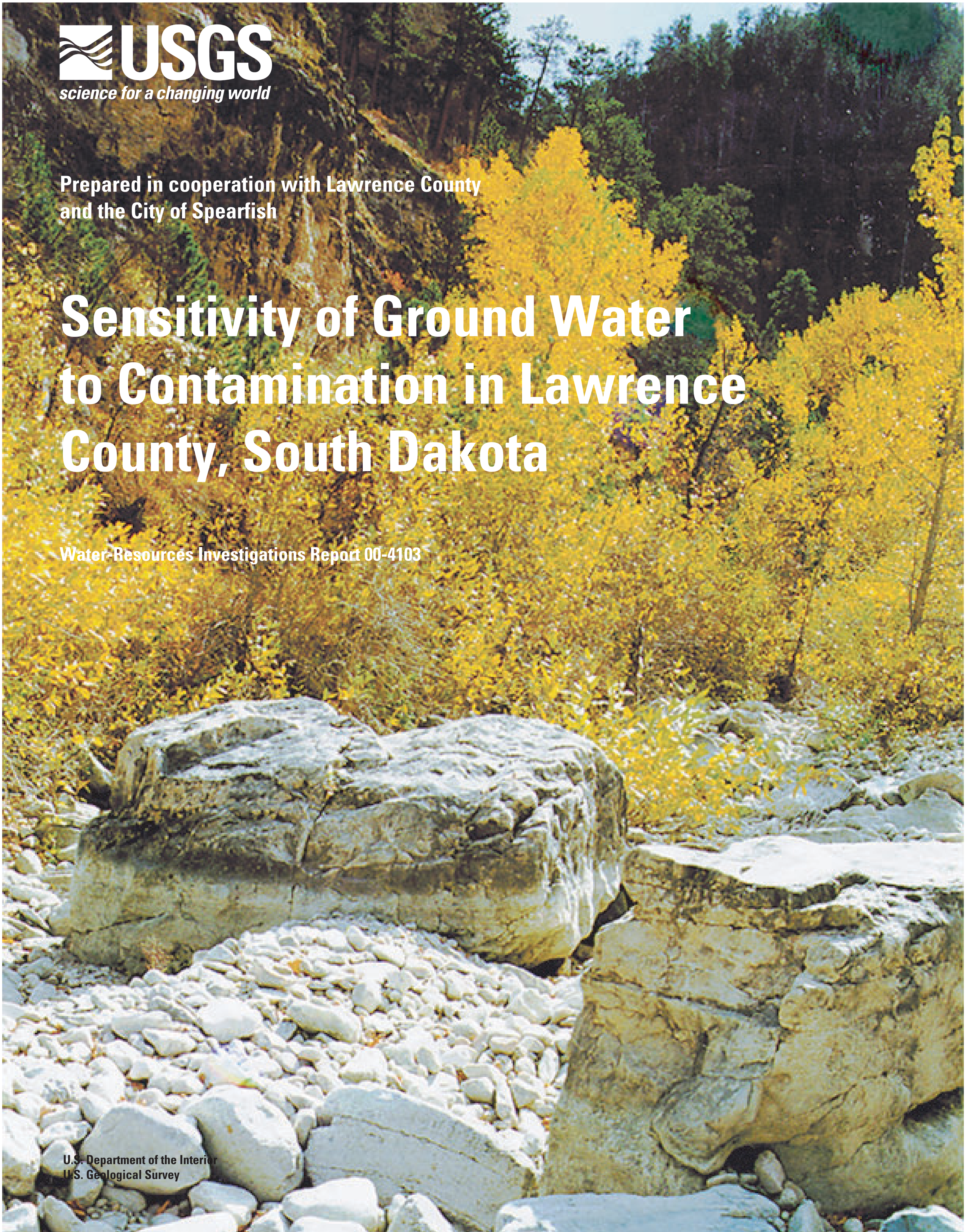
USGS
science for a changing world

Prepared in cooperation with Lawrence County
and the City of Spearfish

Sensitivity of Ground Water to Contamination in Lawrence County, South Dakota

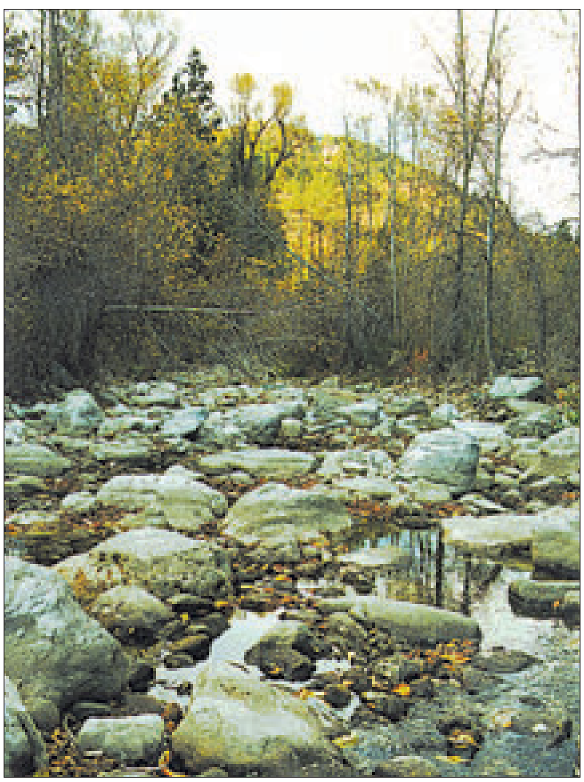
Water-Resources Investigations Report 00-4103

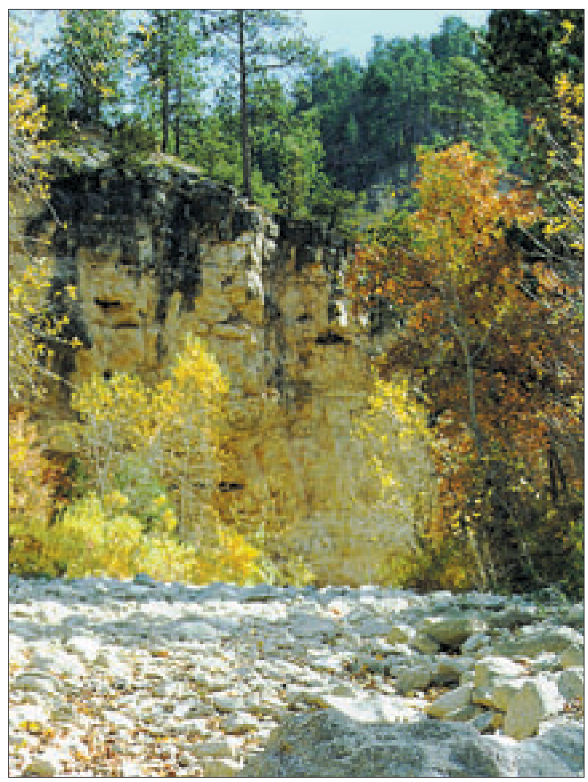


U.S. Department of the Interior
U.S. Geological Survey


1


2


3


4

Inside cover: Photographs of downstream sequence of the Madison Limestone streamflow-loss zone in Spearfish Canyon. Photographs by I.E. Arlton

Front cover: Photograph of Madison Limestone streamflow-loss zone in Spearfish Canyon. Photographs by I.E. Arlton

U.S. Department of the Interior
U.S. Geological Survey

Sensitivity of Ground Water to Contamination in Lawrence County, South Dakota

By Larry D. Putnam

Water-Resources Investigations Report 00-4103

Prepared in cooperation with Lawrence County
and the City of Spearfish

U.S. Department of the Interior

Bruce Babbitt, Secretary

U.S. Geological Survey

Charles G. Groat, Director

The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Rapid City, South Dakota: 2000

For additional information write to:

District Chief
U.S. Geological Survey
1608 Mt. View Road
Rapid City, SD 57702

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

CONTENTS

Abstract 1
Introduction 1
- Purpose and Scope 1
- Description of Study Area 2
- Method of Analysis 7

Ground-Water Regions and Hydrogeologic Settings 9
Sensitivity of Ground Water to Contamination 16
- Hydrogeologic Units 16
  - Criteria for Delineation 17
  - Designated Units 18
- Recharge Rate 30
  - Criteria for Delineation 32
  - Designated Units 37
- Depth to Water 37
  - Criteria for Delineation 39
  - Designated Units 39
- Land-Surface Slope 41
  - Criteria for Delineation 41
  - Designated Units 41
- Streamflow Recharge 41
  - Criteria for Delineation 43
  - Designated Units 43

Use of Ground-Water Sensitivity Map 48
- Relating Sensitivity Units to Hydrogeologic Information 48
- Limitations of Sensitivity Map 49

Summary 50
Selected References 51
Supplemental Information 53

FIGURES

1. Map showing location of study area 3
2. Map showing hydrogeologic units of Lawrence County 5
3. Stratigraphic section for Lawrence County, South Dakota 6
4. Schematic showing simplified hydrogeologic setting in study area 7
5. Map showing excessively to well-drained soil classifications in Lawrence County 10
6. Map showing most common hydrologic group soil classifications in Lawrence County 11
7. Map showing hydrogeologic settings in Lawrence County 12
8. Map showing hydrogeologic-unit sensitivity groups in Lawrence County 29
9. Map showing selected drainage basins and average precipitation in or near study area 31
10. Map showing recharge-rate sensitivity groups in Lawrence County 38
11. Map showing depth-to-water sensitivity groups in Lawrence County 40
12. Map showing land-surface-slope sensitivity groups in Lawrence County 42

TABLES

1. Characteristics of hydrogeologic settings in study area 13
2. Sensitivity ranges for types of aquifer media 17
3. Sensitivity ranges for types of unsaturated media 18
4. Sensitivity ratings for range categories of aquifer hydraulic conductivity 18
5. Sensitivity characteristics of hydrogeologic units 19
6. Base flow within drainage basin above station 06422500 32
7. Estimated recharge rate for hydrogeologic units as a percent of precipitation 33
8. Sensitivity ratings for range categories of recharge rate 37
9. Sensitivity rank for designated recharge-rate groups 37
10. Sensitivity ratings for range categories of depth to water 39
11. Sensitivity rank for designated depth-to-water groups 39
12. Sensitivity rank for designated land-surface-slope groups 41
13. Characteristics of drainage areas upstream from streamflow-loss zones 44
14. Data pertaining to annual yield for selected gaging stations in Lawrence County 48

PLATES

[Plates are in pocket]

1. Map showing sensitivity of ground water to contamination in Lawrence County, South Dakota
2. Map showing drainage areas upstream from potential streamflow-loss zones and locations of selected streamflow-gaging stations in Lawrence County, South Dakota

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	4,047	square meter
acre	0.4047	hectare
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Water year: In U.S. Geological Survey reports, water year is the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends; thus, the water year ending September 30, 1994, is called the "1994 water year."

Sensitivity of Ground Water to Contamination, Lawrence County, South Dakota

By Larry D. Putnam

ABSTRACT

Ground-water supplies in Lawrence County, South Dakota, can be contaminated by agricultural, urban, suburban, commercial, and industrial land uses. To address this issue, the U.S. Geological Survey in cooperation with Lawrence County and the City of Spearfish mapped the sensitivity of ground water to contamination in Lawrence County.

Sensitivity of ground water to contamination was determined by delineating hydrogeologic settings with common hydrogeologic characteristics as described in the DRASTIC method, developed by the U.S. Environmental Protection Agency and the National Water Well Association. Within the framework of 11 hydrogeologic settings, sensitivity to contamination was ranked for six intrinsic hydrogeologic characteristics: (1) aquifer media, (2) unsaturated media (3) hydraulic conductivity, (4) recharge rate, (5) depth to water, and (6) land-surface slope. The rating conventions of DRASTIC were modified to provide a relative ranking of hydrogeologic characteristics without assignment of a combined numerical score. Soil characteristics were not included as a map layer because detailed digital data were not available; however, the general distribution of two soil characteristics were shown.

A total of 956 polygons were delineated and assigned a sensitivity-unit code that represented unique groups of sensitivity rank for the six intrinsic hydrogeologic characteristics. The polygons were created by overlaying and intersecting maps that describe the geology, precipitation, land-surface elevation, and depth to water using a geographic information system. Thirty drainage areas upstream from potential streamflow-loss zones were delineated to describe an additional mechanism of transport of potential contamination. The sensitivity of ground water to contamination was presented on a 1:100,000-scale map with code and label explanations. Limitations of the sensitivity map are described to facilitate appropriate use of the map as a screening tool to compare sensitivity to contamination.

INTRODUCTION

Ground-water supplies in Lawrence County, South Dakota, can be contaminated by agricultural, urban, suburban, commercial, and industrial land uses. Population growth in Lawrence County continues to increase both the demand from and the potential for contamination to aquifers in Lawrence County. Areas sensitive to contamination can be identified and described in ways useful to natural-resource managers, regulatory policy makers, and educators. In an effort to provide this information, the U.S. Geological Survey (USGS), in cooperation with Lawrence County and the City of Spearfish conducted a study to delineate and describe sensitivity of ground water to contamination in Lawrence County.

Purpose and Scope

The purpose of this report is to present maps that describe the sensitivity of ground water to contamination in Lawrence County. Hereinafter in this report, the word "sensitivity" refers to the sensitivity of ground water to contamination. Evaluation of potential contaminant characteristics or land-use practices were not included in the sensitivity delineations. Mechanisms of potential contamination considered were limited to those that can occur near the land surface and did not include deep subsurface injection. Ground water, for the purposes of this report, refers to the water in the uppermost saturated rocks and sediments that can be yielded in usable quantities to a well or spring.

The study area was subdivided into map areas that delineate regions with relative ranking of intrinsic hydrogeologic sensitivity. Map areas showing sensitivity were designated and delineated by sequentially evaluating six intrinsic hydrogeologic characteristics: aquifer media, unsaturated media, hydraulic conductivity, recharge rate, depth to water, and land-surface slope. Transport of a potential contaminant was assumed to occur from infiltration of precipitation from the land surface to the uppermost saturated rocks.

An additional mechanism of transport of potential contaminants is streamflow loss (infiltration). Runoff from precipitation on drainage basins upstream from streamflow-loss zones affects the sensitivity of map areas containing the losing stream. Drainage basins upstream from potential loss zones were delineated and described; however, no attempt was made to produce a relative rating of hydrogeologic sensitivity that included both mechanisms of potential contaminant transport.

The products developed by this study are two 1:100,000-scale maps of Lawrence County showing the areal distribution of sensitivity units and delineated drainage basins above potential streamflow-loss zones. Tables of descriptive information are associated with the map units by the identifying codes and labels.

Description of Study Area

The study area, Lawrence County, consists of about 800 mi^2 in the northwestern part of the topographically distinct Black Hills and adjacent foothills and plains to the north (fig. 1). Land-surface altitudes range from greater than 6,000 ft above sea level in the southwestern part of the county to less than 4,000 ft in the plains to the north, resulting in an orographically induced microclimate characterized by generally greater precipitation and lower temperatures at the higher altitudes. The highest altitude is near 7,000 ft in the southwestern corner of the county, and the lowest altitude is near 3,000 ft in the northeastern corner of the county. Average (30-year) annual precipitation is 22.2 in. at Spearfish and 29.0 in. at Lead. Average annual precipitation is less than 20 in. in the northern and southeastern parts of the county based on precipitation stations outside the study area (U.S. Department of Commerce, 1994). The average (30-year) annual temperature is 46.5° F at Spearfish and 44.3° F at Lead (U.S. Department of Commerce, 1994).

A general classification of land use and land cover in Lawrence County can be determined from aerial photographs. A USGS land-use and land-cover classification system user's guide (U.S. Geological Survey, 1986) describes the use of data compiled at 1:250,000 scale from high-altitude aerial photographs to make these classifications. The digital data for Lawrence County indicates that about 70 percent is forest land and about 25 percent is agriculture or range land. Most of the agriculture and range land is located in the northern part of the county with some small areas located within the forest land, which predominantly is in the southern part of the county. Most of the forest land is evergreen forest with about 5 percent mixed evergreen and deciduous forest.

The Black Hills National Forest, established in 1907 and managed by the U. S. Forest Service (USFS), constitutes about 53 percent of Lawrence County. Privately held lands that were excluded from the USFS land included active mining claims, foothills ranches, and meadows and bottom lands along numerous streams.

Gold mining was an important industry in the early development of the area. Placer mining, small surface pits, and shallow underground mines were common through the late 1800's. This was followed by large-scale underground mining by Homestake Mining Company in Lead and the development of smaller mines. In the 1980's, several new large-scale open-pit gold mines were developed utilizing heap-leach recovery methods for low-grade ores.

The largest component of the agriculture industry is cattle production, with a majority of the crop land used to produce cattle feed. Private land and USFS land in the higher elevations is used for summer pasture. The timber industry primarily consists of harvesting ponderosa pine, which is hauled to local processing mills. Tourism is an important industry and is based on the mountain scenery, recreational opportunities, and cultural history.

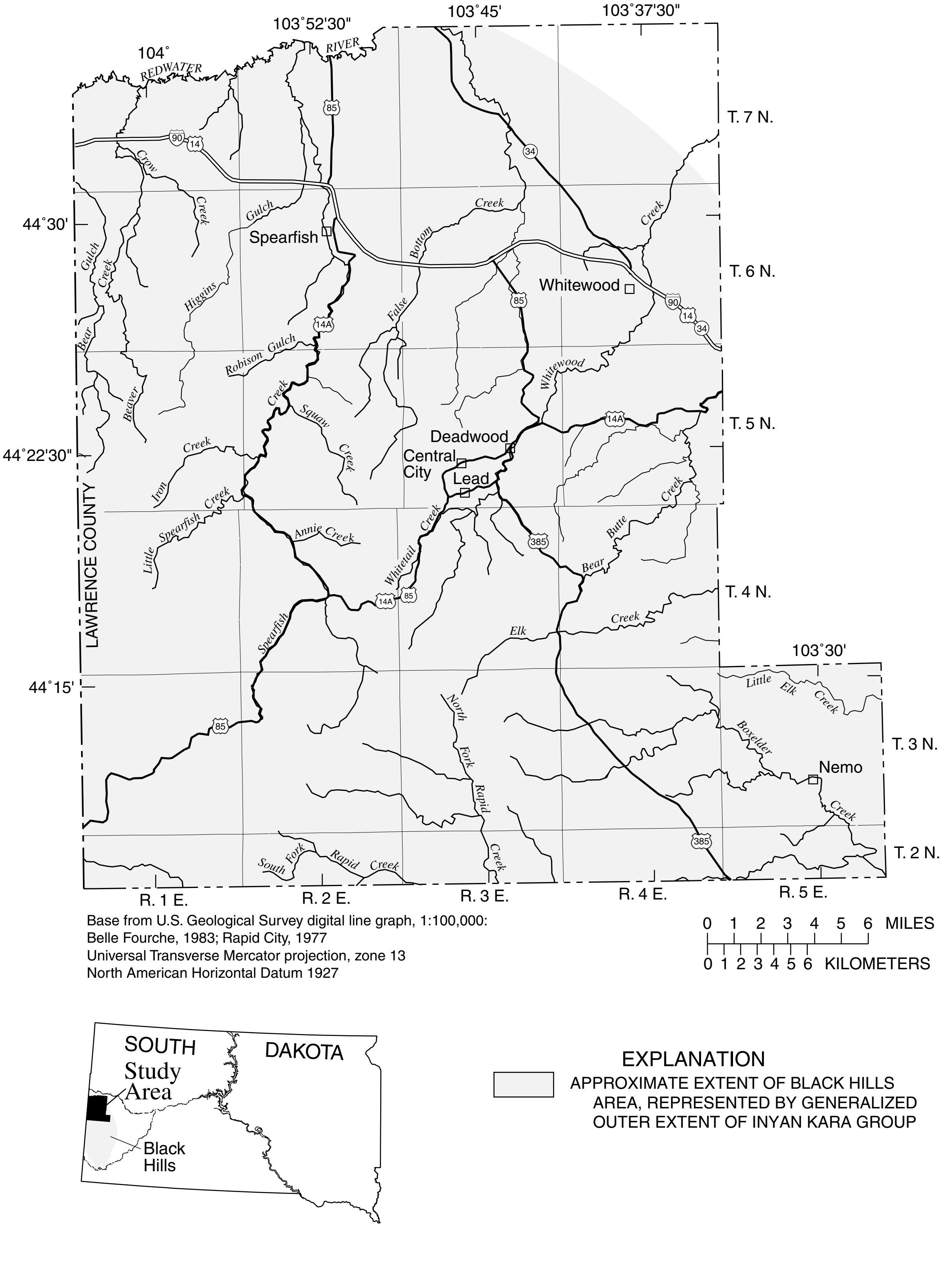


Figure 1. Location of study area.

The population of the county was about 21,000 in 1990 with the primary urban areas being the City of Spearfish and the Deadwood-Lead area, with populations of about 8,000 and 3,000, respectively. Suburban areas have developed near the urban areas and on plots of private land within the forested, higher elevations of the county.

Geologic formations of the study area have been grouped into hydrogeologic units and mapped for the Black Hills area based on similarity in hydraulic properties (Strobel and others, 1999). A generalization of that map (fig. 2) shows the surface exposures of the hydrogeologic units for the study area labeled with the stratigraphic interval abbreviations for the grouped geologic formations (fig. 3). A simplified schematic diagram of the hydrogeologic setting in the study area is shown in figure 4.

Precambrian igneous and metamorphic rocks extend from near Lead to the southeastern corner of the study area. On the west, north, and east is a layered series of sedimentary rocks including limestones, sandstones, and shales that extend concentrically outward from the Precambrian core. The bedrock sedimentary formations typically dip away from the uplifted Black Hills at angles that approach 15 to 20 degrees near the outcrops (Carter and Redden, 1999a, 1999b, 1999c), and decrease with distance from the uplift to about 2 degrees in the northeastern part of the county. Several centers of igneous activity exist across the central part of the study area that contain shallowly emplaced sills, laccoliths, dikes, and plugs (Lisenbee, 1985). Unconsolidated units include alluvium, colluvium and gravel deposits. Mapped alluvial deposits along streams generally are widest in the northern part of the study area, where stream gradients generally are smallest. Gravel deposits in the northern part of the study area also include paleochannels, pediments, and stream terraces along former flood plains (Strobel and others, 1999).

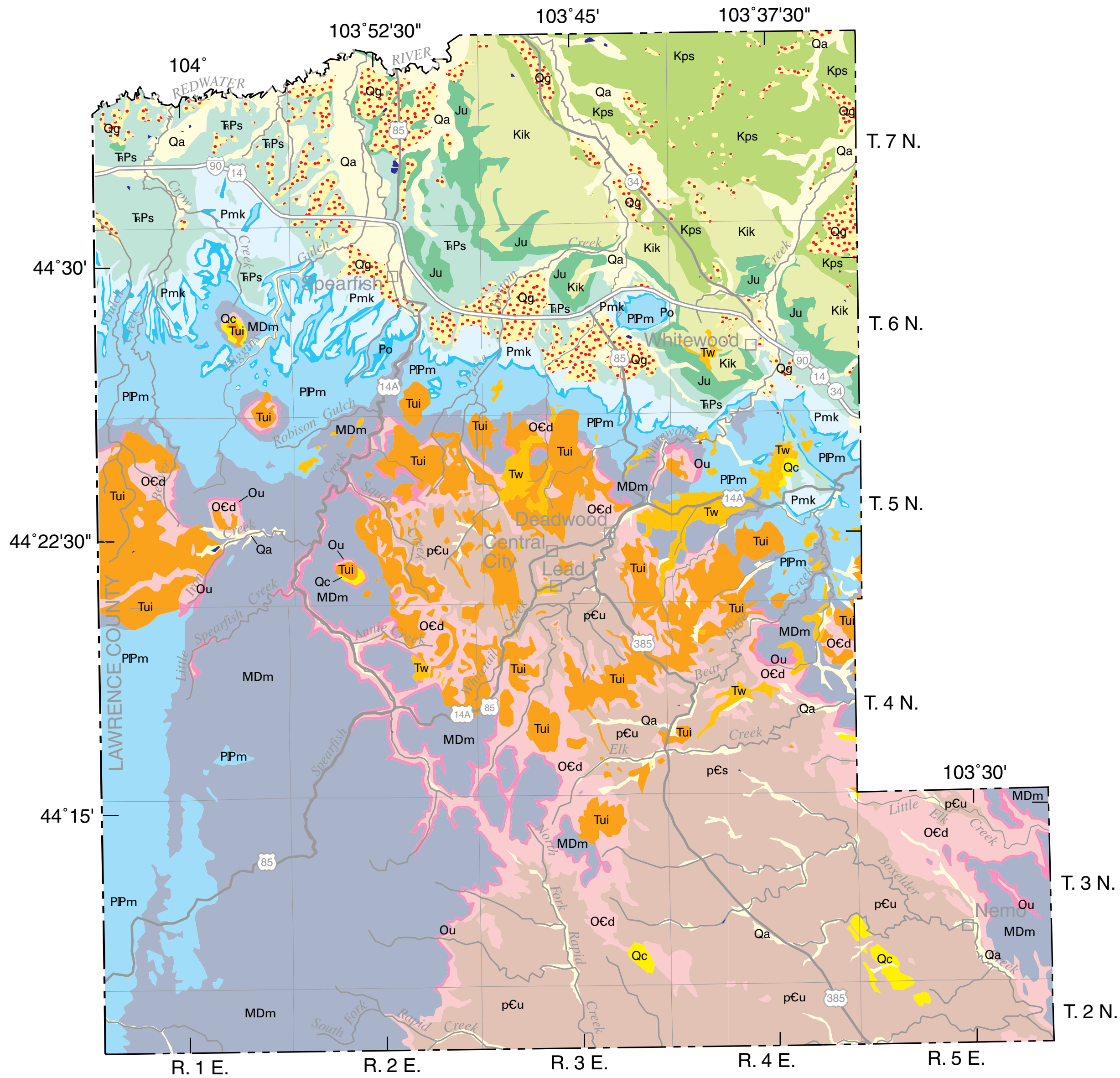
The Inyan Kara, Minnekahta, Minnelusa, Madison, and Deadwood sedimentary bedrock aquifers are major aquifers (Strobel and others, 1999) and are extensively utilized for domestic, community, and agricultural water supplies within Lawrence County. These five important aquifers are recharged from precipitation and/or from streamflow infiltration on the outcrops. Alluvial deposits and fractured Precambrian rocks also are widely used as sources of ground water within the county.

Unconsolidated deposits of colluvium and gravel, that are intermittently saturated, could supply usable quantities of water to wells during part of the year. The White River aquifer is a minor aquifer where saturated (Strobel and others, 1999). Most of the White River Group in the study area has been eroded away and only isolated areas remain. The Tertiary intrusive units are considered relatively impermeable; however, the permeability varies greatly depending on fracturing. Sills, dikes, and plugs could provide usable quantities of water in localized areas.

Some layers within the sedimentary confining units and semiconfining units are utilized locally as sources of water. The Spearfish and Opeche confining units supply limited quantities of water to wells in local areas. The Ordovician semiconfining unit could supply limited quantities of water to wells from fractures.

The Minnekahta, Minnelusa, Madison, and Deadwood aquifers are collectively confined by the underlying Precambrian units and the overlying Spearfish confining unit. Individually the aquifers are separated by minor confining layers, and contain some relatively impermeable layers within them. Leakage between aquifers is extremely variable (Peter, 1985; Greene, 1993, Klemp, 1995). The Inyan Kara aquifer is used extensively. A series of Cretaceous shales acts as the upper confining unit to the Inyan Kara aquifer. Artesian conditions generally exist within the aforementioned aquifers, where they are confined from above. Similarly, artesian springs that originate from confined aquifers are common around the periphery of the Black Hills.

Streamflow yields in Lawrence County, the average annual volume of streamflow divided by the drainage basin area, generally are largest in the highest elevations where precipitation is largest. Numerous streams originate from headwater springs discharging from the Paleozoic formations in the northwestern part of the study area (fig. 2). Many streams generally lose all or part of their flow as they cross outcrops of the Minnekahta Limestone, Minnelusa Formation, Madison Limestone, and Deadwood Formation. Most losses occur on outcrops of the Minnelusa Formation and Madison Limestone with minimal losses to the Deadwood Formation and generally small losses to the Minnekahta Limestone (Hortness and Driscoll, 1998). Karst features of the Madison Limestone are responsible for a large part of the Madison Limestone's capacity to accept streamflow recharge. Large springs occur in many locations downgradient from the streamflow-loss zones providing an important source of base flow in many streams beyond the periphery of the Black Hills (Rahn and Gries, 1973).



Base from U.S. Geological Survey digital line graph, 1:100,000:
Belle Fourche, 1983; Rapid City, 1977
Universal Transverse Mercator projection, zone 13
North American Horizontal Datum 1927

Hydrogeology modified from Strobel and others, 1999

0 1 2 3 4 5 6 MILES

0 1 2 3 4 5 6 KILOMETERS

EXPLANATION

WATER BODY

HYDROGEOLOGIC UNITS

Qa	Alluvium	TRPs	Spearfish confining unit
Qc	Colluvium	Pmk	Minnekahta aquifer
Qg	Gravel deposits	Po	Opeche confining unit
Tw	White River aquifer	PIPm	Minnelusa aquifer
Tui	Tertiary intrusive units	MDm	Madison aquifer
Kps	Cretaceous-sequence confining unit	Ou	Ordovician-sequence semiconfining unit
Kik	Inyan Kara aquifer	O€d	Deadwood aquifer
Ju	Jurassic-sequence semiconfining unit	p€u	Precambrian igneous and metamorphic units

Figure 2. Hydrogeologic units of Lawrence County.

ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	GEOLOGIC FORMATION	SUBSURFACE THICKNESS, IN FEET[1]	DESCRIPTION
CENOZOIC	QUATERNARY & TERTIARY (?)	Qa, Qc, Qg	UNDIFFERENTIATED SANDS AND GRAVELS	[2]0-60	Sand, gravel, and boulders
		Tw	WHITE RIVER GROUP	[3]0-150	Light colored clays with sandstone channel fillings and local limestone lenses.
	TERTIARY	Tui	INTRUSIVE IGNEOUS ROCKS	---	Includes rhyolite, latite, trachyte, and phonolite.
MESOZOIC	CRETACEOUS	Kps	GRANEROS GROUP: BELLE FOURCHE SHALE	[2]150-850	Gray shale with scattered limestone concretions. Clay spur bentonite at base.
			GRANEROS GROUP: MOWRY SHALE	[2]125-230	Light-gray siliceous shale. Fish scales and thin layers of bentonite.
			GRANEROS GROUP: MUDDY SANDSTONE (DYNNESON; NEWCASTLE)	[2]0-100	Brown to light yellow and white sandstone.
			GRANEROS GROUP: SKULL CREEK SHALE	[2]150-270	Dark gray to black siliceous shale.
		Kik	INYAN KARA GROUP: FALL RIVER FORMATION	[4]10-200	Massive to slabby sandstone.
			INYAN KARA GROUP: LAKOTA FM (Fuson Shale; Minnewaste Limestone)	[4]30-300	Coarse gray to buff cross-bedded conglomeratic sandstone, interbedded with buff, red, and gray clay, especially toward top. Local fine-grained limestone.
	JURASSIC	Ju	MORRISON FORMATION	[2]0-150	Green to maroon shale. Thin sandstone.
			UNKPAPA SS	[2]0-275	Massive fine-grained sandstone.
			SUNDANCE FORMATION (Redwater Member; Lak Member; Hulett Member; Stockade Beaver Mem.; Canyon Spr Member)	[2]250-475	Greenish-gray shale, thin limestone lenses. Glauconitic sandstone; red sandstone near middle.
			GYPSUM SPRING FORMATION	[2]0-125	Red siltstone, gypsum, and limestone.
	TRIASSIC	TRPs	SPEARFISH FORMATION (Goose Egg Equivalent)	[2]375-800	Red sandy shale, soft red sandstone and siltstone with gypsum and thin limestone layers. Gypsum locally near the base.
PALEOZOIC	PERMIAN	Pmk	MINNEKAHTA LIMESTONE	[3]35-50	Thin to medium-bedded finely-crystaline, purplish gray laminated limestone.
		Po	OPECHE SHALE	[2]25-150	Red shale and sandstone.
	PERMIAN / PENNSYLVANIAN	PIPm	MINNELUSA FORMATION	[5]350-650	Yellow to red cross-bedded sandstone, limestone, and anhydrite locally at top. Interbedded sandstone, limestone, dolomite, shale, and anhydrite. Red shale with interbedded limestone and sandstone at base.
	MISSISSIPPIAN / DEVONIAN	MDm	MADISON (PAHASAPA) LIMESTONE	[6]350-1000	Massive light-colored limestone. Dolomite in part. Cavernous in upper part.
	DEVONIAN		ENGLEWOOD FORMATION	[4]40-75	Pink to buff limestone. Shale locally at base.
	ORDOVICIAN	Ou	WHITEWOOD (RED RIVER) FORMATION	[2]0-150	Buff dolomite and limestone.
			WINNIPEG FORMATION	[2]0-110	Green shale with siltstone.
	CAMBRIAN	OЄd	DEADWOOD FORMATION	[3]300-500	Massive to thin-bedded buff to purple sandstone. Greenish glauconitic shale flaggy dolomite and flatpebble limestone conglomerate. Sandstone, with conglomerate locally at the base.
PRECAMBRIAN		pЄu	UNDIFFERENTIATED METAMORPHIC AND IGNEOUS ROCKS		Schist, slate, quartzite, and arkosic grit. Intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite.

1 The subsurface thickness was modified from several references to provide a range that was the most specific to the study area.

2 DeWitt and others, 1989.

3 Robinson and others, 1964.

4 Kyllonen and Peter, 1987.

5 Thickness estimated from subtracting surfaces created from structure contours of Madison Limestone and Minnelusa Formation tops (Carter and Redden, 1999b and Carter and Redden, 1999a).

6 Thickness estimated from subtracting surfaces created from structure contours of Deadwood Formation and Madison Limestone tops (Carter and Redden, 1999c and Carter and Redden, 1999b). The subsurface thicknesses of the Madison Limestone greater than 700 feet are in the northeast part of the study area.

Modified from information furnished by the Department of Geology and Geological Engineering, South Dakota School of Mines and Technology (written commun., January 1994)

Figure 3. Stratigraphic section for Lawrence County, South Dakota.

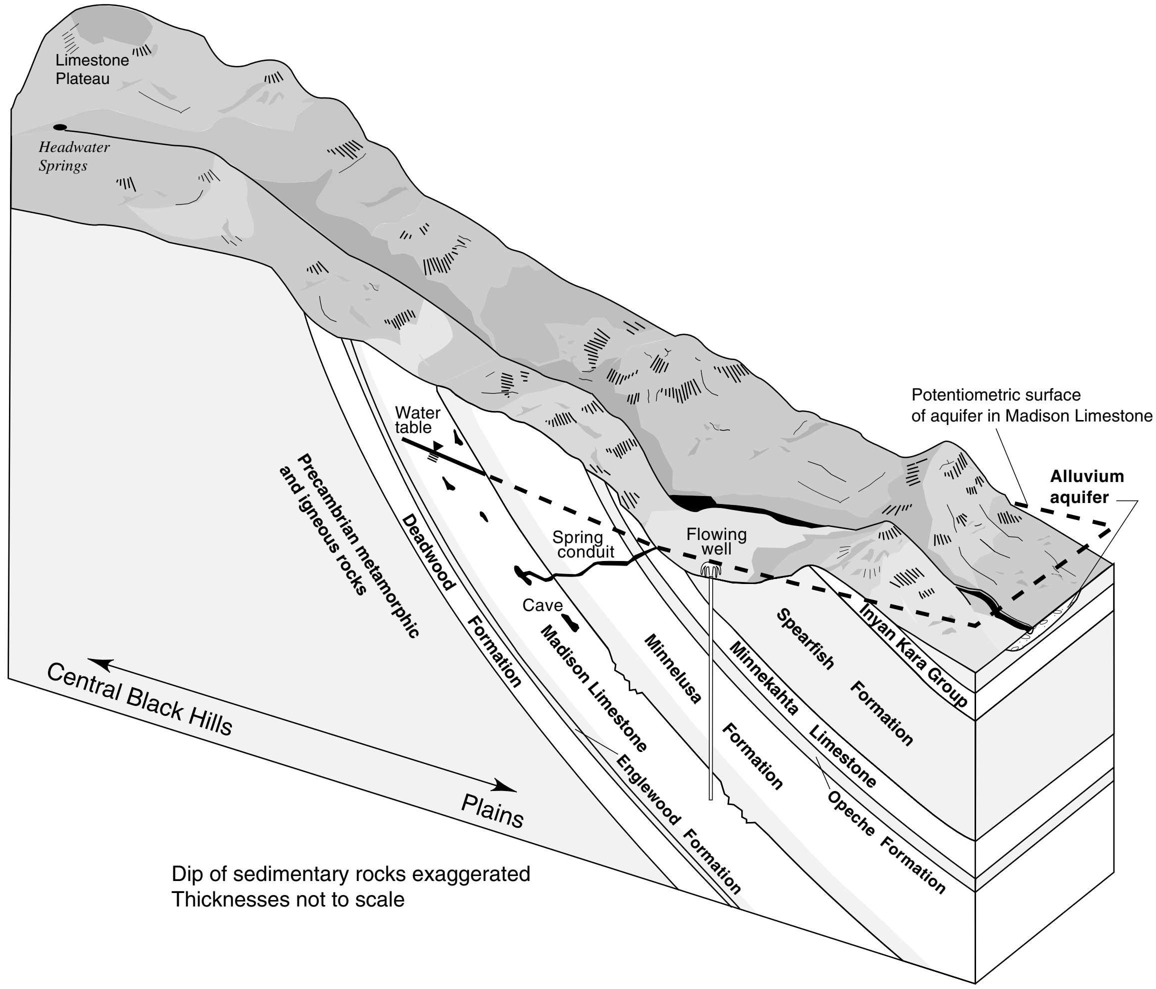


Figure 4. Simplified hydrogeologic setting in study area.

Method of Analysis

The method of aquifer sensitivity mapping used for this study was based on DRASTIC (Aller and others, 1987), with modifications derived from Hearne and others (1995) and Davis and others (1994). Selected parts of each method were combined and modified based on the availability of data and hydrologic characteristics of the study area. Additional modifications were made based on studies comparing DRASTIC scores and observed ground-water quality.

The DRASTIC method, developed by the U.S. Environmental Protection Agency and the National Water Well Association, permits the ground-water pollution potential of any hydrogeologic setting in the United States to be systematically evaluated with existing information. The system is designed to be used as a screening tool and not as a site assessment methodology. According to the documentation for DRASTIC (Aller and others, 1987, p. 11), "the concepts of the system were developed assuming the use of a pollutant having the mobility of water that is introduced at the surface, and carried towards the ground water by recharge from precipitation."

The DRASTIC method analyzes characteristics that affect the potential for ground-water pollution. Each letter in the acronym stands for a characteristic that is rated over the mapped area in terms of contribution to the "Pollution Potential Index" (Aller and others, 1987). The seven layers are combined using a geographic information system (GIS), and the point ratings for each layer are added together to give the total pollution potential index. In DRASTIC, the "D" stands for *depth to water*, "R" is for *recharge rate*, "A" is for *aquifer media*, "S" is for *soil media*, "T" is for *topographic slope*, "I" is for *unsaturated* (vadose) *zone impact*, and "C" is for *aquifer hydraulic conductivity.*

Large DRASTIC ratings suggest greater pollution potential; thus, they generally are higher for shallower *depth to water*, larger (more rapid) *recharge rate*, more porous *aquifer media*, more transmissive *soil media*, less steep *topographic slope* (which yields less runoff), less *unsaturated zone impact* with less residence time, and higher *aquifer hydraulic conductivity.* In DRASTIC, each term's importance can be adjusted by introducing a weighting factor that is multiplied by each term's rating. For example, *conductivity* and *aquifer media* might typically be weighted more than *topographic slope*.

Hearne and others (1995) described the vulnerability of the uppermost ground water to contamination in the greater Denver, Colorado, area by combining the hydrogeologic characteristics *aquifer media*, *unsaturated zone impact*, and *hydraulic conductivity.* A letter code was assigned to each unique combination of the DRASTIC categories determined for the three hydrogeologic characteristics. GIS map layers were constructed for *depth to water*, *soil media*, and *topographic slope*. The *recharge rate* consisted of a single DRASTIC category for the study area; therefore, this category was not included as a map layer. The map layers were overlain and intersected using a GIS to produce polygons with a unique code consisting of a letter designation followed by three numbers (vulnerability response unit). Tables and text describing hydrologic characteristics associated with the digits of the code were developed to compare vulnerability response units. To simplify the final map, areas smaller than 100 acres were eliminated from digital maps by merging the small areas with adjacent polygons. The rating conventions from the DRASTIC method were adapted for each individual map layer, but relative weight between the layers and total pollution potential index were not calculated.

KARSTIC, a modification of the DRASTIC method developed by Davis and others (1994), was used to map ground-water vulnerability in the Rapid Creek Basin upstream from Rapid City, South Dakota (located southeast of the study area). In KARSTIC, the "K" stands for *karst sinkholes* with associated surface recharge, "A" is for *aquifer media*, "R" is for net *recharge rate*, "S" is for *soil media*, "T" is for *topographic slope*, "I" is for *unsaturated zone impact* (includes the *depth to water* factor in DRASTIC as a multiplier), and "C" is for *aquifer hydraulic conductivity.* A major difference between DRASTIC and KARSTIC was introduced when Davis and others (1994) multiplied the k factor times an f factor for *fracture development,* and multiplied the i factor for *unsaturated zone impact* times the d factor for *depth to ground water.* This produced KARSTIC pollution potential indices that are, at selected places, 10 times greater than would have been determined for the same location using the DRASTIC method. Davis and others (1994, p. 73) contended that, "…in terms of relative pollution potential, clearly these larger values for sinkhole areas are indicative of pollution vulnerability that is at least an order of magnitude greater than most settings in alluvial aquifers or in consolidated aquifers with intergranular porosity."

Scoring, weighting, and combining sensitivity characteristics into a single pollution potential index can be misleading because of the different transport characteristics of potential contaminants and the uncertainty in the relative importance of hydrogeologic parameters. A review of studies examining observed pesticide concentrations and predictions of pesticide occurrence and behavior in ground water by Barbash and Resek (1996, p. 395) concluded "…even if an assessment scheme incorporates all of the variables that control the transport and fate of contaminants of interest in the subsurface, its predictive power can be diminished--or eradicated--if the values selected for individual parameters or the relative weights assigned to them are inappropriate."

A method described by Hearne and others (1995) was selected as a model for this study because of the similarity to the hydrogeologic setting in Lawrence County. The method uses comparative descriptions of unique sensitivity characteristics without weighting or combination into a single combined numerical score. Reviews of DRASTIC scores compared to observed concentrations of nitrates and agricultural pesticides in wells (Korterba and others, 1993; U.S. Environmental Protection Agency, 1993; Barbash and Resek, 1996; Rupert, 1998) found that many DRASTIC scores did not correlate well with observed ground-water contamination. Some of the concerns raised by these studies are discussed in the sections that describe the individual map layers.

The first step in the method used by this study was to subdivide the study area into a geographic framework of regions, which were further subdivided into settings with generally similar hydrogeologic characteristics. These regions and settings are discussed in the following section.

Because of the significant differences in sensitivity characteristics of the geologic formations, the hydrogeologic-unit map (collectively representing aquifer media, unsaturated media, and hydraulic conductivity) was selected as the first descriptive map layer within this framework. This map layer was followed by map layers for recharge rate, depth to water, and land-surface (topographic) slope.

The soil category was not included as a map layer because digital soils data were available only at the 1:250,000 scale. STATSGO (State soil geographic database) data are not detailed enough to make interpretations at the county level (U. S. Department of Agriculture, 1994). The U.S. Department of Agriculture, Natural Resources Conservation Service, currently is compiling 1:24,000-scale digital soils data in Lawrence County that would be needed to complete this sensitivity map layer. A generalized description of soil properties was prepared from STATSGO data to show the general distribution of two soil properties that have been used to predict contamination potential. Statistical correlations between STATSGO soil properties and measured contaminant concentrations (Rupert, 1998, 1999) identified two soil properties as predictors of contamination in a regional study of a highly transmissive basalt aquifer. Soil drainage showed a positive correlation with nitrate concentrations in the aquifer, and hydrologic soil group showed a positive correlation with the herbicide atrazine in the aquifer. Soil drainage categorizes the frequency and duration of wet periods of the soil, and hydrologic group categorizes soil infiltration rates (U.S. Department of Agriculture, 1994).

Soil drainage categories range from excessively drained to very poorly drained with five intermediate categories. Most of the soils in Lawrence County are classified in the three categories ranging from excessively to well drained (fig. 5).

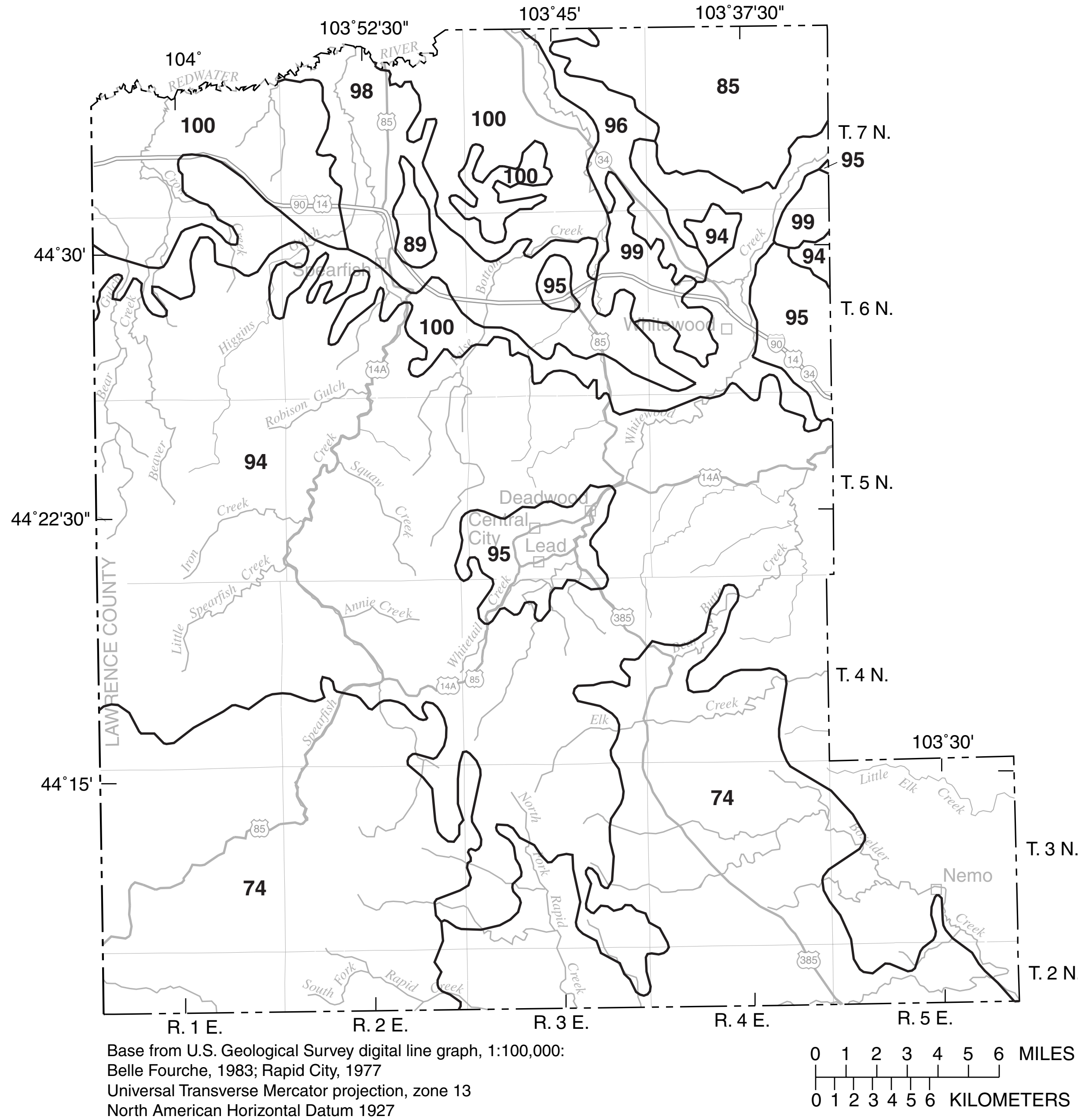
Hydrologic group soil categories include infiltration rates of high, moderate, slow, and very slow with high being the most sensitive to contamination and very slow the least sensitive. The most common category in Lawrence County (fig. 6) is moderate. The southern part of the study area has more moderate infiltration rates and the northeastern part of the county has more very slow infiltration rates. An analysis of sensitivity related to these soil properties also should consider additional information such as the thickness of the soil.

Streamflow loss is an important source of recharge to several major aquifers in the study area. A map layer describing potential streamflow-loss zones and the drainage areas upstream from these loss zones was added for consideration of this additional mechanism of ground-water contamination. The KARSTIC method (Davis and others, 1994) describes karst features associated with the streamflow-loss zones as a significant factor in evaluating ground-water sensitivity to contamination. A numerical rating that could relatively rank streamflow-loss characteristics was not made because of the lack of information on karst flow patterns.

The DRASTIC method was designed to generate pollution potential estimates for any area of 100 acres or larger. This study included a similar process of spatial generalization. If small polygons less than 100 acres were created in overlaying and intersecting map layers, the small polygons were merged with adjacent polygons. The selection of polygons to which the smaller ones were merged was based on similarity to the hydrogeologic-unit map, followed in priority by the recharge-rate, the depth-to-water, and the land-surface-slope (topographic-slope) maps.

GROUND-WATER REGIONS AND HYDROGEOLOGIC SETTINGS

The United States has been divided into 15 ground-water regions (Heath,1984). South Dakota includes four ground-water regions. Two of these regions, Western Mountain Ranges and Non-Glaciated Central, are present in Lawrence County. Because the sensitivity of ground water may be highly variable within a ground-water region, each region was subdivided into hydrogeologic settings, hereinafter referred to as settings (table 1), which were modified from the DRASTIC manual (Aller and others, 1987). Eleven settings were delineated in the study area and are shown as a range of colors on figure 7 and plate 1. The delineation of the areas was based on topography, precipitation patterns, and the hydrogeologic units map (Strobel and others, 1999), which describes the hydrogeologic characteristics of grouped units. The characteristics of each of the 11 settings (table 1) shows the wide range hydrologic and geologic factors that control the occurrence and movement of ground water in the study area.



EXPLANATION

SOIL DRAINAGE CLASSIFICATION--Modified from U.S. Department of Agriculture (1994). Number represents the percent of soil classifications in delineated area that are excessively or well drained.

Figure 5. Excessively to well-drained soil classifications in Lawrence County.

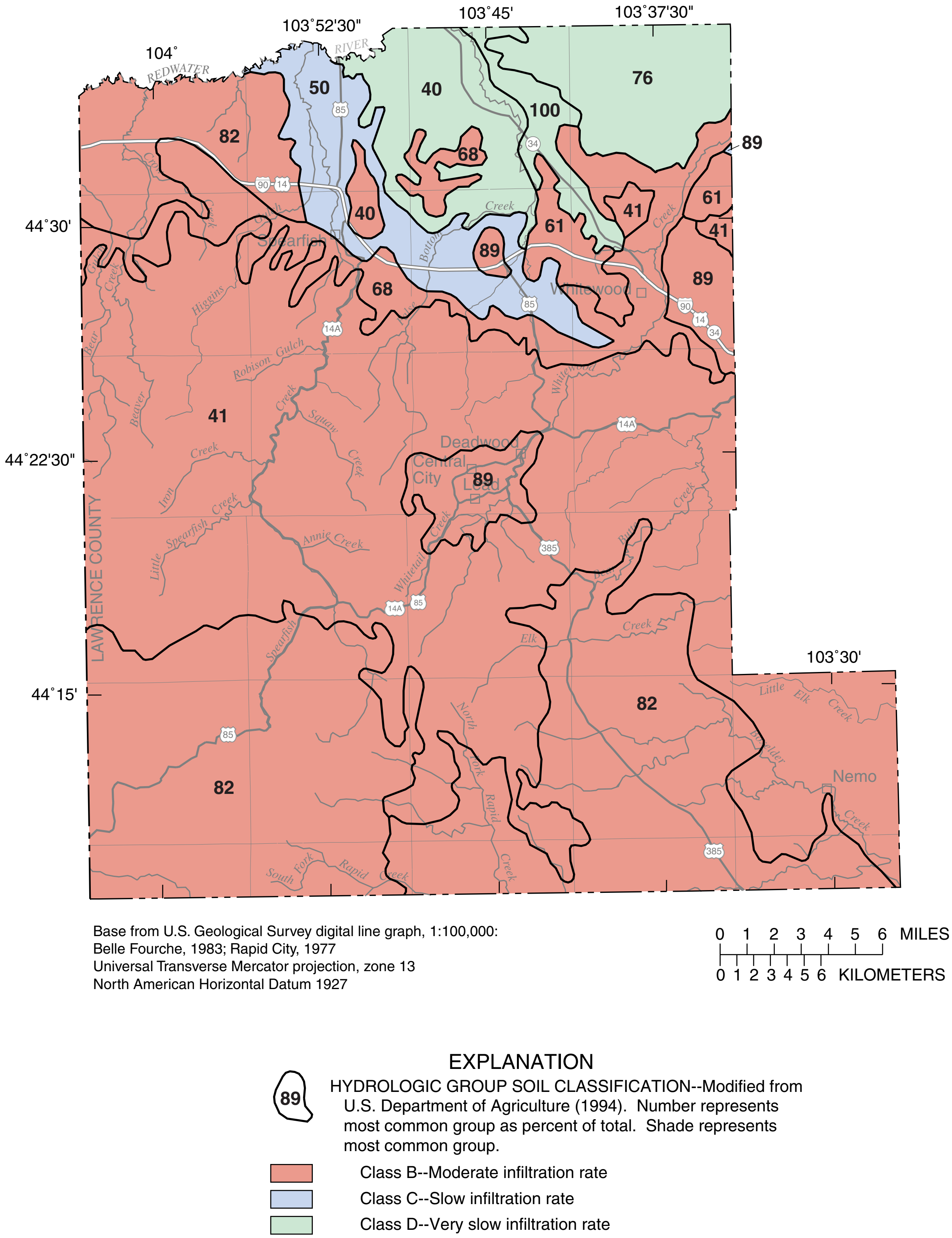


Figure 6. Most common hydrologic group soil classifications in Lawrence County.

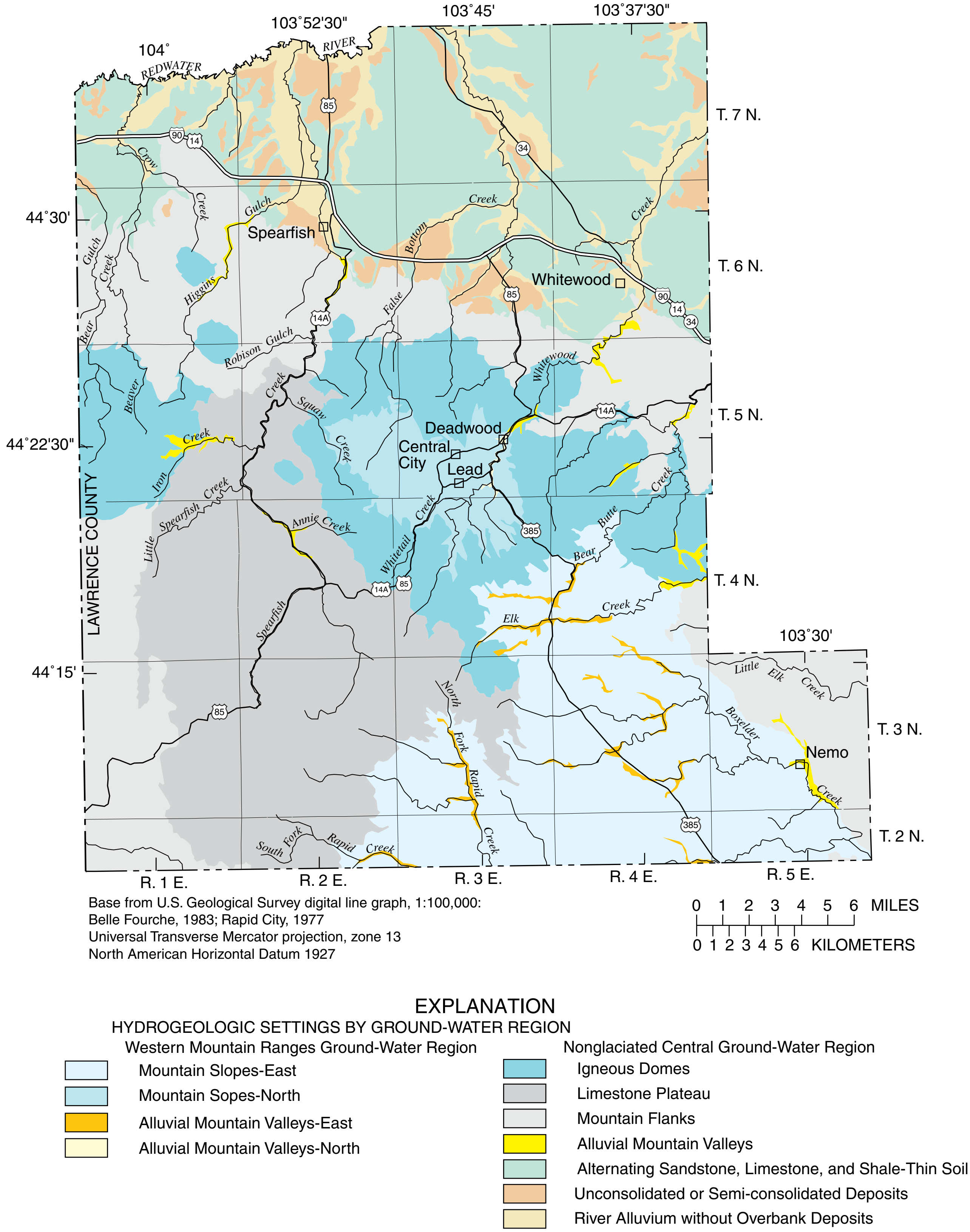


Figure 7. Hydrogeologic settings in Lawrence County.

Table 1. Characteristics of hydrogeologic settings in study area

Hydrogeologic setting	Total area (square miles)	Average land-surface altitude[1] (feet)	Average land-surface slope[1] (percent)	Average precipitation[2] (inches per year)	Description
			Western Mountain Ranges Ground-Water Region		
Mountain Slopes-East	131.2	5,571	15.1	21.1	This setting, located in the southeastern and south-central part of the study area, is characterized by steep slopes, thin soil cover, and fractured bedrock consisting mostly of igneous and metamorphic rocks. Well yields typically are limited, although in local areas the hydraulic conductivity could be high due to fracturing. Thicker weathered zones may develop locally particularly on talus slopes with perched water common. The topographic trend of these slopes is to the east in the rain shadow of the mountains, and limited rainfall is derived from moisture-laden prevailing westerly winds. Because of the orographic effect of the Black Hills, the northern part of this setting receives more rainfall than is typical for this setting. Ground-water levels are extremely variable.
Mountain Slopes-North	25.2	5,460	31.9	28.2	This setting, located on the northern slope of the uplift, is similar to Mountain Slopes-East except precipitation generally exceeds that which falls on eastern slopes. Recharge remains relatively low, however, because of the steep slopes and low primary porosity of the rock. In this particular setting, increased fracturing may occur in areas along the flanks of igneous intrusions.
Alluvial Mountain Valleys-East	4.9	5,505	13.1	22.3	This setting, located in east sloping valleys within the mountain slopes-east setting, is characterized by thin alluvium and boulders derived from the surrounding steep slopes. Soil cover generally is gravel sized. Ground water may be obtained from the alluvial deposits and also from the fractures in the underlying bedrock, which are generally in direct hydraulic connection with the alluvium. This type of setting may be expected along most of the streams within the Mountain Slopes-East setting; however, some contiguous mappable areas may be less than 100 acres and consequently may not be shown on the map.
Alluvial Mountain Valleys-North	.4	4,718	23.5	28.6	This setting, located within the Mountain Slopes-North setting, is similar to the Alluvial Mountain Valleys-East setting. Ground-water levels are typically shallower because of higher amounts of precipitation and subsequently greater recharge. This type of setting may be expected along most of the streams within the mountain slopes-north setting; however, some contiguous mappable areas may be less than 100 acres in many areas and consequently may not be shown on the map.

Table 1. Characteristics of hydrogeologic settings in study area–Continued

Hydrogeologic setting	Total area (square miles)	Average land-surface altitude[1] (feet)	Average land-surface slope[1] (percent)	Average precipitation[2] (inches per year)	Description
Non-Glaciated Central Ground-Water Region					
Igneous Domes	111.6	5,467	24.8	25.9	This setting, located across the central part of the study area, is characterized by igneous intrusive rocks surrounded by dipping sedimentary rocks. Folding and faulting of the sedimentary rocks along the flanks of the domes may increase the permeability and the recharge rate of these units. Well yields are extremely variable depending on the degree of folding and faulting and the type of rock. Where few fractures exist in the igneous domes, well yields are very low or non-existent; however, well yields typically are greater along the fractured areas on the flanks of the domes. Sedimentary rock outcrops, hydraulically connected to the confined regional aquifers, could have relatively large recharge rates because of increased fracturing and relatively large precipitation amounts.
Limestone Plateau	151.4	6,177	20.4	24.6	This setting, located in the southwestern part of the study area, includes most of the area referred to locally as the "Limestone Plateau." This setting has more relief than the moderate and variable topographic relief described in the "Solution Limestone setting" in DRASTIC (Aller and others, 1984). The limestone is characterized by a network of solution openings where the limestone has been partially dissolved along bedding planes and fractures. Soil usually is thin or absent, but where present commonly is a clayey loam. Recharge usually is high because infiltration of precipitation occurs easily through the fractures and solution openings. Return of recharge into surface water courses can be high. Water levels typically are moderately deep except near surface discharge points.
Mountain Flanks	168.1	5,025	18.8	23.1	This setting, located on the mountain flanks along the western, north-central, and eastern parts of the study area, is characterized by moderately dipping, fractured, consolidated sedimentary rocks. Soil usually is thicker than on mountain slopes. Ground water is obtained from the permeable sedimentary rocks or from fractures in the sedimentary rocks. The recharge rate is higher in the western and north-central parts because of greater precipitation. The mountain flanks serve as recharge areas for aquifers that are confined in adjacent areas.

Table 1. Characteristics of hydrogeologic settings in study area–Continued

Hydrogeologic setting	Total area (square miles)	Average land-surface altitude[1] (feet)	Average land-surface slope[1] (percent)	Average precipitation[2] (inches per year)	Description
Non-Glaciated Central Ground-Water Region—Continued					
Alluvial Mountain Valleys	5.0	4,626	20.4	23.7	This setting, located in narrow valleys within the igneous domes and mountain flanks setting, is characterized by thin alluvium and boulders that overlies fractured bedrock of sedimentary or igneous intrusive origin. Surficial deposits have typically weathered to a sandy loam. Ground water is obtained from sand and gravel layers, which commonly are in direct hydraulic connection to underlying bedrock. This type of setting may be expected along most of the streams within the igneous domes and mountain flanks settings; however, some contiguous mappable areas may be less than 100 acres in many areas and consequently may not be shown on the map.
Alternating Sandstone, Limestone and Shale-Thin Soil	138.4	3,577	11.1	20.1	This setting, located in the northern part of the study area, is characterized by low to moderate topographic relief. Relatively thin loamy soils overlie horizontal or slightly dipping alternating layers of fractured, consolidated sedimentary rocks. Ground water primarily is obtained from sandstone layers or fractures along bedding planes or vertical fractures. Recharge generally is moderate to low. Shale or clayey layers often form confining layers and where sufficient relief is present, perched ground-water zones of local importance often are developed.
Unconsolidated or Semi-Consolidated Deposits	26.1	3,594	6.4	20.5	This setting is characterized by moderately low topographic relief and interbedded deposits that consist of layers of clay, silt, and sand. Although soils are typically loamy or sandy, recharge is limited because of moderate precipitation and high evapotranspiration. Ground-water levels typically are less than 50 feet.
River Alluvium without Overbank Deposits	38.9	3,436	4.6	19.9	This setting is characterized by low topographic relief and deposits of alluvium along stream valleys. Ground-water levels typically are shallow. Infiltration of precipitation is rapid but limited by the amount of precipitation. Interaction between the stream and the ground-water system is significant.

[1]Average land-surface altitude and slope were determined from U.S. Geological Survey digital elevation models (DEM's) with 30-meter resolution. For more detailed information describing DEM's, see U.S. Geological Survey (1993) digital elevation model user's guide.

[2]These values were interpreted from precipitation records in and around the study area. For more information describing this interpretation, see the "Recharge Rate" section and figure 9.

The descriptions of the settings listed in the DRASTIC method (Aller and others, 1987) were modified because of the unique orographic effects on weather patterns around the northern perimeter of the Black Hills and the small area of the Black Hills in relation to other mountain ranges. The "Solution Limestone" setting description (Aller and others, 1987) was modified to represent the limestone plateau in the southwestern part of the study area, which has similar hydrologic characteristics. The "Metamorphic/ Igneous Domes and Fault blocks" setting was modified to describe areas where igneous intrusive rocks are the most common rock type. The outline of settings follows lines on the 1:100,000-scale hydrogeologic-unit map of the Black Hills (Strobel and others, 1999) with some dividing lines added that delineate precipitation and topographic changes. This map layer provided the framework for the analysis of the hydrogeologic-unit, recharge-rate, depth-to-water, and land-surface-slope map layers.

SENSITIVITY OF GROUND WATER TO CONTAMINATION

Sensitivity to contamination represents the potential for ground water to be contaminated based on intrinsic hydrogeologic characteristics. Land-use practices or contaminant characteristics are not included. The terms vulnerability and susceptibility generally have evolved to refer to evaluations that may include land-use practices and/or contaminant characteristics, in addition to the intrinsic hydrogeologic characteristics. Mapping the sensitivity of ground water to contamination includes overlaying and combining map layers with attributes that relatively rank intrinsic hydrogeologic characteristics in relation to potential contamination. GIS ARC/INFO (Environmental Systems Research Institute, Inc., 1992) software was used to compile and intersect these map layers. The resulting map delineates areas having particular sensitivity characteristics within a specific hydrogeologic setting.

Hydrogeologic Units

The hydrogeologic-unit combines ratings for the characteristics of aquifer media, unsaturated media, and hydraulic conductivity into one code because the ratings primarily are determined by the geologic materials of the aquifer and the unsaturated zone. Aquifer media refers to the consolidated and unconsolidated rocks that compose the uppermost aquifer (or other hydrogeologic unit). Unsaturated media includes the rocks and sediments above the water table that are unsaturated or partially saturated. The unsaturated material can be the same as the aquifer media; however, in some instances the unsaturated material may include a different material or more than one type of material.

Aquifer media affects the rate at which a contaminant can move in an aquifer and the attenuation of potential contaminants by processes such as adsorption, ion exchange, and dispersion. Adsorption attaches ions and molecules to sediment particles and is a function of surface area and ionic charge. Ion exchange is controlled by ion size and charge, and occurs more frequently on smaller particles such as clays. Dispersion is the mixing of a potential contaminant with ground water as the water moves. In a fine-grained homogeneous medium, the flowpaths of water change directions frequently by dodging around the particles, and a contaminant generally spreads out in an elliptical pattern in the direction of the ground-water gradient (Freeze and Cherry, 1979). In aquifer material with preferential flowpaths in fractures or solution conduits in a limestone, the extent and shape of the mixing pattern can be significantly different. In a limestone with solution conduits, a contaminant could move a great distance with very little attenuation. Where fractures and conduits are highly interconnected, there is more opportunity for a potential contaminant to spread. Generally, limestones, unconsolidated sands and gravels, and sandstones are more sensitive than shales, clays, and unfractured igneous and metamorphic rocks because they typically import less adsorption and ion exchange and more dispersion. Adsorption and ion exchange are more likely in sands and gravels and sandstones with greater clay content or interbedded shale layers.

Unsaturated media affects sensitivity in many of the ways described for aquifer media; however, there are some significant differences. The presence of air in the unsaturated zone results in different biological and chemical processes that can break down or modify a potential contaminant. The potential for these processes to attenuate a potential contaminant generally increases with residence time (Hearne and others, 1995). Retardation of the movement of potential contaminants by adsorption and tortuous flowpaths can affect the chemical and biological degradation processes. Fractured media generally produce rapid flowpaths that significantly reduce residence time. In sands and gravels, and sandstones, the distance from the land surface to the water table significantly affects the residence time. Generally, karst limestones, weathered and fractured rocks, sands and gravels, and sandstones in the unsaturated zone are more sensitive. Silts, clays, and shales are less sensitive.

Hydraulic conductivity, which is a function of the interconnection of void spaces in the aquifer media, is a bulk measurement of the ability of an aquifer to transmit water. Hydraulic conductivity affects the sensitivity of an aquifer because the transport of a contaminant usually is a function of the bulk movement of water. Generally, unconsolidated sands and gravels are more sensitive to contamination because they have high hydraulic conductivities. Unfractured igneous and metamorphic rocks and shales are less sensitive because they have very low hydraulic conductivities. Layers of silts, clays, and shales within sands and gravels and sandstones can reduce the sensitivity of sands and gravels in the saturated zone.

Criteria for Delineation

Hydrogeologic and geologic maps were used to delineate and evaluate aquifer media and unsaturated media. The 1:100,000-scale hydrogeologic-unit map of the Black Hills area (Strobel and others, 1999) was the primary map for the delineation of hydrogeologic units. The 1:100,000-scale hydrogeologic map, modified from several geologic maps at various scales ranging from 1:24,000 to 1:250,000, grouped some geologic units together based on similar hydraulic properties or unit thickness. The generalizations included in the hydrogeologic map were appropriate for the ground-water sensitivity map at the same scale.

An examination of well information in the study area indicated that at least some portion of all the exposed areas delineated on the hydrogeologic map were capable of yielding usable quantities of water to wells. Therefore, the shallowest ground water at any location was assumed to occur within the unit represented on the hydrogeologic-unit map (fig. 2). The thicknesses of most of the exposed hydrogeologic units range from zero near the contact with the underlying unit, to the entire thickness of the unit near the contact with the overlying unit. Because of the dipping strata, the entire unit may not always be saturated. Also, some hydrogeologic units include layers of different geologic materials; however, the hydrogeologic units were not subdivided based on this variable saturation or material. The sensitivity of the aquifer media and the unsaturated media was rated by evaluating the characteristics of the entire unit. Some hydrogeologic units were subdivided by intersection with the hydrogeologic settings map layer.

Geologic maps at more detailed scales (Van Lieu, 1969; DeWitt and others, 1989; Lisenbee, 1991a, 1991b, 1991c, 1991d, 1991e, 1991f, 1991g; Lisenbee and Redden, 1991a, 1991b) were consulted when rating aquifer media, unsaturated media, and hydraulic conductivity. Typically, data describing the depth to water were not available or the depth to water was highly variable in a large part of the study area; therefore, the thickness of the unsaturated media evaluated was based on a range of depths to water estimated from well log information, thickness of the geologic formations, and the setting. The ranges of ratings described in Aller and others (1987) were considered in determining the relative sensitivity ratings for aquifer media and unsaturated media in the study area (tables 2 and 3).

Hydraulic conductivity of the aquifer media was estimated from aquifer tests (Greene, 1993; Greene and others, 1998), ground-water flow models (Downey, 1986; Kyllonen and Peter, 1987), and ranges of hydraulic conductivity for geologic materials (Freeze and Cherry, 1979). The categories of hydraulic conductivity proposed by Aller and others (1987) were used as a guide in determining sensitivity ratings for hydraulic conductivity (table 4).

Table 2. Sensitivity ranges for types of aquifer media

[Modified from Aller and others, 1987, table 6, p. 22]

Type of aquifer media	Sensitivity rating[1]
Karst limestone	9-10
Basalt	2-10
Sand and gravel	4-9
Bedded sandstone, limestone, and shale sequences	5-9
Massive limestone	4-9
Weathered metamorphic and igneous rocks	3-5
Metamorphic and igneous rocks	2-5
Massive shale	1-3

[1]Higher rating indicates higher sensitivity to contamination.

Table 3. Sensitivity ranges for types of unsaturated media

[Modified from Aller and others, 1987, table 9, p. 24]

Type of unsaturated media	Sensitivity rating[1]
Karst limestone	8-10
Basalt	2-10
Sand and gravel	6-9
Sand and gravel having significant silt and clay	4-8
Bedded sandstone, limestone, and shale	4-8
Sandstone	4-8
Metamorphic and igneous rocks	2-8
Limestone	2-7
Silt and Clay	2-6
Shale	2-5

[1]Higher rating indicates higher sensitivity to contamination.

Table 4. Sensitivity ratings for range categories of aquifer hydraulic conductivity

[Modified from Aller and others, 1987, table 10, p. 25]

Hydraulic conductivity (feet per day)	Sensitivity rating[1]
More than 270	10
13-270	8
90-130	6
40-90	4
13-40	2
Less than 13	1

[1]Higher rating indicates higher sensitivity to contamination.

Designated Units

A total of 45 hydrogeologic units (table 5) were designated within the 11 hydrogeologic settings. Each hydrogeologic unit was identified by an alphabetic character beginning with capital letters and continuing with lowercase letters. The hydrogeologic units were sorted in descending order based on the relative sensitivity rating from most sensitive to least sensitive. The primary sort was based on unsaturated media, with a secondary sort based on aquifer media, and a tertiary sort based on hydraulic conductivity. The sort order was based on reports (U.S. Environmental Protection Agency, 1992; Rupert, 1998) that evaluate the measured presence of pesticides and nitrates in relation to DRASTIC scores for each characteristic (subscores). A national survey of pesticides in drinking water wells (U.S. Environmental Protection Agency, 1992) found that "…higher DRASTIC subscores for impact of the vadose zone were found to reflect a greater likelihood of pesticide detections in rural and domestic wells." These reports also noted that the DRASTIC subscores for aquifer media and hydraulic conductivity did not correlate positively with the presence of pesticides and nitrates. Aquifer media and hydraulic conductivity may be more significant in evaluating sensitivity to highly toxic point sources of contamination than indicated by studies evaluating nonpoint sources of contamination. Nonpoint sources by definition are dispersed; therefore, correlation of water-quality samples with changes in aquifer media may not be evident. The DRASTIC method of rating these parameters, which relies on best professional judgment, provides a means for ranking these hydrogeologic characteristics. Relative sensitivity ratings for aquifer media ranged from 2 to 10, for unsaturated media from 2 to 10, and for hydraulic conductivity from 1 to 10.

To provide a generalized representation of the sensitivity of the 45 hydrogeologic units, three groups (fig. 8) were created based on the relative sensitivity rank. The 15 hydrogeologic units with the highest sensitivity rank (A, B, C, D, E, F, G, H, I, J, K, L, M, N, O) include those units that consist of mostly limestones, alluvium, unconsolidated sands and gravels, and some sandstones. The 15 hydrogeologic units with the middle sensitivity rank (P, Q, R, S, T, U, V, W, X, Y, Z, a, b, c, d) include those that consist of mostly sandstones and fractured crystalline rocks. The 15 hydrogeologic units with the lowest sensitivity rank (e, f, g, h, i, j, k, l, m, n, o, p, q, r, s) include units consisting of mostly shales or units with interbedded shale layers. Comments in table 5 include information describing the hydrogeologic unit such as location, well yield, and permeability characteristics.

Estimates of recharge can be made with water budget equations if the uncertainty of estimates of other equation components is small. The equation, "ground-water recharge rate = precipitation rate - evapotranspiration rate - runoff rate - change in ground-water storage" may be simplified by neglecting components whose value approaches zero. Over a long period of time, the average change in storage may approach zero.

Table 5. Sensitivity characteristics of hydrogeologic units

[mi^2, square miles; ft, feet; gal/min, gallons per minute; ft/d, feet per day; --, no data]

Hydrogeologic unit[1]	Hydrogeologic setting	Total surface area of unit (mi^2)	Geologic units	Sub-surface thickness of geologic unit (ft)	Unsaturated and aquifer media[2]	Relative sensitivity rating: Aquifer media	Relative sensitivity rating: Unsaturated media	Relative sensitivity rating: Hydraulic conductivity	Comments[3,4]
A	Igneous Domes	22.9	Madison Limestone	[5]350-1,000	Limestone, more dolomitic with depth. Generally massive, karstic, and cavernous in upper part.	10	10	8	This part of the Madison Limestone outcrop is located across the central part of the study area near intrusive rocks. Inventoried well yields in the regional Madison aquifer are highly variable with the largest group ranging from 10 to 200 gal/min and a significant number of wells between 400 and 1,750 gal/min. Permeability is mainly from enhanced solution openings, which occur predominantly in the upper 200 ft of the formation,[7] and fractures. Additional fracturing is possible due to igneous intrusive activity. Hydraulic conductivity determined from aquifer tests of wells with larger yields are in the range of 200 ft/d.[7,8] Rapid movement of potential contaminants with little attenuation through solution openings or fractures in the aquifer media and unsaturated media is likely. Little well information is available for the Englewood Formation, and hydrogeologic characteristics were assumed to be similar to the overlying lower Madison Limestone.
			Englewood Formation	[5]40-75	Dolomitic limestone.				
B	Limestone Plateau	109.0	Madison Limestone	[6]450-650	Limestone, more dolomitic with depth. Generally massive, karstic, and cavernous in upper part.	10	10	6	This part of the Madison Limestone outcrop, located within the Spearfish Creek drainage basin, includes a large part of Limestone Plateau setting. Inventoried well yields within the unconfined outcrop area are less than 20 gal/min. Permeability is from enhanced solution openings, which occur predominantly in the upper 200 ft of the formation[7] and fractures. Ground-water flow is towards springs discharging to Spearfish Creek and Rapid Creek, and to the regional Madison aquifer. Rapid movement of potential contaminants with little attenuation through solution openings or fractures in the aquifer media and unsaturated media is likely.
			Englewood Formation	[5]40-75	Dolomitic limestone.				
C	Mountain Flanks	21.5	Madison Limestone	[5]350-1,000	Limestone, more dolomitic with depth. Generally massive, cavernous in upper part.	10	10	6	This part of the Madison Limestone outcrop is located in the southeastern and southwestern part of the study area, near Spearfish Creek, and a small area in the east-central part of the study area. Ground-water flow generally is radially outward from the central part of the Black Hills. Sensitivity characteristics are similar to unit A without the additional fracturing due to igneous intrusive activity.
			Englewood Formation	[5]40-75	Dolomitic limestone.				

Table 5. Sensitivity characteristics of hydrogeologic units–Continued

[mi^2, square miles; ft, feet; gal/min, gallons per minute; ft/d, feet per day; --, no data]

Hydrogeologic unit[1]	Hydrogeologic setting	Total surface area of unit (mi^2)	Geologic units	Sub-surface thickness of geologic unit (ft)	Unsaturated and aquifer media[2]	Relative sensitivity rating: Aquifer media	Relative sensitivity rating: Unsaturated media	Relative sensitivity rating: Hydraulic conductivity	Comments[3,4]
D	Limestone Plateau	20.3	Madison Limestone	[6]450-650	Limestone, more dolomitic with depth. Generally massive, karstic, and cavernous in upper part.	9	10	4	This part of the Madison Limestone outcrop is located east of Spearfish Creek. The yields of the few inventoried wells located within the hydrogeologic unit range from 2 to 200 gal/min. Ground-water flow directions are related to topography and surface drainage patterns. The area is not directly connected to the regional Madison aquifer but does contribute base flow to headwaters of Spearfish, Whitewood, Elk, and Rapid Creeks. Hydraulic conductivity probably is less than determined for higher producing wells in the regional aquifer due to limited saturation and erosion of the more permeable upper parts of the formation. Movement of potential contaminants with little attenuation through solution openings or fractures in the aquifer media and unsaturated media is possible.
			Englewood Formation	[5]40-75	Dolomitic limestone.				
E	Mountain Flanks	27.1	Minnekahta Limestone	[9]35-50	Massive laminated crystalline limestone.	8	9	4	This part of the Minnekahta Limestone outcrop is located in an east-west direction across the north-central part of the study area. Most inventoried well yields range from 2 to 200 gal/min with some well yields as much as 500 gal/min. Permeability primarily is from fractures with some solution openings. Estimates of hydraulic conductivity from production well data range from less than 10 to 60 ft/d. Vertical movement in the unsaturated zone is rapid with little attenuation of potential contaminants.
F	Alternating Sandstone, Limestone, and Shale	.6	Minnekahta Limestone	[10]35-50	Massive laminated crystalline limestone.	8	9	4	This part of the Minnekahta Limestone outcrop is exposed in a narrow band around Elkhorn Peak.
G	Alluvial Mountain Valleys-East	4.9	Alluvium	[9]0-50	Clay, silt, sand and gravel.	7	9	10	This alluvium is located in the southern part of the study area within mountain slopes-east. Particle size probably is larger than most alluvium because of high stream velocities. Similar alluvium is likely along all streams in this setting although the area may not be shown due to size and map-scale limitations. Saturation is variable depending on streamflow conditions.
H	Alluvial Mountain Valleys-North	0.4	Alluvium	[9]0-50	Clay, silt, sand and gravel.	7	9	10	This alluvium is located in the central part of the study area within Mountain Slopes-North. Sensitivity characteristics are similar to unit G.

Table 5. Sensitivity characteristics of hydrogeologic units–Continued

[mi^2, square miles; ft, feet; gal/min, gallons per minute; ft/d, feet per day; --, no data]

Hydrogeologic unit[1]	Hydrogeologic setting	Total surface area of unit (mi^2)	Geologic units	Sub-surface thickness of geologic unit (ft)	Unsaturated and aquifer media[2]	Relative sensitivity rating			Comments[3,4]
						Aquifer media	Unsaturated media	Hydraulic conductivity	
I	Alluvial Mountain Valleys	5.0	Alluvium	[9]0-50	Clay, silt, sand and gravel.	7	8	10	This alluvium is located around the perimeter of the Black Hills uplift in the southern and central part of the study area within the Igneous Domes and Mountain Flanks settings. Similar alluvium is likely along streams in this setting although the area may not be shown due to size and map-scale limitations. Saturation is variable depending on streamflow conditions.
J	River Alluvium without Overbank Deposits	38.9	Alluvium	[9]0-50	Clay, silt, sand and gravel.	7	7	10	This alluvium is located along streams in the northern part of the study area with gentler topographic relief than in the mountain settings. Inventoried well yields range from 10 to 60 gal/min. Saturation is more consistent along the perennial streams.
K	Unconsolidated and Semi-Consolidated Deposits	26.1	Gravel deposits	[9]0-60	Clay, silt, sand and gravel.	7	5	6	These deposits are local aquifers where saturated and generally consist of terraces and former flood plains located adjacent to recent alluvial deposits. Inventoried well yields range from 10 to 100 gal/min. Saturation of the unit varies with the altitude of the unit in relation to adjacent alluvium and hydrologic conditions.
L	Mountain Flanks	84.6	Minnelusa Formation	[5]350-650	Cross stratified sandstone, limestone, dolomite, and shale. Anhydrite at depth. Lower part of the formation is interbedded limestone and shale.	7	5	4	This part of the Minnelusa Formation outcrop is located east to west across the central part of the study area and north to south along the southwestern part of the study area. Inventoried well yields are highly variable with the largest group ranging from 10 to 200 gal/min, a considerable number between 200 and 700 gal/min, and a few wells as much as 1,700 gal/min. Permeability is from the primary porosity of sandstone layers. Secondary porosity is from fractures and dissolved anhydrite collapse features. The lower part of the formation, with interbedded shales, generally is considered a confining layer[7] with highly variable leakage to and from the Madison Limestone due to fractures and brecciation. Hydraulic conductivity is variable with values of about 50 ft/d determined from aquifer tests at public supply wells.[8] Some attenuation of potential contaminants is possible with movement through sandstone; however, considerable variability is probable due to fractures and collapse features.

Table 5. Sensitivity characteristics of hydrogeologic units–Continued

[mi^2, square miles; ft, feet; gal/min, gallons per minute; ft/d, feet per day; --, no data]

Hydrogeologic unit[1]	Hydrogeologic setting	Total surface area of unit (mi^2)	Geologic units	Sub-surface thickness of geologic unit (ft)	Unsaturated and aquifer media[2]	Relative sensitivity rating: Aquifer media	Relative sensitivity rating: Unsaturated media	Relative sensitivity rating: Hydraulic conductivity	Comments[3,4]
M	Alternating Sandstone, Limestone, and Shale	1.2	Minnelusa Formation	[5]350-650	Cross stratified sandstone, limestone, dolomite, and shale. Anhydrite at depth. Lower part of the formation is interbedded limestone and shale.	7	5	2	This part of the Minnelusa Formation outcrop is located in the northeastern part of the study area. Erosion of the more permeable upper parts of the formation probably decreases the hydraulic conductivity and vertical movement of a potential contaminant in the unsaturated zone compared to unit L.
N	Igneous Domes	28.9	Deadwood Formation	[10]300-500	Sandstone, shale, limestone, and local conglomerate at the base.	7	5	1	This part of the Deadwood Formation outcrop is located east to west across the central part of the study area. Inventoried well yields are highly variable with the largest group less than 50 gal/min, several between 50 and 300 gal/min, and a few wells as much as 1,100 gal/min. Wells generally are located near to or on the outcrop. Permeability is from the primary porosity of sandstone layers and secondary porosity from fractures. This part of the outcrop is near intrusive igneous bodies and often includes sills, which increase the fracturing. The ground-water flow patterns are very complex because of the intrusive bodies and include a mixture of local and regional ground-water flow systems. Movements of potential contaminants could be highly variable because of the complex fracturing patterns.
O	Limestone Plateau	13.3	Deadwood Formation	[10]300-500	Sandstone, shale, limestone, and local conglomerate at the base.	6	5	1	This part of the Deadwood Formation outcrop is located along Spearfish Creek and the headwaters of Elk, Boxelder, and Rapid Creeks. Ground water could be close to the surface in parts of this area because of the interaction between the streams and the Deadwood aquifer. Many of the smaller tributaries flowing across this area have perennial flow because of springs discharging from the Madison or Deadwood aquifers.
P	Igneous Domes	.5	Minnelusa Formation	[6]400-550	Cross stratified sandstone, limestone, dolomite, and shale. Anhydrite with depth. Lower part of the formation is interbedded limestone and shale.	5	5	1	These small areas of Minnelusa Formation outcrop, located on the eastern and western edges of the central part of the study area, are isolated from the regional Minnelusa aquifer. Erosion of the more permeable upper part of the formation probably decreases hydraulic conductivity and the movement of potential contaminants in the unsaturated zone. No inventoried well information is available for the unit and saturation could be limited because of discharge to the surrounding Madison aquifer, which has a lower altitude.

Table 5. Sensitivity characteristics of hydrogeologic units–Continued

[mi^2, square miles; ft, feet; gal/min, gallons per minute; ft/d, feet per day; --, no data]

Hydrogeologic unit[1]	Hydrogeologic setting	Total surface area of unit (mi^2)	Geologic units	Sub-surface thickness of geologic unit (ft)	Unsaturated and aquifer media[2]	Relative sensitivity rating			Comments[3,4]
						Aquifer media	Unsaturated media	Hydraulic conductivity	
Q	Limestone Plateau	0.4	Minnelusa Formation	[6]450-550	Cross stratified sandstone, limestone, dolomite, and shale. Anhydrite with depth. Lower part of the formation is interbedded limestone and shale.	5	5	1	This small area of Minnelusa Formation outcrop, located within the Limestone Plateau, is isolated from the regional Minnelusa aquifer. Erosion of the more permeable upper part of the formation probably decreases hydraulic conductivity and the sensitivity characteristics of the unsaturated zone. No inventoried well information is available for the unit and saturation could be limited because of discharge to the surrounding Madison aquifer, which has a lower altitude.
R	Mountain Flanks	15.1	Deadwood Formation	[10]300-500	Sandstone, shale, limestone, shale, and local conglomerate at the base.	5	5	1	This part of the Deadwood Formation outcrop is located in the southeastern part of the study area, and a small area is located near Spearfish Creek. Permeability is from the primary porosity of sandstone layers and secondary porosity from fractures. The general direction of ground-water flow in the southeastern area is to the east, and average precipitation is less than on the other Deadwood Formation outcrops.
S	Mountain Slopes-East	2.6	Deadwood Formation	[10]300-500	Sandstone, shale, limestone, shale, and local conglomerate at the base.	5	5	1	This part of the Deadwood Formation outcrop is located within the Precambrian rocks in the southern part of the study area. Permeability is from the primary porosity of sandstone layers and secondary porosity from fractures. Some of the areas may be isolated from the regional Deadwood aquifer with ground-water flow patterns determined by local topography and hydraulic connection to underlying rocks.
T	Mountain Slopes-East	125.1	Igneous and metamorphic rocks	--	Shist, slate, quartzite, amphibolite, diorite, granite, and pegmatite.	4	5	1	This hydrogeologic unit, located in the southeastern and south central part of the study area is a local aquifer where saturated. Wells are located on or very close to the outcrop. Most inventoried well yields range from 5 to 20 gal/min with some well yields up to 60 gal/min. The depth of wells generally are less than 200 ft. Permeability is from fracturing that decreases with depth. Ground-water flow patterns are complex and variable.
U	Mountain Slopes-North	22.0	Igneous and metamorphic rocks	--	Shist, slate, quartzite, amphibolite, diorite, granite, and pegmatite.	4	5	1	This hydrogeologic unit, located in the central part of the study area, is a local aquifer where saturated. Wells are located on or very close to the outcrop. Most inventoried well yields are less than 20 gal/min with one reported yield of 60 gal/min. This well was in an area where numerous sills have penetrated the Precambrian rocks. Permeability is from fracturing that decreases with depth. Ground-water flow patterns are complex and variable.

Table 5. Sensitivity characteristics of hydrogeologic units–Continued

[mi^2, square miles; ft, feet; gal/min, gallons per minute; ft/d, feet per day; --, no data]

Hydrogeologic unit[1]	Hydrogeologic setting	Total surface area of unit (mi^2)	Geologic units	Sub-surface thickness of geologic unit (ft)	Unsaturated and aquifer media[2]	Relative sensitivity rating: Aquifer media	Relative sensitivity rating: Unsaturated media	Relative sensitivity rating: Hydraulic conductivity	Comments[3,4]
V	Mountain Flanks	1.3	Igneous and metamorphic rocks	--	Shist, slate, quartzite, amphibolite, diorite, granite, and pegmatite.	4	5	1	This hydrogeologic unit, located in the southeastern part of the study area and surrounded by the Deadwood Formation, is a local aquifer where saturated. An inventoried well yield was 5 gal/min. Permeability is from fracturing that decreases with depth. Ground-water flow patterns are complex and variable.
W	Mountain Slopes-East	2.0	Colluvium	[9]0-50	Talus and other debris associated with mass wasting.	6	4	4	This hydrogeologic unit, located within the Precambrian rocks in the southern part of the study area, could supply limited quantities of water where saturated. No information is available to describe well yields or hydraulic conductivity. Considerable variation in sensitivity characteristics is likely depending on the particle size and sorting of the deposits.
X	Igneous Domes	.6	Colluvium	[9]0-50	Talus and other debris associated with mass wasting.	6	4	4	This hydrogeologic unit, located on the slopes of igneous domes in the western part of the study area, probably would have limited saturation because of the land-surface slope.
Y	Mountain Flanks	.3	Colluvium	[9]0-50	Talus and other debris associated with mass wasting.	6	4	4	This hydrogeologic unit, located in the east-central part of the study area, could supply limited quantities of water where saturated. No information is available to describe well yields or hydraulic conductivity. Considerable variation in sensitivity characteristics is likely depending on the particle size and sorting of the deposits.
Z	Alternating Sandstone, Limestone, and Shale	35.6	Inyan Kara Group: Fall River Formation and Lakota Formation	[6]10-200 [6]30-300	Sandstone and other clastic rocks.	6	4	1	The Inyan Kara Group outcrop is located in the northeastern part of the study area. Inventoried well yields in the Inyan Kara aquifer mostly are less than 50 gal/min, with a few wells between 50 and 200 gal/min. The majority of permeability is from the primary porosity of the sandstone.
a	Igneous Domes	52.6	Tertiary intrusive igneous rocks	--	Undifferentiated intrusive igneous rocks including rhyolite, latite, trachyte, and phonolite.	4	4	1	This hydrogeologic unit, located in the central part of the study area, includes most of the centers of igneous activity in the northern Black Hills in South Dakota.[11] Inventoried well yields completed in intrusive rocks generally are less than 20 gal/min. Well yields and hydraulic conductivity in the massive domes probably would be low. Larger well yields could be expected where the outcrop is exposed as shallow sills intruding the Deadwood Formation. The lithology for several of the wells in this area that are identified as Deadwood aquifer wells include layers of intrusive rocks. Ground-water flow patterns are complex and variable.

Table 5. Sensitivity characteristics of hydrogeologic units–Continued

[mi^2, square miles; ft, feet; gal/min, gallons per minute; ft/d, feet per day; --, no data]

Hydrogeologic unit[1]	Hydrogeologic setting	Total surface area of unit (mi^2)	Geologic units	Sub-surface thickness of geologic unit (ft)	Unsaturated and aquifer media[2]	Relative sensitivity rating			Comments[3,4]
						Aquifer media	Unsaturated media	Hydraulic conductivity	
b	Mountain Slopes-East	.7	Tertiary intrusive igneous rocks	--	Undifferentiated intrusive igneous rocks including rhyolite, latite, trachyte, and phonolite.	4	4	1	These two hydrogeologic units are located within the Precambrian rocks in the south-central part of the study area. No well inventory information is available.
c	Mountain Slopes-North	3.0	Tertiary intrusive igneous rocks	--	Undifferentiated intrusive igneous rocks including rhyolite, latite, trachyte, and phonolite.	4	4	1	This hydrogeologic unit is located within the Precambrian rocks in the central part of the study area. Larger well yields generally are found adjacent to Precambrian rocks intruded with shallowly placed sills, laccoliths, dikes, and plugs. Ground-water flow patterns are complex and variable.
d	Igneous Domes	2.8	Whitewood Formation	[9]0-150	Limestone and dolomite.	4	4	1	This hydrogeologic unit is located in narrow bands adjacent to Deadwood Formation outcrops and intrusive rocks in the east- to west-central part of the study area. The combined Whitewood Formation and Winnipeg Formation is considered a semiconfining unit in the study area. No well inventory information is available for the unit. The overlying Madison aquifer or the underlying Deadwood aquifer would be more likely sources of water. The Whitewood Formation extends as far south as the intersection of Spearfish Creek and Highway 85 with only few places where the Winnipeg Formation extends farther south.[12] Permeability from fractured limestone, dolomite, and siltstone could produce small quantities of water.
			Winnipeg Formation	[9]0-110	Shale with interbedded siltstone.				
e	Mountain Flanks	.3	Whitewood Formation	[9]0-150	Limestone and dolomite.	4	4	1	This hydrogeologic unit is located in the part of the Spearfish Creek drainage basin just above the City of Spearfish. The unit is exposed along Spearfish Creek and its tributaries.
			Winnipeg Formation	[9]0-110	Shale with interbedded siltstone.				

Table 5. Sensitivity characteristics of hydrogeologic units–Continued

[mi^2, square miles; ft, feet; gal/min, gallons per minute; ft/d, feet per day; --, no data]

Hydrogeologic unit[1]	Hydrogeologic setting	Total surface area of unit (mi^2)	Geologic units	Sub-surface thickness of geologic unit (ft)	Unsaturated and aquifer media[2]	Relative sensitivity rating: Aquifer media	Relative sensitivity rating: Unsaturated media	Relative sensitivity rating: Hydraulic conductivity	Comments[3,4]
f	Limestone Plateau	8.1	Whitewood Formation	[9]0-150	Limestone and dolomite.	4	4	1	This hydrogeologic unit is located in the upper part of the Spearfish Creek drainage basin and the headwaters of Elk, Boxelder, and Rapid Creek in the southern and central parts of the study area. The part of the unit exposed along Spearfish Creek and its tributaries is a narrow band located part way up the canyon wall above the Deadwood Formation outcrop, which is exposed at the bottom of the canyon. Most of these areas have very steep slopes causing most precipitation that falls on the outcrop to run off.
			Winnipeg Formation	[9]0-110	Shale with interbedded siltstone.				
g	Mountain Flanks	2.2	Whitewood Formation	[9]0-150	Limestone and dolomite.	4	4	1	This hydrogeologic unit, located in the southeastern corner of the study area, dips to the east, and the general direction of ground-water flow is to the east.
			Winnipeg Formation	[9]0-110	Shale with interbedded siltstone.				
h	Alternating Sandstone, Limestone, and Shale	16.5	Morrison Formation Unkpapa Sandstone Sundance Formation Gypsum Spring Formation	[9]0-150 [9]0-275 [9]250-475 [9]0-125	Interbedded shale, sandstone, and gypsum	5	3	1	This hydrogeologic unit, located in the northeastern part of the study area, is a semiconfining unit with parts of the unit used as an aquifer locally. Reported well yields, primarily from wells completed in the Sundance Formation, range from 5 to 70 gal/min. Permeability mostly is from sandstone layers within the unit.
i	Mountain Slopes-East	.8	White River Group	[10]0-150	Sandstone, claystone, and siltstone with channel fillings and limestone lenses.	3	3	1	This part of the White River Group outcrop, located in the east-central part of the study area, is a small area within Precambrian rocks that has not been removed by erosion. No well inventory information is available. Permeability mostly is from sand and gravel lenses and fractured limestone. Bentonite within volcanic ash deposits could limit vertical movement of contaminants.
j	Mountain Slopes-North	.2	White River Group	[10]0-150	Sandstone, claystone, and siltstone with channel fillings and limestone lenses.	3	3	1	This part of the White River Group outcrop, located in the central part of the study area is a small area in a valley of Precambrian rocks.

Table 5. Sensitivity characteristics of hydrogeologic units–Continued

[mi^2, square miles; ft, feet; gal/min, gallons per minute; ft/d, feet per day; --, no data]

Hydrogeologic unit[1]	Hydrogeologic setting	Total surface area of unit (mi^2)	Geologic units	Sub-surface thickness of geologic unit (ft)	Unsaturated and aquifer media[2]	Relative sensitivity rating: Aquifer media	Relative sensitivity rating: Unsaturated media	Relative sensitivity rating: Hydraulic conductivity	Comments[3,4]
k	Igneous Domes	3.3	White River Group	[10]0-150	Sandstone, claystone, and siltstone with channel fillings and limestone lenses.	3	3	1	This part of the White River Group outcrop is located in the central part of the study area near igneous intrusive rocks. No well inventory information is available.
l	Limestone Plateau	.3	White River Group	[10]0-150	Sandstone, claystone and siltstone with channel fillings and limestone lenses.	3	3	1	This part of the White River Group outcrop, located in the east-central part of the study area east of Spearfish Creek, is a small area overlying Madison Limestone and Deadwood Formation outcrops.
m	Mountain Flanks	4.1	White River Group	[10]0-150	Sandstone, claystone and siltstone with channel fillings and limestone lenses.	3	3	1	This part of the White River Group outcrop is located near Madison Limestone and Minnelusa Formation outcrops along the northern mountain flanks in the central part of the study area.
n	Alternating Sandstone, Limestone, and Shale	0.3	White River Group	[10]0-150	Sandstone, claystone and siltstone with channel fillings and limestone lenses.	3	3	1	This part of the White River Group outcrop is located near the Inyan Kara Group outcrop in the northeastern part of the study area.
o	Alternating Sandstone, Limestone, and Shale	42.8	Spearfish Formation	[9]375-800	Silty shale interbedded with sandstone, siltstone, and sparse limestone. Lower part contains massive gypsum.	3	3	1	This hydrogeologic unit, located in an east-west direction across the northern part of the study area, is a confining unit that supplies water to several wells. Most reported well yields are less than 20 gal/min with a few between 20 and 100 gal/min and one well yielding 300 gal/min. Thickness ranges from 375-450 ft along the eastern side of the Black Hills uplift to 700-800 ft on the northwestern flank of the uplift.[12] Permeability is from porous lenses and secondary porosity associated with gypsum solution openings. Attenuation of potential contaminants by silts and shale is probable.
p	Mountain Flanks	2.4	Spearfish Formation	[9]375-800	Silty shale interbedded with sandstone, siltstone and sparse limestone. Lower portion contains massive gypsum.	3	2	1	This hydrogeologic unit is isolated areas of the Spearfish Formation that have not eroded away. The part of the unit located on the western side of the study area slopes to the northwest. The part of the unit located on the east side of the study area slopes to the northeast. Limited saturation in these two areas is likely. No inventoried well information is available.

Table 5. Sensitivity characteristics of hydrogeologic units–Continued

[mi^2, square miles; ft, feet; gal/min, gallons per minute; ft/d, feet per day; --, no data]

Hydrogeologic unit[1]	Hydrogeologic setting	Total surface area of unit (mi^2)	Geologic units	Sub-surface thickness of geologic unit (ft)	Unsaturated and aquifer media[2]	Relative sensitivity rating: Aquifer media	Relative sensitivity rating: Unsaturated media	Relative sensitivity rating: Hydraulic conductivity	Comments[3,4]
q	Alternating Sandstone, Limestone, and Shale	41.1	Belle Fourche Shale Mowry Shale Newcastle Sandstone Skull Creek Shale	[9]150-850 [9]125-230 [9]0-100 [9]150-270	Shale, limestone, and sandstone.	2	2	1	This hydrogeologic unit, located in the northeastern corner of the study area, is a confining unit. The Newcastle Sandstone may yield water to wells locally where saturated. A single well in the Belle Fourche Shale produced 20 gal/min. Vertical movement of potential contaminants is limited by shale and bentonite layers.
r	Mountain Flanks	9.2	Opeche Shale	[9]25-150	Siltstone and shale with local gypsum and anhydrite at the top.	2	2	1	This hydrogeologic unit is located in narrow bands between the Minnelusa Formation and Minnekahta Limestone across the north-central part of the study area. The Opeche Formation is a confining unit that produces water to wells in isolated areas. Most reported well yields range from 2 to 20 gal/min with a few wells as much as 75 gal/min. Permeability is from porous lenses, solution features, and/or fractures. Attenuation of potential contaminants by silt and shale is probable. Drainage from the area could recharge the Minnekahta aquifer.
s	Alternating Sandstone, Limestone, and Shale	.3	Opeche Shale	[9]25-150	Siltstone and shale with local gypsum and anhydrite at the top.	2	2	1	This hydrogeologic unit is located in a narrow ring between the Minnelusa Formation and Minnekahta Limestone around a peak in the northeastern part of the study area near Polo Creek. Drainage from the area could recharge the Minnekahta aquifer.

[1]These hydrogeologic units were sorted in descending order based on relative sensitivity ratings with the primary sort based on unsaturated media, the secondary sort on aquifer media, and the tertiary sort on hydraulic conductivity.

[2]Summarized from Strobel and others (1999). For more detailed descriptions of the geologic units, see references listed in footnotes 6 through 12.

[3]Hydraulic conductivity was estimated from production well drawdown, production rate, well diameter, and an assumed storage coefficient using the non-equilibrium equation (Theis, 1935).

[4]Well information compiled from U.S. Geological Survey Ground-Water Site Inventory System.

[5]See figure 3.

[6]Kyllonen and Peter, 1987.

[7]Greene, 1993.

[8]Greene and others, 1998.

[9]Dewitt and others, 1989.

[10]Robinson and others, 1964.

[11]Lisenbee, 1985.

[12]Gries and Martin, 1985.

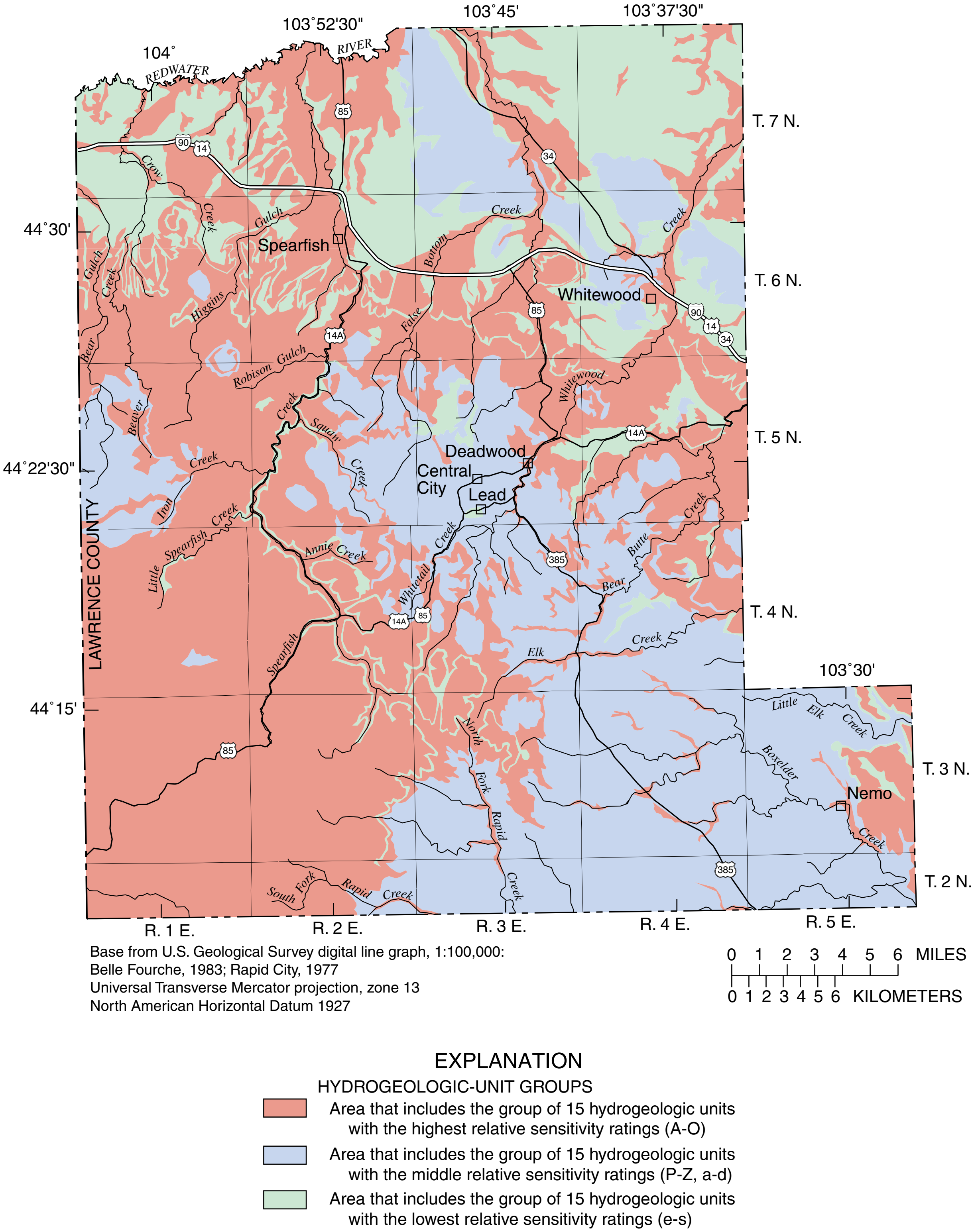


Figure 8. Hydrogeologic-unit sensitivity groups in Lawrence County.

Recharge Rate

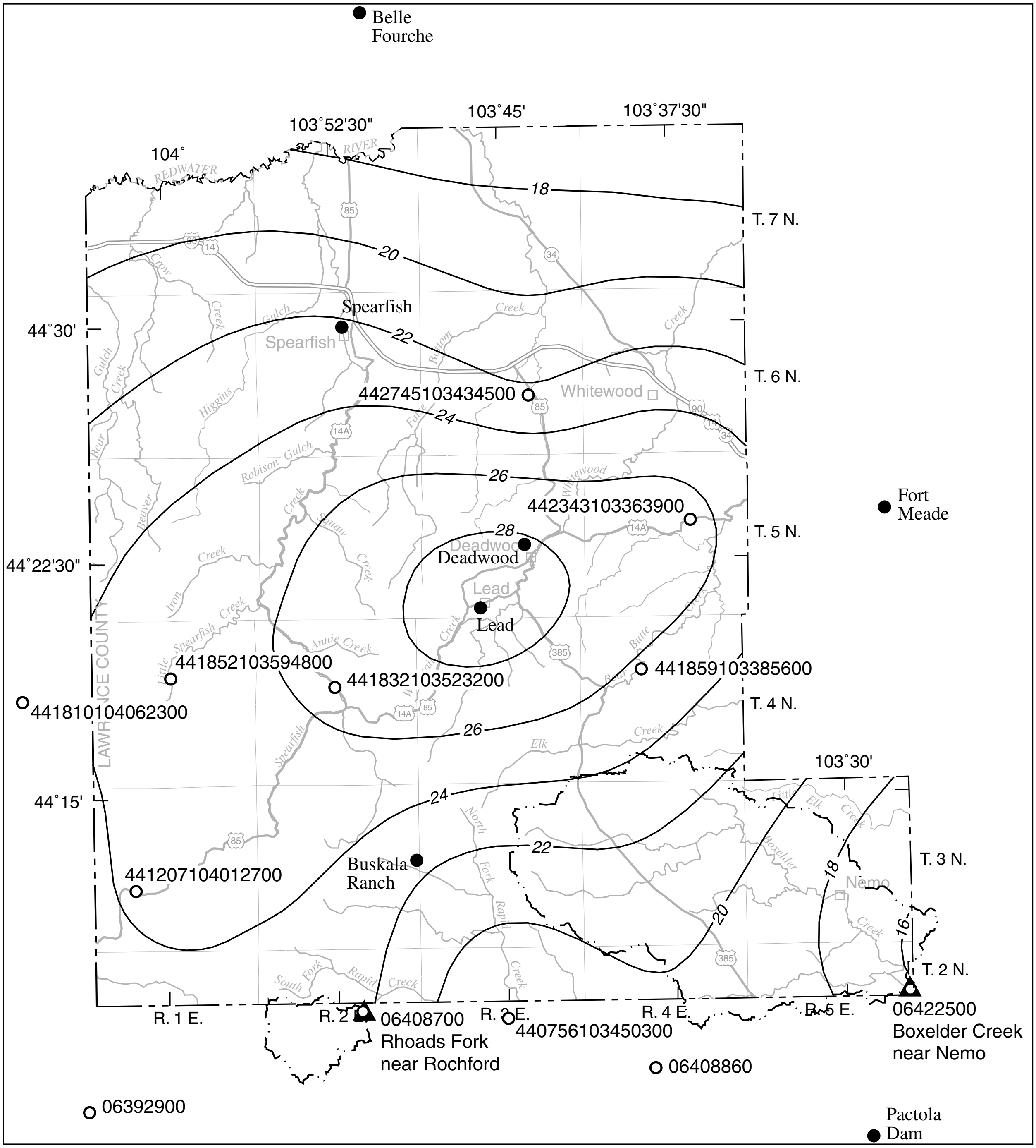
Infiltration of precipitation through the soil and the unsaturated zone to the water table is a common mechanism of ground-water recharge. Recharge rate represents the amount of water that penetrates the land surface and reaches the water table per unit area and unit time. Recharge water can transport a potential contaminant from the land surface to the water table. Large volumes of recharge water or frequency of recharge events increase the mobility of potential contaminants. Generally, the larger the recharge rate the greater the sensitivity; however, in some instances, dilution of contaminants may diminish the impact of larger recharge rates.

Previous estimates of recharge from infiltration of precipitation on outcrops in the northern Black Hills range from 1 to 7 in/yr. Recharge commonly is expressed as a percent of precipitation. A recharge rate of 6.77 in/yr, or 31 percent of precipitation, and an evapotranspiration rate of 15.2 in/year was estimated by Rahn and Gries (1973) from analysis of spring discharge from carbonate basins where no surface runoff was observed. Kyllonen and Peter (1987) estimated recharge rates of 7 in/yr or 32 percent of precipitation for the Madison and Minnelusa aquifers and 1 in/yr or 6 percent of precipitation for the Inyan Kara aquifer in describing the hydrogeology of the northern Black Hills. Kyllonen and Peter (1987) assumed average precipitation that would fall on the outcrop of 22 in/yr for the Minnelusa Formation and Madison Limestone and 16 in/yr for the Inyan Kara Group.

Streamflow records at two USGS gaging stations were analyzed to further characterize the range of plausible recharge rates. The recharge rate for the carbonate basin upstream from USGS gaging station 06408700 (fig. 9) examined by Rahn and Gries (1973) was assumed to represent the highest recharge rate as a percent of precipitation in the study area. The exposed bedrock in the drainage basin above station 06408700, located near the southwest edge of the study area, is about 96 percent Madison Limestone. An analysis of the basin with a longer period of record than that used by Rahn and Gries (1973) was made to refine the estimate of recharge rate. The average (1961-90) precipitation for the basin was 22.8 in., and the average water year 1983-97 runoff at the gaging station was 9.0 in/yr (U.S. Geological Survey, 1984-98). Runoff was assumed to be entirely ground-water discharge because surface-water runoff is not observed in the basin. This lack of surface-water runoff is documented by daily streamflow records at station 06408700 (water years 1983-97), which shows gradual changes in discharge with a minimum flow of 3.1 ft^3/s and a maximum flow of 8.5 ft^3/s. Locations of ground-water divides could be different than the extent of the surface drainage basin. Assuming a range in the area contributing to ground-water flow of 20 percent greater than or less than the drainage basin area, a plausible recharge rate to the Madison aquifer ranges from 7.2 to 10.8 in/yr, or 32 to 47 percent of precipitation.

Analysis of streamflow records for a drainage basin with mostly igneous and metamorphic rocks was made to provide a plausible range for the lower recharge rates as a percent of precipitation in the study area. The bedrock in the basin above USGS gaging station 06422500 (fig. 9) is about 83 percent igneous or metamorphic rocks, 10 percent Deadwood Formation, 5 percent Madison Limestone, and 2 percent other rocks. Average (1961-90) precipitation on the basin (fig. 9) was 20.1 in/yr, and average runoff (water years 1967-96) at the gaging station was 2.4 in/yr. In the central part of the Black Hills with steeply sloping igneous and metamorphic rocks, a large part of the precipitation that becomes recharge reappears in the drainage basin as springflow. Ground-water recharge that reappears as base flow in the basin, estimated from analysis of streamflow-gaging records at station 06422500 (table 6), averages about 3.8 ft^3/s (0.5 in/yr) or about 2.5 percent of precipitation. Runoff or springflow from the Madison Limestone and Deadwood Formation within the basin is unknown; however, a large part of the Madison Limestone and Deadwood Formation is along the east edge of the basin where the strata are dipping to the east. Most ground-water recharge in these areas probably flows to the regional system with little contribution to base flow. Therefore, the estimate of base flow from igneous and metamorphic rocks probably is slightly higher than 2.5 percent of precipitation.

Because of uncertainty in evapotranspiration rates, applying the water budget formula does not produce accurate estimates of relatively small recharge rates that contribute to regional ground-water flow from igneous and metamorphic rocks. Permeability of the igneous and metamorphic rocks decreases with depth (Freeze and Cherry, 1979); therefore, an assumption was made that regional ground-water flow in igneous and metamorphic rocks probably was less than the base flow in the basin. A plausible range of recharge rates for igneous and metamorphic rocks was assumed to be between 3 and 6 percent of precipitation.



Base from U.S. Geological Survey digital line graph, 1:100,000:
Belle Fourche, 1983; Rapid City, 1977
Universal Transverse Mercator projection, zone 13
North American Horizontal Datum 1927

0 1 2 3 4 5 6 MILES
0 1 2 3 4 5 6 KILOMETERS

EXPLANATION

—20—	LINE OF EQUAL ANNUAL PRECIPITATION--Shows 1961-90 average. Interval is 2 inches per year
(triangle with boundary)	STREAMFLOW GAGING STATION--Gaging station name and station identification number. Boundary describes selected drainage basin above gaging staion
● Lead	PRECIPITATION STATION WITH 30-YEAR RECORD--U.S. Department of Commerce (1994)
○ 06408860	PRECIPITATION STATION WITH 30-YEAR AVERAGE INTERPOLATED FROM 1989-96 PRECIPITAITON RECORDS--U.S. Geological Survey (1976-98). Number is station identification number

Figure 9. Selected drainage basins and average precipitation in or near the study area.

Table 6. Base flow within drainage basin above station 06422500

Water year	Estimated base flow (cubic feet per second)	Mean discharge at station (cubic feet per second)
1967	4.0	27.7
1968	4.2	8.7
1969	2.3	8.6
1970	3.5	22.1
1971	4.0	27.9
1972	3.5	55.1
1973	5.5	17.9
1974	3.0	6.0
1975	3.0	15.2
1976	5.5	20.7
1977	5.0	18.7
1978	4.1	22.0
1979	3.5	8.0
1980	2.3	5.4
1981	2.2	4.1
1982	3.0	10.8
1983	6.0	24.5
1984	6.1	23.2
1985	2.6	6.6
1986	3.4	12.3
1987	3.0	10.2
1988	1.4	4.6
1989	1.3	3.8
1990	1.4	5.6
1991	3.2	13.5
1992	3.6	6.9
1993	4.0	24.0
1994	5.2	18.5
1995	6.2	51.4
1996	7.4	42.9

Criteria for Delineation

Based on the range of plausible recharge rates as a percentage of precipitation, the hydrologic setting, unsaturated media, average precipitation, land-surface slope, and land-surface altitude, a comparative estimate of recharge rate as a percent of precipitation was made for each hydrogeologic unit (table 7). Recharge rate is strongly influenced by the unsaturated media. The general order of influence of unsaturated media on recharge rate in descending order was fractured limestone, unconsolidated sands and gravels, sandstones, colluvium, shales with interbedded sandstones, igneous and metamorphic rocks, and shales. Recharge rates, expressed in inches per year, increase with increased precipitation; however, evapotranspiration rates also increase, making the increase in recharge with increased precipitation nonlinear. Greater relative slopes decrease the recharge rate. The land-surface altitude affects recharge rates because of lower temperatures and less evapotranspiration at higher altitudes. A relative ranking of the hydrogeologic units based on the above parameters was used as a guide to estimate a recharge rate as a percent of precipitation for each hydrogeologic unit. These data were converted to a GIS grid data set for the study area and multiplied by the grid of precipitation data (fig. 9) to estimate the spatial distribution of recharge in inches per year.

Because of uncertainty in estimating recharge rates, five broad categories of recharge rate were proposed by Aller and others (table 8). Studies comparing recharge volumes and pesticide concentrations in wells have shown a diversity of results; however, pesticide fluxes appear to be directly related to the amount of recharge entering the subsurface (Barbash and Resek, 1996). The inconsistencies in comparisons of recharge rate and contaminant concentrations are likely related to dilution, lag periods in observed concentrations in wells, and contaminant degradation. The recharge rates in the study area were within the first four recharge-rate groups with recharge rates less than 10 in/yr (table 9).

Table 7. Estimated recharge rate for hydrogeologic units as a percent of precipitation

Hydro-geologic unit	Hydrogeologic setting	Geologic units	Unsaturated media[1]	Average precipitation (inches per year)	Average slope[2] (percent)	Average land-surface altitude[2] (feet above sea level)	Recharge rate (percent of precipitation)
A	Igneous Domes	Madison Limestone	Fractured limestone and dolomitic limestone with enhanced solution openings.	25.7	28.2	5,064	33
		Englewood Formation	Dolomitic limestone.				
B	Limestone Plateau	Madison Limestone	Fractured limestone and dolomitic limestone with enhanced solution openings.	25.6	18.8	6,273	33
		Englewood Formation	Dolomitic limestone.				
C	Mountain Flanks	Madison Limestone	Fractured limestone and dolomitic limestone with enhanced solution openings.	22.7	21.2	5,683	[3]28
		Englewood Formation	Dolomitic limestone.				
D	Limestone Plateau	Madison Limestone	Fractured limestone and dolomitic limestone with enhanced solution openings.	25.1	24.4	5,969	31
		Englewood Formation	Dolomitic limestone.				
E	Mountain Flanks	Minnekahta Limestone	Fractured limestone.	22.8	13.1	4,084	18
F	Alternating Sandstone, Limestone, and Shale	Minnekahta Limestone	Fractured limestone.	21.5	13.7	3,829	17
G	Alluvial Mountain Valleys-East	Alluvium	Clay, silt, sand and gravel.	22.3	13.2	5,505	21
H	Alluvial Mountain Valleys-North	Alluvium	Clay, silt, sand and gravel.	28.6	23.5	4,718	30
I	Alluvial Mountain Valleys	Alluvium	Clay, silt, sand and gravel.	24.5	20.5	4,626	27
J	River Alluvium without Overbank Deposits	Alluvium	Clay, silt, sand and gravel.	19.9	4.6	3,436	19
K	Unconsolidated and Semi-Consolidated Aquifers	Gravel deposits	Clay, silt, sand and gravel.	20.1	6.4	3,594	18
L	Mountain Flanks	Minnelusa Formation	Cross stratified sandstone, limestone, dolomite, and shale with fractures and brecciation.	24.1	19.2	5,300	22

Table 7. Estimated recharge rate for hydrogeologic units as a percent of precipitation–Continued

Hydro-geologic unit	Hydrogeologic setting	Geologic units	Unsaturated media[1]	Average precipitation (inches per year)	Average slope[2] (percent)	Average land-surface altitude[2] (feet above sea level)	Recharge rate (percent of precipitation)
M	Alternating Sandstone, Limestone, and Shale	Minnelusa Formation	Cross stratified sandstone, limestone, dolomite, and shale with fractures and brecciation.	21.8	22.0	4,120	17
N	Igneous Domes	Deadwood Formation	Sandstone, shale, limestone, and local conglomerate at the base.	26.2	22.7	5,633	16
O	Limestone Plateau	Deadwood Formation	Sandstone, shale, limestone, and local conglomerate at the base.	22.7	20.1	5,955	14
P	Igneous Domes	Minnelusa Formation	Cross stratified sandstone, limestone, dolomite, and shale with fractures and brecciation.	24.4	24.8	4,914	22
Q	Limestone Plateau	Minnelusa Formation	Cross stratified sandstone, limestone, dolomite, and shale with fractures and brecciation.	24.9	14.5	6,495	22
R	Mountain Flanks	Deadwood Formation	Sandstone, shale, limestone, and local conglomerate at the base.	19.5	21.4	4,959	10
S	Mountain Slopes-East	Deadwood Formation	Sandstone, shale, limestone, and local conglomerate at the base.	22.0	8.1	5,890	11
T	Mountain Slopes-East	Igneous and metamorphic rocks	Fractured and weathered igneous and metamorphic rocks.	21.3	15.3	5,567	5
U	Mountain Slopes-North	Igneous and metamorphic rocks	Fractured and weathered igneous and metamorphic rocks	28.1	32.1	5,438	7
V	Mountain Flanks	Igneous and metamorphic rocks	Fractured and weathered igneous and metamorphic rocks.	19.3	13.8	4,843	5
W	Mountain Slopes-East	Colluvium	Talus and other debris associated with mass wasting.	19.3	15.7	5,445	12
X	Igneous Domes	Colluvium	Talus and other debris associated with mass wasting.	24.5	34.0	5,406	14
Y	Mountain Flanks	Colluvium	Talus and other debris associated with mass wasting.	26.4	13.5	4,172	15

Table 7. Estimated recharge rate for hydrogeologic units as a percent of precipitation–Continued

Hydro-geologic unit	Hydrogeologic setting	Geologic units	Unsaturated media[1]	Average precipitation (inches per year)	Average slope[2] (percent)	Average land-surface altitude[2] (feet above sea level)	Recharge rate (percent of precipitation)
Z	Alternating Sandstone, Limestone, and Shale	Inyan Kara Group (Fall River Formation and Lakota Formation)	Sandstone and other clastic rocks.	20.2	13.4	3,659	11
a	Igneous Domes	Tertiary intrusive igneous rocks	Intrusive igneous rocks.	25.6	24.7	5,593	6
b	Mountain Slopes-East	Tertiary intrusive igneous rocks	Intrusive igneous rocks.	24.8	11.3	5,541	5
c	Mountain Slopes-North	Tertiary intrusive igneous rocks	Intrusive igneous rocks.	28.7	31.9	5,632	6
d	Igneous Domes	Whitewood Formation Winnipeg Formation	Limestone and dolomite. Shale with interbedded siltstone.	25.5	27.2	5,409	5
e	Mountain Flanks	Whitewood Formation Winnipeg Formation	Limestone and dolomite. Shale with interbedded siltstone.	25.5	53.3	4,447	3
f	Limestone Plateau	Whitewood Formation Winnipeg Formation	Limestone and dolomite. Shale with interbedded siltstone.	24.8	33.6	5,756	5
g	Mountain Flanks	Whitewood Formation Winnipeg Formation	Limestone and dolomite. Shale with interbedded siltstone.	18.8	26.4	4,923	3
h	Alternating Sandstone, Limestone, and Shale	Morrison Formation Unkpapa Sandstone Sundance Formation Gypsum Spring Formation	Interbedded shale, sandstone, and gypsum.	20.9	17.7	3,771	5
i	Mountain Slopes-East	White River Group	Sandstone, claystone and siltstone with channel fillings and limestone lenses.	25.0	9.0	5,467	4
j	Mountain Slopes-North	White River Group	Sandstone, claystone and siltstone with channel fillings and limestone lenses.	29.0	20.3	5,331	4
k	Igneous Domes	White River Group	Sandstone, claystone and siltstone with channel fillings and limestone lenses.	26.5	19.9	5,065	4

Table 7. Estimated recharge rate for hydrogeologic units as a percent of precipitation–Continued

Hydro-geologic unit	Hydrogeologic setting	Geologic units	Unsaturated media[1]	Average precipitation (inches per year)	Average slope[2] (percent)	Average land-surface altitude[2] (feet above sea level)	Recharge rate (percent of precipitation)
l	Limestone Plateau	White River Group	Sandstone, claystone and siltstone with channel fillings and limestone lenses.	27.1	12.9	6,136	4
m	Mountain Flanks	White River Group	Sandstone, claystone and siltstone with channel fillings and limestone lenses.	26.6	16.7	4,613	4
n	Alternating Sandstone, Limestone, and Shale	White River Group	Sandstone, claystone and siltstone with channel fillings and limestone lenses.	23.5	11.8	4,272	4
o	Alternating Sandstone, Limestone, and Shale	Spearfish Formation	Silty shale interbedded with sandstone, siltstone, and sparse limestone. Lower portion contains massive gypsum.	21.1	9.1	3,658	2
p	Mountain Flanks	Spearfish Formation	Silty shale interbedded with sandstone, siltstone, and sparse limestone. Lower portion contains massive gypsum.	24.0	10.3	4,113	3
q	Alternating Sandstone, Limestone, and Shale	Skull Creek Shale Newcastle Sandstone Mowry Shale Belle Fourche Shale	Shale, limestone, and sandstone.	18.4	7.9	3,321	2
r	Mountain Flanks	Opeche Shale	Siltstone and shale with local gypsum and anhydrite at the top.	23.4	23.3	4,336	1
s	Alternating Sandstone, Limestone, and Shale	Opeche Shale	Siltstone and shale with local gypsum and anhydrite at the top.	21.7	17.0	3,890	1

[1]Description was modified from combined unsaturated and aquifer media description in table 5.

[2]Average land-surface altitude and slope were determined from U.S. Geological Survey digital elevation models (DEM's) with 30-meter resolution. For more detailed information describing DEM's, see U.S. Geological Survey (1993) digital elevation model user's guide.

[3]A recharge rate of 20 percent of precipitation was used for a small part of this hydrogeologic unit that was located in the southeastern corner of the study area because the precipitation amounts were considerably less than the average for this hydrogeologic unit.

Table 8. Sensitivity ratings for range categories of recharge rate

[Modified from Aller and others, 1987, table 5, p. 21. <, less than]

Recharge rate (inches per year)	Sensitivity rating[1]
More than 10	9
7 to <10	8
4 to <7	6
2 to <4	3
0 to <2	1

[1]Higher rating indicates higher sensitivity to contamination.

Table 9. Sensitivity rank for designated recharge-rate groups

[<, less than]

Recharge-rate group	Recharge rate (inches per year)	Sensitivity rank
1	7 to <10	Highest to lowest
2	4 to <7	
3	2 to <4	
4	0 to <2	

Designated Units

The distribution of the designated recharge-rate groups is shown in figure 10. Recharge-rate group 1 included most of the Madison Limestone outcrop except areas with lower precipitation on the flanks of the Black Hills uplift. Some alluvium in areas with higher precipitation amounts also were included in this group. The average precipitation rate for recharge-rate group 1 was 24.8 in/yr.

Recharge-rate group 2 included most of the alluvium and terrace gravels, part of the Minnekahta Limestone outcrop, most of the Minnelusa Formation outcrop, the part of the Madison Limestone outcrop with lower precipitation rates, and parts of Deadwood Formation outcrop where the precipitation rate was high. The average precipitation rate for the Minnekahta Limestone outcrop was 23.9 in/yr, Minnelusa Formation outcrop was 24.1 in/yr, the Deadwood Formation outcrop was 26.9 in/yr.

Recharge-rate group 3 included most of the Inyan Kara Group outcrop except for the northern part of the study area that receives lower precipitation amounts. Parts of alluvium and terrace gravels, the Minnekahta Limestone outcrop, the Minnelusa Formation outcrop, and Deadwood Formation outcrop with lower precipitation amounts were included in this group. A small part of Madison Limestone outcrop, located in the southeastern corner of the study area, is included in this group because the average precipitation was 17.1 in/yr. A small part of the igneous and metamorphic rocks near igneous intrusions were included in this group where the average precipitation rate was greater than 28 in/yr.

Recharge-rate group 4 includes all of the igneous intrusive rocks, rock units that are made up predominately of shale, and most of the igneous and metamorphic rocks. The parts of the Deadwood Formation outcrop and the Inyan Kara Group outcrop included in this group had an average precipitation rate of less than 18 in/yr.

The recharge-rate map (fig. 10) was intersected and combined with the hydrogeologic-unit map. Small polygons created when the coverages were intersected were merged with the largest adjacent polygon maintaining the polygon boundaries of the hydrogeologic-unit map.

Depth to Water

Depth to water, the vertical distance that water and a potential contaminant must move to reach the water table, affects the amount of contact with sediments in the unsaturated zone and the travel time to the water table. Generally, there is less sensitivity with greater depth to water. Barbash and Resek (1996, p. 283) reviewed several matrix diffusion studies that show pesticide concentrations or detection frequencies are more likely to be observed as the travel time to the water table decreases. The characteristics of the unsaturated media vary widely in Lawrence County depending on the extent of fracturing. In highly fractured settings, the contact time with the unsaturated media could be very short even at greater depths. Therefore, evaluating the significance of the depth to water categories needs to be considered in conjunction with the unsaturated media.

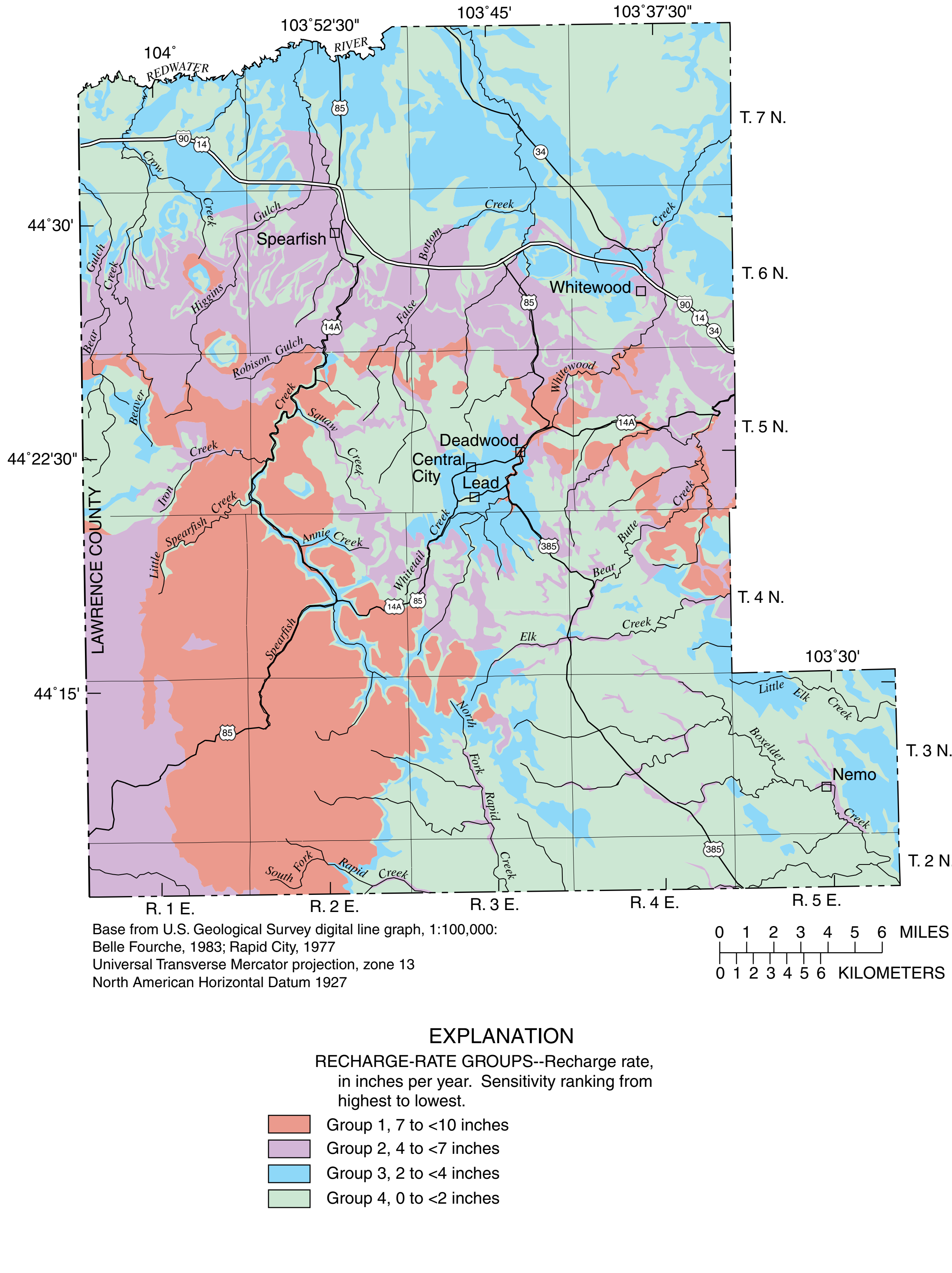


Figure 10. Recharge-rate sensitivity groups in Lawrence County.

Criteria for Delineation

Seven depth-to-water categories were proposed by Aller and others (1987) (table 10). Studies comparing depth to water and pesticide concentrations in wells have shown mixed results (Barbash and Resek, 1996). Druliner and others (1996) found a greater likelihood of contamination with atrazine in areas with shallow water tables in the High Plains aquifer in Nebraska. Rupert (1999) found no statistical difference in nitrate concentrations in a fractured basalt aquifer in Wyoming and Idaho between depth to water from 0 to 100 ft and 101 to 300 ft; however, the differences in concentrations in ground-water samples from depths of 0 to 300 ft and from 301 to 900 ft were statistically significant. Because of the level of detail in available data, the spatial variability in the unsaturated zone, and the complex topography, a modified system of evaluating depth to water was used in this study. The seven categories were grouped together into three broad quantitative categories and two qualitative categories because of the limited spatial distribution of water-level data in the outcrop areas (table 11).

Areas with steeply dipping strata of fractured rocks were not categorized for depth to water because of the large variations in topography and water levels. The shallower depth to water generally exists in stream valleys; therefore, areas with land-surface elevations less than 50 ft above streambed elevations were delineated (group 4, table 11) to make relative comparisons with areas greater than 50 ft (group 5, table 11) above streambed elevations. Other areas with highly variable depths to water included in group 5 were hydrogeologic units consisting mostly of shale with sandstone layers or lenses and gypsum with solution openings.

Designated Units

The distribution of depth-to-water groups is shown in figure 11. Depth-to-water group 1 includes most of the alluvium. Group 2 includes most of the terrace gravels, colluvium, Minnekahta Limestone outcrop, and parts of the Inyan Kara Group outcrop. Group 3 includes parts of the Inyan Kara Group outcrop. Group 4 includes valleys in the Mountain Slopes-East, Mountain Slopes-West, Igneous Domes, Limestone Plateau, and Mountain Flanks hydrogeologic settings. The depth to water within group 4 varies from 0 ft near springs to greater than 100 ft. Vertical movement of water is frequently through rock fractures with rapid travel times. In narrow canyons, the area was too small to show in figure 11 and plate 1; however, the depth to water should be considered less near stream channels than in topographically higher areas. Group 5 includes most of the mountain slopes-east, mountain slopes-west, igneous domes, limestone plateau, and mountain flanks hydrogeologic settings, in areas where land surface is greater than or equal to 50 ft above the streambeds. Also included in group 5 were outcrops of units that primarily consist of shale with highly variable depths to water.

The depth-to-water map was intersected and combined with the hydrogeologic-unit map and recharge-rate map. Small polygons created when the coverages were intersected were merged with the largest adjacent polygon.

Table 10. Sensitivity ratings for range categories of depth to water

[Modified from Aller and others, 1987, table 4, p. 21]

Depth to water (feet)	Sensitivity rating[1]
0 to 5	10
5 to 15	9
15 to 30	7
30 to 50	5
50 to 75	3
75 to 100	2
more than 100	1

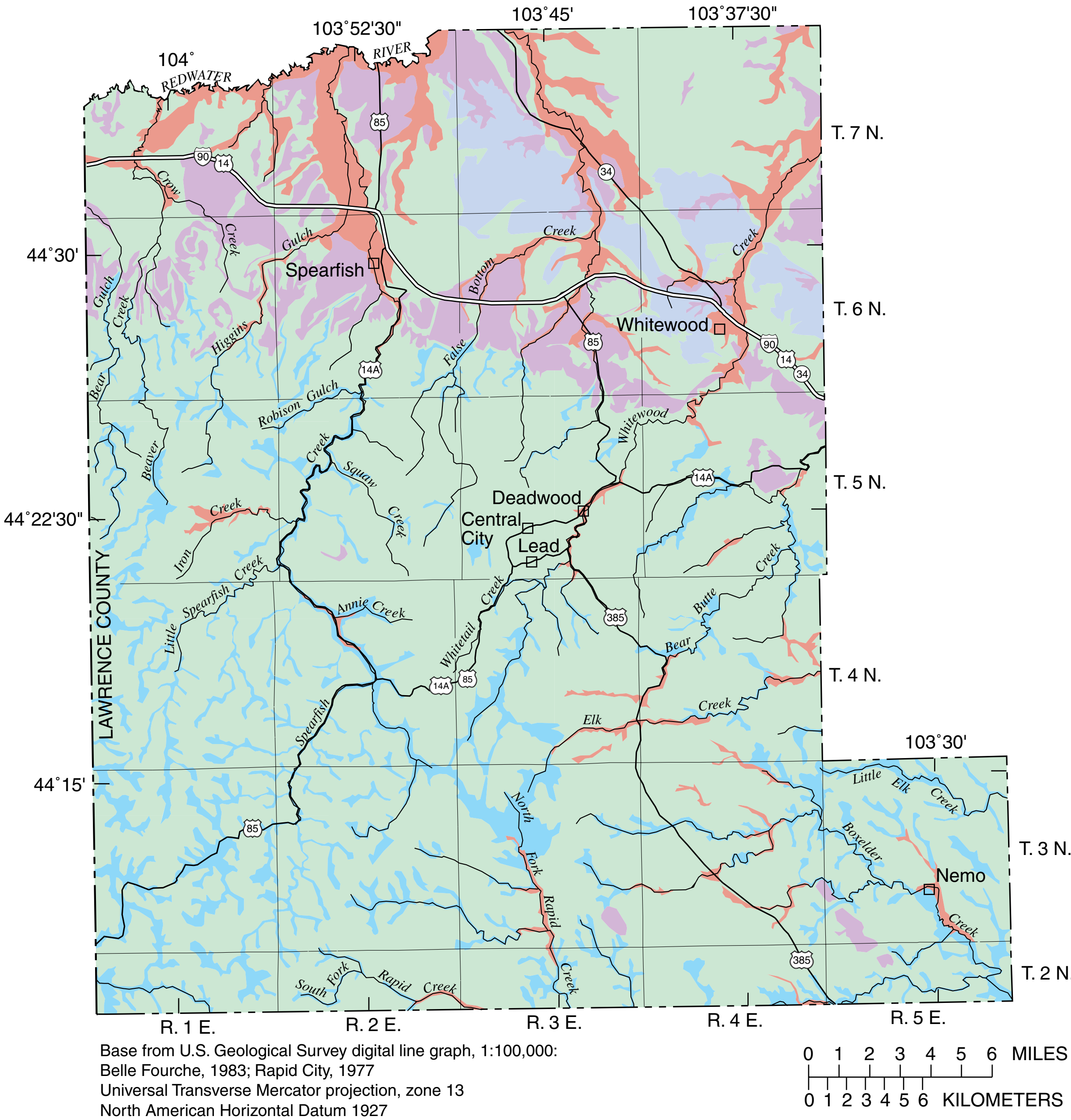
[1]Higher rating indicates higher sensitivity to contamination.

Table 11. Sensitivity rank for designated depth-to-water groups

[<, less than; >, greater than]

Depth-to-water group	Depth to water (feet)		Sensitivity rank
1	0 to <20 feet	Comparison group	Highest to lowest
2	20 to <50 feet		
3	50 or >50		
4	Highly variable (areas of fractured rock in stream valleys)[1]	Comparison group	Highest to lowest
5	Highly variable (other areas)		

[1]Areas with land-surface elevations less than 50 feet above streambed elevations were delineated to make relative comparisons with areas greater than 50 feet above streambed elevations.



EXPLANATION

DEPTH-TO-WATER GROUPS

Depth to water, in feet		Sensitivity rank
Group 1, 0 to <20	Comparison group	Highest
Group 2, 20 to <50		to
Group 3, 50 or >50		lowest
Group 4, highly variable, (areas of fractured rock in stream valleys)	Comparison group	Highest to
Group 5, highly variable (other areas)		lowest

Figure 11. Depth-to-water sensitivity groups in Lawrence County.

Land-Surface Slope

Land-surface slope influences the potential of a contaminant to remain on the land surface long enough to infiltrate into the subsurface. On gentler slopes, precipitation runoff is slow; therefore, a potential contaminant is more likely to be moved towards the water table with the infiltration of precipitation. On steeper slopes, precipitation runoff is rapid; therefore, a potential contaminant is more likely to be moved away before infiltration occurs.

Criteria for Delineation

The five land-surface-slope categories proposed by Aller and others (1987) were used as the designated land-surface-slope groups (table 12). All groups are present in the study area, as topography ranges from steep mountain slopes to alluvial prairie flood plains. Statistical correlations of land-surface slope and contaminant concentrations or detections were not apparent in the reviewed literature. Statistical comparisons are likely to be influenced by dilution and lag periods in observed concentrations in wells, as noted in the "Recharge Rate" section.

Table 12. Sensitivity rank for designated land-surface-slope groups

[Modified from Aller and others, 1987, table 4, p. 21. <, less than; >, greater than]

Land-surface-slope group	Land-surface slope (percent)	Sensitivity rank
1	0 to <2	
2	2 to <6	Highest
3	6 to <12	to
4	12 to <18	lowest
5	18 or >18	

The percent-slope classification was determined from analysis of USGS digital elevation models (DEM). These electronic files provide the same coverage as standard USGS 1:24,000-scale map series 7.5-minute quadrangles. The data are stored as profiles in which the spacing of elevations along and between each profile is 30 meters. A DEM data user's guide (U.S. Geological Survey, 1993) provides a more detailed description of the data sets. The 7.5-minute DEM's were joined together to create a 30-meter resolution grid of elevation data for the study area. These data were used to calculate percent-slope data in a similar grid format and were grouped according to the land-surface slope groups (table 12).

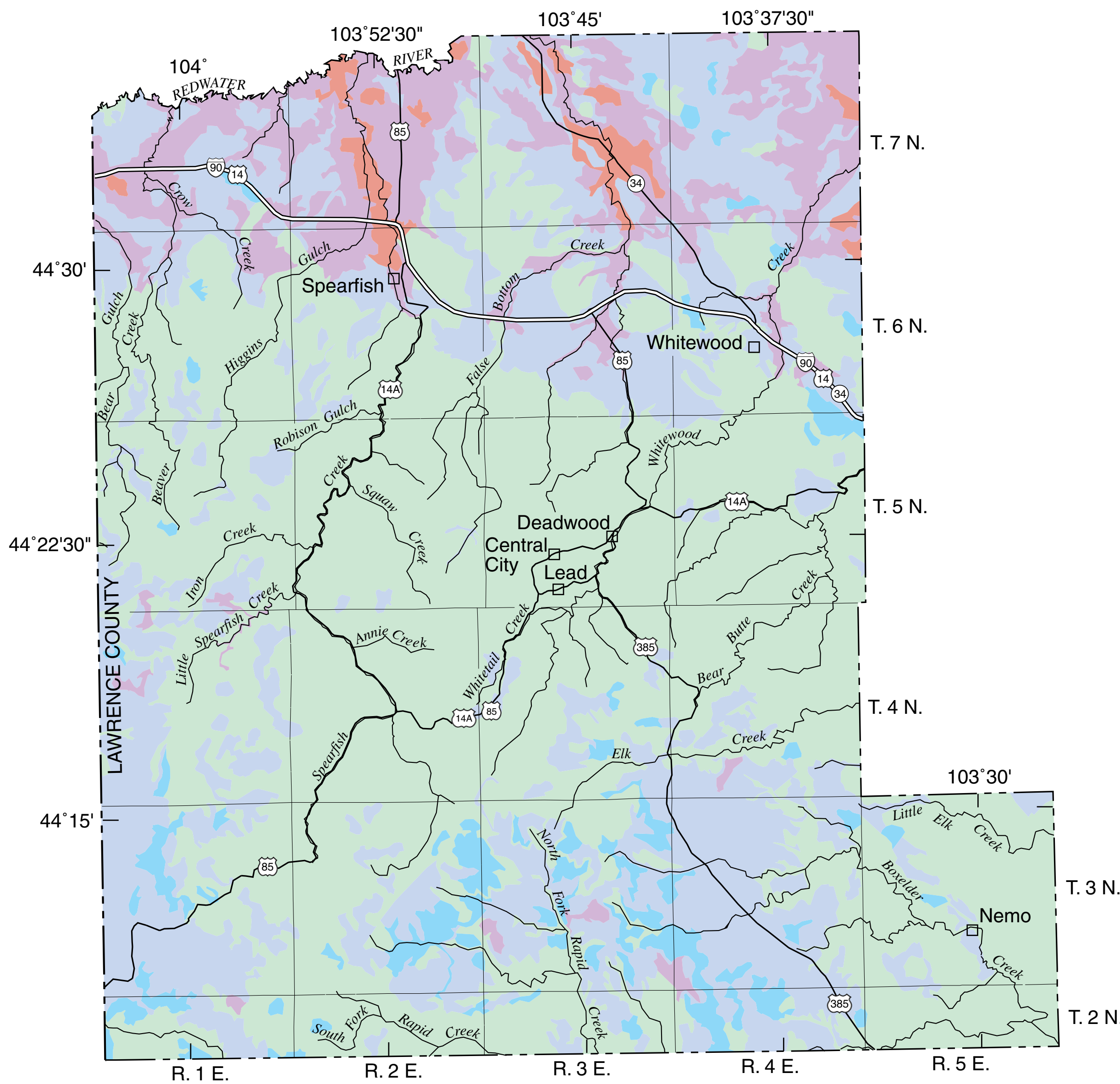
Because of abrupt changes in slope in the mountainous terrain, many land-surface-slope areas were less than 100 acres or were too narrow to show on a 1:100,000-scale map. A GIS algorithm (Command file 1 in the "Supplemental Information" section at the end of this report) was used to merge these areas with adjacent areas.

Designated Units

The distribution of land-surface-slope groups is shown in figure 12. Land-surface-slope group 1 was in the northern part of the study area, and the most common rock type was alluvium and terrace gravels. Land-surface-slope group 2 was mostly in the northern part of the study area with some small areas in the southern part. Land-surface-slope group 3 was located mostly along the flanks of the Black Hills uplift and parts of the plains in the north. Land-surface-slope group 4 was mostly in the southern part of the study area. Land-surface-slope group 5 was mostly in the central and southern part of the study area. The land-surface-slope map was intersected and delineated with the previously delineated map layers.

Streamflow Recharge

Streamflow is an important source of recharge to the Minnekahta, Minnelusa, and Madison aquifers (Hortness and Driscoll, 1998). Because of the dipping strata with fractures, collapse features, and karst solution openings, numerous streams lose all or part of their flow as they cross the outcrops of the formations making up these aquifers. Precipitation that falls on drainage areas upstream from these loss zones (pls. 1 and 2) could transport a contaminant to the water table by direct infiltration, but in many instances the runoff moving to a streamflow-loss zone is a more important mechanism of potential ground-water contamination. Water from streamflow loss is more likely to enter rapid flowpaths through the unsaturated and aquifer media because of the presence of solution openings in limestone or gypsum.



Base from U.S. Geological Survey digital line graph, 1:100,000:
Belle Fourche, 1983; Rapid City, 1977
Universal Transverse Mercator projection, zone 13
North American Horizontal Datum 1927

0 1 2 3 4 5 6 MILES
0 1 2 3 4 5 6 KILOMETERS

EXPLANATION

LAND-SURFACE-SLOPE GROUPS--
Land-surface slope, as percent. Sensitivity rank from highest to lowest.

- Group 1, 0 to <2
- Group 2, 2 to <6
- Group 3, 6 to <12
- Group 4, 12 to <18
- Group 5, 18 or greater

Figure 12. Land-surface-slope sensitivity groups in Lawrence County.

Hortness and Driscoll (1998) documented streamflow-loss thresholds, in drainage basins in Lawrence County, that range from 0 to 50 ft^3/s. The streamflow-loss threshold represents the maximum streamflow that could be lost when adequate streamflow occurs. During low-flow conditions, many of these streams lose all of their flow crossing the Minnekahta Limestone, Minnelusa Formation, and Madison Limestone outcrops. Generally, the Madison Limestone outcrop is the upstream section, followed by the Minnelusa Formation and Minnekahta Limestone outcrops. Numerous small ungaged drainage basins probably lose most streamflow to these bedrock outcrops except during peak flows from large storm events. Extensive intrusive igneous domes exist in the central part of the study area. In several locations, the intrusive rocks form peaks within outcrops of sedimentary rocks that generally include the Deadwood Formation and Madison Limestone. Runoff from these peaks probably provides streamflow recharge primarily to the Madison aquifer. Also, water is diverted from Spearfish Creek by a dam to an aqueduct leading to a hydroelectric power plant (pl. 2). Losses from the aqueduct could recharge the Minnekahta, Minnelusa, or Madison aquifers.

Criteria for Delineation

Drainage basins upstream from outcrops of the Minnekahta Limestone, Minnelusa Formation, or Madison Limestone were delineated using the DEM grid for the study area and GIS algorithms for the analysis of watersheds (Environmental Systems Research Institute, Inc., 1992). Some small tributaries were grouped together in a drainage area and combined with the main stream. Several drainage areas that contain igneous domes were identified by the name of the peak. Some drainage areas contribute to streams whose loss zones are outside the study area. These areas were identified by the main-stem stream that crosses a potential loss zone outside the study area. Drainage areas less than 100 acres were merged with an adjacent drainage area.

Designated Units

Thirty drainage areas were delineated in the study area (pls. 1 and 2) and ranged in area from 0.3 to 142.1 mi^2 (table 13). The site numbers labeling the drainage areas (pls. 1 and 2) were ordered clockwise beginning in the northwest and grouped by drainage basins. Average precipitation, average percent slope, and percent of exposed crystalline (igneous and metamorphic) rocks were calculated for each drainage area for analysis and comparison. Combined loss thresholds (Hortness and Driscoll, 1998) for most of the larger streams crossing the three bedrock aquifer outcrops were listed for comparison with mean discharge (table 13).

Estimates of the annual yield (the total volume of runoff divided by the area of the drainage basin) and mean discharge were calculated for the drainage areas (table 13) by comparison with gaged drainage basins. Miller and Driscoll (1998) calculated annual yield as one of the statistics used to compare characteristics of drainage basins in the Black Hills. Two of the groups they compared, interior sedimentary basins and interior crystalline basins, include several gaging stations on streams within or including the drainage areas delineated upstream from potential streamflow-loss zones (pl. 2). A summary of the area and annual yield for the basins above these gaging stations (table 14) shows a range of annual yields for basins with mostly crystalline rocks and for basins with mostly sedimentary rocks. Annual yields were estimated for the delineated drainage areas (table 13) based on comparisons with the yields for these gaged streams. Estimated mean discharge was calculated for each drainage area by multiplying the estimated annual yield by the area and dividing by time.

The comments in table 13 contain descriptive information related to particular drainage areas. The exposed rock in the Spearfish Creek Basin is mostly Madison Limestone. Streams within this basin generally are gaining flow from numerous headwater springs. Some streamflow-loss zones may be present within this drainage area, depending on topography, water levels, and precipitation cycles; however, the area generally is a discharge area for this part of the Madison Limestone outcrop. Some of the headwaters of other drainage areas also include outcrops of Madison Limestone (pl. 2) where streams generally gain flow.

Bear Gulch, Beaver Creek, False Bottom Creek, Bear Butte Creek, Elk Creek, and Boxelder Creek lose all of their flow during most of the days during the year because flow is generally less than the loss threshold. The flow in Rapid Creek tributaries is large in relation to the streamflow-loss threshold. Comparison of the mean discharge for smaller basins in relation to the length of the stream reach crossing the formation outcrops (pl. 2) indicates that most of these drainage areas probably lose most of their flow to these bedrock outcrops.

Table 13. Characteristics of drainage areas upstream from streamflow-loss zones

[mi^2, square miles; in., inches; ft^3/s, cubic feet per second; --, no data]

Site identification number	Name	Area (mi^2)	Average precipitation (in.)	Average slope (percent)	Percent igneous and metamorphic rocks[1]	Loss threshold[2] (ft^3/s)	Estimated annual yield (in.)	Estimated mean discharge (ft^3/s)	Comments
					Sand Creek Basin				
1	Sand Creek tributaries	0.3	23.6	17.0	100	--	3.5	0.1	This small drainage area, part of an igneous dome, is in the very upper part of the Sand Creek Basin that extends into South Dakota and drains west into Wyoming before crossing the outcrops (Minnekahta Limestone, Minnelusa Formation, and Madison Limestone).
2	Bear Gulch	5.5	23.5	18.5	81	4	3.5	1.4	The predominant rocks exposed in the drainage area are igneous rocks within the Tinton Dome. Streamflow generally is less than the combined loss rate for the outcrops (Minnekahta Limestone, Minnelusa Formation, and Madison Limestone).
					Crow Creek Basin				
3	Beaver Creek	8.5	24.3	17.0	72	9	3.5	2.2	Characteristics are similar to Bear Gulch.
4	Crow Peak	.5	22.6	46.9	45	--	3.5	.1	This area, an igneous dome, drains mostly towards Crow Creek with some runoff draining towards Higgins Gulch on the east side. Most runoff probably is lost as flow crosses the Madison Limestone and Minnelusa Formation outcrops surrounding the dome.
					Spearfish Creek Basin				
5	Citadel Rock	1.1	23.9	28.2	47	--	3.5	.3	Characteristics are similar to Crow Peak.
6	Spearfish Creek (above power plant diversion)	142.1	25.1	21.4	6	[3]23	5	52.3	Most of the flow is diverted around the loss zone by a dam and an aqueduct to a hydroelectric power plant. The diversion rate is between 115 and 135 ft^3/s.[2] The average daily flow (water years 1989-97)[4] exceeded 115 ft^3/s only 7 percent of the days.
7	Rubicon Gulch (Bridal Veil Falls)	1.4	26.2	26.0	60	21	4	.4	Confluence with Spearfish Creek is located downstream from power diversion; thus, entire flow generally is lost.
8	Spearfish Creek (near Robison Gulch	2.7	25.4	41.2	16	21	5	1.0	Driscoll and Hayes (1995) estimated that the combined discharge from this drainage area, Rubicon Gulch, and leakage from the power plant diversion dam averaged about 3 ft^3/s.
9	Spearfish Peak (Spearfish Creek tributaries)	1.1	24.9	28.7	79		4	.3	This drainage area is an igneous intrusion in the Madison Limestone and Minnelusa Formation outcrops draining in several directions to the surrounding bedrock. Most runoff probably is lost to the Madison Limestone and Minnelusa Formation outcrops.

Table 13. Characteristics of drainage areas upstream from streamflow-loss zones–Continued

[mi^2, square miles; in., inches; ft^3/s, cubic feet per second; --, no data]

Site identification number	Name	Area (mi^2)	Average precipitation (in.)	Average slope (percent)	Percent igneous and metamorphic rocks[1]	Loss threshold[2] (ft^3/s)	Estimated annual yield (in.)	Estimated mean discharge (ft^3/s)	Comments
False Bottom Creek Basin									
10	Burno Gulch	2.5	26.4	29.4	73	--	5	0.9	Some streamflow loss is likely as Burno Gulch crosses approximately 0.75 mi of Madison Limestone outcrop and 1 mi of Minnelusa Formation outcrop before joining False Bottom Creek on the Minnelusa Formation outcrop.
11	False Bottom Creek	7.0	27.4	29.7	75	15	4	2.0	Most of the streamflow is lost to the three bedrock aquifers except during intense runoff events. Estimated loss thresholds are 4 ft^3/s for the Madison Limestone outcrop, 7.2 ft^3/s for the Minnelusa Formation outcrop, and about 7 ft^3/s for the Minnekahta Limestone outcrop.[2]
12	False Bottom Creek tributary	.8	25.9	26.1	100	--	4.5	.3	This area, an igneous intrusion within the Madison Limestone and Minnelusa Formation outcrops, drains towards False Bottom Creek. Some of the streamflow probably is lost to the Madison Limestone and Minnelusa Formation outcrops before joining False bottom Creek.
13	Tetro Creek	.7	26.5	25.6	37	--	4	.2	Most of the flow from this area probably is lost as Tetro Creek crosses approximately 2 mi of Madison Limestone and Minnelusa Formation outcrops before joining False Bottom Creek below the Madison Limestone and Minnelusa Formation outcrops.
14	Miller Creek	2.7	26.3	30.4	62	--	4.5	.9	Miller Creek and tributary streams originating in this drainage area cross about 1 to 1.5 mi of Madison Limestone and Minnelusa Formation outcrops before joining Polo Creek downstream.
15	Polo Creek	3.2	27.2	29.3	75	--	4.5	1.0	Polo Creek and tributary streams originating in this drainage area cross some Madison Limestone outcrop and over 1 mi of Minnelusa Formation before joining False Bottom Creek downstream.
Whitewood Creek Basin									
16	Slaughter House Gulch	.4	27.3	25.9	50	--	4.5	.1	Most of the streamflow from this area probably is lost as Slaughter House Gulch crosses approximately 1 mi of Madison Limestone outcrop before joining Whitewood Creek.
17	Whitewood Creek	46.9	27.6	26.2	60	0	4.5	15.5	Significant losses do not occur to the bedrock outcrops along Whitewood Creek. Mine tailings possibly seal the loss zones.[2]

Table 13. Characteristics of drainage areas upstream from streamflow-loss zones–Continued

[mi^2, square miles; in., inches; ft^3/s, cubic feet per second; --, no data]

Site identification number	Name	Area (mi^2)	Average precipitation (in.)	Average slope (percent)	Percent igneous and metamorphic rocks[1]	Loss threshold[2] (ft^3/s)	Estimated annual yield (in.)	Estimated mean discharge (ft^3/s)	Comments
					Bear Butte Creek Basin				
18	Bear Butte tributaries (Boulder Park)	3.5	26.3	15.5	1	--	4	1.0	This area contains about one-third Minnekahta Limestone, with the remainder predominantly shale units. These tributaries join Bear Butte Creek within the Minnelusa outcrop. Estimated loss thresholds are 4 ft^3/s for this downstream reach.[2]
19	Boulder Creek	2.2	27.2	18.3	0	--	4	.6	Boulder Creek crosses approximately 1 mi of Madison Limestone outcrop and 2 mi of Minnelusa Formation outcrop before joining Bear Butte Creek.
20	Two Bit Creek	6.8	27.4	25.8	49	--	4	2.0	Two Bit Creek crosses approximately 1.5 mi of Madison Limestone outcrop before joining Boulder Creek.
21	Boulder Creek tributaries	1.2	26.9	31.5	100	--	4	.4	This area of intrusive igneous rocks includes several small drainage channels that cross about 0.5 to 1 mi of mostly Minnelusa Formation outcrop before joining Boulder Creek.
22	Lost Gulch	1.5	26.8	29.7	80	--	4	.4	Drainage from this area crosses about 2 mi of Madison Limestone and Minnelusa Formation outcrop before joining Bear Butte Creek.
23	Bear Butte Creek	15.9	26.0	20.8	72	12	3.8	4.4	Average streamflow loss[5] was 4.3 ft^3/s for water years 1989-97. During this period, the average daily flow exceeded the loss threshold 15 percent of the days.
24	Park Creek	3.2	24.7	24.2	20	--	3.5	.8	Drainage from this area crosses about 1.5 mi of Madison Limestone outcrop before joining Bear Butte Creek.
					Elk Creek Basin				
25	Elk Creek (north tributary)	1.0	23.8	17.1	29	--	3.5	.3	Parts of this tributary streamflow could be lost to Madison Limestone outcrop before the stream joins Elk Creek above the area of Madison Limestone outcrop crossed by Elk Creek.
26	Elk Creek	22.3	24.2	15.3	58	19	4	6.6	Average streamflow loss[6] was 7.6 ft^3/s for water years 1991-97. During this period, the average daily flow exceeded the loss threshold 18 percent of the days.
27	Meadow Creek	1.9	22.5	16.3	18	--	2.5	.3	Drainage from this area crosses about 0.5 mi of Madison Limestone outcrop before joining Elk Creek within the Madison Limestone outcrop. Most of the sedimentary rock outcrop in the drainage area is Deadwood Formation.

Table 13. Characteristics of drainage areas upstream from streamflow-loss zones–Continued

[mi^2, square miles; in., inches; ft^3/s, cubic feet per second; --, no data]

Site identification number	Name	Area (mi^2)	Average precipitation (in.)	Average slope (percent)	Percent igneous and metamorphic rocks[1]	Loss threshold[2] (ft^3/s)	Estimated annual yield (in.)	Estimated mean discharge (ft^3/s)	Comments
					Elk Creek Basin—Continued				
28	Little Elk Creek	9.0	18.9	22.0	13	3	2.0	1.3	Loss thresholds are 0.7 ft^3/s for the Madison Limestone outcrop and 2.6 ft^3/s for the Minnelusa Formation outcrop.[2] Most of the rock outcrop in the drainage area is the Deadwood Formation.
					Boxelder Creek Basin				
29	Boxelder Creek	90.1	20.1	15.3	78	50	2.2	14.6	Average streamflow loss[7] was 12.4 ft^3/s for the three outcrops for water years 1967-96. During this period, the average daily flow exceeded the loss threshold 7 percent of the days. Over one-half of the total loss threshold is estimated to occur to the Madison Limestone outcrop.[2]
					Rapid Creek Basin				
30	Rapid Creek tributaries	61.0	21.3	15.7	56	10	4	18.0	During water years 1989-97, the flow at station 06412200 (Rapid Creek above Victoria Creek), which is located about 20 mi southeast just above the loss zone, was greater than 10 ft^3/s 97 percent of the time.[4] The Rapid Creek tributaries in this drainage area represent about 17 percent of the total drainage area above the loss zone. The annual mean flow[2] at station 06412200 is 67.3 ft^3/s.

[1]Strobel and others (1999).
[2]Hortness and Driscoll (1998).
[3]Includes 2 ft^3/s estimated loss threshold within the diversion aqueduct (Hortness and Driscoll, 1998).
[4]U.S. Geological Survey (1967-75, 1976-98), station 06430900 (Spearfish Creek above Spearfish).
[5]Calculated from records for station 06437020 (U.S. Geological Survey, 1967-75, 1976-98).
[6]Calculated from records for station 06424000 (U.S. Geological Survey, 1967-75, 1976-98).
[7]Calculated from records for station 06422500 (U.S. Geological Survey, 1967-75, 1976-98),

Table 14. Data pertaining to annual yield for selected gaging stations in Lawrence County

Station number	Station name	Area (square miles)	Period of record (water years)	Annual yield (inches)
		Interior Sedimentary Basins		
06408700	Rhoads Fork near Rochford	7.95	1983-93	8.51
06430770	Spearfish Creek near Lead	63.5	1989-93	3.34
06430850	Little Spearfish Creek near Lead	25.8	1989-93	6.90
		Interior Crystalline Basins		
06422500	Boxelder Creek near Nemo	96.0	1967-93	2.17
06430800	Annie Creek near Lead	3.55	1989-93	3.10
06430898	Squaw Creek near Spearfish	4.07	1989-93	4.07
06436156	Whitetail Creek at Lead	6.15	1989-93	5.59
06437020	Bear Butte Creek near Deadwood	16.6	1989-93	3.77

Runoff from the areas between the Minnekahta and Minnelusa aquifer hydrogeologic units (pl. 2) probably recharges the Minnekahta aquifer. Most runoff from other small areas not delineated within the Minnekahta, Minnelusa, and Madison aquifer hydrogeologic units also becomes recharge to the adjacent hydrogeologic units.

USE OF GROUND-WATER SENSITIVITY MAP

The map of ground-water sensitivity to contamination (pl. 1) is intended to be used as a screening tool to compare the sensitivity of areas in Lawrence County to contamination. Each delineated area (sensitivity unit) on the map is identified by a color and a four-character alphanumeric code—one letter and three digits. Drainage areas upstream from potential streamflow-loss zones also are delineated and described (pl. 2, table 13). The following sections describe how to relate the sensitivity code and the drainage area labels to hydrogeologic information. The limitations of the map also are discussed.

Relating Sensitivity Units to Hydrogeologic Information

The 11 hydrogeologic settings, which group areas with similar hydrologic and geologic characteristics, are identified by shades of color on plate 1. The name of the hydrogeologic setting is related to the predominant rock type or physiographic location. More detailed information about the hydrogeologic settings is given in table 1.

The sensitivity map includes 956 sensitivity polygons that are labeled with identifying codes. The letter code identifies the hydrogeologic unit, which includes relative sensitivity ratings for aquifer media, unsaturated media, and hydraulic conductivity. The relative sensitivity ratings were compiled on a scale of 1 to 10 with 10 being the most sensitive. The 45 hydrogeologic units are organized in descending order that are sorted on the sensitivity rating for unsaturated media, then aquifer media, and then hydraulic conductivity. The codes begin with an uppercase “A” and continue through lower case “s.” When the first 26 uppercase letters were used, the codes were continued with lower case letters. The explanation of alphabetic hydrogeologic-unit codes on the sensitivity map includes the relative sensitivity ratings, the geologic units, and a description of the aquifer and unsaturated media. Comments in table 1 provide additional information describing characteristics unique to each hydrogeologic unit.

The first digit in the sensitivity-unit code represents the recharge rate with group 1 the most sensitive and group 4 the least sensitive. The second digit in the sensitivity-unit code represents the depth to water. The depth-to-water group includes three quantitative groups and two qualitative groups. The three quantitative depth-to-water groups were ranked with group 1 the most sensitive and group 3 the least sensitive. The two qualitative groups were areas with highly variable depths to water. The stream valleys in the mountainous areas were assumed to have shallower depths to water than adjacent areas and were included in group 4. Although the depth to water is highly variable in these areas, the delineation provides a basis for some relative comparisons to group 5. The third digit in the sensitivity-unit code represents the land-surface slope, which consists of five groups, with group 1 the most sensitive and group 5 the least sensitive.

Drainage areas above streamflow-loss zones were delineated on plates 1 and 2 with thick blue lines and a site identification near the upstream end of the streamflow-loss zone. The drainage areas listed on plate 1 also include estimates of streamflow-loss thresholds, if available, and the area of the drainage. Additional analysis and comments describing the drainage area and the loss zone are referenced to the site identification and listed in table 13.

Two areas were selected to describe examples of using the sensitivity map. Example area 1, in the part of section 3 in T. 6 N., R. 2 E. east of Interstate 90 located about 1 mi northeast of Spearfish, includes sensitivity polygons with three unique sensitivity-unit codes, h455, o451, o455. In area h455, the letter code indicates a semiconfining unit with interbedded sandstone, limestone, and shale with a moderate sensitivity rank for aquifer media and a low sensitivity rank for unsaturated media, and hydraulic conductivity. The digit codes indicate that, with regard to sensitivity, the recharge-rate group is low, the depth-to-water group is highly variable, and the land-surface-slope group is low. In area o451, the letter code indicates Spearfish Formation with a low sensitivity rank for aquifer media, unsaturated media and hydraulic conductivity. The digit codes indicate that, with regard to sensitivity, the recharge-rate group is low, the depth-to-water group is highly variable, and the land-surface-slope group is high. Area o455 is similar to area o451 except the land-surface-slope group has a low sensitivity rank.

Example area 2, which is complicated by streamflow loss, is located in section 8 in T. 5 N., R. 2 E. west of Spearfish Creek located about 6 mi south of Spearfish, and includes sensitivity polygons with two unique sensitivity-unit codes, B155 and f455. In area B155, the letter code indicates Madison Limestone, with a high sensitivity rank for aquifer media and unsaturated media, and a moderately high sensitivity rank for hydraulic conductivity. The digit codes indicate that the recharge-rate group is high, the depth-to-water group is highly variable, and the land-surface-slope group is low. In area f455, the letter code indicates Whitewood and Winnipeg Formations, with a low sensitivity rank for aquifer media, unsaturated media and hydraulic conductivity. The area also is within drainage areas upstream from potential streamflow-loss zones beginning at sites 6 and 7. Most of the area is Madison Limestone, which produces very little surface runoff. However, runoff from the drainage area upstream from site 6 would contribute to a loss zone that usually has flow less than the loss threshold (table 13). The drainage area upstream from site 8 would contribute to a stream with larger flow, except that flow is usually directed to the hydroelectric power plant diversion.

A comparison of the sensitivity characteristics of the two areas indicate that example area 2 is much more sensitive than example area 1. The small part of example area 2 with the lower sensitivity characteristics also contributes runoff that recharges the Madison aquifer through streamflow loss. The recharge rate is much greater in example area 2. The depth to water in both areas is highly variable. The significance of the land-surface-slope groups in comparing these areas is not as important because of the large difference in hydrogeologic unit and recharge-rate groups.

Limitations of Sensitivity Map

Some limitations need to be considered when using the map. One of the most important limitations is that of scale. On a 1:100,000-scale map, a section of land, 5,280 ft on a side (640 acres), is described in an area less than 1-in. square; therefore, the hydrogeologic information includes numerous generalizations because of the complex geology in the study area. Modifying or overlaying the map at a scale that is more detailed than the original map is inappropriate and may be extremely misleading.

Available hydrologic data, such as hydraulic heads and descriptions of ground-water flowpaths, provide a limited description of the complex hydrology. Predicting the fate and transport of a potential contaminant is difficult because of fractured rocks and solution openings. This map assumes that a potential contaminant has the mobility of water. Some potential contaminants may have mobility characteristics different than water, such as oil, which floats on top of water, or some solvents, which may be more dense than water and sink. Also, the analysis of potential ground-water contaminants from nonpoint sources such as agricultural fields may require different considerations and approaches than a site-specific spill of a highly toxic substance.

The intended use of the sensitivity map is as a screening tool used in conjunction with other information and analysis. The map is not designed to replace the need for site-specific investigations or to be the sole criterion in making land-use decisions.

SUMMARY

Sensitivity of ground water to contamination in Lawrence County was mapped by subdividing the study area into map areas with relative ranking of intrinsic hydrogeologic sensitivity. Six intrinsic hydrogeologic characteristics, aquifer media, unsaturated media, hydraulic conductivity, recharge rate, depth to water, and land-surface slope were evaluated sequentially and overlaid to delineate polygons with comparable sensitivity characteristics. Streamflow loss, an additional mechanism of transport of potential contaminants, was considered by delineating and describing drainage areas upstream from the potential streamflow-loss zones.

The method used for this study was a modification of the DRASTIC method (Aller and others, 1987). Hydrogeologic characteristics were evaluated and identified with a comparable code as described by Hearne and others (1995). A single weighted pollution potential index was not calculated. Streamflow-loss characteristics were considered based on the modification of DRASTIC by Davis and others (1994) that identified increased pollution potential for karst sinkholes. The rating conventions of DRASTIC were modified to provide a relative ranking of hydrogeologic characteristics without assignment of a combined numerical score. The results of studies that compared observed water-quality and selected hydrogeologic characteristics at other locations were considered in the analysis of individual map layers. Additional modifications were made based on the availability of data. Soil characteristics were not included as a map layer because detailed digital data were not available; however, the general distribution of two soil characteristics were shown. A limited comparison of depth to water was made because of the highly variable depth to water in a large part of the study area.

The study area was subdivided into a framework of 11 hydrogeologic settings with unique hydrologic and geologic factors that control the movement of ground water. Within this framework, the hydrogeologic-units map layer was delineated by evaluating aquifer media, unsaturated media, and hydraulic conductivity for sensitivity to contamination. A total of 45 hydrogeologic units were delineated and comparatively ranked. The most sensitive hydrogeologic units included the limestones, alluvium, unconsolidated sands and gravels, and some sandstones. The least sensitive units included shales or units with interbedded shales.

The recharge-rate map delineated sensitivity areas by four recharge-rate groups ranging from 0 to 10 in/yr. The highest recharge-rate group (most sensitive) included most of the Madison Limestone outcrop except in the southeastern corner of the study area where precipitation rates are lowest. The lowest recharge-rate group (least sensitive) included mostly igneous intrusive rocks, shale units, and igneous and metamorphic rocks.

The depth-to-water map delineated sensitivity areas by five depth-to-water groups. The first three categories compared areas where data were available to estimate depth to water. The shallowest depth to water (most sensitive) included the alluvium. Group 3 (least sensitive of these three categories) included some of the sandstones. The depth to water in most of the study area was highly variable and was included in groups 4 and 5. Group 4 included delineated stream valleys, which generally would have shallower depth to water compared to adjacent areas with higher land-surface altitudes. Group 5 also included the remaining areas with highly variable depth to water.

The land-surface-slope map delineated sensitivity areas by five land-surface-slope groups that compared percent slope calculated from Digital Elevation Models. The smallest percent slopes (most sensitive) were in the northern part of the study area. The largest percent slopes (least sensitive) were in the south and central part of the study area.

Thirty drainage areas were delineated upstream from potential streamflow-loss zones ranging in area from 0.3 to 142.1 mi^2. Mean discharge estimated for the drainage areas ranged from 0.1 to 52.3 ft^3/s. Approximate streamflow-loss thresholds were available for several of the loss zones. Comparisons of mean discharges with loss thresholds showed that runoff from most of these drainage areas during most of the year would become ground-water recharge.

The various map layers were overlain and intersected to produce a 1:100,000-scale map (pl. 1) showing 956 delineated polygons identified with a sensitivity-unit code, a letter code, and three digits. The letter code represents the hydrogeologic unit, with the first digit representing the recharge-rate group, the

second digit representing the depth-to-water group, and the third digit representing the land-surface-slope group. The hydrogeologic settings were color shaded. Drainage areas above streamflow-loss zones were outlined and identified with a number referring to a table of information describing the drainage areas. A second plate showed the drainage areas in relation to the streamflow-loss zones, selected hydrogeologic units from Strobel and others (1999), and selected streamflow-gaging stations. The sensitivity maps were designed as screening tools and do not replace the need for site-specific investigations.

SELECTED REFERENCES

Aller, L., Bennett, T., Lehr, J.H., Petty, R.J., and Hackett, G., 1987, DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings: U.S. Environmental Protection Agency, EPA/600/2-87/035, 455 p.

Barbash, J.E., and Resek, E.A., 1996, Pesticides in ground water—distribution, trends, and governing factors: Chelsea, Mich., Ann Arbor Press, Inc., 588 p.

Carter, J.M., and Redden, J.A., 1999a, Altitude of the top of the Minnelusa Formation in the Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA-744-C, 2 sheets, scale 1:100,000.

———1999b, Altitude of the top of the Madison Limestone in the Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA-744-D, 2 sheets, scale 1:100,000.

———1999c, Altitude of the top of the Deadwood Formation in the Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA-744-E, 2 sheets, scale 1:100,000.

Davis, A.D., Long, A.J., Nazir, M., and Xiaodan, T., 1994, Ground-water vulnerability in the Rapid Creek Basin above Rapid City, South Dakota: Final Technical Report prepared for the U.S. Environmental Protection Agency, Contract X008788-01-0, 78 p.

DeWitt, Ed, Redden, J.A., Buscher, David., and Wilson, A.B., 1989, Geologic map of the Black Hills area, South Dakota and Wyoming: U.S. Geological Survey Map I-1910, scale 1:250,000.

Downey, J.S., 1986, Geohydrology of bedrock aquifers in the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.

Driscoll, D.G., and Bradford, W.L., 1994, Compilation of selected hydrologic data, through water year 1992, Black Hills Hydrology Study, western South Dakota: U.S. Geological Survey Open-File Report 94-319, 158 p.

Druliner, A.D., Chen, H.H., and McGrath, T.S., 1996, Relations of nonpoint-source nitrate and atrazine concentrations in the High Plains aquifer to selected explanatory variables in six Nebraska study areas: U.S. Geological Survey Water-Resources Investigations Report 95-4202, 51 p.

Environmental Systems Research Institute, Inc., 1992, ARC/INFO users guide—the geographic information system software: Redlands, Calif. [variously paged].

Freeze, R.A. and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Greene, E.A., 1993, Hydraulic properties of the Madison aquifer system in the western Rapid City area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 93-4008, 56 p.

Greene, E.A., Shapiro, A.M., and Carter, J.M., 1998, Hydrogeologic characterization of the Minnelusa and Madison aquifers near Spearfish, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 98-4156, 64 p.

Gries, J.P., and Martin J.E., 1985, Composite outcrop section of the Paleozoic and Mesozoic strata in the Black Hills and surrounding areas, *in* Rich, F.J., ed., Geology of the Black Hills, South Dakota and Wyoming (2d ed.): Alexandria, Va., American Geological Institute, p. 261-292.

Hearne, G.A., Wireman, Michael, Campbell, A.S., Turner, Sandy, and Ingersoll, G.P., 1995, Vulnerability of the uppermost ground water to contamination in the Greater Denver area, Colorado: U.S. Geological Survey Water-Resources Investigations Report 92-4143, 244 p.

Heath, R.C., 1984, Ground-water regions of the United States: U.S. Geological Survey Water-Supply Paper 2242, 78 p.

Hortness, J.E., and Driscoll, D.G., 1998, Streamflow losses in the Black Hills of western South Dakota: U.S. Geological Survey Water-Resources Investigations Report 98-4116, 99 p.

Klemp, J.A., 1995, Source aquifers for large springs in northwestern Lawrence County, South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished M.S. thesis, 175 p.

Koterba, M.T., Banks, W.S.L., and Shedlock, R.J., 1993, Pesticides in shallow groundwater in the Delmarva Peninsula: Journal of Environmental Quality, v. 22, no. 3, p. 500-518.

Kyllonen, D.P. and Peter, K.D., 1987, Geohydrology and water quality of the Inyan Kara, Minnelusa, and Madison aquifers of the northern Black Hills, South Dakota and Wyoming, and Bear Lodge Mountains, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 86-4158, 61 p.

Lisenbee, A.L., 1985, Studies of the Tertiary intrusions of the northern Black Hills uplift, South Dakota and Wyoming; a historical review, *in* Rich, F.J., ed., Geology of the Black Hills, South Dakota and Wyoming (2d ed.): Alexandria, Va., American Geological Institute, p. 106-125.

———1991a, Geologic map of the Deadwood North quadrangle, Lawrence County, South Dakota: South Dakota School of Mines and Technology, scale 1:24,000.

———1991b, Geologic map of the Lead quadrangle, Lawrence County, South Dakota: South Dakota School of Mines and Technology, scale 1:24,000.

———1991c, Geologic map of the Maurice quadrangle, Lawrence County, South Dakota: South Dakota School of Mines and Technology, scale 1:24,000.

———1991d, Geologic map of the Savoy quadrangle, Lawrence County, South Dakota: South Dakota School of Mines and Technology, scale 1:24,000.

———1991e, Geologic map of the Spearfish quadrangle, Lawrence County, South Dakota: South Dakota School of Mines and Technology, scale 1:24,000.

———1991f, Geologic map of the Deadman Mountain quadrangle, Lawrence County, South Dakota: South Dakota School of Mines and Technology, scale 1:24,000.

———1991g, Geologic map of the Tilford quadrangle, Lawrence County, South Dakota: South Dakota School of Mines and Technology, scale 1:24,000.

Lisenbee, A.L., and Redden, J.A., 1991a, Geologic map of the Deadwood South quadrangle, Lawrence County, South Dakota: South Dakota School of Mines and Technology, scale 1:24,000.

———1991b, Geologic map of the Sturgis quadrangle, Lawrence County, South Dakota: South Dakota School of Mines and Technology, scale 1:24,000.

Miller, L.D., and Driscoll, D.G., 1998, Streamflow characteristics for the Black Hills of South Dakota, through water year 1993: U.S. Geological Survey Water-Resources Investigations Report 97-4288, 322 p.

Peter, K.D., 1985, Availability and quality of water from the bedrock aquifers in the Rapid City area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 85-4022, 34 p.

Rahn, P.H., and Gries, J.P., 1973, Large springs in the Black Hills, South Dakota and Wyoming: South Dakota Geological Survey Report of Investigations 107, 46 p.

Robinson, C.S., Mapel, W.J., and Bergendahl, M.H., 1964, Stratigraphy and structure of the northern and western flanks of the Black Hills uplift, Wyoming, Montana, and South Dakota: U.S. Geological Survey Professional Paper 404, 134 p.

Rupert, M.G., 1998, Probability of detecting atrazine/desethyl-atrazine and elevated concentrations of nitrate in ground water in the Idaho part of the Upper Snake River basin: U.S. Geological Survey Water-Resources Investigations Report 98-4203, 32 p.

———1999, Improvements to the DRASTIC ground-water vulnerability mapping method: U.S. Geological Survey Water-Resources Fact Sheet FS-066-99, 6 p.

Strobel, M.L., Jarrell, G.J., Sawyer, J.F., Schleicher, J.R., and Fahrenbach, M.D., 1999, Distribution of hydrogeologic units in the Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA-743, 3 sheets, scale 1:100,000.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: American Geophysical Union Transactions, v. 16, p. 518-524.

U.S. Department of Agriculture, 1994, State soil geographic data base (STATSGO): U.S. Department of Agriculture, Publication no. 1492, 114 p.

U.S. Department of Commerce, 1994, Climatological data for South Dakota, annual summary: Asheville, N.C. (issued annually).

U.S. Environmental Protection Agency, 1992, National survey of pesticides in drinking water wells, Phase II report: U.S. Environmental Protection Agency, EPA/579/09-91-020, 176 p.

———1993, A review of methods for assessing aquifer sensitivity and ground water vulnerability to pesticide contamination: U.S. Environmental Protection Agency, EPA/813/R-93/002, 147 p.

U.S. Geological Survey, 1967-75, Water resources data for South Dakota, 1966-74—part 1. Surface-water records (published annually).

———1976-98, Water resources data for South Dakota, water years 1975-97: U.S. Geological Survey Water-Data Reports SD-75-1 to SD-97-1 (published annually).

———1986, Land use land cover digital data from 1:250,000 and 1:100,000-scale maps: U.S. Geological Survey Data Users Guide 4, 36 p.

———1993, Digital elevation models data user's guide (3d ed.): National Mapping Program, 47 p.

Van Lieu, J.A., 1969, Geologic map of the Four Corners quadrangle, Wyoming and South Dakota: U.S. Geological Survey Map I-581, scale 1:48,000.

SUPPLEMENTAL INFORMATION

Command File 1--Command file to create generalized slope categories and eliminate polygons with areas less than 100 acres.

```
grid
/***Group slope grid into categories (table 12).
rc10 = reclass(lawco_slp, reclass.tab)
/***Merge contiguous areas less than 10 acres by nibbling area from adjacent areas.
mask10 = setnull(zonalarea(regiongroup(rc10)) < 40469.5, 1) /*10 acres
n10 = nibble(rc10, mask10, dataonly)
/***Merge contiguous areas less than 20 acres by nibbling area from adjacent areas.
mask20 = setnull(zonalarea(regiongroup(n10)) < 80939, 1) /*20 acres
n20 = nibble(n10, mask20, dataonly)
***Merge contiguous areas less than 50 acres by nibbling area from adjacent areas.
mask50 = setnull(zonalarea(regiongroup(n20)) < 202347.5, 1) /*50 acres
n50 = nibble(n20, mask50, dataonly)
***Merge contiguous areas less than 100 acres by nibbling area from adjacent areas.
mask100 = setnull(zonalarea(regiongroup(n50)) < 404695, 1) /*100 acres
n100 = nibble(n50, mask100, dataonly)
/***Remove narrow sliver polygons by replacing the value in each cell with the majority /***of the values within a circle with a 5 cell radius.
n100fm = focalmajority(n100, circle, 5, data)
***Merge contiguous areas less than 100 acres created in the step above (focalmajority) /***by nibbling area from adjacent areas greater than 100 acres.
mask100fm = setnull(zonalarea(regiongroup(n100fm)) < 404695, 1) /*100 acres
slp_cat = nibble(n100fm, mask100fm, dataonly)
/***Remove temporary working coverages
&if [exists rc10 -grid] &then kill rc10 all
&if [exists n10 -grid] &then kill n10 all
&if [exists mask10 -grid] &then kill mask10 all
&if [exists n20 -grid] &then kill n20 all
&if [exists mask20 -grid] &then kill mask20 all
&if [exists n50 -grid] &then kill n50 all
&if [exists mask50 -grid] &then kill mask50 all
&if [exists mask100 -grid] &then kill mask100 all
&if [exists n100 -grid] &then kill n100 all
&if [exists n100fm -grid] &then kill n100fm all
&if [exists mask100fm -grid] &then kill mask100fm all
```