/035. Cincinnati, Ohio.
- Barbash, J.E., and E.A. Resek. 1996. Pesticides in Ground Water: Distribution, Trends, and Governing Factors. Chelsea, Michigan: Ann Arbor Press.
- Berry, D.W. 1960. Geology and Ground Water Resources of the Rawlins Area, Carbon County, Wyoming. U.S. Geological Survey Water-Supply Paper 1458. Scale 1:63,360.
- Berry, D.W., and R.T. Littleton. 1961. Geology and Ground Water Resources of the Owl Creek Area, Hot Springs County, Wyoming. U.S. Geological Survey Water-Supply Paper 1519. Scale 1:63,360.
- Bradley, E. 1956. Geology and Ground Water Resources of the Upper Niobrara River Basin, Nebraska and Wyoming. U.S. Geological Survey Water-Supply Paper 1368. Scale 1:316,800.
- Burgess, T.M., and R. Webster. 1980. Optimal Interpolation and Isarithmic Mapping of Soil Properties: I. The Semi-Variogram and Punctual Kriging. *Journal of Soil Science*. 31:315-331.
- Case, J.C., and C.S. Arneson. 1998. Part III: Study of the Sensitivity of Aquifers to Contamination. Wyoming Geo-notes #60. Wyoming State Geological Survey, Laramie, Wyo.
- Case, J.C., Arneson, C.S., and L.L. Hallberg. 1998. Surficial Geology Map of Wyoming Digitally at 1:500,000 Scale. Wyoming State Geological Survey Hazards Section Digital Map 98-1. Wyoming State Geological Survey, Laramie, Wyo.
- Crist, M.A. 1974. Selenium in Waters in and Adjacent to the Kendrick Project, Natrona County, Wyoming. U.S. Geological Survey Water-Supply Paper 2023. Scale 1:62,500.
- Crist, M.A., and M.E. Lowry. 1972. Ground Water Resources of Natrona County, Wyoming. U.S. Geological Survey Water Supply Paper 1897. Scale 1:125,000.

- Collentine, M., Libre, R., and K.R. Feathers. 1981 . Occurrence and Characteristics of Ground Water in the Great Divide and Washakie Basins, Wyoming. Wyoming Water Resources Research Institute report to U.S. Environmental Protection Agency, vol. VI-A.
- Cooley, M.E., and M.A. Crist. 1994. Geohydrology of the High Plains Aquifer System, Cheyenne Urban Area, Wyoming. U.S. Geological Survey Water-Resources Investigations Report 92-4047. Various scales.
- Cox, E.R. 1976. Water Resources of Northwestern Wyoming. U.S. Geological Survey Hydrologic Investigations Atlas HA-558. Scale 1:250,000.
- Daly, C., R.P. Neilson, and D.L. Phillips, 1994: A Statistical-Topographic Model for Mapping Climatological Precipitation over Mountainous Terrain. *J. Appl. Meteor.*, 33,140-158.
- DeBruin, R.H. 1981a (1984 corrected version). Index map to U.S. Geological Survey Geologic Quadrangle Maps (GQ) in Wyoming. Wyoming State Geological Survey Map Series 9B. Scale 1:1,000,000.
- DeBruin, R.H. 1983a (1984 corrected version). Index to U.S. Geological Survey Hydrologic Investigations Atlases (HA) in Wyoming. Wyoming State Geological Survey Map Series 9E. Scale 1:1,000,000.
- DeBruin, R.H. 1983b (1985 corrected version). Index to U.S. Geological Survey Miscellaneous Investigations Maps (I) in Wyoming . Wyoming State Geological Survey Map Series 9D. Scale 1:1,000,000.
- DeBruin, R.H. 1983c. Index to U.S. Geological Survey Geologic Water-Supply Paper Maps in Wyoming. Wyoming State Geological Survey Map Series 9F. Scale 1:1,000,000.
- DeBruin, R.H. 1985a. Index to U.S. Geological Survey Circulars, Folios, and Annual Reports that Contain Geologic Maps for Wyoming. Wyoming State Geological Survey Map Series 9K. Scale 1:1,000,000.
- DeBruin, R.H. 1985b. Index to U.S. Geological Survey Oil and Gas Investigations Maps (OM) in Wyoming. Wyoming State Geological Survey Map Series 9I. Scale 1:1,000,000.
- DeBruin, R.H. 1985c. Index to U.S. Geological Survey Open-File Reports that Contain Geologic Maps for Wyoming. Wyoming State Geological Survey Map Series 9J. Scale 1:1,000,000.
- DeBruin, R.H., and P.L. Greer. 1986a. Index Map to Geologic Maps for Wyoming Included in 1928-1949 Graduate Theses from the University of Wyoming. Wyoming State Geological Survey Map Series 9N. Scale 1:1,000,000.
- DeBruin, R.H., and P.L. Greer. 1986b. Index Map to Geologic Maps for Wyoming Included in 1950-1959 Graduate Theses from the University of Wyoming. Wyoming State Geological Survey Map Series 9O. Scale 1:1,000,000.
- DeBruin, R.H., and P.L. Greer. 1986c. Index Map to Geologic Maps for Wyoming Included in 1960-1969 Graduate Theses from the University of Wyoming. Wyoming State Geological Survey Map Series 9P. Scale 1:1,000,000.
- DeBruin, R.H., and Greer, P.L. 1986d. Index Map to Geologic Maps for Wyoming Included in 1970-1979 Graduate Theses from the University of Wyoming. Wyoming State Geological Survey Map Series 9Q. Scale 1:1,000,000.
- Feathers, K.R., Libre, R., and T. R. Stephenson. 1981. Occurrence and Characteristics of Ground Water in the Powder River Basin, Wyoming. Wyoming Water Research Institute report to U.S. Environmental Protection Agency, vol. I-A.
- Freeze, R.A. and J.A. Cherry. 1979. Groundwater. Englewood Cliffs, N.J.: Prentice-Hall.
- Glass, G.B. 1981 (1984 corrected version). Index Map to U.S. Geological Survey Coal Resource Occurrence and Coal Development Potential Open-File Reports in Wyoming. Wyoming State Geological Survey Map Series 9A. Scale 1:1,000,000.

- Green, G.N. and P.H. Drouillard. 1994. The Digital Geologic Map of Wyoming in ARC/INFO Format. U.S. Geological Survey Open File Report 94-0425.
- Greer, P.L., and A.J. Ver Ploeg. 1989a. Index of Geological Survey of Wyoming Open File Reports that Contain Geologic Maps. Wyoming State Geological Survey Map Series 9M. Scale 1:1,000,000.
- Greer, P.L., and A.J. Ver Ploeg. 1989b. Index of Geological Survey of Wyoming Publications that Contain Geologic Maps, Excluding Open File Reports. Wyoming State Geological Survey Map Series 9L. Scale 1:1,000,000.
- Greer, P.L., and A.J. Ver Ploeg. 1989c. Index to Selected U.S. Geological Survey Bulletins that Contain Geologic Maps for Wyoming. Wyoming State Geological Survey Map Series 9G. Scale 1:1,000,000.
- Greer, P.L., and A.J. Ver Ploeg. 1989d. Index to Selected U.S. Geological Survey Professional Papers that Contain Geologic Maps for Wyoming. Wyoming State Geological Survey Map Series 9H. Scale 1:1,000,000.
- Hodson, W.G., Pearl, R.H., and S.A. Druse. 1973. Water Resources of the Powder River Basin and Adjacent Areas, Northeastern Wyoming. U.S. Geological Survey Hydrologic Investigations Atlas HA-465. Scale 1:250,000.
- Hudson, B.D. 1992. The soils survey as a paradigm-based science. *Soil Sci. Soc. Am. J.* 56:838-841.
- Jenny, H. 1941. *Factors of Soil Formation*. New York: McGraw-Hill.
- Kilburn, C. 1964. Ground Water in the Upper Part of the Teton Valley, Teton Counties, Idaho and Wyoming. U.S. Geological Survey Water-Supply Paper 1789. Scale 1:125,000.
- King, J.K., and A.J. Ver Ploeg. 1990. Index of Geologic Maps of Wyoming Included in 1980-1989 Graduate Theses and Dissertations from the University of Wyoming. Wyoming State Geological Survey Map Series 9Q. Scale 1:1,000,000.
- Kohout, F.A. 1957. Geology and Ground Water Resources of the Kaycee Irrigation Project, Johnson County, Wyoming. U.S. Geological Survey Water-Supply Paper 1360-E. Scale 1:31,680.
- Libra, R.D., Collentine, M., and K.R. Feathers. 1981. Occurrence and Characteristics of Ground Water in the Denver-Julesburg Basin, Wyoming. Wyoming Water Resources Research Institute report to U.S. Environmental Protection Agency, vol. VII-A.
- Libra, R., Doremus, D., and C. Goodwin. 1981. Occurrence and Characteristics of Ground Water in the Bighorn Basin, Wyoming. Wyoming Water Resources Research Institute report to U.S. Environmental Protection Agency, vol II-A.
- Lines, G.C., and W.R. Glass. 1975. Water Resources of the Thrust Belt of Western Wyoming. U.S. Geological Survey Hydrologic Investigations Atlas HA-539. Scale 1:250,000.
- Love, J. D. And A. C. Christiansen. 1985. *Geology of Wyoming*. Department of the Interior. U.S. Geologic Survey. Reston, VA.
- Love, J.D., Christiansen, A.C., and A.J. Ver Ploeg. 1993. Stratigraphic Chart Showing Phanerozoic Nomenclature for the State of Wyoming. Wyoming State Geological Survey Map Series 41.
- Lowry, M.E., Smalley, M.L., and others. 1993. Hydrology of Park County, Wyoming, Exclusive of Yellowstone National Park. U.S. Geological Survey Water-Resources Investigations Report.
- Lowry, M.E., Crist, M.A., and J.R. Tilstra. 1967. Geology and Ground Water Resources of Laramie County, Wyoming. U.S. Geological Survey Water-Supply Paper 1834. Scale 1:125,000.

- Lowry, M.E., and T.R. Cummings. 1966. Ground water Resources of Sheridan County, Wyoming. U.S. Geological Survey Water-Supply Paper 1807. Scale 1:125,000.
- Lowry, M.E., Rucker, S.J., and K.L. Wahl. 1973. Water Resources of the Laramie, Shirley, Hanna Basins and Adjacent Areas, Southeastern Wyoming. U.S. Geological Survey Hydrologic Investigations Atlas HA-471. Scale 1:250,000.
- Lowry, M.E., Lowham, H.W., and G.C. Line. 1976. Water Resources of the Bighorn Basin, Northwestern Wyoming. U.S. Geological Survey Hydrologic Investigations Atlas HA-512. Scale 1:250,000.
- Merchant, J.W., Whittemore, D.O., Whistler, J.L., McElwee, C.D., and J.J. Woods. 1987. Groundwater Pollution Hazard Assessment: A GIS Approach. Proceedings of the International Geographic Information Systems (IGIS) Symposium, Association of American Geographers. Washington, D.C., 3:103-115.
- Merchant, J.W. 1994. GIS-Based Groundwater Pollution Hazard Assessment: A Critical Review of the DRASTIC Model. Photogrammetric Engineering and Remote Sensing. 60(9).
- Merrill, E.H., Kohley, T.W., Herdendorf, M.E., Reiners, W.A., Driese, K.L., Marrs, R.W., and S.H. Anderson. 1996. Wyoming Gap Analysis: A Geographic Analysis of Biodiversity. Final Report, WY. Coop. Fish Wildlife Resources Unit, University of Wyoming, Laramie, WY.
- Morgan, C.O. and J.M. McNellis. 1965. TR-LL: A Program to Convert Township and Range Locations to Latitude and Longitude Coordinates for Wyoming. WY-K601 Kansas District Product, U.S. Geological Survey. (FORTRAN Computer Program)
- Morris, D.A., Hackett, O.M., Vanlier, K.E., and E.A. Moulder. 1959. Ground Water Resources of the Riverton Irrigation Project Area, Wyoming. U.S. Geological Survey Water-Supply Paper 1375. Scale 1:63,360.
- Morris, D.A., and H.M. Babcock. 1960. Geology and Ground Water Resources of Platte County, Wyoming. U.S. Geological Survey Water-Supply Paper 1490. Scale 1:125,000.
- Munn, L.C. and C.S. Arneson. 1998a. Soils of Wyoming: A Digital ARC/INFO Map at 1:500,000 Scale. Agricultural Experiment Station Report B-1069. University of Wyoming, College of Agriculture, Laramie, Wyo.
- Munn, L.C. and C.S. Arneson. 1998b. County Soils of Wyoming: Digital ARC/INFO Maps at 1:100,000 Scale. Agricultural Experiment Station Reports. University of Wyoming, College of Agriculture, Laramie, Wyo. Draft.
- Nolan, B.T., and K.A. Miller. 1995. Water Resources of Teton County, Wyoming, Exclusive of Yellowstone National Park. U.S. Geological Survey Water-Resources Investigations Report 95-4204.
- Ogle, K.M. 1992. Surface and Ground Water Quality in the Owl Creek Basin, North-Central Wyoming. U.S. Geological Survey Water-Resources Investigations Report 91-4108.
- Plafcan, M., Cassidy, E.W., and M.L. Smalley. 1993. Water Resources of Big Horn County, Wyoming. U.S. Geological Survey Water-Resources Investigations Report 93-4021.
- Plafcan, M., and K.M. Ogle. 1994. Water Resources of Hot Springs County, Wyoming. U.S. Geological Survey Water-Resources Investigations Report 93-4141.
- Plafcan, M., Eddy-Miller, C.A., Ritz, G.F., and J.P.R. Holland II. 1995. Water Resources of Fremont County, Wyoming. U.S. Geological Survey Water-Resources Investigations Report 95-4095.
- Rapp, J.R., Visher, F.N., and R.T. Littleton. 1957. Geology and Ground Water Resources of Goshen County, Wyoming. U.S. Geological Survey Water-Supply Paper 1377. Scale 1:43,560.
- Rapp, J.R., Warner, D.A., and A.M. Morgan. 1953. Geology and Ground Water Resources of the Egbert-Pine Bluffs-Carpenter Area, Laramie County, Wyoming. U.S. Geological Survey Water-Supply Paper 1140. Scale 1:95,000.

- Richards, C.J., Roaza, H., and R.M. Roaza. 1993. Integrating Geographic Information Systems and MODFLOW for Ground Water Resource Assessments. *Water Resources Bulletin*, 29(5).
- Richter, A.R. 1981a. Occurrence and Characteristics of Ground Water in the Laramie, Shirley, and Hanna Basins, Wyoming. Wyoming Water Resources Research Institute report to U.S. Environmental Protection Agency, vol. III-A.
- Richter, A.R. 1981b. Occurrence and Characteristics of Ground Water in the Wind River Basin, Wyoming. Wyoming Water Resources Research Institute report to U.S. Environmental Protection Agency, vol IV-A.
- Robinove, C.J., and D.W. Berry. 1963. Availability of Ground Water in the Bear River Valley, Wyoming. U.S. Geological Survey Water-Supply Paper 1539-V. Scale 1:63,360.
- Robinove, C.J., and T.R. Cummings. 1963. Ground Water Resources and Geology of the Lyman-Mountain View Area, Uinta County, Wyoming. U.S. Geological Survey Water-Supply Paper 1669-E. Scale 1:62,500.
- Robinove, C.J., and R.H. Langford. 1963. Geology and Ground Water Resources of the Greybull River-Dry Creek Area, Wyoming. U.S. Geological Survey Water-Supply Paper 1596. Scale 1:63,360.
- Soil Science Society of America. 1996. *Glossary of Soil Science Terms*. Soil Science Society of America: Madison, WI.
- Soil Survey Staff. 1975. *Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys*. USDA-SCS Agric. Handbook 436. U.S. Government Printing Office: Washington, D.C.
- Soil Survey Staff. 1996. *Keys to Soil Taxonomy*. USDA-NRCS. U.S. Government Printing Office: Washington, D.C.
- Soil Survey Division Staff. 1993. *Soil Survey Manual*. USDA Handbook 18. USDA Soil Conservation Service. U.S. Government Printing Office: Washington, D.C.
- Susong, D.D., Smalley, M.L., and E.R. Banta. 1993. *Water Resources of Washakie County, Wyoming*. U.S. Geological Survey Water-Resources Investigations Report 91-4044.
- Swenson, F.A.. 1957. *Geology and Ground Water, Heart Mountain and Chapman Bench Divisions, Shoshone Irrigation Project, Wyoming*. U.S. Geological Survey Water-Supply Paper 1418. Scale 1:84,270.
- U.S. Environmental Protection Agency (USEPA). 1993. *A Review of Methods for Assessing Aquifer Sensitivity and Ground-water vulnerability to Pesticide Contamination*. EPA 813-R-93-002. U.S. Environmental Protection Agency: Washington, D.C.
- Walker, E.H. 1965. *Ground Water in the Upper Star Valley, Wyoming*. U.S. Geological Survey Water-Supply Paper 1809-C. Scale 1:63,360.
- Weeks, E.P. 1964. *Hydrologic Conditions in the Wheatland Flats Area, Platte County, Wyoming*. U.S. Geological Survey Water-Supply Paper 1783. Scale 1:63,360.
- Welder, G.E., and L.J. McGreevy. 1966. *Ground Water Reconnaissance of the Great Divide and Washakie Basins and some Adjacent Areas, Southwestern Wyoming*. U.S. Geological Survey Hydrologic Investigations Atlas HA-219. Scale 1:250,000.
- Welder, G.E., and E.P. Weeks. 1965. *Hydrologic Conditions Near Glendo, Platte County, Wyoming*. U.S. Geological Survey Water-Supply Paper 1791. Scale 1:48,000.
- Whitcomb, H.A. 1965. *Ground Water Resources and Geology of Niobrara County, Wyoming*. U.S. Geological Survey Water-Supply Paper 1788. Scale 1:125,000.
- Whitcomb, H.A., Cummings, T.R., and R.A. McCullough. 1966. *Ground Water Resources and Geology of Northern and Central Johnson County, Wyoming*. U.S. Geological Survey Water-Supply Paper 1806. Scale 1:125,000.

Whitcomb, H.A., and M.E. Lowry. 1968. Ground Water Resources and Geology of the Wind River Basin Area, Central Wyoming. U.S. Geological Survey Hydrologic Investigations Atlas HA-270. Scale 1:250,000.

Whitcomb, H.A., and D.A. Morris. 1964. Ground Water Resources and Geology of Northern and Western Crook County, Wyoming. U.S. Geological Survey Water-Supply Paper 1698. Scale 1:96,000.

CHAPTER V: AQUIFER SENSITIVITY RESULTS

This chapter details results of the aquifer sensitivity mapping portion of the project, as well as the future directions of this effort.

SMALL-SCALE SENSITIVITY ANALYSIS

The aquifer sensitivity map for Wyoming is a product of the six individual parameters sensitivity rating maps discussed in Chapter IV. Grid overlay techniques were employed in the geographic information system (GIS) to combine the individual rating layers into a composite data layer. Integrating the characteristic layers required converting the three polygon-based layers (soils, geohydrologic setting, and vadose zone) from arc-node format to grid format with a 500-meter resolution. The result is a final product in raster or grid-cell form which can be contoured or classed as necessary.

Uniform Classification Scheme Development

The purpose in developing a small-scale (1:500,000-scale) state-wide sensitivity map was to better understand the range and distribu-

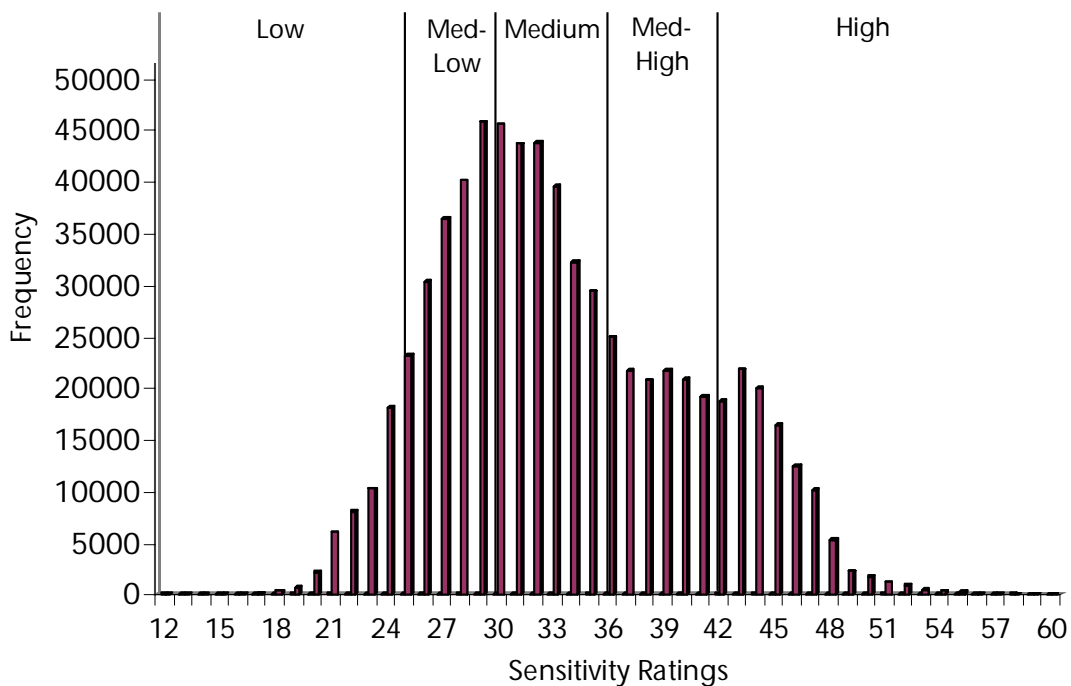


Figure V-1: Sensitivity ratings histogram

tion of sensitivity values across the state prior to a county-by-county analysis. Figure V-1 shows a histogram of the statewide rating value frequencies obtained. Potential values range from a minimum of 6 to maximum of 60; however, the actual range of aquifer sensitivity rating values for Wyoming was only 12 to 60. The histogram displays the total area within the state assigned to each sensitivity rating value. The histogram shows a positively skewed, weak bi-modal distribution, containing several lesser peaks as part of the two major peaks.

Wyoming Department of Environmental Quality (WDEQ) personnel proposed using a five-class categorization to aid in implementation of the final maps. Classes were then developed using a natural break categorization routine (Jenks 1977) applied to the sensitivity rating distribution. (This routine is readily available within ArcView GIS software.) The calculated classes capture the natural grouping of the ratings (low = 12-25, medium-low = 26-30, medium = 31-36, medium-high = 37-42, and high = 43 and above).

This initial analysis allowed a standard sensitivity classification to be developed and applied uniformly in all counties as they were completed. Without this first step, classification categories could not be compared across county boundaries.

Small-Scale Sensitivity Results

Figure V-2 delineates the aquifer sensitivity map for Wyoming into the five sensitivity rating classes. The highest rated lands (ratings above 42) are located primarily in the alluvial deposits adjacent to rivers, streams, and lakes or in the highly fractured mountainous belts that bound these basins. The alluvial areas' high ranking results from the combination of very shallow ground-water depths within independent alluvial aquifers, a deep layer of saturated material, very porous soils and geologic media, and extremely flat lands. The mountainous zones' high rankings come from heavily fractured bedrock, shallow soils, and a high natural recharge rate.

Medium-high ranked lands generally extend outward from the highly rated lands. These lands are mostly situated in alluvial materials or in mountain transition zones. The lower rating is likely due to an

increasingly deeper ground-water table, a smaller saturated media thickness and more mature soils exhibiting greater clay and loam content in the alluvial zones or a less fractured geologic base in the mountainous transition zones.

Medium-ranked lands are prevalent in the remaining areas of the agricultural zones of Wyoming. Dryland agricultural zones such as those in Laramie County fall almost completely within this range. These zones generally have deep, mature soils, rolling topography with mild slopes, and an increasing depth-to-initial-water table.

Medium-low-ranked lands generally occur in areas of low natural recharge resulting from low precipitation levels coupled with very deep water tables. Geologic formations underlying these areas are generally unfractured, and the topography is rolling. The majority of these areas occur within the structural basins of Wyoming such as the Green River Basin or the Great Divide Basin.

Low sensitivity-rated lands are commonly areas with ever-increasing depth-to-water, diminished vadose zone hydraulic conductivities, and stable geologic environments such as those found within the Green River Basin. Soils in these zones are generally poor for agriculture with very low precipitation levels.

INTERMEDIATE-SCALE COUNTY SENSITIVITY ANALYSES

A brief description of county-wide sensitivity will be included with each county appendice in this volume. Techniques used in the county analyses were identical to the statewide analysis but used more detailed data in most situations. The raster computations for these maps were conducted using 100-meter grid cells and therefore portray more detail in the final products. These maps should still be considered suitable for regional analysis but should never be assumed to be accurate for site-specific applications. Any analysis or decisions based on these 1:100,000-scale maps should be verified by an on-site inspection.

FUTURE DIRECTIONS

Aquifer sensitivity and ground water vulnerability concepts continue to evolve. Neither is an absolute property that can be measured directly. Instead, each provides a relative indication of where contamination is more likely to occur. Each must be inferred from measurable hydrogeologic characteristics (NRC 1993). That inference entails an inherent uncertainty in all assessments of aquifer sensitivity and ground-water vulnerability. However, if conducted in a scientifically rigorous manner, the results of these assessments can be useful tools for comprehensive ground-water resource management applications.

To continue this scientific progression of thought, additional research is planned on the products produced by this project to enhance or better understand their potential applications. The first effort will be a validation study that is currently underway and will analyze what statistical relationship exists between map results of this project and actual well monitoring data collected within recent years. By analyzing this statistical relationship, it is hoped that a better understanding of the relative importance of each parameter layer in determining the true vulnerability of ground water. In the future, research may focus on assessing ground-water vulnerability to additional land uses such as municipal landfills and industrial zoning among others.

References

- Jenks, G.F. 1977. Optimal Data Classification for Choropleth Maps. University of Kansas Department of Geography Occasional Paper No. 2. Lawrence, Kansas.
- National Research Council (NRC). 1993. *Ground Water Vulnerability Assessment: Predicting relative contamination potential under conditions of uncertainty*. Washington, D.C.: National Academy Press.

CHAPTER VI: APPLICATIONS AND DATA AVAILABILITY

To properly use the products created by this project, a person must understand both the proper applications and more importantly, the limitations of these products. Details on availability of digital and non-digital mapping products is also provided.

LIMITATIONS

It is important to understand the limitations associated with the sensitivity analysis layers and maps. The sensitivity map portrays a relative ranking of susceptibility to ground water contamination. Thus the sensitivity values can only be used to evaluate one location with respect to another and do not represent an absolute sensitivity quantity. Due to differing methodologies, the Wyoming sensitivity values cannot be compared across state boundaries or with other areas that have undergone similar studies.

In addition, the sensitivity data layers were produced for regional-scale analysis only. Most data layers were developed at a 1:100,000 scale in which local characteristic detail was generalized. Because the geohydrologic factors affecting aquifer sensitivity can vary dramatically over very short distances, it should be recognized that such variations may not be fully represented at this intermediate-scale mapping level. Consequently, the sensitivity results are not appropriate for use in site-specific applications. For example, a localized deposit of

Map scale issues

This chapter refers to appropriate uses of the handbook map products. Understanding geographic scale in terms of these appropriate uses is critical.

“Regional-scale,” for example, which is an appropriate scale at which to use the maps produced by this project, refers to non-site-specific applications. This scale identifies general areas that have similar hydrogeological characteristics while recognizing that some small areas within the larger area may be significantly different. Therefore, each specific area of interest should be investigated on-site before a management decision is made.

“Site-specific” mapping or analysis, which these products are not suitable for, describes products that could be used to describe a definite attribute on the land surface. Decisions could then be made with near certainty without the step of verifying the attributes on the ground.

porous material contained within an otherwise impermeable region would not be reflected in the location's relatively low sensitivity rating even though this feature could potentially contribute significantly to the movement of water and transport of introduced contaminants. It is also possible in certain areas of the state that a single factor may dominate the hydrogeologic environment to such a degree that other contributing factors are inconsequential in calculating a ratings value for such locations.

These maps can not identify existing ground water contamination in the state nor can they absolutely predict areas of future contamination. The likelihood of contamination within an area depends on many factors including potential for contaminant release, the type of contaminants released, and the quantity of these releases. The sensitivity maps reflect only the relative ability of these contaminants to move from the land surface to the uppermost aquifer.

The methods used in the sensitivity analysis can not adequately compensate for the scenarios described above. Once again, while the sensitivity data layers and resulting map products will prove valuable in regional assessments of aquifer systems, preliminary site selections, and general planning efforts, expectations of the value of these layers at the local scale (< 1:100,000-scale) are misguided. Users must remember that a low sensitivity rating is not an invitation for uncontrolled land use practices. Low ratings merely suggest there is a lower probability for contamination relative to higher rated areas, given the same land use practices. Few ground water resources will avoid contamination if they are subjected to improper land use practices. If a high-risk land use practice must be applied to any area, it should only be done after an analysis of subsurface conditions confirms that the practice will not adversely affect Wyoming's ground water resource.

AQUIFER SENSITIVITY AND GROUND WATER VULNERABILITY MAPPING APPLICATIONS

Resource Planning and Management

Statewide Management Plan for Pesticides

The primary intent in developing statewide and county-by-county aquifer sensitivity maps was to meet certain objectives of Wyoming's Generic Statewide Management Plan (SMP) for Pesticides in ground water including:

- development of a means to identify geographic areas where ground water is susceptible (i.e. ground water vulnerability maps) to effects of pesticides applied at the surface; and
- monitoring of groundwater to provide a reasonable likelihood that contamination (from pesticides leaching to ground water) representing an unreasonable risk to the environment will not go undetected (GPSC 1997).

More information on Best Management Practices available

Best Management Practices (BMPs) for the application, storage and disposal of pesticides are included as Appendix J of Wyoming's State Management Plan (SMP), available through regional offices of WDA and WDEQ (GPSC 1997).

Aquifer sensitivity maps can be used to determine areas where conditions appear to be most conducive for pesticide leaching to ground water. Because sensitivity maps readily identify geographic areas where ground water is most likely to have been affected by the leaching of pesticides, they can be used to direct and focus ground water monitoring resources most effectively and efficiently. Without such tools, the design (i.e., siting and construction) of ground water monitoring networks is potentially more subjective in nature, with resources directed toward monitoring ground water in inappropriate areas or locations.

Wyoming's SMP also requires descriptions of how detections of pesticides in ground water will be addressed or responded to. In those instances where pesticides have been detected in ground water at allowable levels, state agencies will coordinate with local partners to discuss options for implementing pesticide Best Management Practices (BMPs) and educational programs to reduce pesticide leaching to

ground water. Where pesticides have been detected in ground water at unacceptable levels, state agencies will use appropriate authorities

to protect ground water users and restore ground-water quality to acceptable conditions.

Both aquifer-sensitivity and ground water vulnerability maps can be used to identify areas in which pesticides should be managed with the utmost care. Vulnerability maps identify and illustrate geographic areas where ground water may be most suscep-

Interested in wellhead protection?

Copies of Wyoming's Wellhead and Source Water Protection Guidance Document, designed to assist communities in developing local Wellhead Protection Plans, are available at all regional WDEQ offices, as well as on the Internet at WDEQ's home page <http://DEQ.state.wy.us>.

tible to effects from the leaching of pesticides by coupling the degree of sensitivity of the aquifer, with existing land use and pesticide application. Such knowledge provides state agencies, weed and pest districts, and their local partners with an understanding of where to focus and direct education and use of BMPs relating to pesticide use, storage, and disposal in order to minimize or eliminate the potential for pesticides to leach into ground water.

Wellhead and Source Water Protection Planning

Many Wyoming communities have established Wellhead or Source Water Protection Committees to develop and implement local Wellhead or Source Water Protection plans to protect their drinking water supplies from existing and potential contaminant sources that lie within their well or source water area (WWPSC 1997). The success of such plans usually depends upon the effectiveness of implementing educational programs, management practices, and local controls to minimize or reduce the potential for toxic

Help for rural homeowners

WDEQ has developed a series of Rural Wellhead Protection Fact Sheets and Work Sheets for rural homeowners to use in evaluating the potential for well or wellfield contamination and tips for properly siting, protecting, developing, and abandoning rural wells. Copies are available at WDEQ regional offices, as well as, on the Internet at <http://DEQ.state.wy.us>.

substances to be released into the aquifer and potentially impair the drinking water supply. Wellhead and source water protection plans also include contingency measures in the event of a disruption to the water supply system and important factors to consider when evaluating sites for new wells or surface water intakes.

Pesticides in Wyoming Ground Water

USGS has established a special web page dedicated to presenting valuable information regarding pesticide sampling of ground water. Results, fact sheets, and related information can be accessed at <http://wy.water.usgs.gov/projects/pests/pesticides.html>.

The majority of rural homeowners within Wyoming also rely upon ground water for drinking water and other domestic uses as well as to irrigate crops and provide water for livestock. Frequently, these water supplies are drawn from shallow, uppermost aquifers. Most rural homeowners are interested in ensuring that the quality of the ground water they use remains suitable for their continued use. As with communities, aquifer sensitivity maps can be used to illustrate and identify rural areas where the uppermost aquifer is most susceptible to the release of a potential toxic substance at or near the ground's surface. Knowing where the sensitive areas lie with respect to the location of the private well, rural homeowners can evaluate whether potential sources of contamination (e.g., fuel tanks, fertilizer/pesticide/hazardous substance application and storage areas, animal confinement areas, septic systems) are likely to impair ground water quality in the event of an accident or system failure.

Underground Injection Control

The Wyoming Department of Environmental Quality, Water Quality Division (WDEQ/WQD) is responsible for managing the state's Underground Injection Control (UIC) program, with oversight of facilities injecting fluids into the subsurface (Osborne 1991). Aquifer sensitivity data layers and ratings results are being incorporated into a vulnerability assessment effort addressing potential contamination related to Class V (shallow) injection facilities (UIPC 1990). UIC vulnerability issues will be addressed in Volume III of this handbook.

Statewide Water Planning

The Wyoming Water Development Commission (WWDC) is currently leading an effort addressing the need to update the state's water planning process. Combined with data on ground water use permits, aquifer storage, yield potential, and monitoring site information, the aquifer sensitivity data products should prove to be valuable components of the comprehensive basin plans proposed for completion with the process's implementation.

Other Planning and Management Applications

Watershed Management

Aquifer sensitivity maps and their associated products can be used for watershed planning and management by many of the state's conservation districts. A pilot study sponsored by the Wyoming Association of Conservation Districts (WACD) and funded by Section 319 of the U.S. Environmental Protection Agency (EPA) Non-Point Source Section is currently underway which will implement geographic information system (GIS)-based planning tools to aid in decision making at the conservation district level.

Local Land-Use Planning

Aquifer sensitivity maps can be used to illustrate and identify areas within wellhead or source water protection areas where the uppermost aquifer is most susceptible to the release of a potential toxic substance at or near the ground's surface. By using sensitivity ratings for these areas, citizens, local government officials, city/county planners, and public water supply (PWS) operators can begin to evaluate existing and potential contaminant sources (point and non-point) to decide whether existing land use plans, local controls, and management practices are adequate and appropriate to protect drinking water quality.

Facilities Management and Industrial Siting

Many businesses and industries handle, store, and dispose of potentially toxic substances and wastes as part of their day-to-day operations. More often than not, these activities are performed in a responsible manner with no adverse effects upon ground water sup-

plies. When problems do arise, they are frequently a result of equipment or system failure, accidents, or human error, all of which are difficult to anticipate or prevent.

Business and industry can use aquifer sensitivity maps to determine the relative degree to which their operations may potentially threaten ground water quality in the event of a toxic release. Sensitivity maps can be used by operators to evaluate the adequacy of existing pollution prevention measures and, if necessary, initiate plant and equipment upgrades, training programs, monitoring plans, and contingency plans to minimize the potential for adversely affecting ground water supplies, disrupting drinking-water supplies, or assuming environmental liability for cleanup.

Sensitivity maps are also useful tools for businesses and industries when planning expansions of operations, relocating operations, and siting new facilities. Given the choice, some operators might prefer to focus their activities on or in areas where ground water is least sensitive and the risk of impacting ground water supplies is minimized.

INFORMATION TRANSFER AND EDUCATION

By contributing new information on the susceptibility of aquifers to potential contamination, the handbook will serve as a valuable educational tool for helping Wyoming's citizens better understand the state's ground water resources. Transfer of sensitivity mapping results to the public through outreach programs such as WDEQ's Pollution Prevention Program, the Wyoming Association of Conservation Districts (WACD), and the Wyoming Cooperative Extension Service is critical to ensuring the greatest utility of the digital and non-digital map products. Such knowledge will provide land owners with an opportunity to recognize and evaluate areas for implementation of BMPs. In effect, sensitivity and vulnerability maps can be used with local knowledge of existing and potential sources of contamination (e.g., leaking underground tanks, septic systems, landfills, fertilizer/pesticide application areas) to begin to evaluate the question "Are we doing enough to protect our source of drinking water?" By informing the public of the

products' existence and potential use, citizens can address concerns as to whether the aquifer which supplies their drinking water is susceptible to contamination from a toxic substance released at the ground's surface.

Other nontraditional educational programs are being explored within Wyoming which utilize products from the Wyoming Ground Water Vulnerability Mapping Project. For example, several sensitivity products are being introduced into the elementary school classrooms of the state by the Earth System Science Information Project (ESSIP) at the University of Wyoming (McClurg and Lerner 1998). By providing young children with digital natural resources information, ESSIP enhances students' spatial awareness as well as scientific inquiry. Products of the aquifer sensitivity project are also being incorporated into the Spatial Data and Visualization Center's (SDVC) Wyoming Internet Map Server (WIMS). This internet site (<http://wims.sdvc.uwyo.edu>), utilizing the latest internet mapping technology, seeks to put the economic and natural resources data available for Wyoming readily in the hands of businesses, researchers, managers, educators, and the general public to allow for better informed decisions.

REGIONAL OUTREACH AND TRAINING WORKSHOPS

To help increase awareness of the potential utility of the sensitivity/vulnerability mapping products, SDVC is developing workshop materials and management application exercises based on the analyses described in this handbook. Plans call for presentation of these materials through a series of on-site regional events targeting area resource managers and open to the general public. Six one- to two-day workshops are currently being planned for presentation at regional community colleges or similar venues in Summer and Fall 1999.

AVAILABILITY OF DIGITAL AND NON-DIGITAL MAPPING PRODUCTS

Copies of all digital and non-digital mapping products and their supporting documentation have been provided to the WDEQ/WQD as well as the State Engineer's Office (SEO) Water Library in Cheyenne and

the Water Resources Data System (WRDS) Water Library at the University of Wyoming. In addition, copies of these materials will be provided to designated local resource management entities in each county.

Additional copies of all non-digital products (including paper maps and this handbook) are available for purchase from the SDVC for the costs of reproduction. (See Appendix D for product details and pricing.) Digital copies of this handbook as well as all GIS data layers and map plot files are available at no charge via the Internet at SDVC's world wide web site (<http://www.sdvc.uwyo.edu>). The GIS products have also been bundled by county on a personal computer compact disc (CD) medium (Appendix D).

References

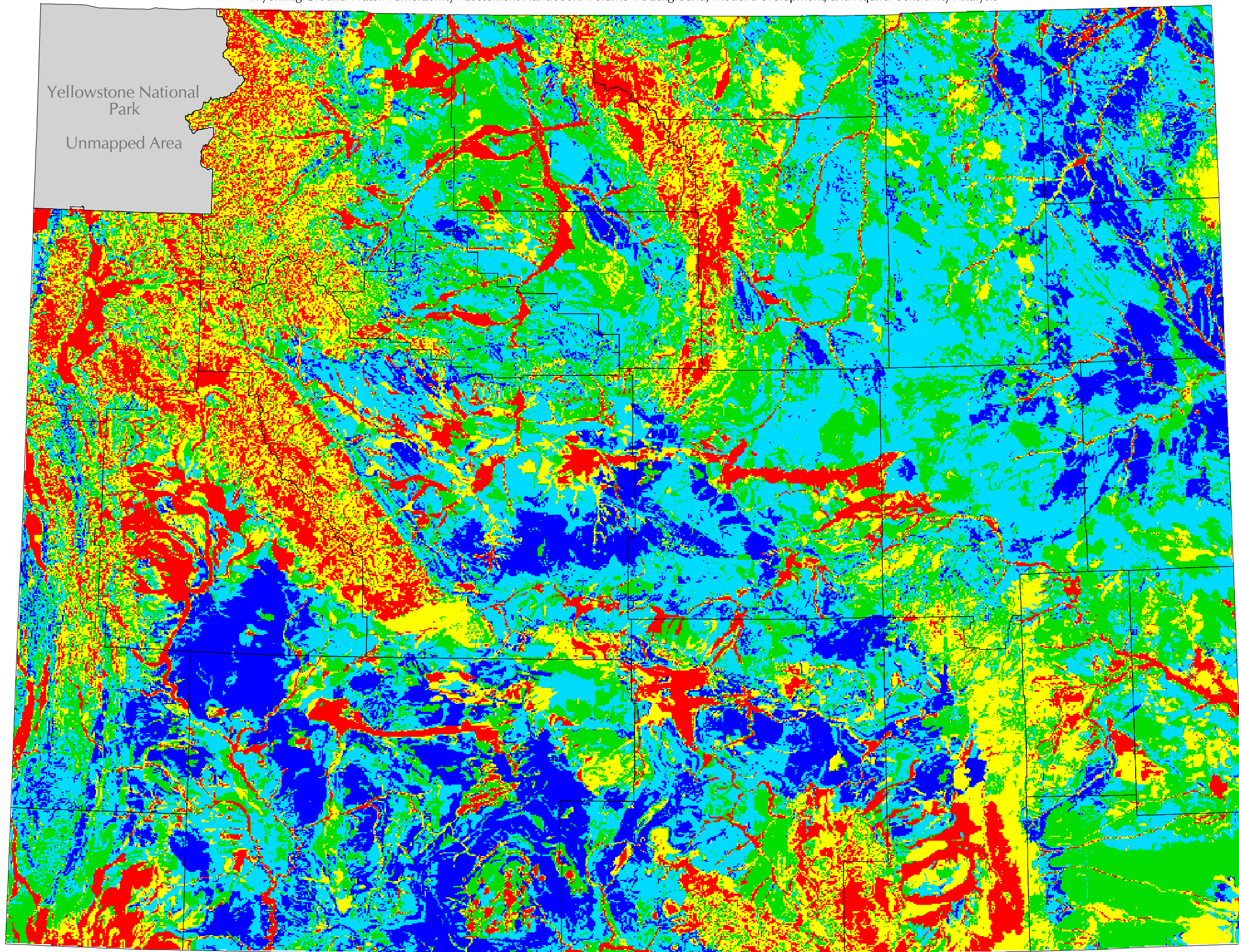
Ground Water and Pesticides Strategy Committee (GPSC). 1997. "Generic State Management Plan for Pesticides in Ground Water for the State of Wyoming" (Draft). Cheyenne, Wyo.

McClurg, P.A. and H.E. Lerner. 1998. Earth System Science Internet Project Widens Wyoming Students' World. *Geo Info Systems*: 8(3)34-37.

Osborne, P.S. 1991. *Program overview: Underground injection control, Region VIII*. U.S. Environmental Protection Agency: Denver, CO.

Underground Injection Practices Council (UIPC). 1990. *Injection wells: An introduction to their use, operation, and regulation*. Underground Injection Practices Council: Oklahoma City, Okla.

Wyoming Wellhead Protection Strategy Committee (WWPSC). 1997. "Wyoming State Wellhead Protection Plan" (Draft). Cheyenne, Wyo.



Aquifer Sensitivity

- Low
- Medium
- High



0 30 60 Miles

Produced by the Wyoming Water Resources Center, University of Wyoming, and the Wyoming State Geological Survey in cooperation with the Wyoming Department of Environmental Quality / Water Quality Division, Wyoming State Engineer's Office and the US Environmental Protection Agency



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APPENDIX A: PRINCIPAL PROJECT PERSONNEL

Arneson, Christopher S., *Research Scientist, Spatial Data and Visualization Center (formerly with Wyoming Water Resources Center), University of Wyoming.* GIS database development, manipulation, and analysis, digital cartographic design and production.

Case, James C., *Hazards Geologist, Wyoming State Geological Survey.* Surficial geology, geohydrologic environment, vadose zone characterization.

Frederick, Kevin D., *Groundwater Pollution Control Program Supervisor, Wyoming Department of Environmental Quality, Water Quality Division.* Ground water pollution prevention and management applications, project guidance.

Gloss, Steven P., *Associate Professor, Department of Zoology and Physiology (former Director of Wyoming Water Resources Center), University of Wyoming.* Project administration.

Gribb, William J., *Associate Professor, Department of Geography and Recreation, University of Wyoming.* GIS database design, cropland mapping.

Hamerlinck, Jeffrey D., *Technical Coordinator and Research Scientist, Spatial Data and Visualization Center (former GIS coordinator of Wyoming Water Resources Center), University of Wyoming.* Project Supervision, GIS analysis and results interpretation.

Hasfurther, Victor R., *Professor and Head, Department of Civil and Architectural Engineering, University of Wyoming.* Aquifer recharge.

Huntoon, Peter W., *Chair, Department of Environmental Studies, University of Nevada, Las Vegas (formerly Professor Department of Geology and Geophysics, University of Wyoming).* Geohydrologic setting, depth-to-water determination.

Marrs, Ronald W., *Professor, Department of Geology and Geophysics, University of Wyoming.* Surficial geology.

Munn, Larry C., *Professor, Department of Renewable Resources, University of Wyoming.* Soils, recharge.

Needham, Scott, *former GIS Coordinator and Research Scientist, Wyoming Water Resources Center, University of Wyoming.* Project supervision. Model parameter manipulation.

Wireman, Michael, *Hydrogeologist, Region VIII Ecosystem Protection Program, U.S. Environmental Protection Agency.* Project guidance.

APPENDIX B: METHODOLOGY FOR COUNTY MAPPING PRIORITIZATION

INTRODUCTION

One of the major objectives in conducting an initial pilot study for the Wyoming Ground Water Vulnerability Mapping Project was to design and undertake a feasibility assessment to determine and prioritize areas of the state where aquifer-sensitivity and ground water vulnerability mapping should proceed. The prioritization determinations considered both availability of selected digital data layers for sensitivity model parameter input, as well as county pesticide use estimations required for vulnerability assessment. The following narrative discusses the information used, the procedures employed, and the results generated in carrying out this feasibility study.

DATA INPUTS

The data sources involved in the prioritization were selected from sensitivity model parameter inputs and from data sources identified as vulnerability, or contamination potential indicators. Input scales of the data considered ranged from 1:24,000 to 1:1,000,000.

The data layers identified as inputs to assessment of aquifer sensitivity include bedrock geology, surficial geology, wells, streams, elevation, and precipitation (Chapter IV). The prioritization determination focused specifically on the bedrock and surficial geology layers, due to their importance in deriving many of the sensitivity model parameters.

At the time that the prioritization determinations were made, digital bedrock and surficial geology data layers existed for areas of the state in varying scales and resolutions. For this analysis, each source was ranked according to its input scale or resolution. Data layers of a scale larger than 1:100,000 received a higher score (three), while maps at smaller scales (e.g., 1:500,000) received a lower score (one).

The information initially considered as contamination potential indicators included major land use category delineations and aquifer material characterization (Table B-1).

Table B-1 : Map feature ground-water contamination potential ranking

<i>Map Feature</i>		<i>Ranking</i>
Irrigated Cropland		5
Dryland Agriculture		2
Urban Areas		5
Aquifer Materials*	Valley Alluvia	5
	Terrace Alluvia	4
	Glacial Deposits	3
	Late, Middle, and Early Tertiary Deposits	2
	Cretaceous Permian, Pennsylvanian/Cambrian and Pre-Cambrian	1

* Assigned a ranking between 1 and 5 based upon inherent capacity to transport pollutants

ANALYSIS

Identification of Vulnerable Areas

Assigning a quantitative rank to both sensitivity and vulnerability prioritization data sources enabled a framework for ordinal-based analysis using geographic information system (GIS)-based map overlay techniques. Characterization of available geologic data was obtained by assigning normalized ranking scores of one to three across the state. Results indicated that large portions of the state lacked digital surficial geology map data. Moderate rankings are interspersed throughout the state. High rankings were focused in the coal mining regions of northeastern Wyoming. Cumulative land use and aquifer material rankings were also normalized to a score of one to three, with high values concentrated in lands overlying alluvial or terraced aquifers.

The next step in the prioritization analysis combined the sensitivity and vulnerability rankings to generate a composite data layer map depicting the occurrence of both sensitivity data availability and areas of potentially vulnerable ground water. High scores indicated areas of higher vulnerability and the presence of the information required to carry out ground water vulnerability mapping. Low scores indicated areas of low vulnerability and the absence of needed data. Scores were normalized from one to five, with five being the most efficient locations for continuing aquifer sensitivity and ground water

vulnerability mapping and one being the least efficient. A few areas around the state where extensive pesticide application areas overlay shallow alluvial aquifers received a rank of five. The most obvious concentrations are located in the Big Horn Basin along the Greybull and Bighorn Rivers and Owl Creek, Star Valley, Platte County surrounding Wheatland, and Goshen County along the North Platte River.

The following formula was employed to rank areas within the state to be mapped upon completion of the Goshen County pilot study. The ranking was based at the county level and used information on the extent of cropland and urban areas in the county and the volume of pesticides applied within the county. The analysis used only the pesticides 2,4-D, Aldicarb, Atrazine, Alachlor, Picloram, and Dicamba, which were chosen from the pesticide evaluation list in the statewide management plan (SMP) for pesticides (GPSC 1997). Weights were assigned in the formula based upon the intensity of chemical use on cropland and urban areas. The formula assumes that irrigated cropland and urban land receive higher rates of pesticide application and, as a result, are more prone to leaching chemicals to the ground water. Chemical data used in the analysis were obtained from a draft copy of the Pesticide Evaluation List compiled by Lars Baker (1991).

$$\begin{aligned}
 U_{\text{rbanindex}} &= C_{\text{hemintense}} \times U_{\text{rbanwt}} \times U_{\text{rbanarea}} \times \\
 I_{\text{rrindex}} &= C_{\text{hemintense}} \times I_{\text{rrwt}} \times I_{\text{rrarea}} \times C_{\text{hemr}} \\
 D_{\text{ryindex}} &= C_{\text{hemintense}} \times D_{\text{rywt}} \times D_{\text{ryarea}} \times C_{\text{hemr}} \\
 I_{\text{ndex}} &= \frac{(U_{\text{rbanindex}} + I_{\text{rrindex}} + D_{\text{ryindex}})}{1,000}
 \end{aligned}$$

The pesticide use intensity formula resulted in the ranking of counties based on the calculated index shown in Table B-3.

SUMMARY

The relative county rankings generated from the pesticide use intensity formula were used to prioritize sensitivity and vulnerability mapping efforts beyond the Goshen County pilot study. (In fact, Goshen County ranked third in priority for mapping in this determination, behind Washakie and Park

Table B-2: County-based ground-water vulnerability code explanations and defaults

<i>Term</i>	<i>Explanation</i>
INDEX	Final index value relating chemical application intensity to land use
URBANINDEX	Urban index value relating chemical application intensity to urban land use
IRRINDEX	Irrigated agriculture index value relating chemical application intensity to irrigated agriculture land use
DRYINDEX	Dryland agriculture index value relating chemical application intensity to dryland agriculture land use
CHEMINTENSE	Intensity of total chemical use on all possible chemical use lands, including irrigated and dryland agriculture lands and urban land
URBANWT	Urban weight assigned to reflect urban chemical use (Default = 6)
IRRWT	Irrigation agriculture weight assigned to reflect irrigated agriculture chemical use (Default = 4)
DRYWT	Dryland agriculture weight assigned to reflect irrigated agriculture chemical use (Default = 1)
URBANAREA	Total urban area per county
IRRAREA	Total irrigation agriculture area per county
DRYAREA	Total dryland agriculture area per county
CHEMRATIO	The ratio of the six above identified chemicals to all chemicals

counties in central and northwest Wyoming.) The initial goal in prioritizing the counties was to determine how best to utilize limited funding resources, while still addressing areas with high contamination potential. Original plans called for delineating agriculturally-intense 7.5' map quadrangles for priority mapping within each county. However, efforts were expanded to countywide when an economy of scales was achieved during development of many of the digital base data layers. It should also be noted that the prioritization process determined a need for more intermediate-scale surficial geology and soils information in Wyoming. Consequently, the original mapping project was modified to include development of new statewide digital surficial geology and soils map data products.

At the time of this publication, county-wide sensitivity and vulnerability analyses are being completed in the order of their prioritization. Completion

Table B-3 : County rankings based on pesticide use index

<i>Rank</i>	<i>County</i>	<i>Index</i>	<i>Rank</i>	<i>County</i>	<i>Index</i>
1	Washakie	590.45	13	Natrona	14.27
2	Park	200.17	14	Teton	*4.58
3	Goshen	176.37	15	Sweetwater	*7.74
4	Fremont	146.11	16	Uinta	22.53
5	Lincoln	74.31	17	Albany	21.17
6	Laramie	63.47	18	Converse	19.31
7	Big Horn	62.34	19	Hot Springs	16.46
8	Sheridan	58.44	20	Carbon	15.07
9	Platte	47.23	21	Campbell	12.43
10	Johnson	31.75	22	Sublette	9.26
11	Crook	28.36	23	Niobrara	3.39
12	Weston	*12.84			

* Weston, Natrona, Teton and Sweetwater have been elevated in ranking as per instruction by Wyoming DEQ, Water Quality Division based upon the knowledge of existence of pesticides in ground water.

of all county results is anticipated by summer 1999 and will be incorporated as appendices in Volumes I (aquifer sensitivity results) and II (ground water vulnerability results) of this handbook.

References

Baker, L. 1991. Pesticide Evaluation List. Unpublished Appendix to Statewide Management Plan. (Draft).

Ground Water and Pesticides Strategy Committee (GPSC). 1997. "Generic State Management Plan for Pesticides in Ground Water for the State of Wyoming" (Draft). Cheyenne, Wyoming.

APPENDIX C: METADATA DOCUMENTATION FOR DIGITAL LAYERS

Bedrock Geology	C-3
Surficial Geology	C-7
Well Permits	C-23
Hydrography	C-29
Digital Elevation Model	C-43
Precipitation	C-51
Public Land Survey System	C-59
County Boundaries	C-69
Roads	C-75
Depth to Initial Ground Water (1:500,000)	C-81
Depth to Ground Water Sensitivity Ratings (1:500,000)	C-89
Depth to Initial Ground Water (1:100,000)	C-97
Depth to Ground Water Sensitivity Ratings (1:100,000)	C-105
Geohydrologic Setting Sensitivity Ratings	C-113
Soils (1:500,000)	C-125
Soils Sensitivity Ratings (1:500,000)	C-141
Soils (1:100,000)	C-147
Recharge (1:500,000)	C-155
Recharge Sensitivity Ratings (1:500,000)	C-165
Recharge (1:100,000)	C-171
Slope	C-179
Slope Sensitivity Ratings	C-185
Vadose Zone Ratings	C-193

APPENDIX D: PRODUCT DETAILS AND PRICING

To make the data provided by this project more useful to the public, the Spatial Data and Visualization Center has constructed a number of products that can be ordered for the price of their reproduction and shipping. When ordering from these lists, please ensure that the product you are interested in is clearly marked on the order form and that the check or money order is made out to Spatial Data and Visualization Center.

Remit these payments to:

Spatial Data and Visualization Center
University of Wyoming
P.O. Box 4008
University Station
Laramie, Wyoming 82071

To order by phone, call (307) 766-2532.

To order by fax, dial (307) 766-2744.

Product Name	Product Number	Price	Quant.	Total
Volume 1: Background Model Development and Aquifer Sensitivity Analysis		\$20.00		
Vol. 1 County Appendices	Washakie County	Appendix 1-E-1	\$5.00	
	Park County	Appendix 1-E-2	\$5.00	
	Goshen County	Appendix 1-E-3	\$5.00	
	Fremont County	Appendix 1-E-4	\$5.00	
	Lincoln County	Appendix 1-E-5	\$5.00	
	Laramie County	Appendix 1-E-6	\$5.00	
	Big Horn County	Appendix 1-E-7	\$5.00	
	Sheridan County	Appendix 1-E-8	\$5.00	
	Platte County	Appendix 1-E-9	\$5.00	
	Johnson County	Appendix 1-E-10	\$5.00	
	Natrona County	Appendix 1-E-11	\$5.00	
	Uinta County	Appendix 1-E-12	\$5.00	
	Sweetwater County	Appendix 1-E-13	\$5.00	
	Campbell County	Appendix 1-E-14	\$5.00	
	Teton County	Appendix 1-E-15	\$5.00	
	Crook County	Appendix 1-E-16	\$5.00	
	Weston County	Appendix 1-E-17	\$5.00	
	Albany County	Appendix 1-E-18	\$5.00	
	Converse County	Appendix 1-E-19	\$5.00	
	Hot Springs County	Appendix 1-E-20	\$5.00	
	Carbon County	Appendix 1-E-21	\$5.00	
	Sublette County	Appendix 1-E-22	\$5.00	
	Niobrara County	Appendix 1-E-23	\$5.00	
Total, Vol. 1				

Product Name	Product Number	Price	Quant.	Total
Volume 2: Ground Water Vulnerability to Pesticides		\$5.00		
Vol. 2 County Appendices	Washakie County	Appendix 2-D-1	\$5.00	
	Park County	Appendix 2-D-2	\$5.00	
	Goshen County	Appendix 2-D-3	\$5.00	
	Fremont County	Appendix 2-D-4	\$5.00	
	Lincoln County	Appendix 2-D-5	\$5.00	
	Laramie County	Appendix 2-D-6	\$5.00	
	Big Horn County	Appendix 2-D-7	\$5.00	
	Sheridan County	Appendix 2-D-8	\$5.00	
	Platte County	Appendix 2-D-9	\$5.00	
	Johnson County	Appendix 2-D-10	\$5.00	
	Natrona County	Appendix 2-D-11	\$5.00	
	Uinta County	Appendix 2-D-12	\$5.00	
	Sweetwater County	Appendix 2-D-13	\$5.00	
	Campbell County	Appendix 2-D-14	\$5.00	
	Teton County	Appendix 2-D-15	\$5.00	
	Crook County	Appendix 2-D-16	\$5.00	
	Weston County	Appendix 2-D-17	\$5.00	
	Albany County	Appendix 2-D-18	\$5.00	
	Converse County	Appendix 2-D-19	\$5.00	
	Hot Springs County	Appendix 2-D-20	\$5.00	
	Carbon County	Appendix 2-D-21	\$5.00	
	Sublette County	Appendix 2-D-22	\$5.00	
	Niobrara County	Appendix 2-D-23	\$5.00	
Total, Vol. 2				

Vol. 1 Individual Large-Format Maps (1:100,000-scale / approx. 34" x 44")

Please check each box of interest

		Properties													
		Depth		Slope		Soils		Recharge		Sensitivity		Land Use		Vulnerability	
County	Washakie	SDVC-1AA		SDVC-1AB		SDVC-1AC		SDVC-1AD		SDVC-1AE		SDVC-1AF		SDVC-1AG	
	Park	SDVC-1BA		SDVC-1BB		SDVC-1BC		SDVC-1BD		SDVC-1BE		SDVC-1BF		SDVC-1BG	
	Goshen	SDVC-1CA		SDVC-1CB		SDVC-1CC		SDVC-1CD		SDVC-1CE		SDVC-1CF		SDVC-1CG	
	Fremont	SDVC-1DA		SDVC-1DB		SDVC-1DC		SDVC-1DD		SDVC-1DE		SDVC-1DF		SDVC-1DG	
	Lincoln	SDVC-1EA		SDVC-1EB		SDVC-1EC		SDVC-1ED		SDVC-1EE		SDVC-1EF		SDVC-1EG	
	Laramie	SDVC-1FA		SDVC-1FB		SDVC-1FC		SDVC-1FD		SDVC-1FE		SDVC-1FF		SDVC-1FG	
	Big Horn	SDVC-1GA		SDVC-1GB		SDVC-1GC		SDVC-1GD		SDVC-1GE		SDVC-1GF		SDVC-1GG	
	Sheridan	SDVC-1HA		SDVC-1HB		SDVC-1HC		SDVC-1HD		SDVC-1HE		SDVC-1HF		SDVC-1HG	
	Platte	SDVC-1IA		SDVC-1IB		SDVC-1IC		SDVC-1ID		SDVC-1IE		SDVC-1IF		SDVC-1IG	
	Johnson	SDVC-1JA		SDVC-1JB		SDVC-1JC		SDVC-1JD		SDVC-1JE		SDVC-1JF		SDVC-1JG	
	Natrona	SDVC-1KA		SDVC-1KB		SDVC-1KC		SDVC-1KD		SDVC-1KE		SDVC-1KF		SDVC-1KG	
	Uinta	SDVC-1LA		SDVC-1LB		SDVC-1LC		SDVC-1LD		SDVC-1LE		SDVC-1LF		SDVC-1LG	
	Sweetwater	SDVC-1MA		SDVC-1MB		SDVC-1MC		SDVC-1MD		SDVC-1ME		SDVC-1MF		SDVC-1MG	
	Campbell	SDVC-1NA		SDVC-1NB		SDVC-1NC		SDVC-1ND		SDVC-1NE		SDVC-1NF		SDVC-1NG	
	Teton	SDVC-1OA		SDVC-1OB		SDVC-1OC		SDVC-1OD		SDVC-1OE		SDVC-1OF		SDVC-1OG	
	Crook	SDVC-1PA		SDVC-1PB		SDVC-1PC		SDVC-1PD		SDVC-1PE		SDVC-1PF		SDVC-1PG	
	Weston	SDVC-1QA		SDVC-1QB		SDVC-1QC		SDVC-1QD		SDVC-1QE		SDVC-1QF		SDVC-1QG	
	Albany	SDVC-1RA		SDVC-1RB		SDVC-1RC		SDVC-1RD		SDVC-1RE		SDVC-1RF		SDVC-1RG	
	Converse	SDVC-1SA		SDVC-1SB		SDVC-1SC		SDVC-1SD		SDVC-1SE		SDVC-1SF		SDVC-1SG	
	Hot Springs	SDVC-1TA		SDVC-1TB		SDVC-1TC		SDVC-1TD		SDVC-1TE		SDVC-1TF		SDVC-1TG	
Carbon	SDVC-1UA		SDVC-1UB		SDVC-1UC		SDVC-1UD		SDVC-1UE		SDVC-1UF		SDVC-1UG		
Sublette	SDVC-1VA		SDVC-1VB		SDVC-1VC		SDVC-1VD		SDVC-1VE		SDVC-1VF		SDVC-1VG		
Niobrara	SDVC-1WA		SDVC-1WB		SDVC-1WC		SDVC-1WD		SDVC-1WE		SDVC-1WF		SDVC-1WG		

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