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Geochemistry of the Madison and Minnelusa Aquifers in the Black Hills Area, South Dakota

By Cheryl A. Naus, Daniel G. Driscoll, and Janet M. Carter

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CONTENTS

Abstract.....	1
Introduction	3
Purpose and Scope.....	3
Previous Investigations	3
Acknowledgments	4
Description of Study Area	4
Geologic Setting	4
Hydrologic Setting.....	10
Regional Setting	10
Local Setting.....	12
Methods Used and Data Sets Considered.....	16
Geochemistry of Madison and Minnelusa Aquifers.....	16
Major-Ion Chemistry	16
Distribution of Major Ions	17
Saturation State.....	20
Evolutionary Processes.....	24
Isotope Chemistry.....	26
Background Information and Isotopic Composition of Recharge Water	26
Stable Isotopes of Oxygen and Hydrogen	29
Tritium	32
Conceptual Mixing Models	36
Description of Models	36
Limitations of Models	40
Areal Flowpaths, Ages, and Mixing Conditions	41
Isotope Distributions and General Considerations	41
Stable Isotopes.....	41
Tritium	46
Site-Specific Considerations.....	51
Rapid City Area.....	51
Headwater Springs.....	54
Northern Black Hills Area.....	55
Southern Black Hills Area.....	56
Regional Flowpaths	56
Interactions Between Madison and Minnelusa Aquifers.....	60
Interactions at Well Pairs	60
Hydraulic Considerations	60
Geochemical Considerations	61
Interactions at Artesian Springs.....	63
Hydraulic Considerations	63
Geochemical Considerations	65
Synopsis of Interaction Processes.....	67
Summary and Conclusions	68
References	72
Supplemental Information	77

FIGURES

1. Map showing generalized outcrops of Madison Limestone, Minnelusa Formation, and outer extent of Inyan Kara Group within the study area for Black Hills Hydrology Study.....	5
2. Stratigraphic section for the Black Hills	6
3. Map showing distribution of hydrogeologic units in the Black Hills area.....	7
4. Geologic cross section A-A'.....	9
5. Schematic showing hydrogeologic setting of the Black Hills area	10
6. Map showing general direction of ground-water flow in Paleozoic aquifers in the northern Great Plains.....	11
7. Map showing potentiometric surface of the Madison aquifer and locations of major artesian springs.....	14
8. Map showing potentiometric surface of the Minnelusa aquifer and locations of major artesian springs	15
9. Trilinear diagrams showing proportional concentrations of major ions in the Madison and Minnelusa aquifers	17
10. Selected Stiff diagrams showing the distribution of major-ion chemistry in the Madison aquifer	18
11. Selected Stiff diagrams showing the distribution of major-ion chemistry in the Minnelusa aquifer.....	19
12. Graph showing relation between gypsum saturation index and dissolved sulfate in the Madison and Minnelusa aquifers	23
13. Boxplots showing calcite and dolomite saturation indices for selected samples from the Madison and Minnelusa aquifers	23
14-17. Graphs showing:	
14. Modeled relations between calcium and magnesium concentrations, pH, and dissolved sulfate.....	25
15. Relations between dissolved calcium and magnesium concentrations and dissolved sulfate in the Madison and Minnelusa aquifers	27
16. Relation between pH and dissolved sulfate in the Madison and Minnelusa aquifers.....	28
17. Relation between dissolved oxygen and distance from outcrop in the Madison and Minnelusa aquifers	28
18. Schematic showing fractionation of stable oxygen and hydrogen isotopes during rainout	29
19. Graph showing relation between $\delta^{18}\text{O}$ and δD in Black Hills samples in comparison to the Global Meteoric Water Line.....	30
20. Map showing generalized distribution of $\delta^{18}\text{O}$ in surface water and ground water in near-recharge areas	31
21. Graphs showing temporal variation of $\delta^{18}\text{O}$ for selected sites	33
22. Map showing cumulative tritium deposition on the continental United States, 1953-83, and location of selected collection sites	34
23. Graph showing monthly tritium concentrations in precipitation at Ottawa, Canada	34
24. Graph showing weighted annual tritium concentrations in precipitation at selected locations	35
25. Schematic diagrams illustrating mixing models for age dating for various ground-water flow conditions	37
26. Graph showing estimated tritium concentrations in precipitation for Black Hills area and decay curves for selected years	39
27-32. Maps showing:	
27. Distribution of $\delta^{18}\text{O}$ in selected Madison and Minnelusa wells and springs in the northern Black Hills area	42
28. Distribution of $\delta^{18}\text{O}$ in selected Madison and Minnelusa wells and springs in the Rapid City area	43
29. Distribution of $\delta^{18}\text{O}$ in selected Madison and Minnelusa wells and springs in the southern Black Hills area.....	44
30. Distribution of tritium for selected sites in the northern Black Hills.....	47
31. Distribution of tritium for selected sites in the Rapid City area	48
32. Distribution of tritium for selected sites in the southern Black Hills area.....	49
33. Boxplots of tritium concentrations for selected ground-water and surface-water samples collected during 1990-98 in the Black Hills area.....	50
34. Map showing distribution of $\delta^{18}\text{O}$ in selected Madison wells and springs and generalized flowpaths in the Black Hills of South Dakota and Wyoming	57
35. Selected Stiff diagrams showing the distribution of major-ion chemistry in selected well pairs and artesian springs in the Black Hills area.....	59
36. Graphs showing decay-curve families for time-delay mixing model	79
37. Hydrographs of selected well pairs	84

TABLES

1. Saturation indices for selected samples from wells completed in the Madison and Minnelusa aquifers.....	21
2. Selected results of geochemical modeling.....	25
3. Selected data for observation well pairs.....	45
4. Tritium data for selected sites having data for 2000.....	52
5. Generalized age estimates for headwater springs, derived using immediate-arrival mixing model.....	54
6. Selected hydraulic and geochemical information for major artesian springs.....	64
7. Selected site information and isotope data for sites used in report.....	87
8. Stable isotope data for sites with multiple samples.....	103
9. Weighted annual tritium concentrations in precipitation for Black Hills area.....	114
10. Monthly estimated tritium concentrations in precipitation, monthly precipitation, and weighted annual tritium concentrations in precipitation for Black Hills area.....	115
11. Estimated tritium concentrations in precipitation for Black Hills area, adjusted for decay.....	117

CONVERSION FACTORS, ACRONYMS, AND ABBREVIATIONS

	Multiply	By	To obtain
	acre	4,047	square meter
	acre	0.4047	hectare
	acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
	acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
	cubic foot per second (ft ³ /s)	0.02832	cubic meter per second
	foot per year (ft/yr)	0.3048	meter per year
	gallon per minute (gal/min)	0.06309	liter per second
	inch	2.54	centimeter
	inch	25.4	millimeter
	inch per year (in/yr)	25.4	millimeter per year
	foot (ft)	0.3048	meter
	mile (mi)	1.609	kilometer

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

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

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

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$$

Water year: Water year is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends. Thus, the water year ending September 30, 1998, is called the “1998 water year.”

Per mil (‰): A unit expressing the ratio of stable-isotopic abundances of an element in a sample to those of a standard material. Per mil units are equivalent to parts per thousand. Stable-isotopic ratios are computed as follows:

$$\delta X = \left(\frac{R(\text{sample})}{R(\text{standard})} - 1 \right) \times 1,000$$

where

X is the heavier isotope and

R is the ratio of the heavier, less abundant stable isotope to the lighter, stable isotope in a sample or standard.

The δ values for oxygen and hydrogen stable isotopic ratios discussed in this report are referenced to the following standard material:

Ratio (R)	Standard identity and reference
hydrogen-2:hydrogen-1	Vienna Standard Mean Ocean Water (VSMOW)
oxygen-18:oxygen-16	Vienna Standard Mean Ocean Water (VSMOW)

Geochemistry of the Madison and Minnelusa Aquifers in the Black Hills Area, South Dakota

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ABSTRACT

The Madison and Minnelusa aquifers are two of the most important aquifers in the Black Hills area because of utilization for water supplies and important influences on surface-water resources resulting from large springs and stream-flow-loss zones. Examination of geochemical information provides a better understanding of the complex flow systems within these aquifers and interactions between the aquifers.

Major-ion chemistry in both aquifers is dominated by calcium and bicarbonate near outcrop areas, with basinward evolution towards various other water types. The most notable differences in major-ion chemistry between the Madison and Minnelusa aquifers are in concentrations of sulfate within the Minnelusa aquifer. Sulfate concentrations increase dramatically near a transition zone where dissolution of anhydrite is actively occurring.

Water chemistry for the Madison and Minnelusa aquifers is controlled by reactions among calcite, dolomite, and anhydrite. Saturation indices for gypsum, calcite, and dolomite for most samples in both the Madison and Minnelusa aquifers are indicative of the occurrence of dedolomitization. Because water in the Madison aquifer remains undersaturated with respect to gypsum, even at the highest sulfate concentrations, upward leakage into the overlying Minnelusa aquifer has potential to drive increased dissolution of anhydrite in the Minnelusa Formation.

Isotopic information is used to evaluate ground-water flowpaths, ages, and mixing conditions for the Madison and Minnelusa aquifers. Distinctive patterns exist in the distribution of stable isotopes of oxygen and hydrogen in precipitation for the Black Hills area, with isotopically lighter precipitation generally occurring at higher elevations and latitudes. Distributions of $\delta^{18}\text{O}$ in ground water are consistent with spatial patterns in recharge areas, with isotopically lighter $\delta^{18}\text{O}$ values in the Madison aquifer resulting from generally higher elevation recharge sources, relative to the Minnelusa aquifer.

Three conceptual models, which are simplifications of lumped-parameter models, are considered for evaluation of mixing conditions and general ground-water ages. For a simple slug-flow model, which assumes no mixing, measured tritium concentrations in ground water can be related through a first-order decay equation to estimated concentrations at the time of recharge. Two simplified mixing models that assume equal proportions of annual recharge over a range of years also are considered. An "immediate-arrival" model is used to conceptually represent conditions in outcrop areas and a "time-delay" model is used for locations removed from outcrops, where delay times for earliest arrival of ground water generally would be expected. Because of limitations associated with estimating tritium input and gross simplifying assumptions of equal annual recharge and thorough mixing conditions, the conceptual models are used only for general evaluation of mixing conditions and approximation of age ranges.

Headwater springs, which are located in or near outcrop areas, have the highest tritium concentrations, which is consistent with the immediate-arrival mixing model. Tritium concentrations for many wells are very low, or nondetectable, indicating general applicability of the time-delay conceptual model for locations beyond outcrop areas, where artesian conditions generally occur. Concentrations for artesian springs generally are higher than for wells, which indicates generally shorter delay times resulting from preferential flowpaths that typically are associated with artesian springs.

In the Rapid City area, a distinct division of isotopic values for the Madison aquifer corresponds with distinguishing $\delta^{18}\text{O}$ signatures for nearby streams, where large streamflow recharge occurs. Previous dye testing in this area documented rapid ground-water flow (timeframe of weeks) from a streamflow loss zone to sites located several miles away. These results are used to illustrate potential errors that may result from the simplified conceptualization of this complex ground-water setting with dual-porosity hydraulic characteristics. For Rapid City sites with time-series data, minimal variability in $\delta^{18}\text{O}$ values corresponded with tritium data indicative of dominant proportions of older water. Other sites showed response to temporal $\delta^{18}\text{O}$ trends in streamflow recharge, with tritium data indicating larger proportions of modern recharge. Several large production wells located near the isotopic transition zone had changes in $\delta^{18}\text{O}$ values indicative of changes in capture zones associated with recent production.

Evaluation of major-ion and isotope data indicates that regional flowpaths for the Madison aquifer are essentially deflected around the study area, with the possible exception of the southwestern and northwestern corners. Two wells just north of the study area clearly show influence of regional flow, and a well just within the study area shows possible influence. Large artesian springs near the northern axis of the uplift show no regional influence and are concluded to be recharged within the uplift area. Ion concentrations for wells west of the study area in Wyoming

indicate deflection of regional flowpaths, with minor influence possible for several wells. The $\delta^{18}\text{O}$ values for large springs along the southern axis of the uplift essentially preclude regional influence, which also is supported by ion chemistry, and indicate potential recharge areas extending along the entire southwestern flank of the uplift. Low, but detectable, tritium concentrations in these springs along the southern axis confirm the influence of recharge from within the study area, but indicate relatively long travel times.

Hydrographs for 9 of 13 well pairs are fairly well separated and do not indicate direct hydraulic connection between the Madison and Minnelusa aquifers. Comparison of geochemical information provides no evidence of extensive mixing resulting from general, areal leakage between the aquifers.

Aquifer interactions can occur at artesian springs, which discharge about one-half of average recharge to the Madison and Minnelusa aquifers in the Black Hills area. Various investigators have hypothesized that the Madison aquifer is the primary source for many artesian springs, based on geochemical modeling. The Madison aquifer is inferred as the primary source for several springs where artesian conditions in the Minnelusa aquifer are precluded by nearby outcrop sections. For many springs, quantifying relative contributions from each aquifer is hampered by geochemical similarities between the Madison and Minnelusa aquifers, especially near recharge areas. For some springs, high sulfate concentrations indicate Minnelusa influence, but may result from dissolution of Minnelusa minerals by water from the Madison aquifer.

Generally higher hydraulic head in the Madison aquifer, in combination with gypsum undersaturation, is concluded to be a primary mechanism driving interactions with the Minnelusa aquifer, in areas where artesian conditions exist in the Madison aquifer. Upward leakage from the Madison aquifer probably contributes to general dissolution of anhydrite deposits in the Minnelusa aquifer and development of breccia pipes, which enhances vertical hydraulic conductivity. Breccia pipes are a likely mechanism for

upward movement of large quantities of water through the Minnelusa aquifer at artesian spring locations and many exposed breccia pipes of the upper Minnelusa Formation probably are the throats of abandoned artesian springs. Dissolution processes are an important factor in a self-perpetuating process associated with development of artesian springs and preferential flowpaths, which initially develop in locations with large secondary porosity and associated hydraulic conductivity, with ongoing enhancement resulting from dissolution activity.

Outward (downgradient) migration of the artesian springs probably occurs as upgradient spring-discharge points are abandoned and new ones are occupied, keeping pace with regional erosion over geologic time. In response, hydraulic heads in the Madison and Minnelusa aquifers also have declined over geologic time. Artesian springflow and general leakage are concluded to be important factors in governing water levels in the Madison and Minnelusa aquifers. Artesian springs are especially important in acting as a relief mechanism that provides an upper limit for hydraulic head, with springflow increasing in response to increasing water levels.

INTRODUCTION

The Madison and Minnelusa aquifers are two of the most important aquifers in the Black Hills area. These aquifers are used extensively for domestic, municipal, irrigation, and industrial uses and have a major influence on the surface-water resources because of large spring discharges and large streamflow losses that occur along many stream channels.

Population growth, resource development, and periodic droughts have the potential to affect the quantity, quality, and availability of water within the Black Hills area. Because of this concern, the Black Hills Hydrology Study was initiated in 1990 to assess the quantity, quality, and distribution of surface and ground water in the Black Hills area of South Dakota (Driscoll, 1992). This long-term study is a cooperative effort between the U.S. Geological Survey, the South Dakota Department of Environment and Natural Resources, and the West Dakota Water Development District, which represents various local and county cooperators.

The Madison and Minnelusa aquifers are the primary focus of the Black Hills Hydrology Study.

Ground-water conditions in the Madison and Minnelusa aquifers are extremely complex because of several factors. Water recharged in the uplifted Black Hills area mixes with the regional flow system at lower elevations; however, interfaces and mixing conditions are not well defined. Both aquifers are potential sources for numerous large springs in the Black Hills area, and hydraulic connections are possible in other locations because of large secondary porosity and permeability in both aquifers. Ground-water flowpaths and velocities in both aquifers are influenced by anisotropic and heterogeneous hydraulic properties caused by secondary porosity resulting from fractures, faults, and dissolution activity. Karst features, including sinkholes, collapse features, solution cavities, and caves, in the Madison aquifer, and collapse breccia associated with dissolution of interbedded evaporites in the Minnelusa aquifer, create the potential for the introduction and rapid transport of contaminants within the Madison and Minnelusa aquifers.

Geochemistry is a useful tool for better understanding the complex flow systems in the Madison and Minnelusa aquifers. The major-ion chemistry of water from these aquifers is an important water-quality consideration. Isotope information provides insights regarding recharge areas and travel times. Both major-ion and isotope information provide insights regarding flowpaths within the Madison and Minnelusa aquifers and potential interconnections between them.

Purpose and Scope

The purpose of this report is to present geochemical information for the Madison and Minnelusa aquifers in the Black Hills area of South Dakota, with an emphasis on information relating to understanding the ground-water flow conditions in these aquifers. The report includes discussions of major-ion and isotope chemistry of the Madison and Minnelusa aquifers, possible influences from regional flowpaths, and interactions that may occur between the two aquifers.

Previous Investigations

Previous investigations have provided various information regarding the geochemistry of the Madison and Minnelusa aquifers in the Black Hills area. The geochemical evolution of ground water in the Madison

and Minnelusa aquifers has been studied by Bowles and Braddock (1963), Braddock and Bowles (1963), Back and others (1983), Busby and others (1983, 1991, 1995), Plummer and others (1990), and Naus (1999). Potential source aquifers for springs in the Black Hills area were investigated by Alexander and others (1988, 1989), Whalen (1994), Klemp (1995), and Wenker (1997). Browne (1992) studied water-quality characteristics and geochemical differentiation of the Madison and Minnelusa aquifers near Rapid City. Applications of oxygen and hydrogen isotopes to the study of ground-water source areas, flowpaths, and mixing in the Madison aquifer in the Black Hills area have been presented by Back and others (1983), Busby and others (1983), Greene (1997, 1999), and Anderson and others (1999).

Acknowledgments

The authors acknowledge the efforts of the West Dakota Water Development District for helping to develop and support the Black Hills Hydrology Study. West Dakota's coordination of various local and county cooperators has been a key element in making this study possible. The authors also recognize the numerous local and county cooperators represented by West Dakota, as well as the numerous private citizens who have helped provide guidance and support for the Black Hills Hydrology Study. The South Dakota Department of Environment and Natural Resources has provided support and extensive technical assistance to the study. David Parkhurst, U.S. Geological Survey, provided extensive guidance and numerous insights regarding this report. In addition, the authors acknowledge technical assistance from many faculty and students at the South Dakota School of Mines and Technology.

DESCRIPTION OF STUDY AREA

The study area consists of the topographically defined Black Hills and adjacent areas located in western South Dakota (fig. 1). Outcrops of the Madison Limestone and Minnelusa Formation, as well as the generalized outer extent of the Inyan Kara Group, which approximates the outer extent of the Black Hills area, also are shown in figure 1. The study area includes most of the larger communities in western South Dakota and contains about one-fifth of the State's population.

The Black Hills are a dome-shaped uplift about 125 miles long and 60 miles wide (Feldman and Heimlich, 1980). Land-surface elevations range from about 7,200 ft at the highest peaks to about 3,000 ft in the surrounding plains. The overall climate of the study area is continental, with generally low precipitation amounts, hot summers, cold winters, and extreme variations in both precipitation and temperatures (Johnson, 1933). Local climatic conditions are affected by topography, with generally lower temperatures and higher precipitation at the higher elevations.

The average annual precipitation for the study area (1931-98) is 18.61 inches, and has ranged from 10.22 inches for water year 1936 to 27.39 inches for water year 1995 (Driscoll, Hamade, and Kenner, 2000). The largest precipitation amounts typically occur in the northern Black Hills near Lead, where average annual precipitation exceeds 29 inches. Annual averages (1931-98) for counties within the study area range from 16.35 inches for Fall River County to 23.11 inches for Lawrence County. The average annual temperature is 43.9°F (U.S. Department of Commerce, 1999) and ranges from 48.7°F at Hot Springs to approximately 37°F near Deerfield Reservoir. Average annual evaporation generally exceeds average annual precipitation throughout the study area. Average pan evaporation for April through October is about 30 inches at Pactola Reservoir and about 50 inches at Oral.

Geologic Setting

The oldest geologic units in the study area are the Precambrian metamorphic and igneous rocks (fig. 2), which underlie the Paleozoic, Mesozoic, and Cenozoic rocks and sediments, except where exposed at the land surface. The Precambrian rocks range in age from about 1.7 to 2.5 billion years, and were eroded to a gentle undulating plain at the beginning of the Paleozoic era (Gries, 1996). The Paleozoic and Mesozoic rocks were deposited as nearly horizontal beds and were later uplifted during the rise of the Black Hills during the Laramide orogeny. Uplift during the Laramide orogeny and related erosion exposed the Precambrian rocks in the central core of the Black Hills with the Paleozoic and Mesozoic sedimentary rocks exposed in roughly concentric rings around the core. Deformation during the Laramide orogeny contributed to the numerous fractures, folds, and other features present throughout the Black Hills. Tertiary intrusive activity in the northern Black Hills (fig. 3) also contributed to rock fracturing.

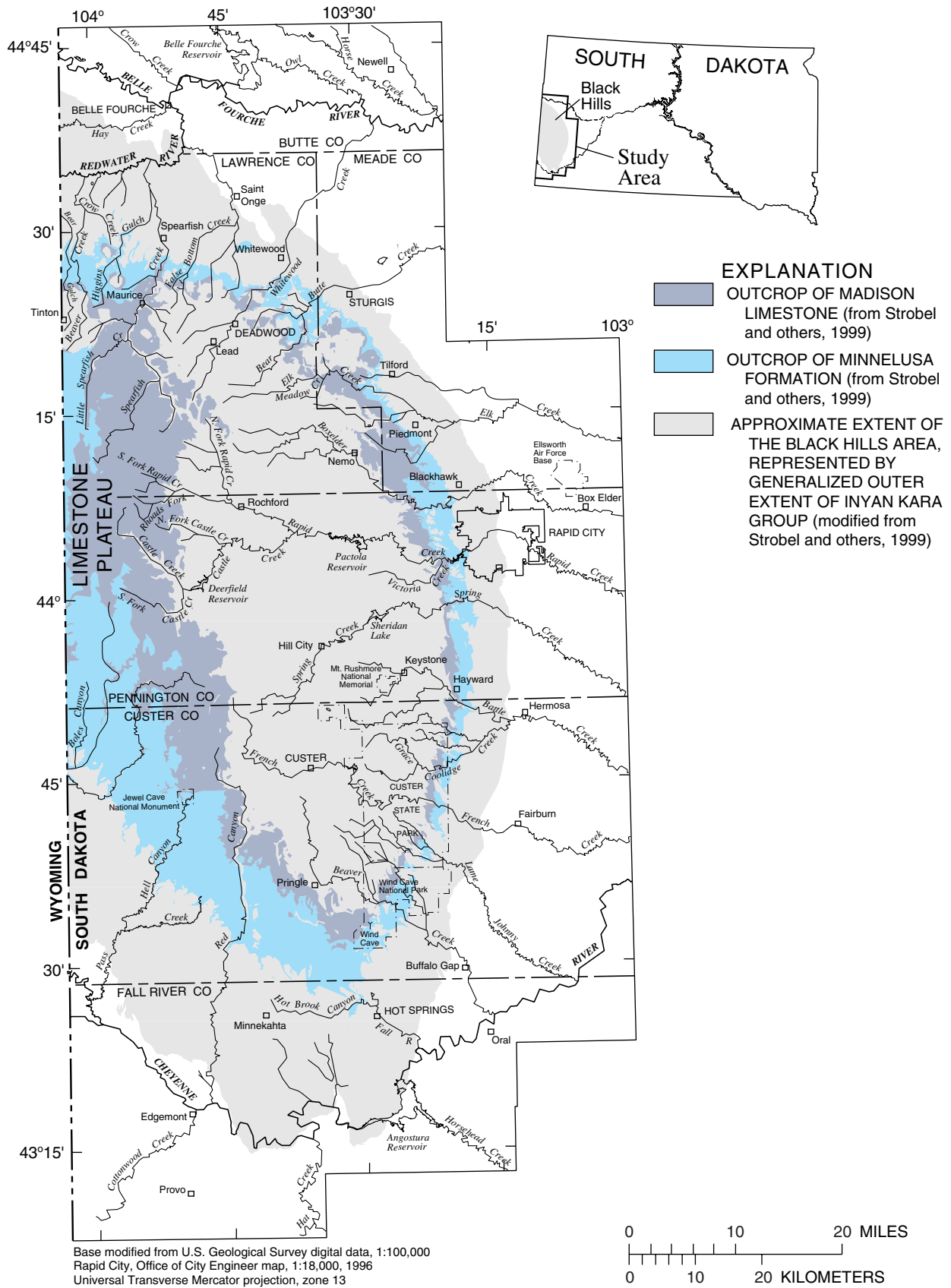


Figure 1. Generalized outcrops of Madison Limestone, Minnelusa Formation, and outer extent of Inyan Kara Group within the study area for Black Hills Hydrology Study.

ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	STRATIGRAPHIC UNIT	THICKNESS IN FEET	DESCRIPTION			
CENOZOIC	QUATERNARY & TERTIARY (?)	Q ^{Tec}	UNDIFFERENTIATED SANDS AND GRAVELS	0-50	Alluvial and colluvial materials.			
	TERTIARY	Tw	WHITE RIVER GROUP	0-300	Light colored clays with sandstone channel fillings and local limestone lenses.			
		Tu	INTRUSIVE IGNEOUS ROCKS	--	Includes rhyolite, tuffe, trachyte, and phonolite. Principal horizon of limestone lenses giving tepee buttes.			
MESOZOIC	CRETACEOUS	Kps	PIERRE SHALE	1,200-2,700	Dark-gray shale containing scattered concretions. Widely scattered limestone masses, giving small tepee buttes. Black fissile shale with concretions. Impure chalk and calcareous shale.			
			NIORAPA FORMATION	180-300	Light-gray shale with numerous large concretions and sandy layers. Dark-gray shale.			
			CARLILE SHALE	Turner Sandy Member Wall Creek Member	1,350-750	Impure silty limestone. Weathers buff. Dark-gray calcareous shale, with thin Orman Lake limestone at base.		
			GREENHORN FORMATION	225-380	Gray shale with scattered limestone concretions. Clay spur bentonite at base.			
			BELLE FOURCHE SHALE	150-850	Light-gray siliceous shale. Fish scales and thin layers of bentonite.			
				125-230	Brown to light-yellow and white sandstone.			
				0-150	Dark-gray to black siliceous shale.			
				150-270	Massive to silty sandstone.			
				10-200	Coarse gray to buff cross-bedded conglomeratic sandstone, interbedded with buff, red, and gray clay, especially toward top. Local fine-grained limestone.			
			GRANEROS GROUP	Kik	FALL RIVER FORMATION	10-190	Green to maroon shale. Thin sandstone. Massive fine-grained sandstone.	
					LAKOTA FM	0-25		
			PALEOZOIC	JURASSIC	Ju	MORRISON FORMATION	0-220	Red silty shale, soft red sandstone and siltstone with gypsum and thin limestone layers. Gypsum locally near the base. Thin to medium-bedded fine-grained, purplish-gray laminated limestone. Red shale and sandstone. 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. Massive light-colored limestone. Dolomite in part. Cavemous in upper part.
						UNKPAPA SS	0-225	
						SUNDANCE FORMATION	250-450	
						GYPSUM SPRING FORMATION	0-45	
SPEARFISH FORMATION	375-800							
MINNEKAHTA LIMESTONE	125-65							
OPECHE SHALE	125-150							
PERMIAN	PIPm	MINNELUSA FORMATION				1,375-1,175		
						1,250-1,000		
PENNSYLVANIAN	MDm	MADISON (PAHASAPA) LIMESTONE				30-60		
			ENLEWOOD FORMATION	10-235				
			WHITEWOOD (RED RIVER) FORMATION	10-150				
			WINNIPEG FORMATION	10-150				
			DEADWOOD FORMATION	10-500				
MISSISSIPPIAN	Ou	DEADWOOD FORMATION	10-500					
			10-500					
DEVONIAN	Ocd	DEADWOOD FORMATION	10-500					
			10-500					
ORDOVICIAN	pCu	DEADWOOD FORMATION	10-500					
			10-500					
CAMBRIAN	pCu	DEADWOOD FORMATION	10-500					
			10-500					
PRECAMBRIAN	pCu	UNDIFFERENTIATED METAMORPHIC AND IGNEOUS ROCKS	10-500					
			10-500					

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

Figure 2. Stratigraphic section for the Black Hills.

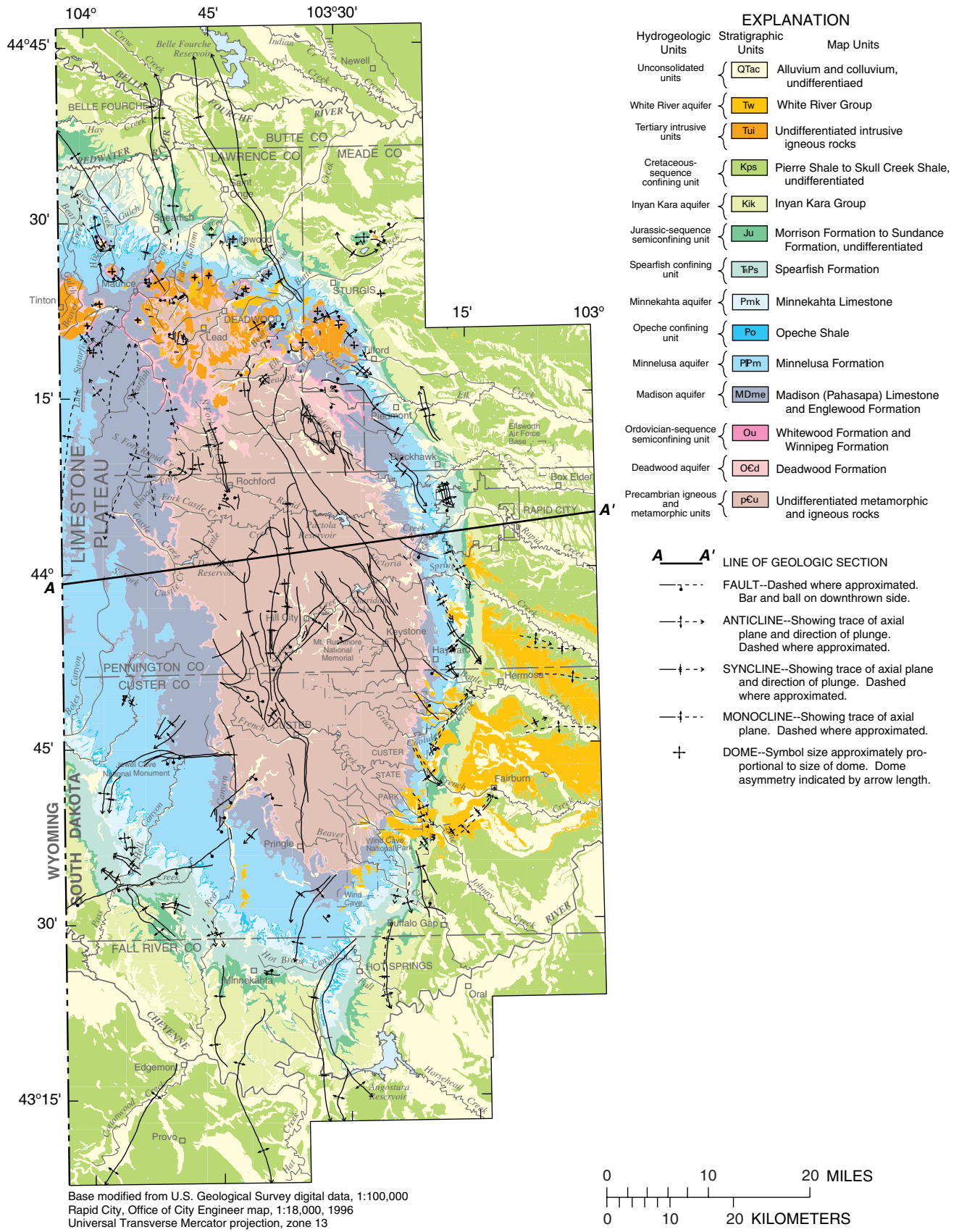


Figure 3. Distribution of hydrogeologic units in the Black Hills area (modified from Strobel and others, 1999).

Surrounding the central core is a layered series of sedimentary rocks including outcrops of the Madison Limestone (also locally known as the Pahasapa Limestone) and the Minnelusa Formation (fig. 3). The bedrock sedimentary units typically dip away from the uplifted Black Hills at angles that can approach or exceed 15 to 20 degrees near the outcrops, and decrease with distance from the uplift to less than 1 degree (Carter and Redden, 1999a, 1999b, 1999c, 1999d, 1999e) (fig. 4). Following are descriptions for selected bedrock formations from the Deadwood Formation through the Inyan Kara Group.

The oldest sedimentary unit in the study area is the Cambrian- and Ordovician-age Deadwood Formation, which is composed primarily of brown to light-gray glauconitic sandstone, shale, limestone, and local basal conglomerate (Strobel and others, 1999). These sediments were deposited on top of a generally horizontal plain of Precambrian rocks in a coastal to near-shore environment (Gries, 1975). The thickness of the Deadwood Formation increases from south to north in the study area and ranges from 0 to 500 ft (Carter and Redden, 1999e). In the northern and central Black Hills, the Deadwood Formation is disconformably overlain by Ordovician rocks, which include the Whitewood and Winnipeg Formations. The Winnipeg Formation is absent in the southern Black Hills, and the Whitewood Formation has eroded to the south and is not present south of the approximate latitude of Nemo (DeWitt and others, 1986). In the southern Black Hills, the Deadwood Formation is unconformably overlain by the Devonian- and Mississippian-age Englewood Formation because of the absence of the Ordovician sequence.

The Mississippian-age Madison Limestone is a massive, gray to buff limestone that is locally dolomitic (Strobel and others, 1999). The Madison Limestone, which was deposited as a marine carbonate, was exposed at land surface for approximately 50 million years. During this period, significant erosion, soil development, and karstification occurred (Gries, 1996). There are numerous caves and fractures within the upper part of the formation (Peter, 1985). The thickness of the Madison Limestone increases from south to north in the study area and ranges from almost zero in the southeast corner of the study area (Rahn, 1985) to 1,000 ft east of Belle Fourche (Carter and Redden, 1999d). Local variations in thickness are due largely to the karst topography that developed before

the deposition of the overlying formations (DeWitt and others, 1986). Because the surface of the Madison Limestone was exposed to weathering and karstification for millions of years, the formation is unconformably overlain by the Pennsylvanian- and Permian-age Minnelusa Formation. The Madison Limestone is underlain by the Englewood Formation, which Gries (1996) included as an impure basal phase of the Madison Limestone but Fahrenbach (1995) described as a separate unit from the Madison Limestone. The Madison Limestone and equivalent units are regionally extensive throughout the northern Great Plains area and pinch out in southern and eastern South Dakota.

The Pennsylvanian- and Permian-age Minnelusa Formation consists mostly of yellow to red cross-stratified sandstone, limestone, dolomite, and shale (Strobel and others, 1999). Anhydrite cements are prevalent in many layers within the subsurface, but generally have been removed by dissolution at or near outcrop areas (DeWitt and others, 1986). Collapse features filled with breccia (breccia pipes) occur within the upper part of the Minnelusa Formation in many locations (Braddock, 1963; Long and others, 1999; Epstein, 2000). The thickness of the Minnelusa Formation in the study area increases from north to south in the study area and ranges from about 375 ft near Belle Fourche to 1,175 ft near Edgemont (Carter and Redden, 1999c). The Minnelusa Formation was deposited in a coastal environment, and dune structures at the top of the formation may represent beach sediments (Gries, 1996). Along the northeastern flank of the Black Hills, there is little anhydrite in the subsurface due to a change in the depositional environment (Carter and Redden, 1999c). On the south and southwest side of the study area, there is a considerable increase in thickness of clastic units as well as a thick section of anhydrite. The Minnelusa Formation disconformably is overlain by the Permian-age Opeche Shale, which is overlain by the Minnekahta Limestone. The Minnelusa Formation and equivalent units are regionally extensive throughout the northern Great Plains area and pinch out in eastern South Dakota.

The Permian-age Minnekahta Limestone is a fine-grained, purple to gray laminated limestone (Strobel and others, 1999), which ranges in thickness from 25 to 65 ft in the study area. The Minnekahta Limestone is overlain by the Triassic- and Permian-age Spearfish Formation.

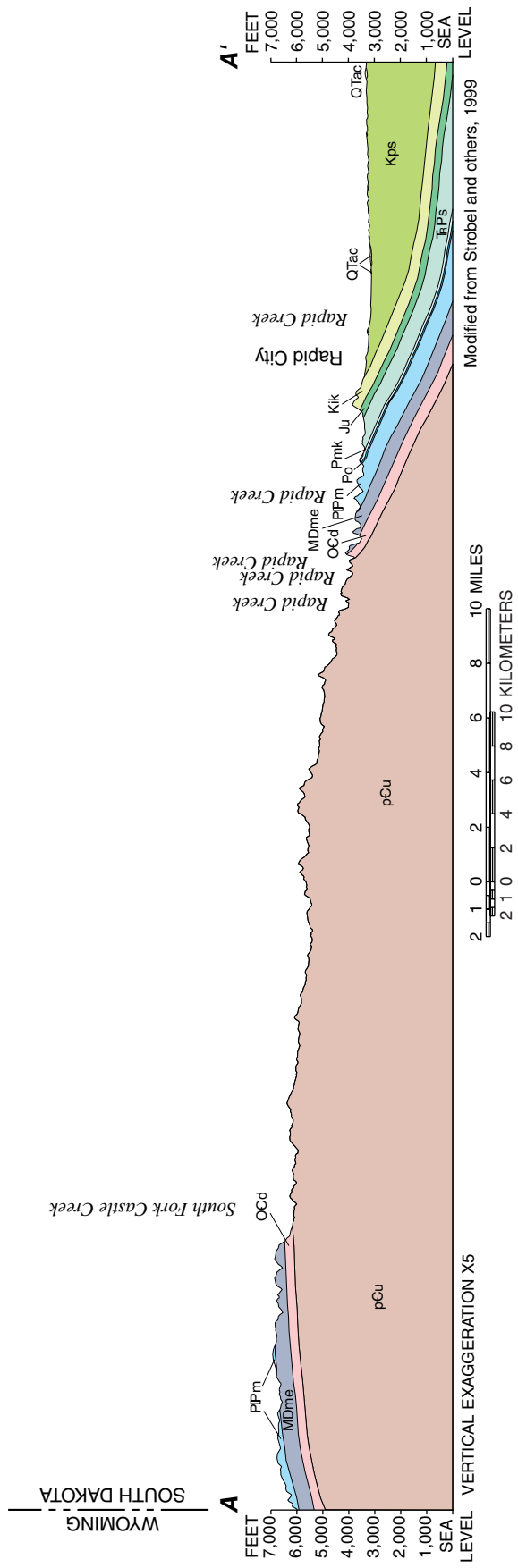


Figure 4. Geologic cross section A-A' (Location of section is shown in figure 3. Abbreviations for stratigraphic intervals are explained in figure 2.)

The Spearfish Formation is a red, silty shale with interbedded red sandstone and siltstone, which ranges in thickness from about 375 to 800 ft (Strobel and others, 1999). The Spearfish Formation contains massive gypsum throughout. The overlying Mesozoic-age units are composed primarily of shale, siltstone, and sandstone deposits, and include the Cretaceous-age Inyan Kara Group. The thickness of the Inyan Kara Group ranges from about 135 to 900 ft in the study area (Carter and Redden, 1999a).

Hydrologic Setting

The hydrologic setting of the Black Hills area is schematically illustrated in figure 5, and the areal distribution of hydrogeologic units is shown in figure 3. Four of the major bedrock aquifers in the Black Hills area (Deadwood, Madison, Minnelusa, and Inyan Kara aquifers) are regionally extensive and are discussed in the following sections in the context of both regional

and local hydrologic settings. A fifth major aquifer (Minnekahta) generally is used only locally, as are aquifers in the metamorphic and igneous rocks within the central core area.

Regional Setting

The Paleozoic aquifers underlie parts of Montana, North Dakota, South Dakota, Wyoming, and Canada (Downey, 1984). The Canadian part of the regional aquifer system is not described or shown in this report. For the description of the regional setting (a large part of the northern Great Plains), it is convenient to use aquifer names of Downey and Dinwiddie (1988) and Whitehead (1996). The Paleozoic aquifers include the Cambrian-Ordovician aquifer (or Deadwood aquifer in the Black Hills), Mississippian aquifer (or Madison aquifer in the Black Hills), and the Pennsylvanian aquifer (or Minnelusa aquifer in the Black Hills). The Paleozoic aquifers are recharged in outcrop areas around major uplifts (fig. 6).

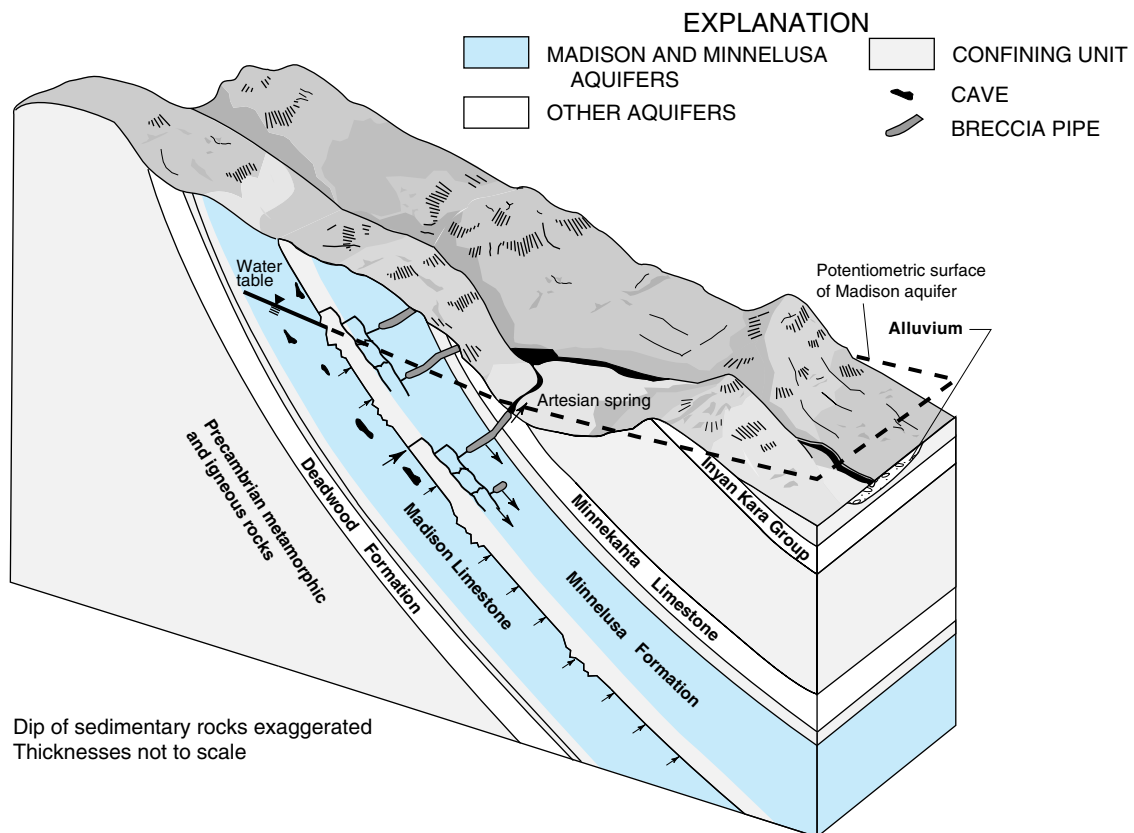


Figure 5. Schematic showing hydrogeologic setting of the Black Hills area. Figure also shows caves and breccia pipes, which contribute to secondary porosity in the Madison and Minnelusa aquifers. Breccia pipes may result from upward leakage from the Madison aquifer, creating conduits for artesian springs.

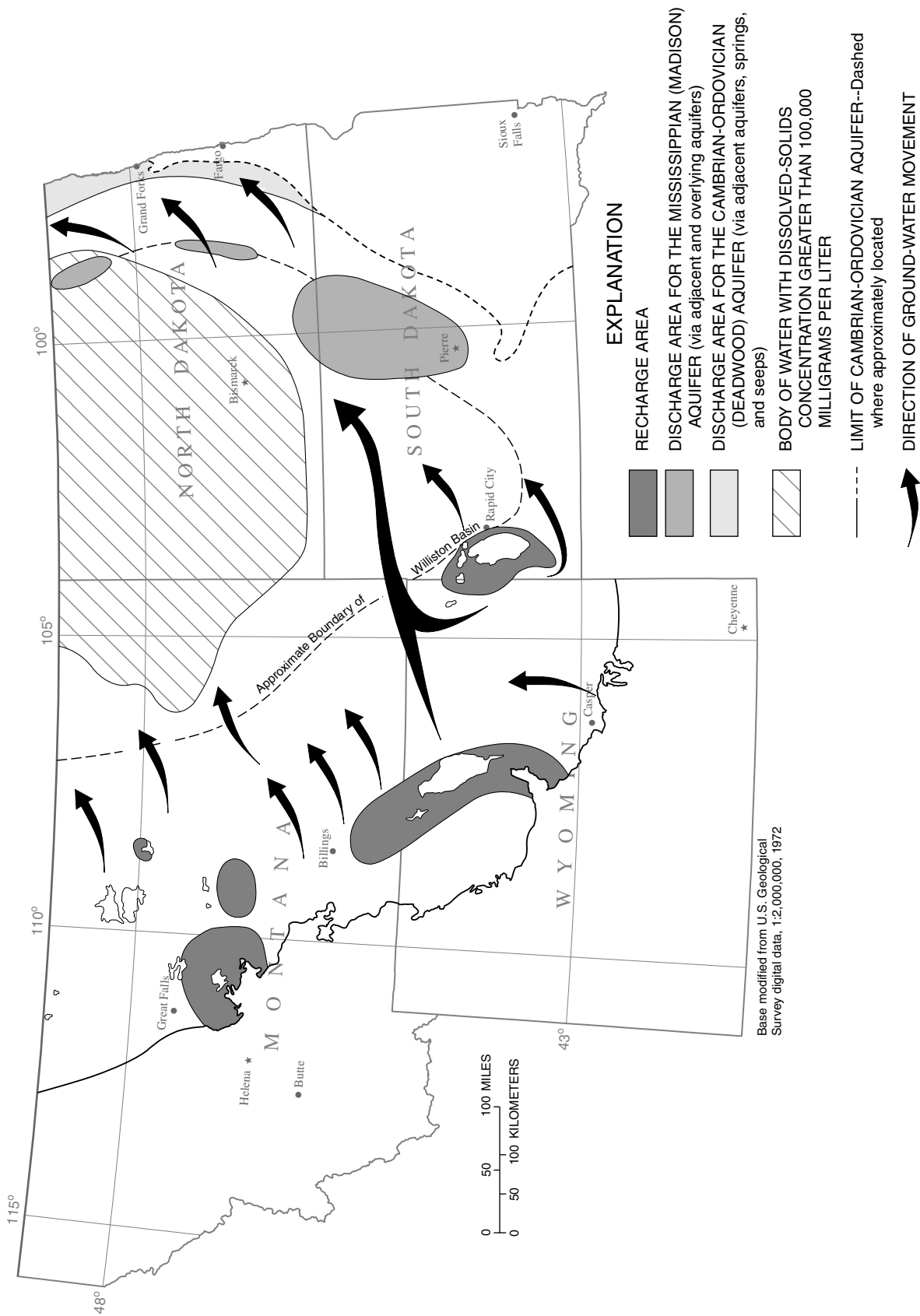


Figure 6. General direction of ground-water flow in Paleozoic aquifers in the northern Great Plains (modified from Downey and Dinwiddie, 1988 and Whitehead, 1996).

The Cambrian-Ordovician (or Deadwood) aquifer consists of sandstones of Cambrian age (Deadwood Formation and equivalents) and limestones of Ordovician age. The Cambrian-Ordovician aquifer contains freshwater, with dissolved solids concentrations less than 1,000 mg/L (milligrams per liter), only in an area surrounding the Black Hills and in a small area in north-central Wyoming (Whitehead, 1996).

The Mississippian (or Madison) aquifer is contained within the limestones, siltstones, sandstones, and dolomite of the Madison Limestone and equivalent units. Generally, water in the Mississippian aquifer is confined except in outcrop areas. Flow in the Mississippian aquifer generally is from the recharge areas to the northeast (fig. 6). Discharge from the Mississippian aquifer occurs by upward leakage to the lower Cretaceous aquifer in central South Dakota and eastern flow to the Cambrian-Ordovician aquifer in eastern North Dakota (Downey, 1984). Water in the Mississippian aquifer is fresh only in small areas near recharge areas and becomes slightly saline to saline as it moves downgradient. The water is a brine with dissolved solids concentrations greater than 300,000 mg/L in the deep parts of the Williston basin (Whitehead, 1996).

The Pennsylvanian (or Minnelusa) aquifer is comprised of sandstones and limestones of the Minnelusa Formation and equivalent units of Pennsylvanian age. Water in the Pennsylvanian aquifer moves from recharge areas to discharge areas in eastern South Dakota (Downey and Dinwiddie, 1988). Some water discharges by upward leakage to the lower Cretaceous aquifer (Swenson, 1968; Gott and others, 1974).

Several sandstone units compose the lower Cretaceous aquifer, which generally is known as the Inyan Kara aquifer in South Dakota and the Dakota aquifer in North Dakota. Generally, water in the lower Cretaceous aquifer is confined by several thick shale layers except in aquifer outcrop areas around structural uplifts, such as the Black Hills. Water in the lower Cretaceous aquifer generally moves northeasterly from high-elevation recharge areas to discharge areas in eastern North Dakota and South Dakota (Whitehead, 1996). Although the aquifer is widespread, it contains little freshwater. Much of the saline water is believed to be from upward leakage of mineralized water from the Paleozoic aquifers (Whitehead, 1996).

Local Setting

Many of the sedimentary units in the Black Hills area contain aquifers, both within and beyond the study

area. Within the Paleozoic rock interval, aquifers in the Deadwood Formation, Madison Limestone, Minnelusa Formation, and Minnekahta Limestone are used extensively. These aquifers are collectively confined by the underlying Precambrian rocks (fig. 5) and the overlying Spearfish Formation (fig. 2). Individually, these aquifers are separated by minor confining units or by relatively impermeable layers within the individual units. Extremely variable leakage can occur between these aquifers (Peter, 1985; Greene, 1993).

Artesian (confined) conditions generally exist within the sedimentary aquifers where an upper confining unit is present. Under artesian conditions, water in a well will rise above the top of the aquifer in which it is completed. Flowing wells will result when drilled in areas where the potentiometric surface is above the land surface. Flowing wells and artesian springs that originate from confined aquifers are common around the periphery of the Black Hills.

Numerous headwater springs from the Paleozoic units on the western side of the study area (fig. 3) provide base flow for many streams. These streams flow across the central core of the Black Hills, and most Black Hills streams lose all or part of their flow as they cross outcrops of the Madison Limestone and Minnelusa Formation (Hortness and Driscoll, 1998). Karst features of the Madison Limestone, including sinkholes, collapse features, solution cavities, and caves are responsible for the Madison aquifer's capacity to accept streamflow recharge. Large streamflow losses also occur in many locations within the outcrop of the Minnelusa Formation (Hortness and Driscoll, 1998). Large artesian springs occur in many locations downgradient from these loss zones, most commonly within or near the outcrop of the Spearfish Formation, providing an important source of base flow in many streams beyond the periphery of the Black Hills (Rahn and Gries, 1973; Miller and Driscoll, 1998).

Although the Precambrian basement rocks generally have low permeability and form the lower confining unit for the series of overlying aquifers, localized aquifers occur in many locations in the central core of the Black Hills, where enhanced secondary permeability has resulted from weathering and fracturing. Where the Precambrian-rock aquifers are saturated, water-table (unconfined) conditions generally occur and land-surface topography can strongly control ground-water flow directions.

Overlying the Precambrian rocks is the Deadwood aquifer, which is contained within the Deadwood Formation and is utilized primarily near its outcrop area. Regionally, the Precambrian rocks act as a lower confining unit to the Deadwood aquifer, and the Whitewood and Winnipeg Formations, where present, act as overlying semiconfining units (Strobel and others, 1999). Where the Whitewood and Winnipeg Formations are absent, the Deadwood aquifer is overlain by the Englewood Formation, which Strobel and others (1999) included as part of the Madison aquifer.

The Madison aquifer generally is considered to consist primarily of the karstic upper part of the Madison Limestone, where numerous fractures and solution openings provide extensive secondary porosity. Strobel and others (1999) included the entire Madison Limestone and the Englewood Formation in their delineation of the Madison aquifer, which receives recharge from streamflow losses and precipitation on its outcrop. In this report, outcrops of the Madison Limestone and Englewood Formation (fig. 3) are referred to as the outcrop of the Madison Limestone for simplicity. Low-permeability layers in the lower part of the Minnelusa Formation generally act as an upper confining unit to the Madison aquifer. However, karst features in the top of the Madison Limestone may contribute to reduced competency of the overlying confining unit in some locations.

The potentiometric surface of the Madison aquifer is shown in figure 7. In many locations, ground-water flow in the Madison aquifer follows the bedding dip, which generally is radially away from the central core of the Black Hills. Ground-water flowpaths and velocities also are heavily influenced by anisotropic and heterogeneous hydraulic properties of the Madison aquifer. Flowpaths are not necessarily orthogonal to potentiometric contours because of highly variable directional transmissivities and may be further influenced by vertical flow components between the Madison and Minnelusa aquifers. Long (2000) described anisotropy in the Madison aquifer in the Rapid City area that causes ground-water flow to be nearly parallel to the potentiometric contours in some cases. Regional ground-water flow from the west may influence the potentiometric surface in the northern and southwestern parts of the study area.

The Minnelusa aquifer is contained within the thin layers of sandstone, dolomite, and anhydrite in the lower portion of the Minnelusa Formation and within

sandstone and anhydrite in the upper portion. Shales in the lower portion of the Minnelusa Formation act as a confining unit to the underlying Madison aquifer; however, the extent of hydraulic separation is spatially variable and is not well defined, as discussed in a subsequent section of this report. The Minnelusa aquifer may have enhanced vertical hydraulic conductivity in areas of collapse breccia (breccia pipes in fig. 5) associated with dissolution of interbedded evaporites (Long and others, 1999). Hayes (1999) concluded that upward leakage of relatively fresh water from the Madison aquifer is a probable agent for dissolution of anhydrite within the Minnelusa Formation, which is a likely mechanism for development of breccia pipes within the Minnelusa Formation. Exposed breccia pipes, which are common in many areas, were hypothesized to be conduits for abandoned springs, which migrate outwards from the flanks of the Black Hills over geologic time, keeping pace with regional erosion.

The Minnelusa aquifer receives recharge from streamflow losses and precipitation on its outcrop. Streamflow losses to the Minnelusa aquifer generally are less than to the Madison aquifer (Carter, Driscoll, and Hamade, 2001) because most of the flow is lost to the Madison aquifer before reaching the outcrop of the Minnelusa Formation. The Minnelusa aquifer is confined by the overlying Opeche Shale.

The potentiometric surface of the Minnelusa aquifer is shown in figure 8. Ground-water flow in the Minnelusa aquifer in the study area generally follows the bedding dip, but may be affected by structural features. Regional ground-water flow from the west may influence the potentiometric surface in the northern and southwestern parts of the study area.

The Minnekahta aquifer, which overlies the Opeche Shale, is contained within the Minnekahta Limestone. The Minnekahta aquifer typically is very permeable, but well yields are limited by the aquifer thickness. The overlying Spearfish Formation acts as a confining unit to the Minnekahta aquifer.

Within the Mesozoic rock interval, the Inyan Kara aquifer is used extensively and various other aquifers are used locally to lesser degrees. The Inyan Kara aquifer receives recharge primarily from precipitation on its outcrop and also may receive recharge from leakage from the underlying Paleozoic aquifers (Swenson, 1968; Gott and others, 1974). As much as 4,000 ft of Cretaceous strata (primarily shales) act as the upper confining unit to aquifers in the Mesozoic rock interval.

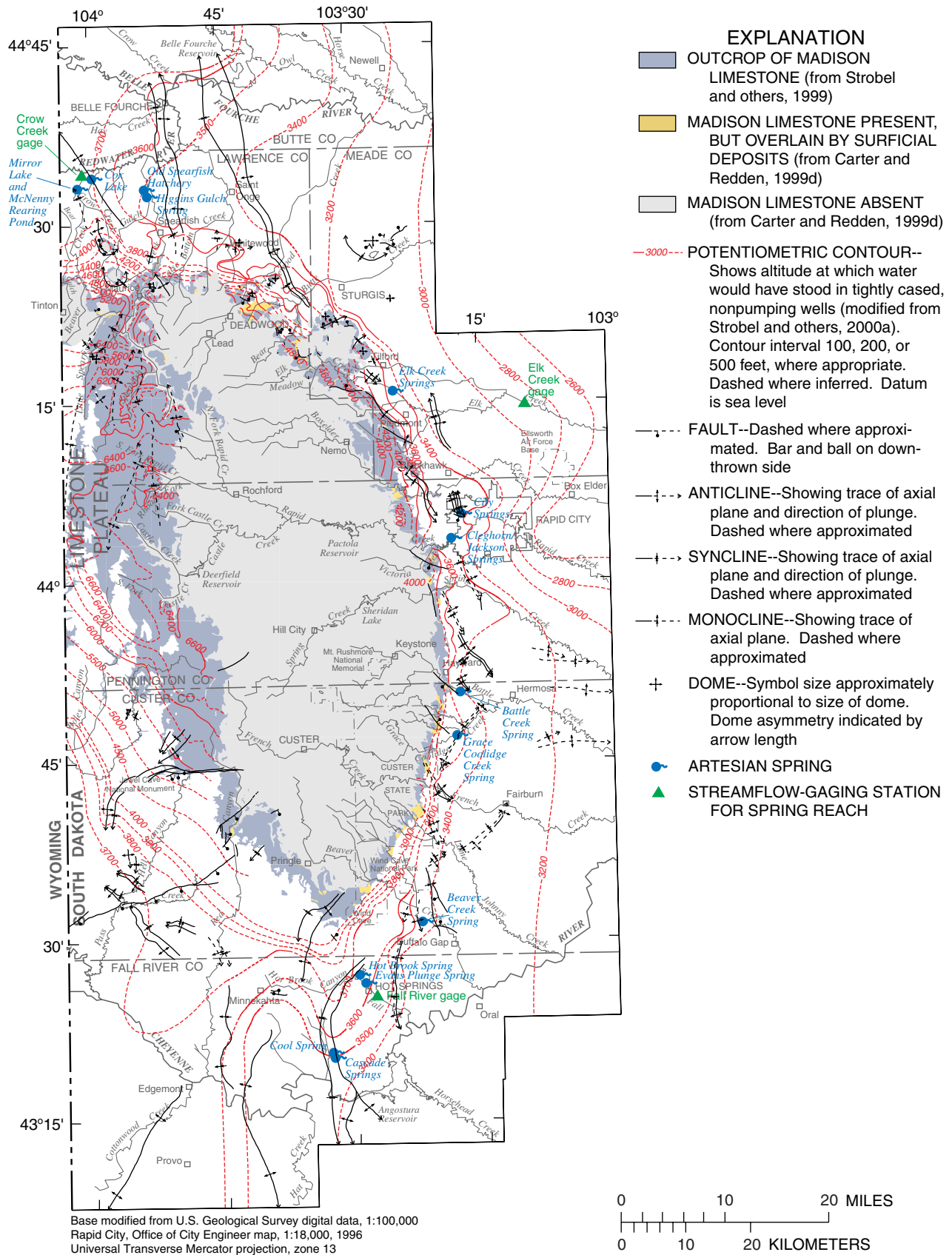


Figure 7. Potentiometric surface of the Madison aquifer and locations of major artesian springs.

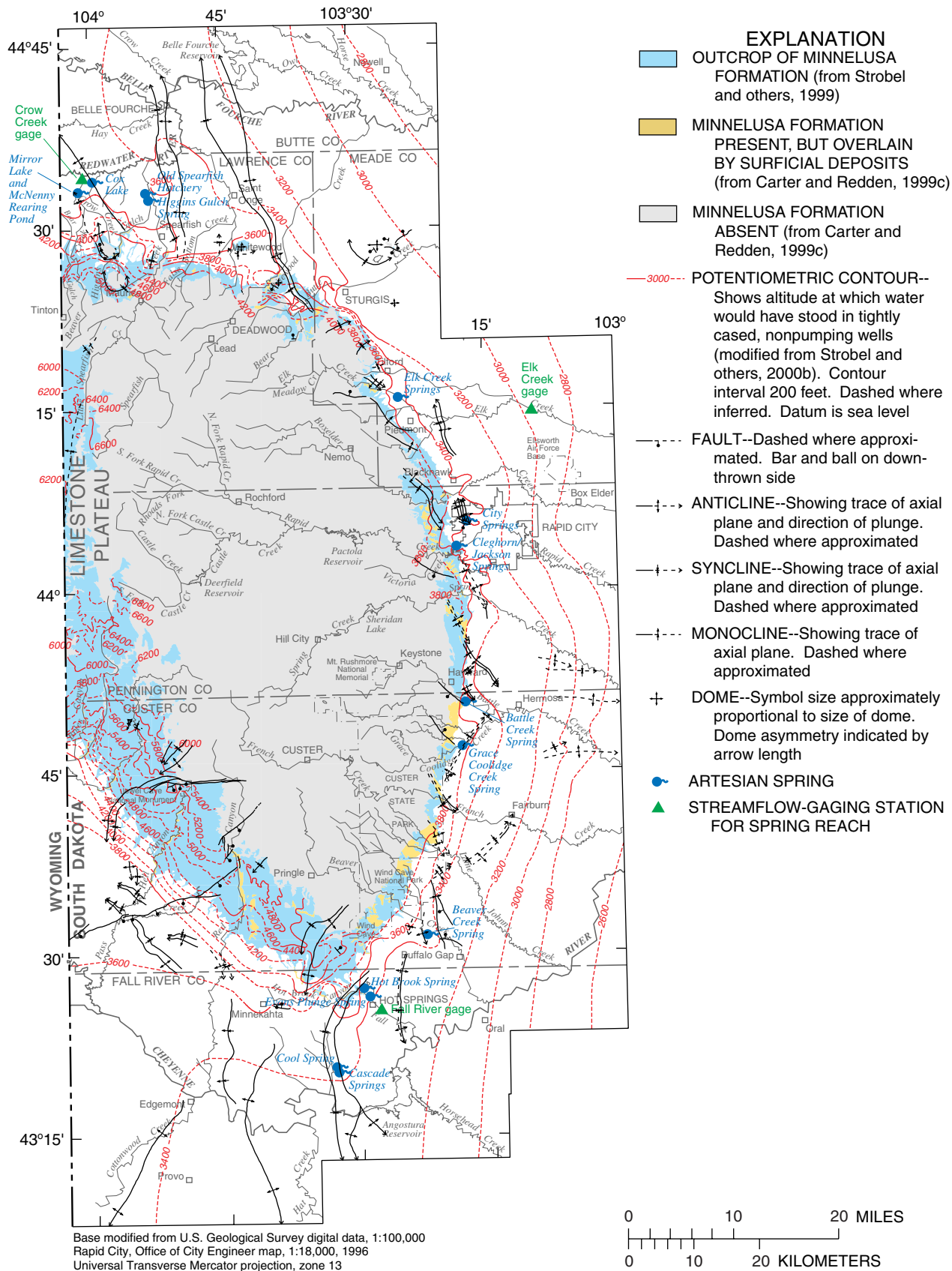


Figure 8. Potentiometric surface of the Minnelusa aquifer and locations of major artesian springs.

METHODS USED AND DATA SETS CONSIDERED

Most of the data used in this study were collected as part of the U.S. Geological Survey Regional Aquifer System Analysis Program (Busby and others, 1983, 1991) or the Black Hills Hydrology Study, using applicable methods and protocols. Data sets considered primarily include samples collected prior to the end of water year 1998, when data collection for the Black Hills Hydrology Study was completed. However, several isotope samples collected during water year 2000 also are considered. Additional chemical data for precipitation in Newcastle, Wyoming, were obtained from the National Atmospheric Deposition Program/National Trends Network (1999).

For geochemical analyses involving major ions, a cation/anion balance within 10 percent was used as a general sample selection criterion. For some selected single constituents, all applicable data were used. For geochemical analyses based on pH or results of speciation calculations, only samples collected specifically for the Black Hills Hydrology Study were used because these samples were collected using a closed-system device, thereby avoiding reaction with the atmosphere during sampling. Field measurement of pH values included temperature compensation to correct for the effect of temperature on electrode response.

For some samples used in speciation calculations, an estimated temperature was calculated from a linear regression of temperature with distance from outcrop area. The geochemical program PHREEQC (Parkhurst and Appelo, 1999) was used for speciation calculations and for conducting forward geochemical modeling to illustrate relations among chemical parameters that would be expected for certain chemical reactions.

Selected site information for all samples considered in this report is presented in table 7 in the Supplemental Information section at the end of this report. The same site numbers are used consistently throughout the report.

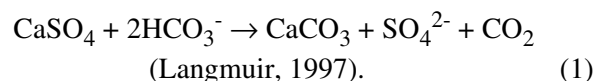
GEOCHEMISTRY OF MADISON AND MINNELUSA AQUIFERS

The major-ion and isotope chemistry of the Madison and Minnelusa aquifers are discussed in the following sections. The discussion of major-ion chemistry includes information regarding distribution of major ions, saturation state, and evolutionary

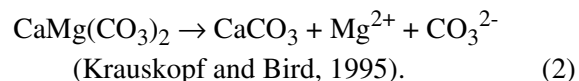
processes. Stable isotopes of oxygen and hydrogen are used to evaluate ground-water recharge areas and flow-paths. Tritium, which is an unstable hydrogen isotope, is used for analysis of ground-water ages.

Major-Ion Chemistry

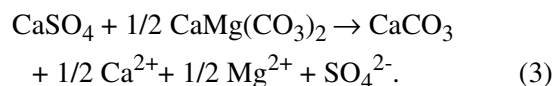
Major reactive minerals in the Madison and Minnelusa aquifers are calcite (CaCO_3), dolomite ($\text{CaMg}(\text{CO}_3)_2$), and anhydrite (CaSO_4). The interactions of these minerals with water and dissolved gases, to a large extent, defines the chemical composition of ground water in the two aquifers. An important consequence of the presence of both calcite and anhydrite in the Madison and Minnelusa aquifers is the potential for precipitation of calcite by the common-ion effect, which can be represented as



In partially dolomitized limestone, dolomite dissolution also can lead to precipitation of calcite:



The term “dedolomite” was originally used to describe the replacement of dolomite by calcite during near-surface chemical weathering (von Morlot, 1847). Strictly speaking, “dedolomitization” describes the formation of the mineral phase dedolomite, which is calcite pseudomorphous after dolomite. In this report, “dedolomitization” is used to describe a combination of the above two reactions (eqs. 1 and 2), in which the irreversible dissolution of anhydrite in waters saturated with calcite and dolomite drives additional dissolution of dolomite and concurrent precipitation of calcite (Back and others, 1983). The dedolomitization reaction can be represented as:



The extent to which dedolomitization occurs in the Madison and Minnelusa aquifers can be illustrated through the major-ion chemistry and saturation indices of the ground water as well as through identification of trends in pH and calcium, magnesium, and sulfate concentrations.

Distribution of Major Ions

The major-ion chemistry of water in the Madison and Minnelusa aquifers can be illustrated with trilinear and Stiff (1951) diagrams, which show spatial variations and possible trends in the major-ion chemistry of the waters. In constructing Stiff diagrams, the average milliequivalent value was used where more than one sample existed for a site. For clarity, not all diagrams were plotted on the maps, but an effort was made to include diagrams representative of the water chemistry in a particular area.

A trilinear diagram showing percentages of major ions in the Madison aquifer is shown in figure 9, and the distribution of major-ion chemistry in the Madison aquifer throughout the study area is shown in figure 10. Figure 9 shows two main types of water in the Madison aquifer: calcium magnesium bicarbonate type and calcium sodium chloride sulfate type. Figure 10 shows that water in the Madison aquifer is dominated by calcium, magnesium, and bicarbonate ions throughout most of the study area. The high concentrations of chloride, sulfate, and sodium in the southwestern part of the study area relative to the rest of the study area probably reflect the presence of more evolved ground water and regional flow, or greater amounts of evaporite minerals available for

dissolution. Ion chemistry is somewhat anomalous for site 188 (Rapid City area), which has high chloride with calcium and magnesium, rather than sodium.

A trilinear diagram showing percentages of major ions in the Minnelusa aquifer is shown in figure 9, and Stiff diagrams representative of the major-ion chemistry in water from Minnelusa wells are shown in figure 11. Figure 9 illustrates three main types of water in the Minnelusa aquifer: calcium magnesium bicarbonate type, calcium magnesium sulfate type, and calcium magnesium bicarbonate sulfate chloride type. Figure 11 shows that water in the Minnelusa aquifer generally evolves downgradient from a calcium magnesium bicarbonate type to a calcium magnesium sulfate type due to dissolution of anhydrite. In the Hot Springs area, ground water in the Minnelusa aquifer is characterized by higher concentrations of sodium and chloride. Because chloride is conservative in water, it can be used to identify leakage between aquifers (Busby and others, 1995). The high chloride concentrations in this area in both the Madison and Minnelusa aquifers could reflect hydraulic connection between the aquifers. The dissolution of evaporite minerals and the presence of more evolved ground water contributed by regional flow also are possible explanations for the occurrence of this water type in the Minnelusa aquifer.

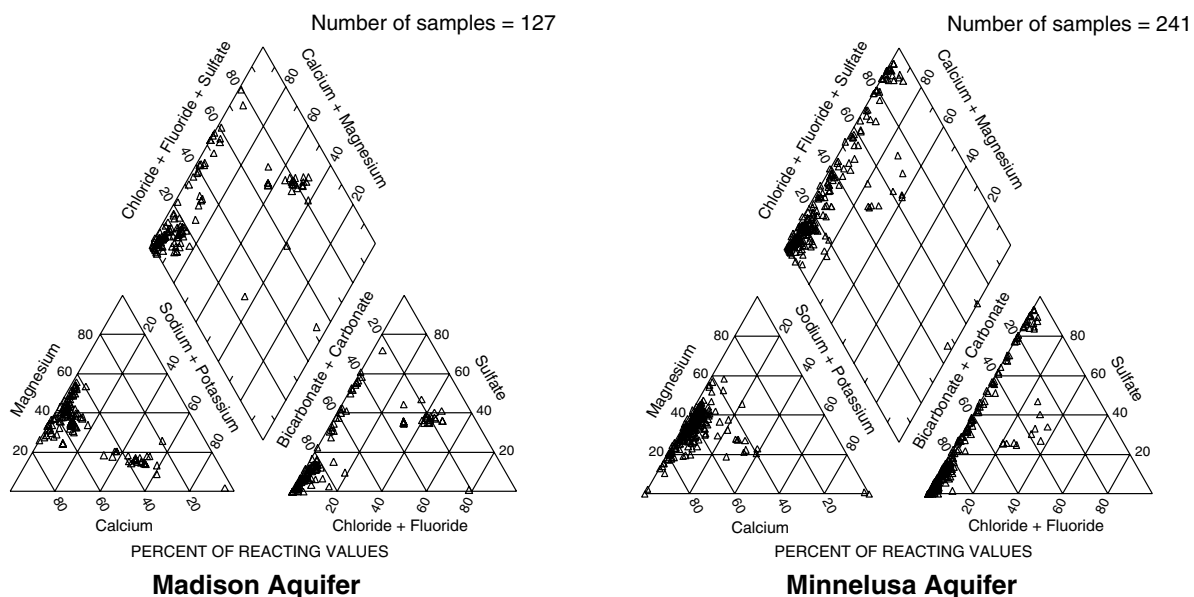


Figure 9. Trilinear diagrams showing proportional concentrations of major ions in the Madison and Minnelusa aquifers.

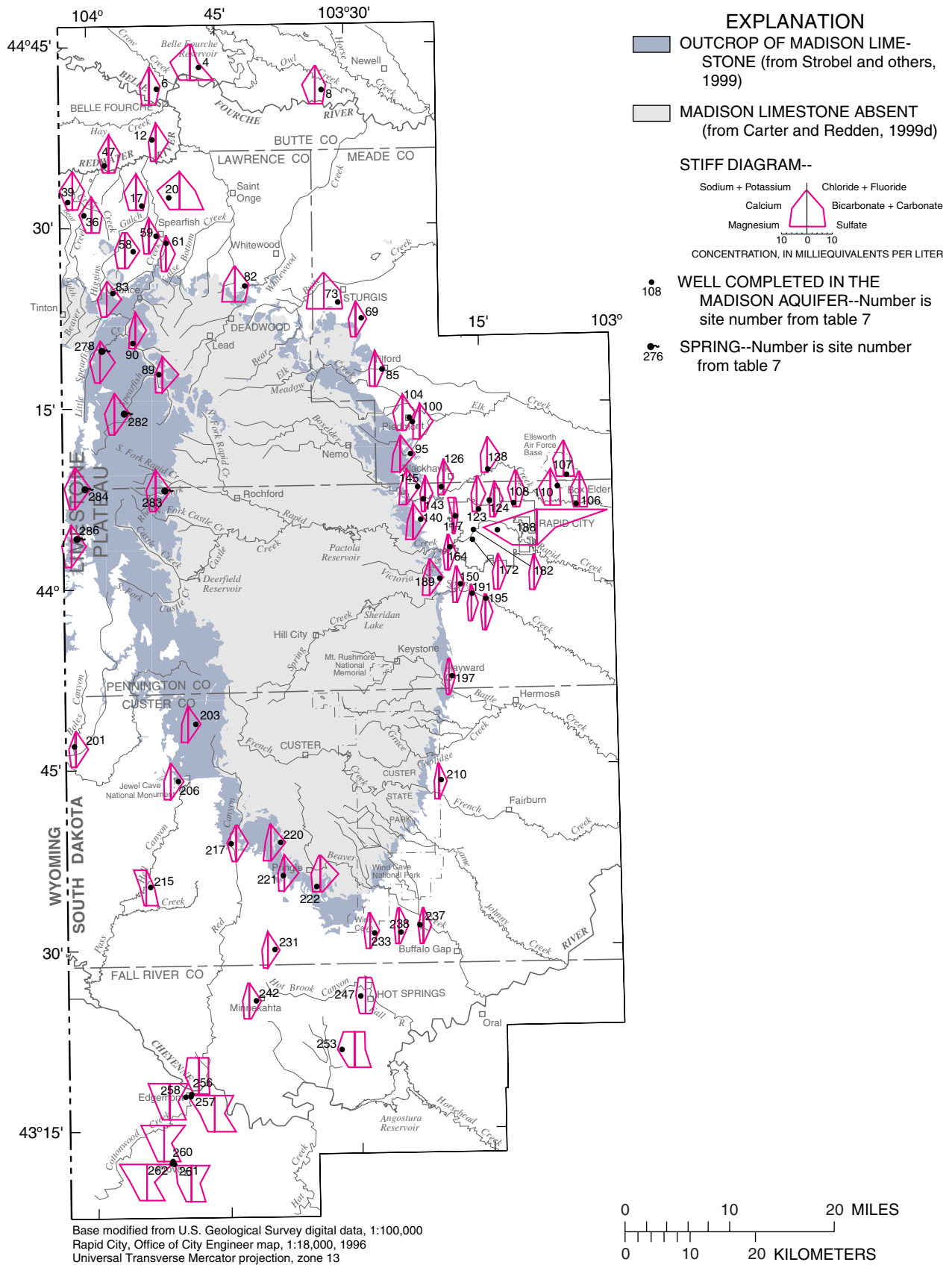


Figure 10. Selected Stiff diagrams showing the distribution of major-ion chemistry in the Madison aquifer.

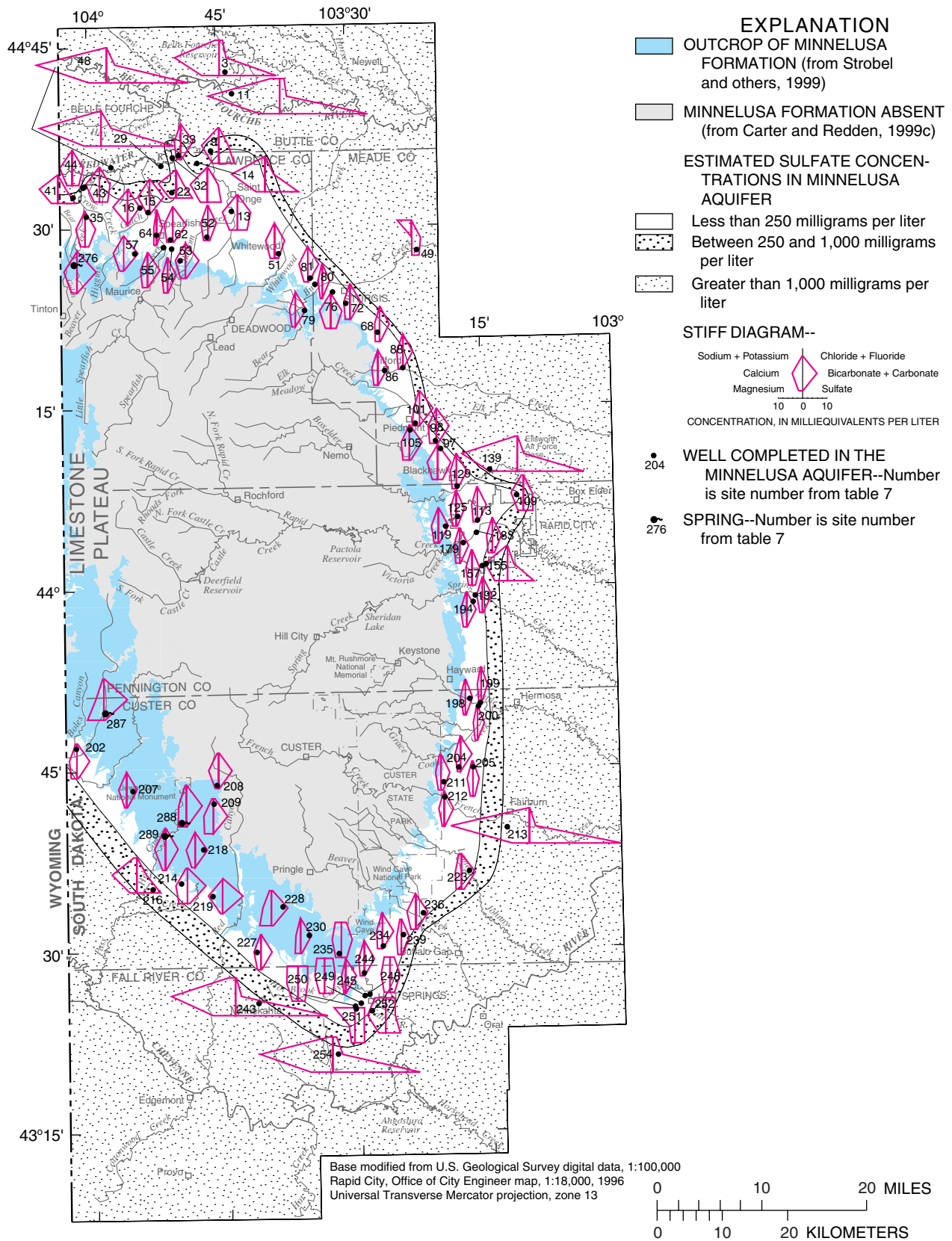


Figure 11. Selected Stiff diagrams showing the distribution of major-ion chemistry in the Minnelusa aquifer. Approximate location of anhydrite dissolution front showing transition between low and high sulfate concentrations also is shown.

Sulfate concentrations in the Madison aquifer generally are low and increase slightly with increasing distance from outcrop areas (fig. 10). In contrast, an extremely sharp gradation in sulfate concentrations occurs in the Minnelusa aquifer, such as near sites 22, 29, 32, and 33 in the northern part of the study area. Sulfate concentrations in the Minnelusa aquifer are dependent on the amount of anhydrite present in the Minnelusa Formation. Thick anhydrite beds were observed in cores from Minnelusa Formation drill holes in the southern Black Hills (Braddock and Bowles, 1963; Brobst and Epstein, 1963). These thick anhydrite deposits are mostly absent in and near outcrops because of earlier removal by dissolution in the subsurface (Epstein, 2000).

Where dissolution of anhydrite currently is taking place (Epstein, 2000), a transition zone from low to high sulfate concentrations is postulated, as shown in figure 11. Sulfate concentrations less than 250 mg/L delineate a zone in which anhydrite probably has been largely removed by dissolution. The zone in which sulfate concentrations are between 250 and 1,000 mg/L marks the position of the "anhydrite dissolution front," an area of active removal of anhydrite by dissolution. Downgradient from the anhydrite dissolution front, sulfate concentrations are greater than 1,000 mg/L, which delineates a zone in which thick anhydrite beds remain in the formation. A similar approach was presented by Klemp (1995), who used specific conductance of ground-water samples from the Minnelusa aquifer to identify a line of dissolution of anhydrite. Brobst and Epstein (1963), Gott and others (1974), Kyllonen and Peter (1987), and Epstein (2000) also presented models of this anhydrite dissolution front, wherein the Minnelusa Formation is thinner near the outcrop area because of removal of the anhydrite and thicker where the anhydrite still remains. Epstein (2000) proposed that sinkholes in overlying formations are caused by collapses in the Minnelusa Formation because of removal of anhydrite, and that the sinkholes mark the zone of active dissolution of anhydrite.

Dissolution of anhydrite cements could increase hydraulic conductivity and secondary porosity in the Minnelusa aquifer; thus, low sulfate concentrations may indicate areas of greater hydraulic conductivity and enhanced secondary porosity where anhydrite has been removed from the aquifer. The anhydrite dissolution front in the northern Black Hills generally is located farther from outcrop areas than in other locations, although basinward deflections of the front also

are apparent in the Rapid City area and along the southeastern flank of the uplift. In some areas, basinward deflections may correspond with structural features where enhanced hydraulic conductivity can occur; however, available data are insufficient for conclusive determinations.

Saturation State

Saturation indices measure departures from thermodynamic equilibrium and can be used to develop hypotheses related to the reactivity of minerals in an aquifer. The saturation index (SI) for a particular mineral generally indicates whether the ground water is undersaturated ($SI < 0$), at equilibrium ($SI = 0$), or supersaturated ($SI > 0$) with respect to that particular mineral. If ground water is undersaturated with respect to a mineral, as indicated by a negative SI, the ground water would theoretically dissolve the mineral if present. Conversely, if ground water is supersaturated with respect to a mineral, then the mineral would theoretically precipitate from the ground water. There is some uncertainty associated with the range in SI values that indicates equilibrium because of uncertainties in field-measured pH, laboratory-analyzed concentrations, and ionic strength and equilibrium constants involved in calculations of SI values (Langmuir, 1997).

The geochemical program PHREEQC (Parkhurst and Appelo, 1999) was used to calculate SI values for 41 samples (35 wells) from the Madison aquifer and 25 samples (24 wells) from the Minnelusa aquifer (table 1). The default thermodynamic database, phreeqc.dat (Parkhurst, 1995), provided the thermodynamic data for calculations. Although anhydrite is more common than gypsum in the Madison and Minnelusa aquifers, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is the more stable phase. Therefore, SI_{gypsum} is used as an indicator for both anhydrite and gypsum throughout the remainder of this report.

Calculated SI values show that water in the Madison aquifer is greatly undersaturated with respect to halite (NaCl) and, to a lesser extent, with respect to gypsum. These minerals should, if present, continue to dissolve in the Madison aquifer. However, ground water in the Madison aquifer remains undersaturated with respect to gypsum even at the highest sulfate concentrations (fig. 12). Figure 13 shows that most waters in the Madison aquifer are in equilibrium with respect to calcite and are slightly undersaturated with respect to dolomite.

Table 1. Saturation indices for selected samples from wells completed in the Madison and Minnelusa aquifers

[SI_{calcite}, calcite saturation index; SI_{dolomite}, dolomite saturation index; SI_{gypsum}, gypsum saturation index; SI_{halite}, halite saturation index; e, estimated; --, no data]

Site number	Station identification number	Temperature (degrees Celsius)	pH (standard units)	SI _{calcite}	SI _{dolomite}	SI _{gypsum}	SI _{halite}
Madison Aquifer							
6	444129103514801	29.4	7.2	0.0	0.0	-1.6	-10.2
36	443100104002001	11.3	7.4	.1	-.3	-1.3	-10.3
58	442802103544601	11.3	7.3	.1	-.1	-1.8	-7.7
59	442919103511601	12.3	7.4	-.1	-.4	-2.3	-9.6
61	442842103505501	7.8	7.6	-.1	-.4	-2.4	-9.4
83	442435103571101	e10.9	7.2	.0	-.4	-3.1	-10.5
85	441759103261202	11.5	7.5	-.1	-.4	-2.1	-10.6
95	441055103230501	13.8	7.4	.1	.2	-3.2	-11.0
100	441337103225002	12.5	7.3	-.1	-.3	-2.7	-10.5
106	440629103040901	47.5	6.9	-.2	-.3	-1.5	-9.9
112	440519103160701	20.6	7.7	.1	.2	-2.8	-10.2
116	440526103173001	13.6	7.7	.0	-.1	-2.7	-9.7
116	440526103173001	13.2	7.6	.0	-.2	-2.6	-9.2
121	440500103193601	13.8	7.6	.0	-.1	-2.5	-9.4
123	440612103152001	15.3	7.5	-.2	-.4	-2.7	-10.1
123	440612103152001	15.2	7.5	-.1	-.3	-2.6	-8.9
124	440655103140501	20.0	7.5	-.1	-.1	-2.7	-9.4
138	440931103141401	20.3	7.3	-.1	.0	-2.7	-10.4
145	440811103222201	16.8	7.3	-.1	-.1	-3.0	-10.2
161	440205103172001	13.7	7.6	-.1	-.5	-2.4	-8.9
164	440308103184601	7.0	7.6	-.2	-.8	-2.3	-9.0
168	440300103173501	e12.7	7.0	-.7	-1.7	-2.4	-9.1
168	440300103173501	18.4	7.7	.1	.0	-2.3	-8.9
169	440220103164001	15.2	7.7	.0	-.2	-2.3	-9.2
169	440220103164001	16.0	7.6	-.1	-.4	-2.4	-9.1
172	440342103160701	16.5	7.6	-.1	-.2	-2.3	-9.1
172	440342103160701	17.8	7.7	.1	.1	-2.0	-9.4
176	440310103173802	14.8	7.7	-.1	-.2	-2.0	-9.2
178	440338103173302	12.0	7.7	.0	-.2	-2.3	-9.3
182	440430103160202	15.5	7.7	.0	.0	-2.5	-9.6
185	440443103161301	16.2	7.7	.1	.0	-2.7	-9.7
186	440446103161701	e16.3	7.4	-.3	-.6	-2.7	-10.2
186	440446103161701	16.4	7.7	.1	.0	-2.7	-10.4
188	440427103131701	26.4	6.1	-.3	-.8	-2.1	-6.9

Table 1. Saturation indices for selected samples from wells completed in the Madison and Minnelusa aquifers—Continued[SI_{calcite}, calcite saturation index; SI_{dolomite}, dolomite saturation index; SI_{gypsum}, gypsum saturation index; SI_{halite}, halite saturation index; e, estimated; --, no data]

Site number	Station identification number	Temperature (degrees Celsius)	pH (standard units)	SI _{calcite}	SI _{dolomite}	SI _{gypsum}	SI _{halite}
Madison Aquifer—Continued							
195	435851103143501	13.3	7.5	-0.3	-0.8	-2.4	-8.7
201	434700104021401	10.1	8.1	.6	1.0	-2.7	-9.8
210	434350103201901	14.5	7.9	.2	.3	-2.4	-9.6
215	433517103534201	14.5	8.3	.6	.6	-1.4	-7.9
238	433115103251401	17.2	7.7	.1	.0	-2.4	-8.6
242	432548103414801	21.0	7.5	.2	.3	-2.0	-8.7
253	432136103321001	21.3	7.3	.2	.0	-1.0	-6.5
Minnelusa Aquifer							
29	443515103513901	13.4	7.3	.4	.3	-.1	-9.8
35	443100104002002	10.4	7.4	.0	-.4	-1.7	-10.6
44	443320104004501	11.5	7.4	.1	-.2	-1.4	-10.3
48	443515103572501	18.3	7.1	.2	-.1	.0	-9.7
65	443100103543001	13.0	8.6	1.3	2.1	-2.5	-10.4
81	442545103343701	12.5	8.6	1.2	2.0	-2.2	-10.3
86	441759103261201	11.2	7.5	-.1	-.4	-2.7	-10.3
113	440528103155201	15.2	7.5	-.1	-.3	-2.4	-10.3
118	440544103180001	10.8	7.9	.2	.1	-2.3	-9.1
119	440516103194001	19.6	7.6	.2	.3	-2.4	-9.2
129	440818103180801	18.5	7.6	.2	.2	-2.5	-10.3
177	440310103173801	12.6	7.8	.1	.0	-2.3	-9.4
179	440338103173301	12.0	7.8	.2	.1	-2.4	-9.8
181	440414103164601	16.1	7.5	.1	.0	-1.6	-9.2
183	440430103160201	11.7	7.7	.0	-.2	-2.6	--
183	440430103160201	14.2	7.7	.1	.1	-2.2	-9.6
187	440452103155301	14.8	7.7	.1	.2	-2.2	--
192	435916103161802	12.4	7.2	-.4	-1.1	-2.5	-9.7
199	435018103155801	12.8	7.7	-.2	-.7	-2.7	-9.6
211	434350103201902	e11.5	7.7	.0	-.3	-2.1	-9.0
216	433517103534202	13.6	7.4	.3	.0	-.7	-8.7
227	433003103420701	13.8	7.5	.1	-.1	-2.5	-9.5
239	433115103251402	14.2	7.8	.1	.0	-2.3	-8.8
243	432548103414802	17.2	7.3	.2	.0	.0	-7.8
254	432127103325601	19.6	7.0	.2	.0	.0	-7.4

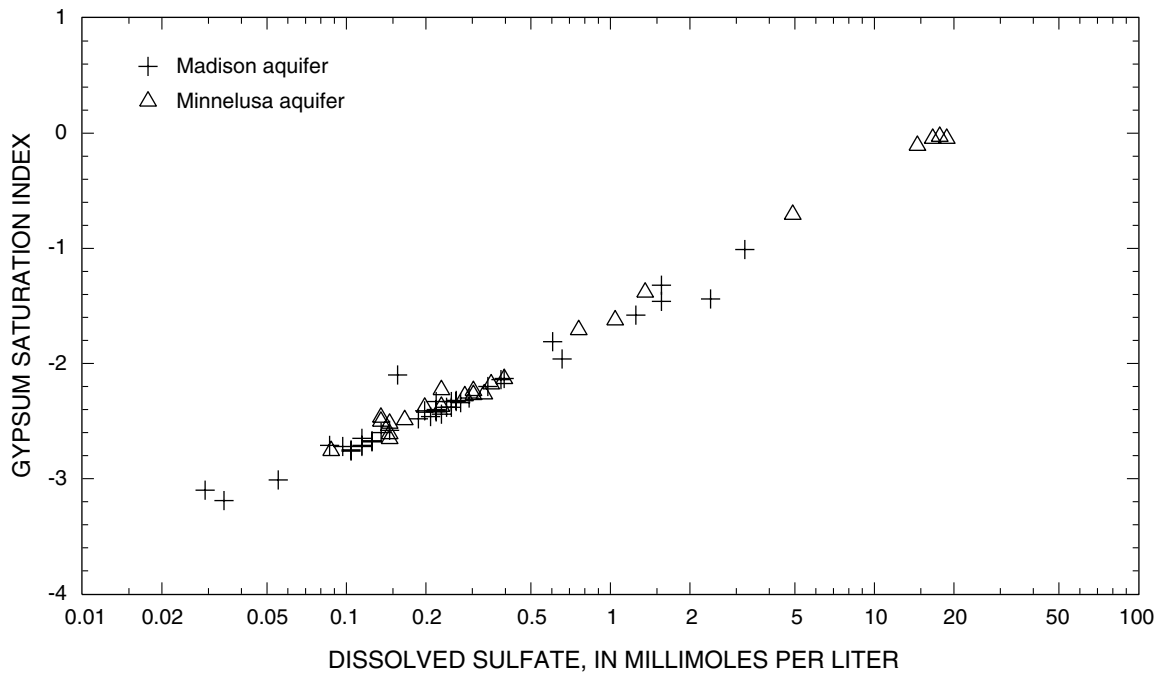


Figure 12. Relation between gypsum saturation index and dissolved sulfate in the Madison and Minnelusa aquifers.

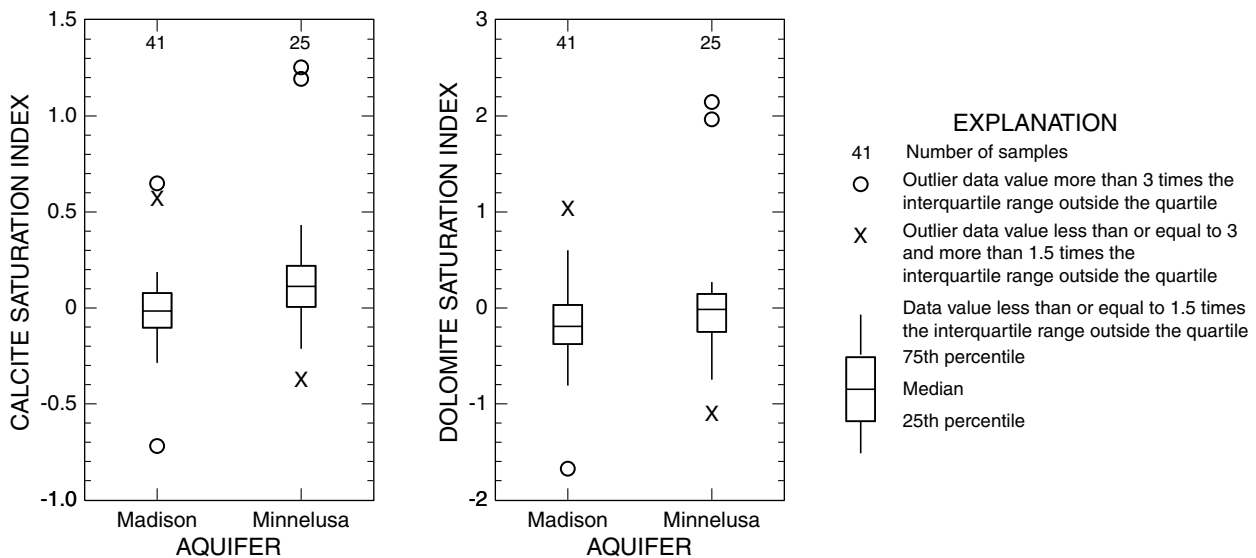


Figure 13. Boxplots showing calcite and dolomite saturation indices for selected samples from the Madison and Minnelusa aquifers.

All samples from the Minnelusa aquifer are undersaturated with respect to halite, and most are undersaturated with respect to gypsum. In some samples, SI values for gypsum approach zero, indicating near equilibrium with respect to gypsum at high sulfate concentrations (fig. 12). Most samples in the Minnelusa aquifer are near equilibrium to slightly supersaturated with respect to calcite and are saturated with respect to dolomite (fig. 13).

For most samples in both the Madison and Minnelusa aquifers, SI values for gypsum, calcite, and dolomite are indicative of the occurrence of dedolomitization. Busby and others (1983) noted that conditions consistent with the dedolomitization process generally include waters that are in equilibrium with respect to calcite, undersaturated but approaching saturation with respect to dolomite, and undersaturated with respect to gypsum. Samples that are undersaturated with respect to gypsum, calcite, or dolomite may be indicative of large hydraulic conductivity, especially in the Madison aquifer, where fast flow velocities and short ground-water residence times in karst conduits may limit the extent of mineral dissolution. Undersaturation with respect to these minerals also could result from the influence of streamflow recharge for samples collected near loss zones in outcrops of the Madison Limestone and Minnelusa Formation. The contribution of calcium from anhydrite dissolution could cause slight supersaturation with respect to calcite or dolomite due to the common-ion effect. Samples with high SI values for calcite and dolomite may reflect errors in pH measurements, which are not uncommon primarily because of instrumentation problems. All of the positive outlier values in figure 13 are associated with pH values greater than 8 (table 1), which may be of questionable validity.

The saturation state with respect to gypsum of water in the Madison and Minnelusa aquifers may provide insight into mechanisms controlling hydraulic connection between the aquifers. Because water in the Madison aquifer remains undersaturated with respect to gypsum even at the highest sulfate concentrations (fig. 12), upward leakage could drive increased dissolution of anhydrite in the Minnelusa Formation, especially where Minnelusa aquifer water is nearly saturated with respect to gypsum.

Evolutionary Processes

As shown in figures 10 and 11, dissolved sulfate concentrations generally increase with distance from

outcrops in the Madison and Minnelusa aquifers, indicating that sulfate can be used as a measure of the reaction progress. Variations in pH and concentrations of calcium and magnesium as a function of dissolved sulfate can be used to evaluate chemical processes occurring in the aquifers.

Forward geochemical modeling was used in this study to illustrate trends in pH and calcium and magnesium concentrations with increasing dissolution of anhydrite. It is assumed in the modeling that the aquifer contains calcite, dolomite, and anhydrite and is recharged by rainwater. Hypothetical recharge water was created by defining water with a temperature of 15°C and a pH of 5.4, which was the average pH of rainwater at Newcastle, Wyoming, from August 1981 through December 1998 (National Atmospheric Deposition Program/National Trends Network, 1999). The recharge water was allowed to equilibrate with calcite and dolomite at a P_{CO_2} of 10^{-2} bar, typical of values in the soil zone (Freeze and Cherry, 1979). Conceptually, the recharge water then moved into a saturated zone containing calcite, dolomite, and anhydrite. The saturation index of dolomite was fixed at -0.2 to represent slight undersaturation with respect to dolomite, and the saturation index of calcite was fixed at 0 to represent equilibrium conditions. These values are consistent with the dedolomitization process and reflect median SI values in the Madison aquifer (fig. 13). Dissolution of anhydrite occurred incrementally and was limited not to exceed gypsum equilibrium. Reactions were carried out at a constant temperature of 15°C, which is representative of average temperatures in the Madison and Minnelusa aquifers in the study area (table 1).

For the simulated reactions occurring in the saturated zone, changes in modeled pH values and concentrations of calcium and magnesium, relative to increasing sulfate concentrations, are summarized in table 2 and figure 14. Table 2 shows the pH; molality of calcium ($m\text{Ca}$), magnesium ($m\text{Mg}$), and sulfate ($m\text{SO}_4$) in solution; number of moles of anhydrite ($\Delta m_{\text{anhydrite}}$), calcite ($\Delta m_{\text{calcite}}$), and dolomite ($\Delta m_{\text{dolomite}}$) dissolved or precipitated (negative values indicate precipitation); and saturation index for gypsum ($\text{SI}_{\text{gypsum}}$) for each reaction step. Figure 14 shows how the modeled pH, calcium molality, and magnesium molality change with reaction progress. Calcite precipitated while dolomite dissolved, pH decreased, and concentrations of dissolved magnesium and sulfate increased during reaction with anhydrite. In the ninth model reaction step, the solution reached saturation with respect to gypsum.

Table 2. Selected results of geochemical modeling

[°C, degrees Celsius; mCa , calcium molality; mMg , magnesium molality; mSO_4 , sulfate molality; $\Delta m_{anhydrite}$, number of moles of anhydrite dissolved or precipitated (negative values indicate precipitation); $\Delta m_{calcite}$, number of moles of calcite dissolved or precipitated (negative values indicate precipitation); $\Delta m_{dolomite}$, number of moles of dolomite dissolved or precipitated (negative values indicate precipitation); SI_{gypsum} , gypsum saturation index]

Temperature (°C)	pH (standard units)	mCa	mMg	mSO_4	$\Delta m_{anhydrite}$	$\Delta m_{calcite}$	$\Delta m_{dolomite}$	SI_{gypsum}
15	7.20	0.0029	0.0019	0.0025	0.0025	-0.0010	0.0006	-1.1316
15	7.11	.0044	.0028	.0050	.0050	-.0030	.0015	-.7708
15	7.05	.0059	.0038	.0075	.0075	-.0050	.0025	-.5555
15	7.01	.0074	.0047	.0100	.0100	-.0070	.0034	-.4020
15	6.98	.0089	.0057	.0125	.0125	-.0090	.0044	-.2830
15	6.95	.0104	.0066	.0150	.0150	-.0110	.0053	-.1859
15	6.92	.0119	.0076	.0175	.0175	-.0130	.0063	-.1041
15	6.90	.0135	.0085	.0200	.0200	-.0150	.0073	-.0334
15	6.89	.0143	.0090	.0213	.0225	-.0160	.0078	.0000
15	6.89	.0143	.0090	.0213	.0250	-.0160	.0078	.0000

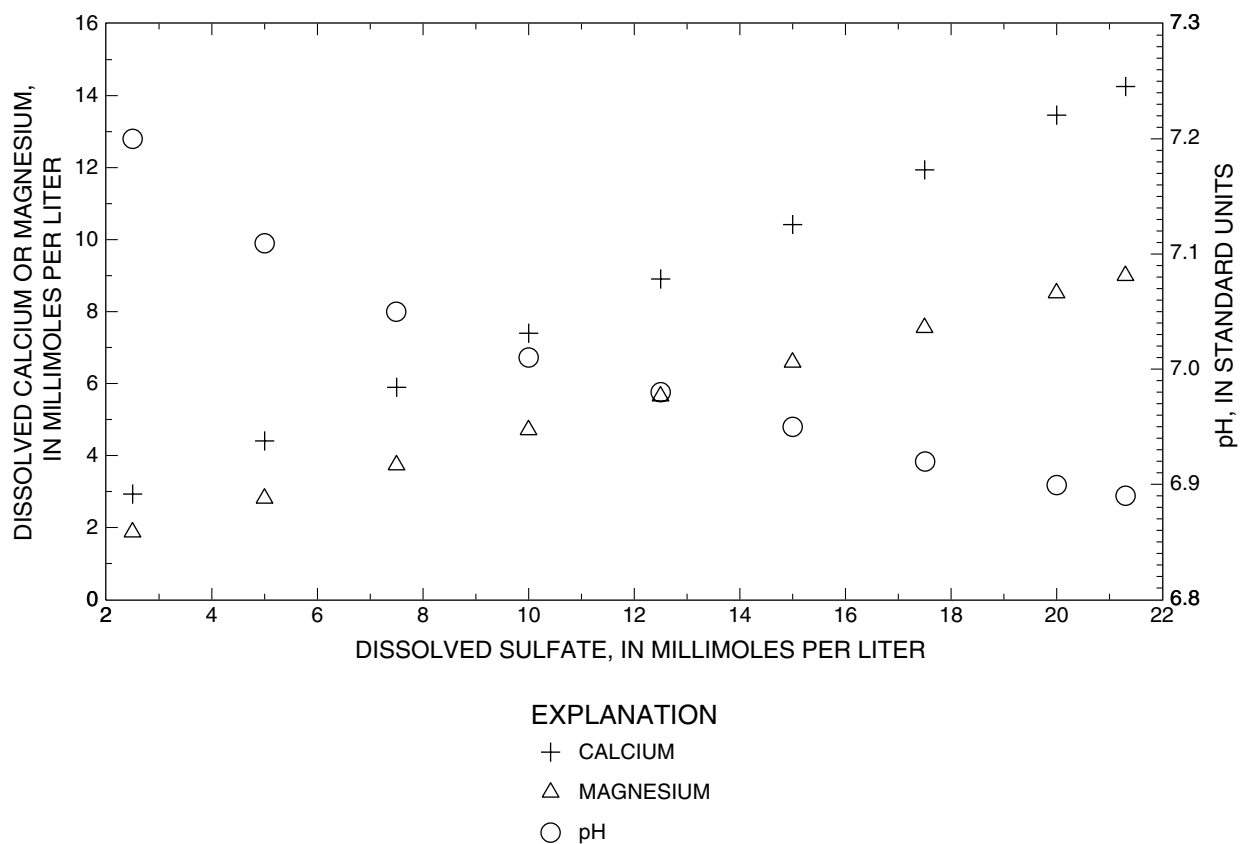


Figure 14. Modeled relations between calcium and magnesium concentrations, pH, and dissolved sulfate.

The forward modeling results indicate that the incongruent dissolution of dolomite occurring in conjunction with anhydrite dissolution should result in increases in calcium and magnesium concentrations and a decrease in pH. Figure 15 shows the relation between dissolved calcium and magnesium concentrations and dissolved sulfate in the Madison and Minnelusa aquifers. To show only data reflecting significant reaction progress, only samples with sulfate concentrations greater than 1 millimole per liter are included. The variations of dissolved calcium and magnesium concentrations with dissolved sulfate shown in figure 15 for the Madison and Minnelusa aquifers are similar to those resulting from the geochemical modeling shown in figure 14 in that both calcium and magnesium concentrations increase with increasing sulfate concentrations, with calcium increasing at a greater rate. However, the modeled calcium/magnesium ratio is lower than observed in the Madison and Minnelusa aquifers. The relative rates of increase of calcium and magnesium concentrations are affected by the equilibrium constants (K) as well as temperature. Comparison of actual calcium and magnesium concentrations to model results indicates that if dedolomitization is occurring in both the Madison and Minnelusa aquifers, conditions in the aquifers (temperature, K_{dolomite}) are similar but not identical to those that were modeled.

Figure 16 shows the relation between pH and dissolved sulfate in the Madison and Minnelusa aquifers. In the Minnelusa aquifer, pH generally is lower at high sulfate concentrations, which supports the occurrence of dedolomitization. In the Madison aquifer, the data are consistent with dedolomitization, but pH trends are limited by the extent of anhydrite dissolution.

Other processes that could cause a decrease in pH along a flowpath include nitrate reduction, denitrification, and sulfate reduction. These reactions become important in environments in which the oxygen introduced by ground-water recharge has been depleted (Langmuir, 1997). Oxygen is supplied to ground water by the movement of air through unsaturated material above the water table as well as by recharge (Hem, 1992). This oxygen is consumed by reaction with organic materials and reduced inorganic minerals such as pyrite and siderite. Well-oxygenated ground water may persist for long distances along a flowpath if little reactive material is available. In both the Madison and Minnelusa aquifers, most samples have dissolved oxygen concentrations greater than 2 mg/L (fig. 17), which indicates that the aquifers are

well oxygenated, even at considerable distances from the outcrops. Much of the recharge to the aquifers is from streamflow losses or through outcrop areas with limited soil development. Thus, recharge has limited interaction with organic materials in the soil horizon and consumption of oxygen is incomplete. Reduction of sulfate, nitrate, and ferric iron minerals, methane fermentation, and anaerobic decay of organic matter, therefore, are not likely in the Madison and Minnelusa aquifers in the study area.

Isotope Chemistry

This section presents information regarding the isotope chemistry of the Madison and Minnelusa aquifers in the Black Hills area. Stable isotopes of oxygen (^{18}O and ^{16}O) and hydrogen (^2H , deuterium; and ^1H) are used to evaluate ground-water flowpaths, recharge areas, and mixing conditions. The radioisotope tritium (^3H) provides additional information for evaluation of mixing conditions and ground-water ages.

Isotope data for selected sampling sites are presented in tables 7 and 8 in the Supplemental Information section. The majority of sampling sites are ground-water sites, including wells (or caves) and springs. Spring samples are categorized as either headwater springs (generally located upgradient of streamflow loss zones) or downgradient springs (within or downgradient of loss zones). Two of the downgradient springs (sites 291 and 299) are perched springs that are located along stream channels where streamflow losses occur. The remainder of the downgradient springs are located downgradient of loss zones and are presumed to be artesian springs. Data also are included for 14 surface-water sites, all of which are located immediately upgradient from loss zones where recharge occurs to the Madison or Minnelusa aquifers. Data for three meteorological sites also are provided.

Background Information and Isotopic Composition of Recharge Water

This section provides background information regarding stable isotopes and tritium. Because of spatial variations in isotopic signatures for precipitation in the Black Hills area, stable isotopes can be used for identification of potential recharge areas and evaluation of ground-water flowpaths. Tritium is useful for evaluation of ground-water ages because large temporal variations of concentrations in precipitation have resulted from atmospheric testing of thermonuclear bombs during the 1950's and 1960's.

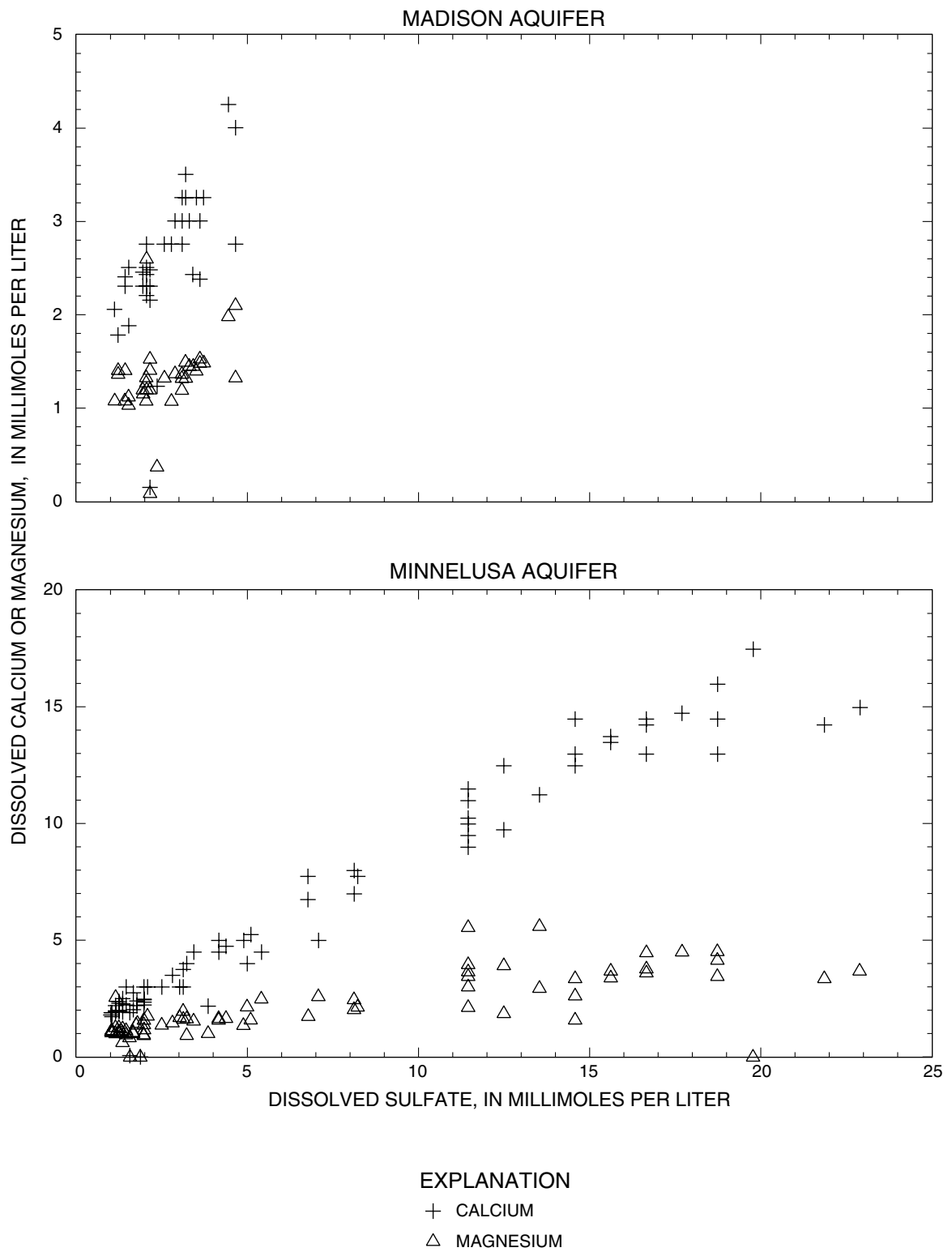


Figure 15. Relations between dissolved calcium and magnesium concentrations and dissolved sulfate in the Madison and Minnelusa aquifers.

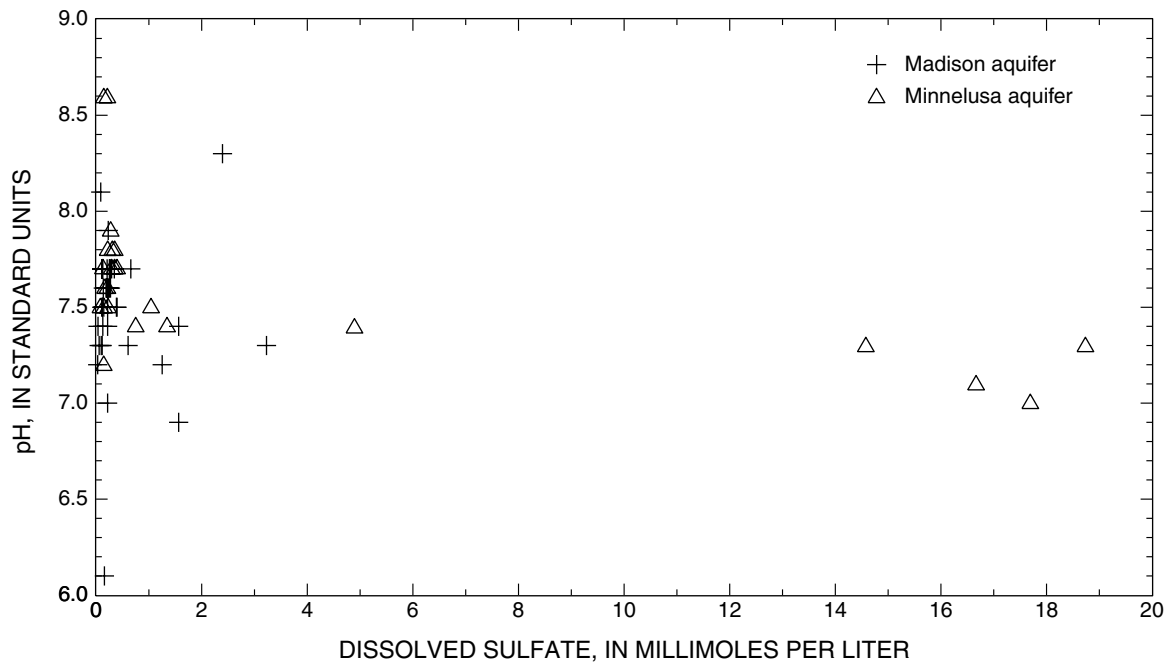


Figure 16. Relation between pH and dissolved sulfate in the Madison and Minnelusa aquifers.

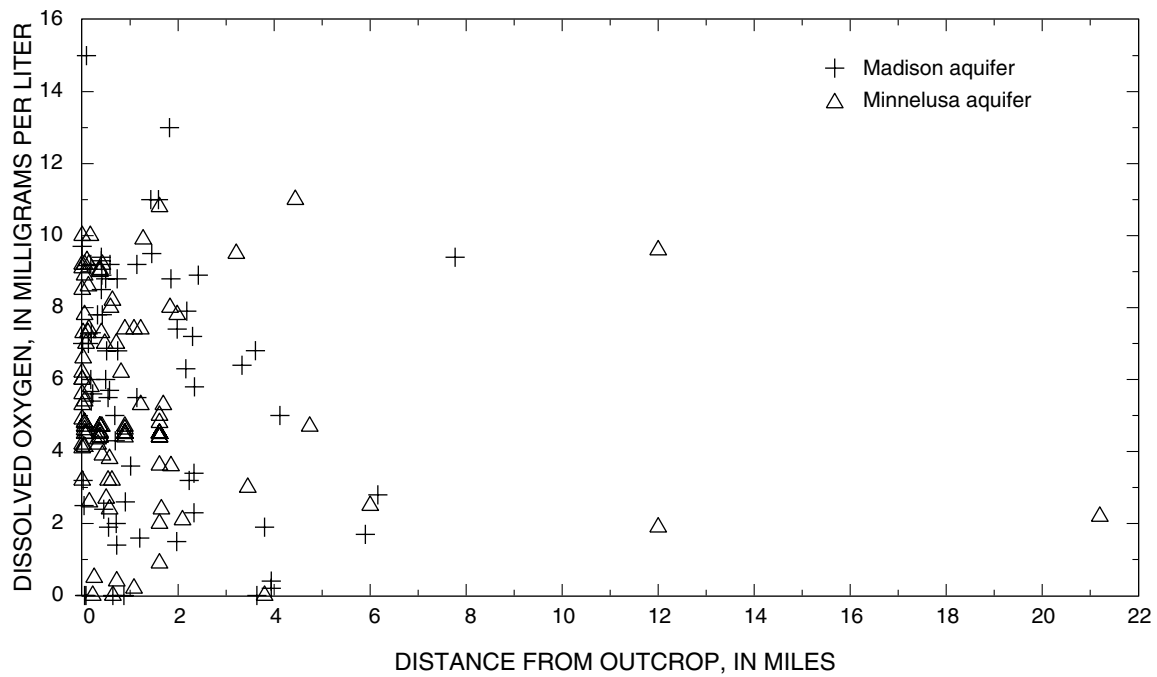


Figure 17. Relation between dissolved oxygen and distance from outcrop in the Madison and Minnelusa aquifers.

Stable Isotopes of Oxygen and Hydrogen

Stable isotopes, unlike radioisotopes, do not decay by any known mechanisms. Stable isotopes of oxygen are ideal indicators of ground-water flowpaths because the ratios of these isotopes in water are affected by meteorological processes but generally not by interactions between minerals and ground water at temperatures less than about 100°C.

Stable isotope values are given in “delta notation,” which compares the ratio between heavy and light isotopes of a sample to that of a reference standard. Delta values are expressed as a difference, in parts per thousand, or per mil (‰), from value reference standard. For example, the oxygen isotope ratio of a sample written in delta notation is:

$$\delta^{18}\text{O}_{\text{sample}} = \frac{{}^{18}\text{O}/{}^{16}\text{O}_{\text{sample}} - {}^{18}\text{O}/{}^{16}\text{O}_{\text{standard}}}{{}^{18}\text{O}/{}^{16}\text{O}_{\text{standard}}} \times 1,000 \text{ ‰ VSMOW.}$$

A sample with a δ value of -20 ‰ is depleted by 20 parts per thousand (2 percent) in the heavier isotope of the element relative to the standard. In this report, $\delta^{18}\text{O}$ ($^{18}\text{O}/^{16}\text{O}$) and δD (deuterium/hydrogen) values are reported in per mil relative to Vienna Standard Mean Ocean Water (VSMOW) and are described as lighter and heavier in relation to each other. The lighter values are more negative relative to the heavier values, which are less negative.

Distinct isotopic signatures can result from isotope fractionation, which occurs during “rainout,” a term used to describe the loss of water vapor from a cooling air mass as it passes from its oceanic source over continents (fig. 18). As air masses rise to higher elevations, lower temperatures and the subsequent formation of precipitation cause fractionation to occur within the cloud, and ^{18}O and D are partitioned preferentially into the rain or snow. The heavy isotopes thus are distilled from the vapor, which is progressively depleted in ^{18}O and D (Clark and Fritz, 1997).

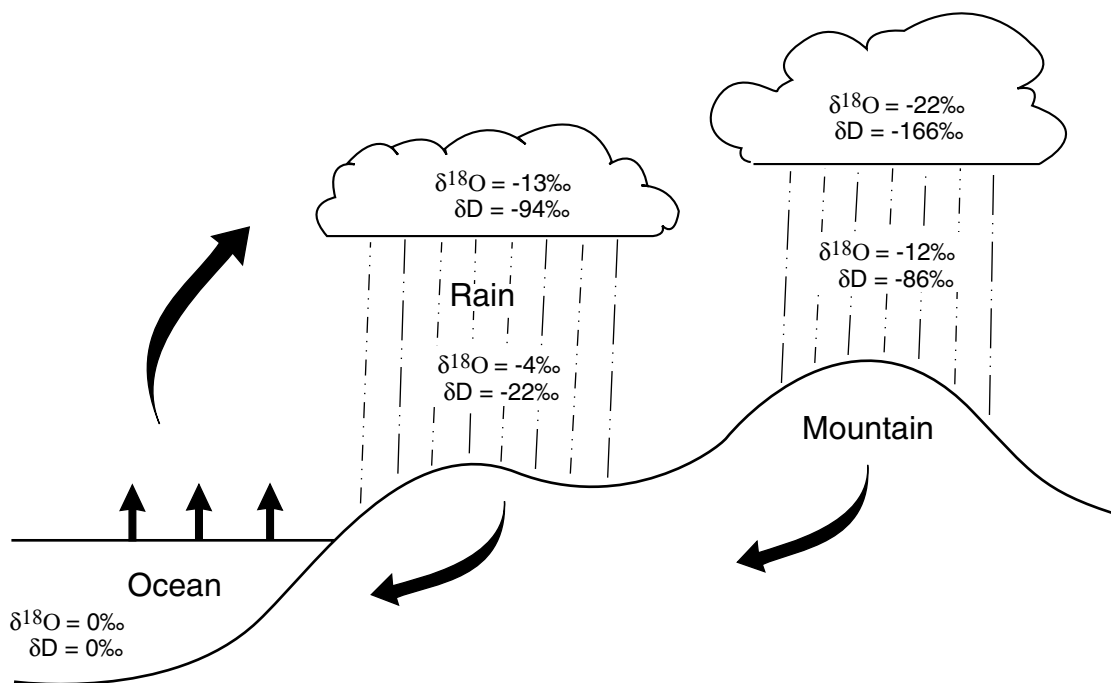


Figure 18. Schematic showing fractionation of stable oxygen and hydrogen isotopes during rainout. Stable isotope values, which compare isotopic ratios relative to ocean water, are expressed in per mil (‰).

Data for Black Hills sites include both $\delta^{18}\text{O}$ and δD values (table 7). For sites with more than one set of $\delta^{18}\text{O}$ and δD values, a mean value is listed in table 7, and individual values are listed in table 8. A linear relation exists between $\delta^{18}\text{O}$ and δD (fig. 19); thus, subsequent discussions and illustrations generally refer only to $\delta^{18}\text{O}$ for simplicity. Most samples for the Black Hills area fall along or slightly below Craig's (1961) global meteoric water line.

Precipitation in the northern Black Hills generally is isotopically lighter than in the south because of relatively high elevations and the influence of Pacific storms that are isotopically depleted due to rainout in crossing the Rocky Mountains. The generally lower elevations in the southern Black Hills, combined with warm, moist weather patterns from the south, result in

precipitation that is isotopically heavier than in the north (Back and others, 1983; Busby and others, 1983; Greene, 1997). The resulting distribution of isotopes in near-recharge areas of the Black Hills serves as a natural tracer for ground-water flowpaths. A generalized distribution of $\delta^{18}\text{O}$ values in near-recharge areas of the study area is presented in figure 20, which is derived using samples from headwater springs with localized recharge areas, selected (Minnekahta) wells and caves in outcrop areas, and streams upstream from loss zones. The approximate centroids of drainage basins were used to represent stream sampling locations for contouring purposes; thus, gaging stations shown in figure 20 do not necessarily fall within the respective contours.

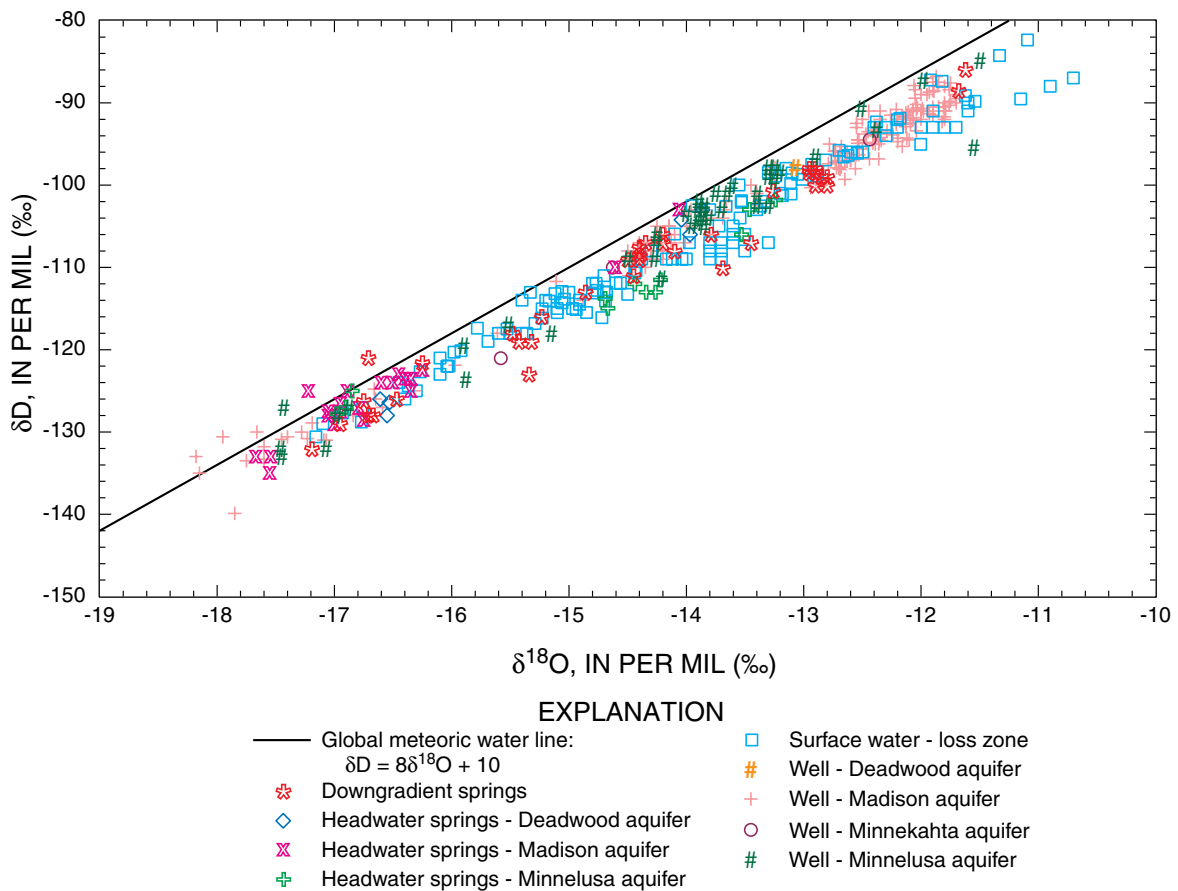


Figure 19. Relation between $\delta^{18}\text{O}$ and δD in Black Hills samples in comparison to the global meteoric water line (Craig, 1961).

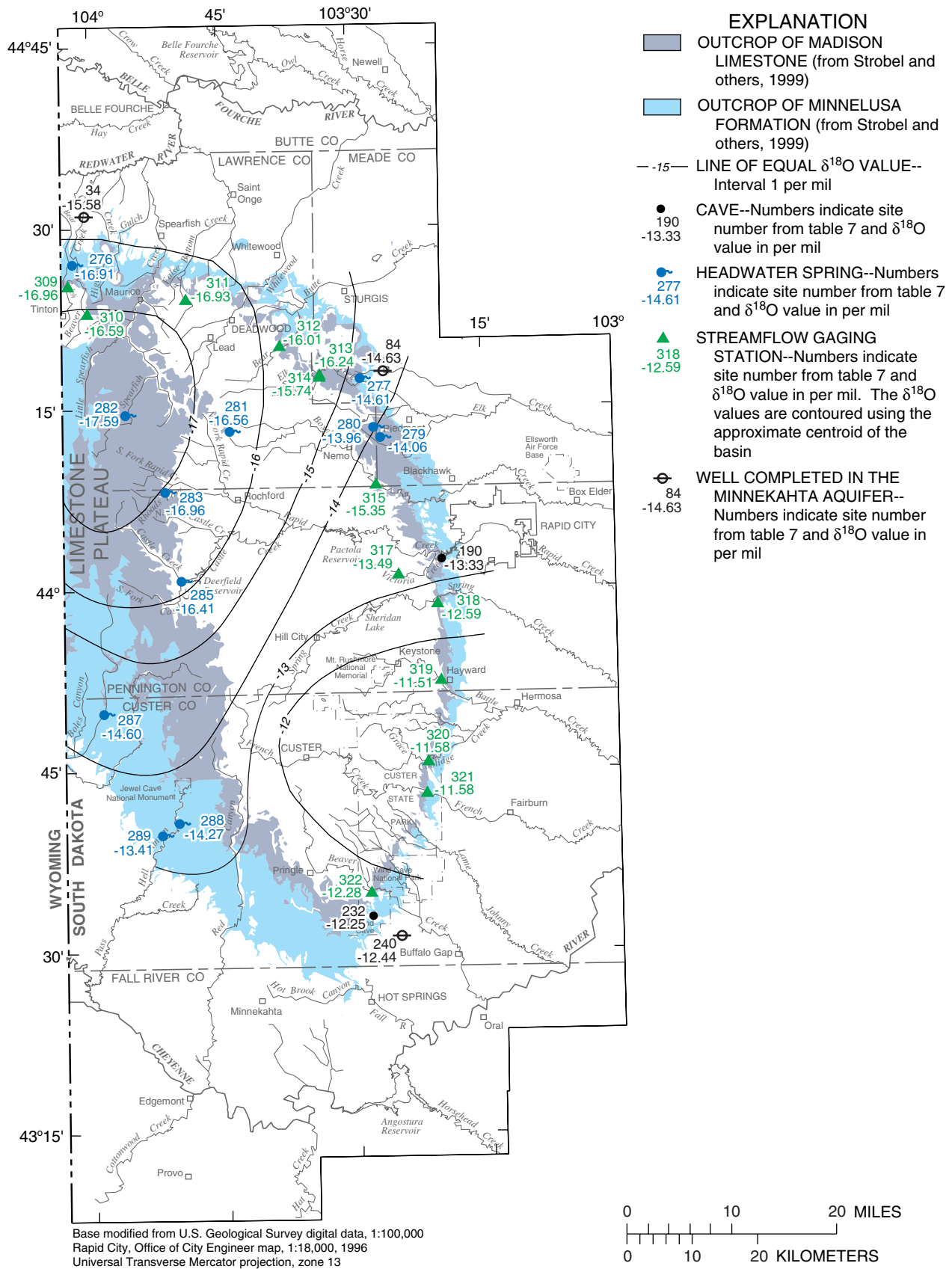


Figure 20. Generalized distribution of $\delta^{18}\text{O}$ in surface water and ground water in near-recharge areas.

Many of the data points used to develop figure 20 are ground-water samples, which generally have small temporal variability in $\delta^{18}\text{O}$ values relative to surface-water samples. A perspective on temporal variability in precipitation is presented in figure 21A, which shows $\delta^{18}\text{O}$ values for selected loss-zone streams and headwater springs. Some temporal variability in loss-zone streams (Spring Creek, Rapid Creek, and Boxelder Creek) is due to seasonal variability in isotopic composition of precipitation. Data sets for Rhoads Fork and Castle Creek are somewhat limited, but indicate less variability because of mixing associated with ground-water storage. Thus, for the wells and headwater springs shown in figure 20, variability in $\delta^{18}\text{O}$ is assumed to be small and values are considered representative of average isotopic composition in near-recharge areas.

Temporal variability of $\delta^{18}\text{O}$ is shown in figures 21B and 21C for selected wells and down-gradient springs for which time-series data are available. Temporal variability for these sites is magnified somewhat by use of different Y-axis scales, but is much smaller than for the surface-water samples (fig. 21A). Temporal variability for some sites is influenced by ground-water mixing conditions, as discussed in subsequent sections.

Tritium

Tritium (^3H), which beta-decays to ^3He with a half-life of 12.43 years (Clark and Fritz, 1997), is produced naturally in small concentrations by cosmic radiation in the stratosphere. Naturally occurring background concentrations of tritium in continental precipitation are estimated to range from 1 to 20 TU (tritium units), depending on location (Michel, 1989). One TU is defined as one ^3H atom per 10^{18} atoms of hydrogen, which is equivalent to 3.19 pCi/L (picocuries per liter) in water (International Atomic Energy Agency, 1981). Because of nuclear testing during the 1950's and 1960's and a subsequent treaty limiting such tests, tritium concentrations in atmospheric water increased sharply in 1953, peaked in 1963, and then declined. Current sources of tritium, such as nuclear power production, contribute to atmospheric tritium concentrations that are slightly higher than background concentrations prior to nuclear testing.

Tritium concentrations in precipitation have been collected at numerous locations around the world (International Atomic Energy Agency, 1999). Locations of collection sites in and near the United States that are considered for this report are shown in figure 22, which shows estimated cumulative deposition of tritium (weighted average concentration multiplied by precipitation depth) for 1953-83 (Michel, 1989). Tritium concentrations are low in oceans; thus, concentrations in precipitation generally are low in coastal areas but tend to increase in inland areas because of increasing stratospheric influence.

Monthly tritium concentrations in precipitation are shown in figure 23 for Ottawa, Canada, which has the longest available period of record. Three precipitation samples collected in the Black Hills area during the late 1990's (table 7) also are shown. Figure 23 shows that in addition to the long-term trends, there is considerable seasonal variability in tritium concentrations, with highest concentrations generally in the spring.

Tritium concentrations in ground water can be related through a first-order decay equation to estimated concentrations at the time of recharge. Because recharge to the Madison and Minnelusa aquifers occurs from infiltration of precipitation on outcrops and from streamflow losses, tritium input from both sources must be considered.

A combination of methods has been used to estimate annual tritium concentrations for precipitation recharge for the Black Hills area. Annual estimates are presented in table 9 in the Supplemental Information section and are shown by dashed lines in figure 24, which also shows the three actual samples for the Black Hills area.

Estimates of tritium concentrations from Michel (1989) for 2- by 5-degree blocks were used for the period 1953-83. These estimates are based on interpolations between stations with relatively long periods of record. Michel (1989) extended station records, for periods prior to initiation of data collection, using regression coefficients developed by the International Atomic Energy Agency (1981) for correlations with long-term records for Ottawa, Canada.

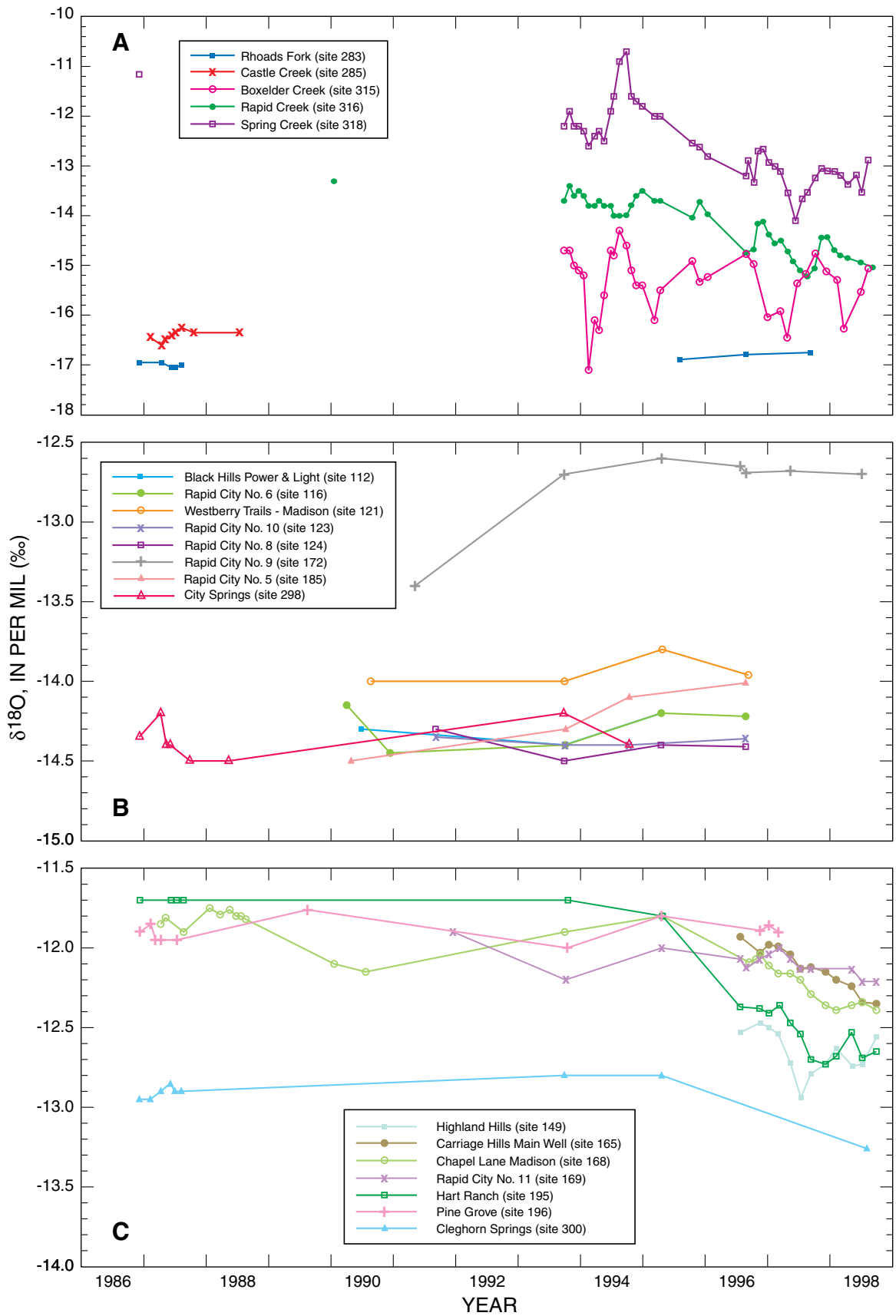


Figure 21. Temporal variation of $\delta^{18}\text{O}$ for selected sites. Graph A shows selected loss-zone streams and headwater springs. Graphs B and C show selected wells and artesian springs.

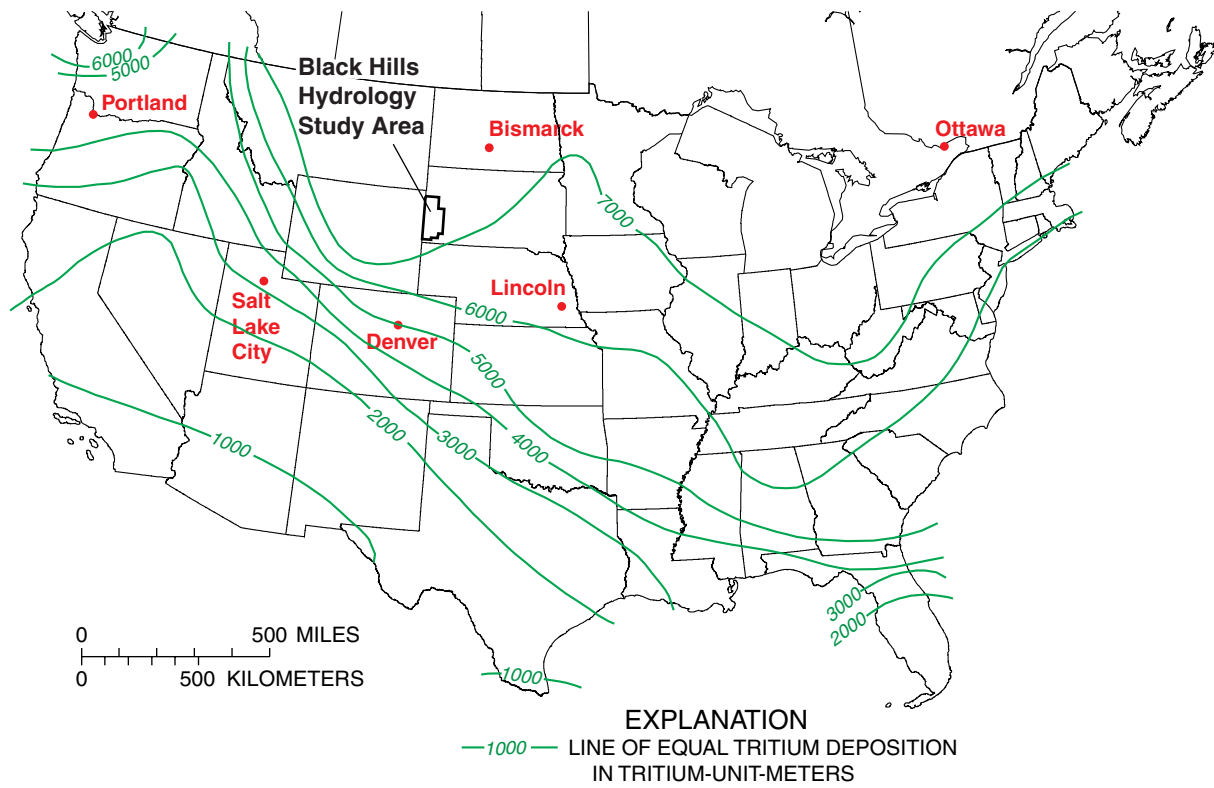


Figure 22. Cumulative tritium deposition on the continental United States, 1953-83, and location of selected collection sites (modified from Michel, 1989).

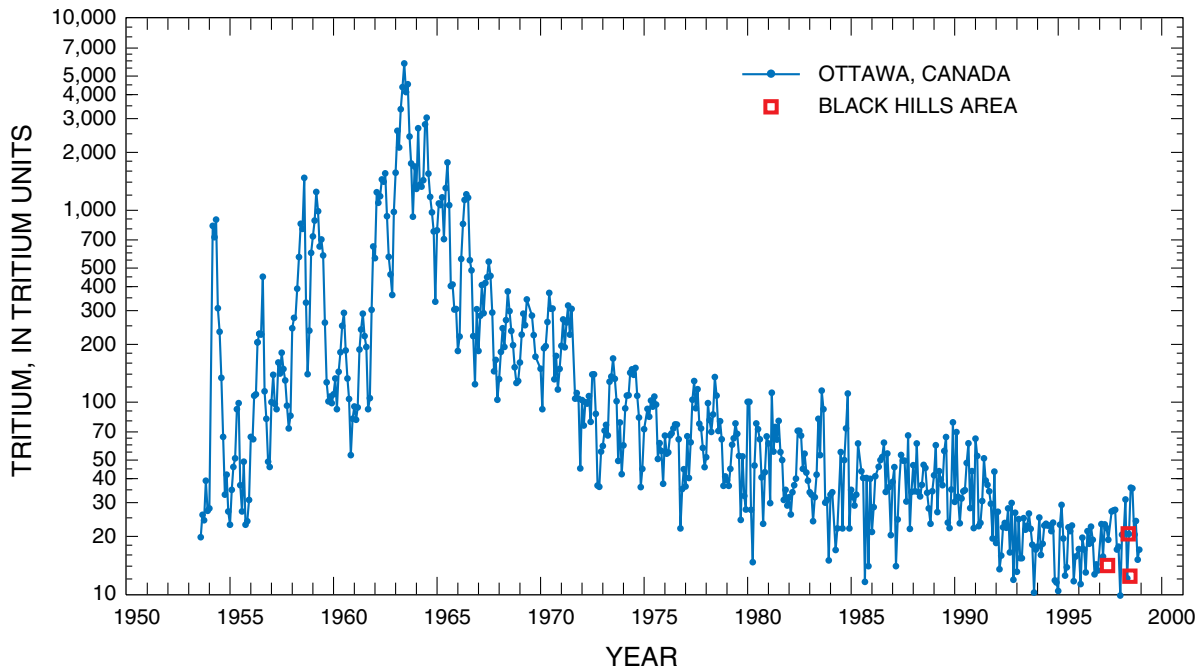


Figure 23. Monthly tritium concentrations in precipitation at Ottawa, Canada. Samples collected in Black Hills area of South Dakota also are shown.

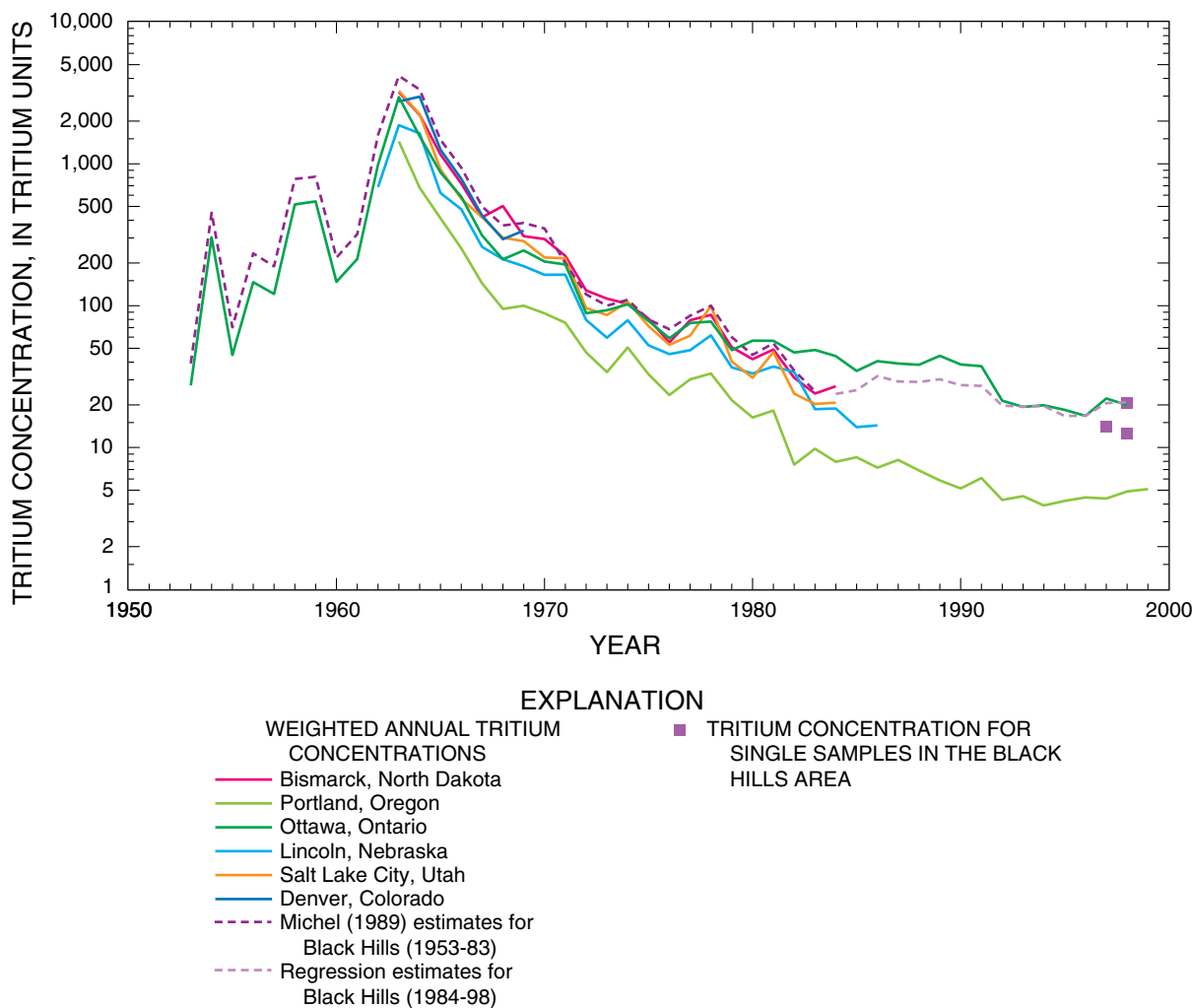


Figure 24. Weighted annual tritium concentrations in precipitation at selected locations. Estimated input and samples for Black Hills area of South Dakota also are shown.

For 1984, monthly tritium concentrations in precipitation for the Black Hills area were estimated by averaging data for Bismarck, North Dakota, and Lincoln, Nebraska. For 1985-98, estimates for the Black Hills area were derived by averaging forward extensions of data for Bismarck and Lincoln, based on least-squares linear regression with monthly data for Ottawa. The regression equation is of the form: $TU = a TU_{OTTAWA} + b$; where: TU is tritium in precipitation (for either Bismarck or Lincoln), and TU_{OTTAWA} is tritium in precipitation at Ottawa. The coefficients a and b are obtained from regression analysis using all available months of data from January 1979 through July 1984 for Bismarck, and from January 1970 through May 1986 for Lincoln. During these periods, annual concentrations for Bismarck and Lincoln were consistently less than

concentrations for Ottawa (fig. 24), which recently has been affected by localized tritium sources (Bob Michel, U.S. Geological Survey, oral commun., 2000). For Bismarck, the resulting coefficients for a and b are 0.483 and 0.732, respectively, and for Lincoln, the coefficients are 0.881 and 0.028.

For 1984-98, annual weighted tritium concentrations were calculated from the reconstructed monthly data (table 9) and Black Hills precipitation records (Driscoll, Hamade, and Kenner, 2000) as follows:

$$TU_{weighted} = \frac{\sum_{i=1}^{12} Precip_i TU_i}{\sum_{i=1}^{12} Precip_i} \quad (4)$$

where $Precip_i$ and TU_i denote monthly precipitation and tritium concentrations, respectively.

Estimated monthly and weighted annual tritium concentrations in precipitation for the Black Hills area for 1984-98 are presented in table 10 in the Supplemental Information section. Estimates for 1985-98 have larger uncertainty than for previous periods because of discontinuation of data collection at Bismarck and Lincoln. All concentrations prior to 1953 are assumed equal to 15.0 TU. Actual background concentrations probably were slightly lower (Bob Michel, U.S. Geological Survey, written commun., 2000); however, estimated input of 15 TU results in essentially negligible decayed tritium concentrations for the primary sampling period (1990-98).

Additional inferences regarding recent tritium concentrations in precipitation are available from examination of tritium concentrations in samples collected from 14 streams (table 7) where streamflow recharge occurs. These streams generally are relatively responsive to short-term precipitation influences (Miller and Driscoll, 1998); however, the range of tritium values indicates considerable variability in tritium concentrations in precipitation and streamflow responses. The lowest concentrations are near 15 TU, which probably is representative of the lower end of the range of average tritium concentrations in recent (since about 1992) precipitation. The upper end of the range for stream samples (25 to 40 TU) is considerably higher, however, than estimated concentrations in precipitation during the mid-1990's (fig. 24), which may indicate slight underestimation of precipitation input during this period or large seasonal variability.

The streams with higher tritium concentrations generally have larger influence from ground-water discharge than streams with lower tritium concentrations. This observation is consistent with the work of Rose (1993), who investigated tritium systematics of base flow and effects on tritium concentrations in streams.

Conceptual Mixing Models

Complex ground-water flow conditions within the Madison and Minnelusa aquifers necessitate formulation of conceptual models for evaluation of mixing conditions and ground-water ages. Within this section, three conceptual mixing models are described and limitations of the models are discussed.

Description of Models

Within the Madison aquifer, primary porosity and hydraulic conductivity generally are small and hydraulic properties are dominated by fractures and solution openings, which range in size from microfractures to massive caverns. In this dual-porosity system (Long, 2000), a large part of ground-water flow may occur in preferential flowpaths within openings, with smaller influence from the low-porosity matrix. A significant amount of ground-water storage, however, may occur in dead-end or poorly connected openings. Within some water-bearing layers of the Minnelusa aquifer, relatively homogenous aquifer characteristics probably occur; however, extensive fracturing and solution activity also contribute to dual-porosity characteristics in many locations. Overall, the Minnelusa aquifer generally is heterogeneous across the Black Hills area.

Three conceptual models (fig. 25) are considered for general evaluation of mixing conditions and ground-water ages within the Madison and Minnelusa aquifers. Given the large range of hydraulic characteristics within these aquifers, the simplified models cannot address all of the complex mixing and flow conditions that occur. Under the best conditions, none of these simplified models would be expected to exactly represent complicated ground-water flow conditions that occur. Under the worst conditions, large errors in estimated ages can occur. The conceptual models do, however, provide a mechanism by which finite numerical age estimates can be derived for water samples.

Mathematically, the three conceptual models illustrated in figure 25 belong to a general group of models known as lumped-parameter models (Yurtsever and Payne, 1986), where the system description (relating tracer input to tracer output) is attained by assuming a system response function (transit-time distribution function). Models of this type often are used to interpret radioisotope tracer data in ground-water studies (Katz and others, 1999; Manga, 1999). Although this approach is simplistic in that the aquifer is assumed to be homogeneous (detailed spatial variations are not represented), it is appropriate when the available data are limited to temporal observations at the input and output of the system (Yurtsever and Payne, 1986; Manga, 1999) and may be particularly useful for karst and fractured-rock systems (Zuber, 1986).

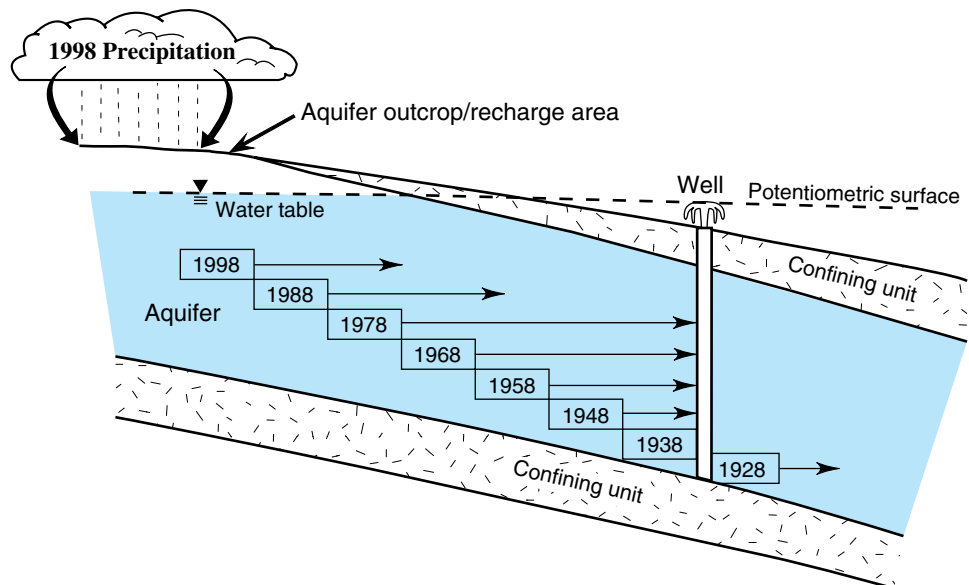
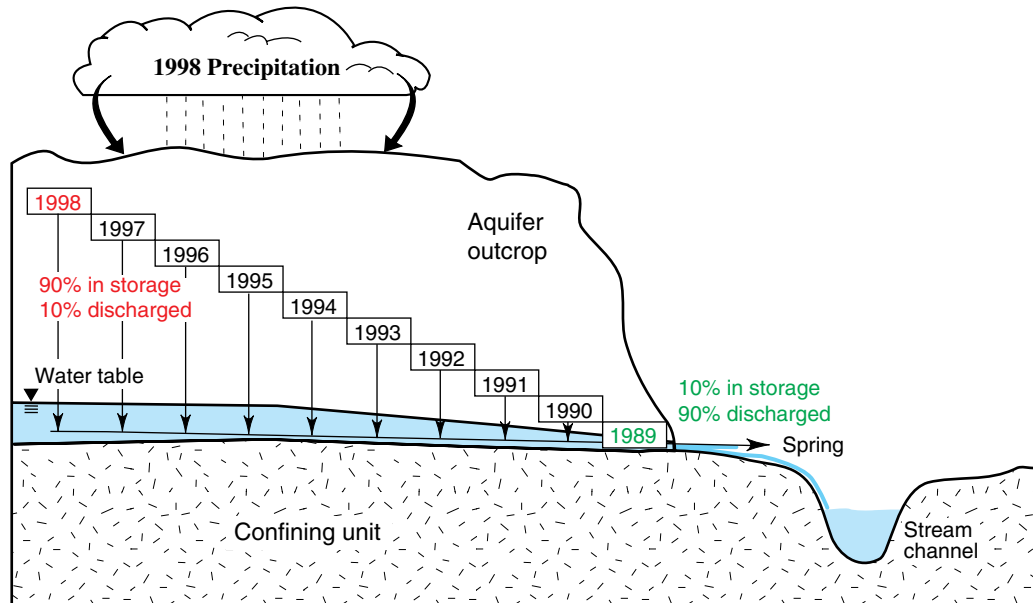
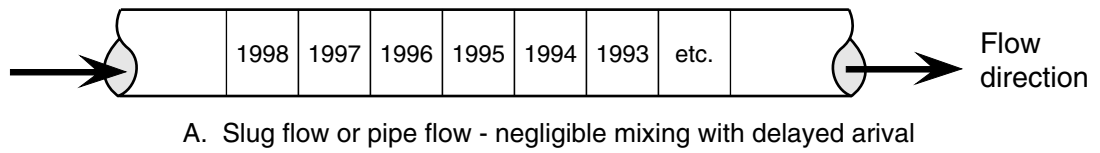


Figure 25. Schematic diagrams illustrating mixing models for age dating for various ground-water flow conditions.

For a lumped-parameter model, the relation between time-variable tracer input and output concentrations (Zuber, 1986) can be expressed as:

$$C_{out}(t) = \int_0^{\infty} C_{in}(t-t')e^{-\lambda t'} g(t') dt' \quad (5)$$

where, $C_{out}(t)$ and $C_{in}(t-t')$ are the output and input concentrations, t is the calendar time at which the output is to be evaluated, t' is the traveltime of the tracer, λ is the radioactive decay constant, and $g(t')$ is a system response, or weighting, function. The three models shown in figure 25 are represented mathematically by using different system response functions in equation 5.

Figure 25A depicts slug flow (often termed pipe or piston flow), which is a common assumption in tracer-based dating of ground water. In slug flow, a given water front advances with a uniform velocity and little dispersion or mixing. Existing water is completely, immiscibly displaced by the advancing water. The slug-flow model often is applied to the percolation of water through the unsaturated zone and also may be appropriate for isotropic, confined aquifers (Zuber, 1986; Gonfiantini and others, 1998) as well as unconfined, surficial aquifers (Reilly and others, 1994). For the Madison and Minnelusa aquifers, a slug-flow model could approximate ground-water flow conditions in dual-porosity settings if the dominant flow proportions are in fractures and solution openings, with minimal contributions from the low-porosity matrix.

For slug flow, the system response function is described by a mathematical function called the Dirac delta function (sometimes called the unit impulse function), $\delta(t-\tau)$, where τ is the turnover time or mean transit time of water (τ = volume of water in the system/volumetric flow rate through the system). In this case, the traveltime of the tracer is equivalent to the turnover time; in all other cases, the two differ considerably (Maloszewski and Zuber, 1982). Use of this system response function reduces equation 5 to:

$$C_{out}(t) = C_{in}(t-t')e^{-\lambda t'} \quad (\text{Zuber, 1986}). \quad (6)$$

Equation 6 describes the decrease in concentration due to decay during the time span t' of a tracer that entered the system at time $(t-t')$ and exited the system at time t .

Tritium concentrations remaining in ground water after decaying to a particular sample-collection date can be computed for a given recharge year using the weighted annual tritium concentration (table 9) as the initial concentration in equation 6. Estimated tritium concentrations in precipitation for recharge years through 1998 and decay-corrected tritium concentrations for sample-collection dates ranging from 1978 through 1998 are included as table 11 in the Supplemental Information section.

Figure 26 shows estimated concentrations of tritium in precipitation for the Black Hills area for 1940-98 and decay curves in 5-year increments between 1978 and 1998, which covers the primary period for which samples are available. For slug-flow conditions, a recharge date (or range of dates) for any sample can be estimated by selecting the appropriate decay curve for the year of sample collection (or interpolating between curves) and identifying the point(s) on the curve that are equal to the measured tritium concentration. As an example, for a sample collected during 1993 with a concentration of 5 TU, the estimated recharge date for slug-flow conditions is about 1953. Two or more recharge dates are possible for many samples. Numerous solutions are possible for a 1993 sample with a concentration of 20 TU. For this example, recharge may have occurred anytime in the range of about 1954-57 or 1980-93, considering within-year variability in tritium concentrations in precipitation and uncertainty in estimating tritium input for the Black Hills area.

Figure 25B depicts a simplified mixing model that generally is applicable for locations where water-table conditions exist within outcrop areas, such as headwater springs. For this "immediate-arrival" model, it is assumed that some percentage of the water recharged during a given year is discharged during that same year; in other words, the minimum traveltime for a portion of the water is zero. For this scenario, water recharged during a given year is mixed with equal proportions of water recharged during previous years. For the hypothetical water-table spring with a maximum traveltime of about 10 years that is shown in figure 25B, 10 percent of the water recharged during the current year is discharged as springflow during that same year. The remaining 90 percent of the water discharged is composed of equal proportions of water recharged during each of the previous 9 years. Thus, tritium composition for this scenario can be represented as the average of decay-corrected tritium input concentrations over the previous 10 years.

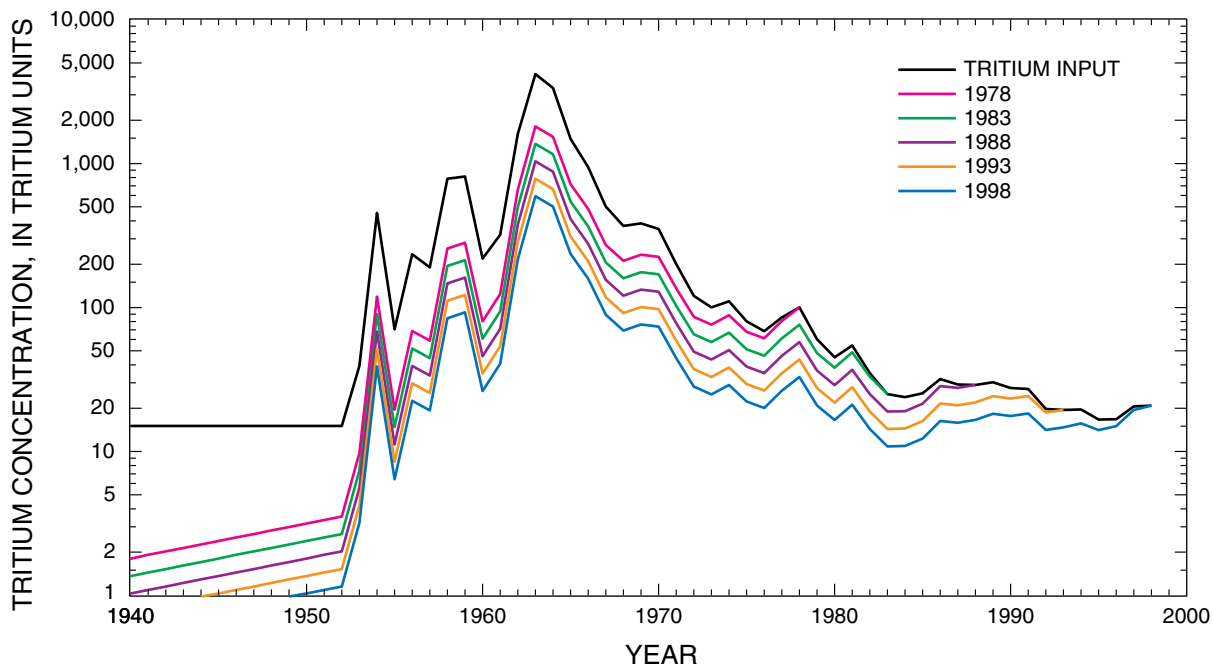


Figure 26. Estimated tritium concentrations in precipitation for Black Hills area and decay curves for selected years. Decay curves depict decayed tritium concentrations for selected sampling years.

The mathematical expression for this immediate-arrival mixing model utilizes a simple system response function such that the observed output concentration is represented as a mix of equal proportions of decay-corrected tritium input concentrations for all years between the minimum (0 years for immediate arrival) and maximum traveltimes:

$$C_{out}(t) = \frac{1}{T} \sum_{t'_{min}}^{t'_{max}-1} C_{in}(t-t')e^{-\lambda t'} \quad (7)$$

Equation 7 is identical to the example of a simple lumped-parameter model given by Zuber (1986, p. 12) except that all input concentrations for the range of years between the minimum and maximum traveltimes are weighted equally in equation 7. Here, T is the mixing time period, computed as the difference between the maximum (t'_{max}) and minimum (t'_{min}) traveltimes in the system.

For the hypothetical water-table spring shown in figure 25B, the summation is calculated using decay-corrected tritium input concentrations for recharge years 1998 ($C_{in}(1998 - 0)$) through 1989

($C_{in}(1998 - 9)$). With the equal-weight system response function, equal proportions of water are contributed each year; in this case the proportion is $\frac{1}{(t'_{max} - t'_{min})} = 10$ percent.

Figure 25C depicts a conceptual model that assumes a delay time before any recharge water reaches a discharge point. Use of this model requires a minimum delay time of 1 year because annual input is used for calculation purposes. This “time-delay” mixing model is appropriate where an upper confining unit is present and wells or springs are located some distance from outcrop areas, which is applicable for many locations around the periphery of the Black Hills, especially where artesian conditions occur. For example, the hypothetical artesian well shown in figure 25C withdraws a mixture of water that was recharged during a 50-year period from 1929 to 1978. The minimum traveltime (delay time) in this case is 20 years; in other words, the earliest arrival of recharge water is delayed by about 20 years before reaching the discharge point. The maximum traveltime is 70 years. In this case, the summation (eq. 7) is calculated using decay-corrected tritium input concentrations for recharge years 1978 ($C_{in}(1998 - 20)$) through 1929

($C_{in}(1998 - 69)$). The equal-weight system response function in this case results in a mix consisting of contributions of 2 percent, $(1/(t'_{max} - t'_{min}))$ for each input year.

Curves for estimating ages for both immediate-arrival and time-delay mixing models (figs. 25B and C) are presented in figure 36 in the Supplemental Information section. Each graph includes a family of curves depicting minimum traveltimes, or delay times, in 4-year increments. The 0-year delay curve in each curve family is applicable for the immediate-arrival mixing model (fig. 25B), and the other curves are applicable for time-delay mixing scenarios. Individual curves in each family were constructed from output concentrations calculated for ranges of input years using equation 7. Curve families are presented for sampling years 1978 and 1989-97, which cover the majority of samples considered. Calculations should theoretically be carried out for all possible traveltimes, from zero to infinity (Zuber, 1986); however, the curves are arbitrarily extended only to possible recharge years through 1800.

Using a 1993 sample (fig. 36F) with a concentration of 30 TU as an example, if an immediate-arrival mixing model is considered appropriate, the estimated maximum traveltime is either 23 years (earliest recharge occurring about 1970) or 130 years (earliest recharge occurring about 1863). For this example, no solutions exist for time-delay mixing scenarios with delay times exceeding about 36 years, and only one possible solution exists for delay times in the range of about 20 to 36 years. Two solutions are possible for each of the delay times up to about 20 years.

Limitations of Models

As discussed, the three simplified, conceptual models that are considered cannot address all of the complex mixing and flow conditions that occur within the Madison and Minnelusa aquifers within the study area. The conceptual models do, however, provide a mechanism by which finite numerical age estimates can be derived for water samples. Readers are cautioned that accurate age dating is not possible because of large potential errors resulting from numerous limitations associated with the simplified models, which are intended only for general evaluation of mixing conditions and approximate age ranges. Sources of potential error are associated primarily with estimation of tritium concentrations in recharge and with assumptions regarding the mixing models that are considered.

Estimates of tritium concentrations in precipitation are subject to large potential error because of the sparsity of data-collection points near the Black Hills area, especially since discontinuation of data collection at Bismarck and Lincoln. Age estimates for recent years have progressively increasing sensitivity to errors in estimated tritium concentrations in precipitation because atmospheric tritium has progressively decreased since 1963.

The use of annual averages for tritium in precipitation is another source of potential error because of the episodic nature of recharge; however, some within-year proportioning is obtained because monthly concentrations are precipitation weighted. The immediate- and delayed-arrival mixing models are based on an implicit assumption of equal recharge each year; however, recharge may vary by as much as an order of magnitude from one year to the next (Carter, Driscoll, and Hamade, 2001).

Variability of tritium concentrations in streamflow creates an additional complication for areas influenced by streamflow recharge. The age of water in a stream always lags that of precipitation, whether by minutes, days, or many years. The extent of this effect is highly variable and depends on the lag time associated with a particular stream, the degree of variability of tritium concentrations in the base-flow component of streamflow (Rose, 1993), and the proportion of ground-water recharge resulting from streamflow losses relative to direct precipitation on aquifer outcrops. Although stream water is inherently older than precipitation, systematic influences on age dating probably are overshadowed, in most cases, by seasonal variability in tritium input and by other sources of uncertainty.

Various hydrologic and hydraulic factors also complicate the paramount assumption that samples contain a mix of equal proportions of water from various years. Variability in recharge rates probably causes temporal variability in ground-water traveltimes and flowpaths from recharge areas to discharge areas. Variable residence times in the unsaturated zone in recharge areas and in confining units also may be complicating factors. For applications of the immediate-arrival model in unconfined headwater settings, the effects of the shape of a contributing ground-water basin on the relative contributions of recharge from different parts of the basin also could seriously violate this assumption.

The cumulative effects of all of the aforementioned factors probably are small, relative to error potential associated with the spatial variability in hydraulic properties of the aquifers. Dual-porosity hydraulic characteristics contribute to large variability in ground-water flow and mixing conditions, which cannot be generically accommodated by the conceptual mixing models. Actual conditions may be more accurately represented as a combination of mixing models, with influence from slug-flow effects in fractures and solution features. Even in cases where one conceptual model may be appropriate, there are important limitations. In settings where ground-water flow is predominantly in fractures and solution openings, which may be approximated by the slug-flow model, some mixing of ground water occurs during convergence upon the screened interval of wells (Reilly and others, 1994). A limitation of the immediate- and delayed-arrival mixing models is the assumption of thorough ground-water mixing. Specific examples and additional details regarding model limitations are provided in subsequent sections of this report.

As discussed, two or more age estimates are possible for many samples, depending on the tritium concentration and the mixing model that is considered most applicable. Multiple samples for any site improve the ability to make credible age estimates; however, effects of large well withdrawals at a site could change the age characteristics between successive samples.

Areal Flowpaths, Ages, and Mixing Conditions

Within this section, isotopic interpretations are used to evaluate areal flowpaths, ages, and mixing conditions for the Madison and Minnelusa aquifers in the Black Hills area. General considerations regarding isotope distributions are discussed first, after which various site-specific considerations are addressed. Potential influences of regional flow from the west are discussed in a subsequent section.

Isotope Distributions and General Considerations

Distributions for stable isotopes and tritium are presented in this section. Various general considerations associated with the isotope distributions also are discussed.

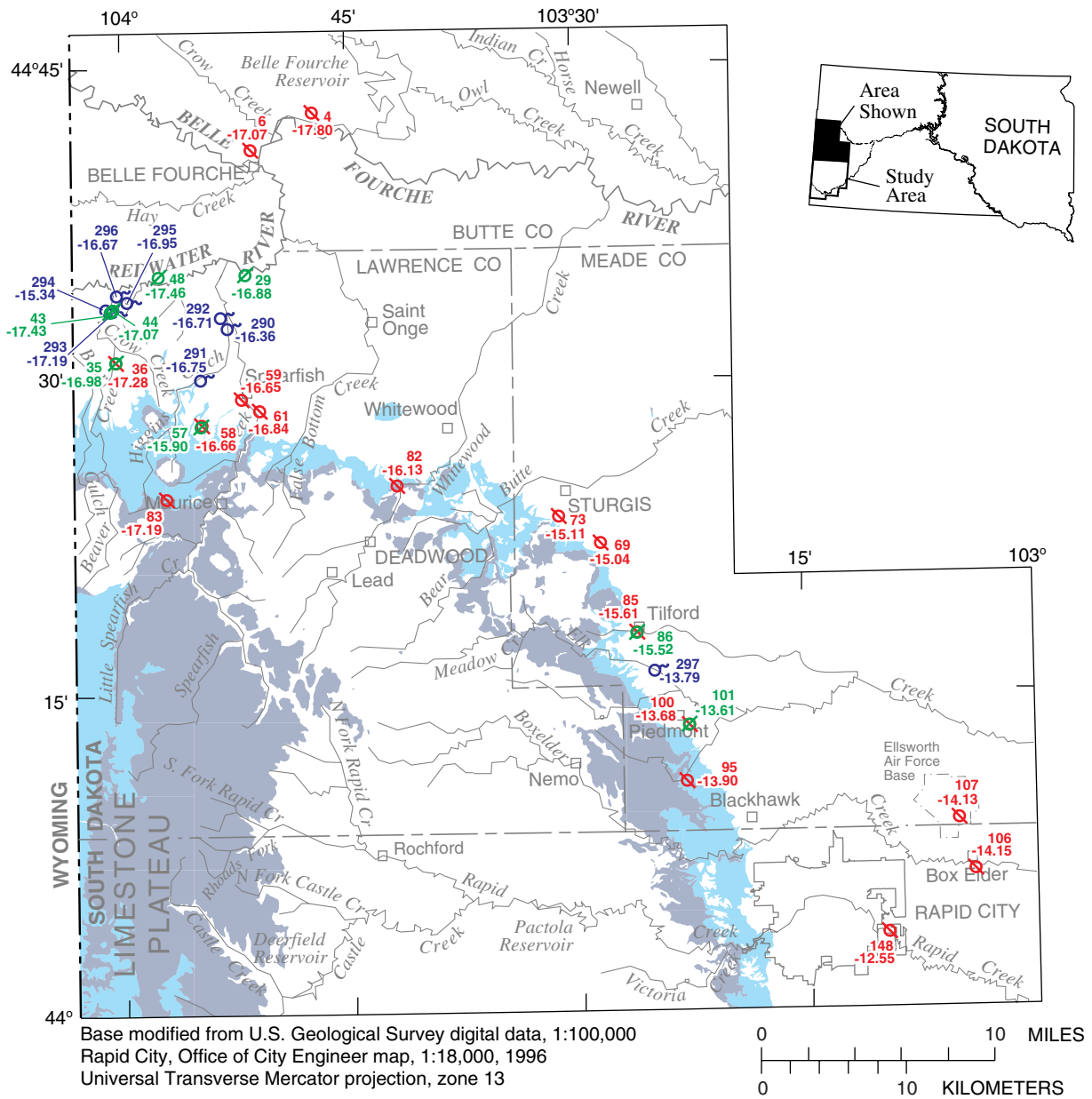
Stable Isotopes

Distributions of $\delta^{18}\text{O}$ values in Madison and Minnelusa wells and selected springs are shown in

figures 27, 28, and 29. Mean values are shown for sites with multiple samples. Figures 27 and 29 show the northern and southern Black Hills, respectively, and figure 28 shows the Rapid City area. These figures generally include sites near or downgradient from the Madison and Minnelusa outcrops, which probably are influenced primarily by recharge originating from within the study area. Sites considered representative of the isotopic composition of recharge in the study area were presented earlier in figure 20 and are excluded from figures 27-29.

Distributions of stable isotopes generally are consistent with spatial patterns in recharge areas (fig. 20), with isotopically lighter precipitation generally occurring at higher elevations and latitudes. Effects of recharge elevation are examined in table 3, which shows that $\delta^{18}\text{O}$ values are lighter in the Madison aquifer than in the Minnelusa aquifer for 10 of 13 well pairs. An example is provided by sites 35 and 36 (State Line wells, fig. 27), along with a co-located Minnekahta well (site 34, fig. 20), which show the typical progression of isotopically lighter water associated with progressively higher elevation recharge sources. The Madison aquifer also is influenced by preferentially larger volumes of isotopically light streamflow recharge, relative to the Minnelusa aquifer.

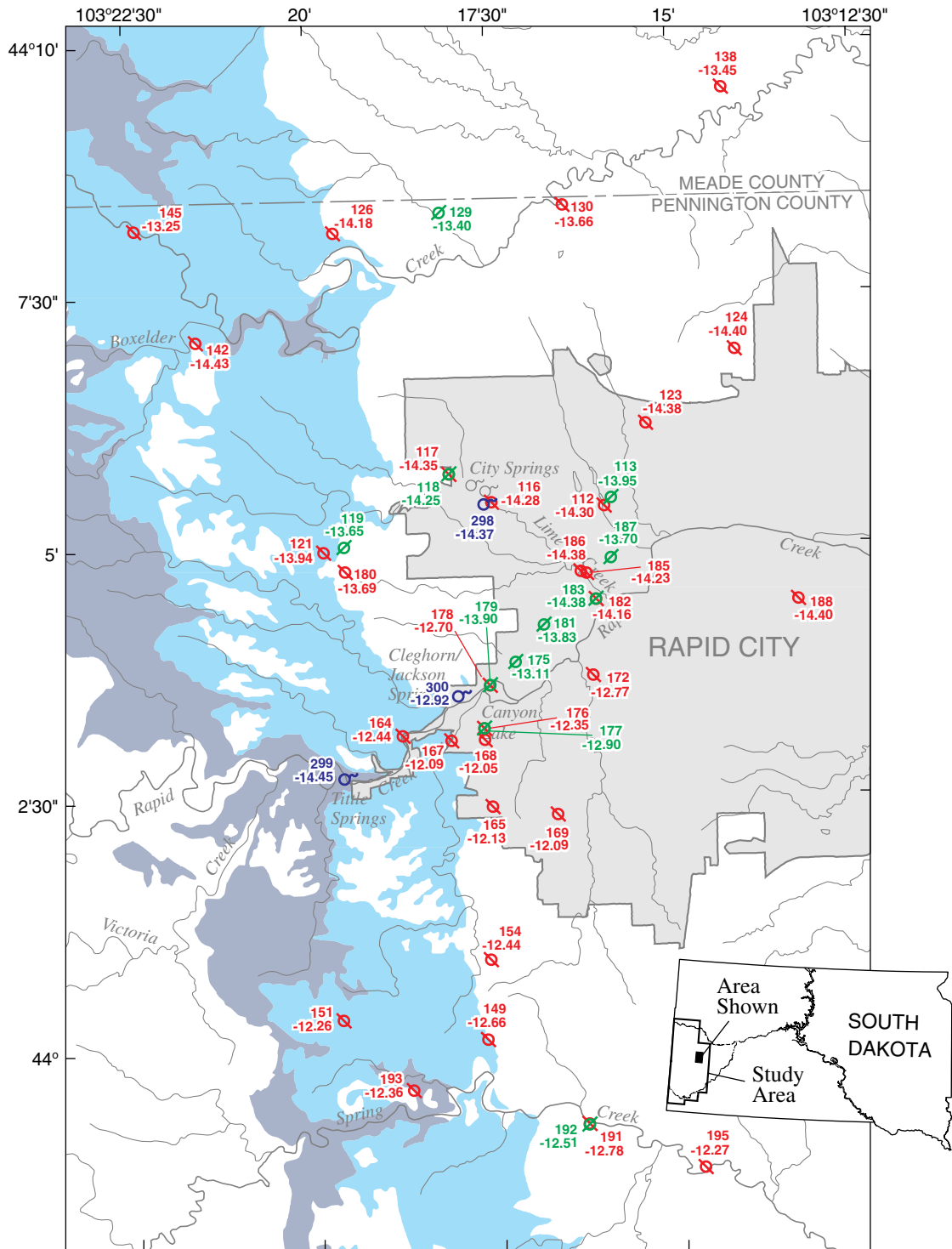
In some areas, effects of streamflow recharge on isotopic composition can be identified. For example, the $\delta^{18}\text{O}$ values (by aquifer) for sites 35 and 36 (State Line wells, fig. 27) are distinctly lighter than values for sites 57 and 58 (Tinton Road wells), which probably results from the influence of streamflow recharge from Beaver Creek or Bear Gulch. The Tinton Road wells probably are recharged primarily by precipitation on outcrops because no major streamflow loss zones are nearby. Similarly, values for sites 85 and 86 (Tilford wells) are nearly identical (fig. 27) and are somewhat lighter than in nearby outcrop areas (fig. 20), where $\delta^{18}\text{O}$ values are predominantly in the range of -14 to -15 ‰, indicating that these wells probably are heavily influenced by streamflow recharge from Elk Creek. In contrast, Madison and Minnelusa wells at Piedmont (sites 100 and 101) and springflow along Elk Creek (site 297) probably are influenced primarily by precipitation recharge on large outcrop areas southwest of Piedmont.



EXPLANATION

- OUTCROP OF MADISON LIMESTONE (from Strobel and others, 1999)
- OUTCROP OF MINNELUSA FORMATION (from Strobel and others, 1999)
- 148 -12.55 ⊗ WELL COMPLETED IN MADISON AQUIFER--Numbers indicate site number and $\delta^{18}\text{O}$ value in per mil
- 101 -13.61 ⊗ WELL COMPLETED IN MINNELUSA AQUIFER--Numbers indicate site number and $\delta^{18}\text{O}$ value in per mil
- 297 -13.79 ⊖ DOWNGRADIENT SPRING--Numbers indicate site number and $\delta^{18}\text{O}$ value in per mil

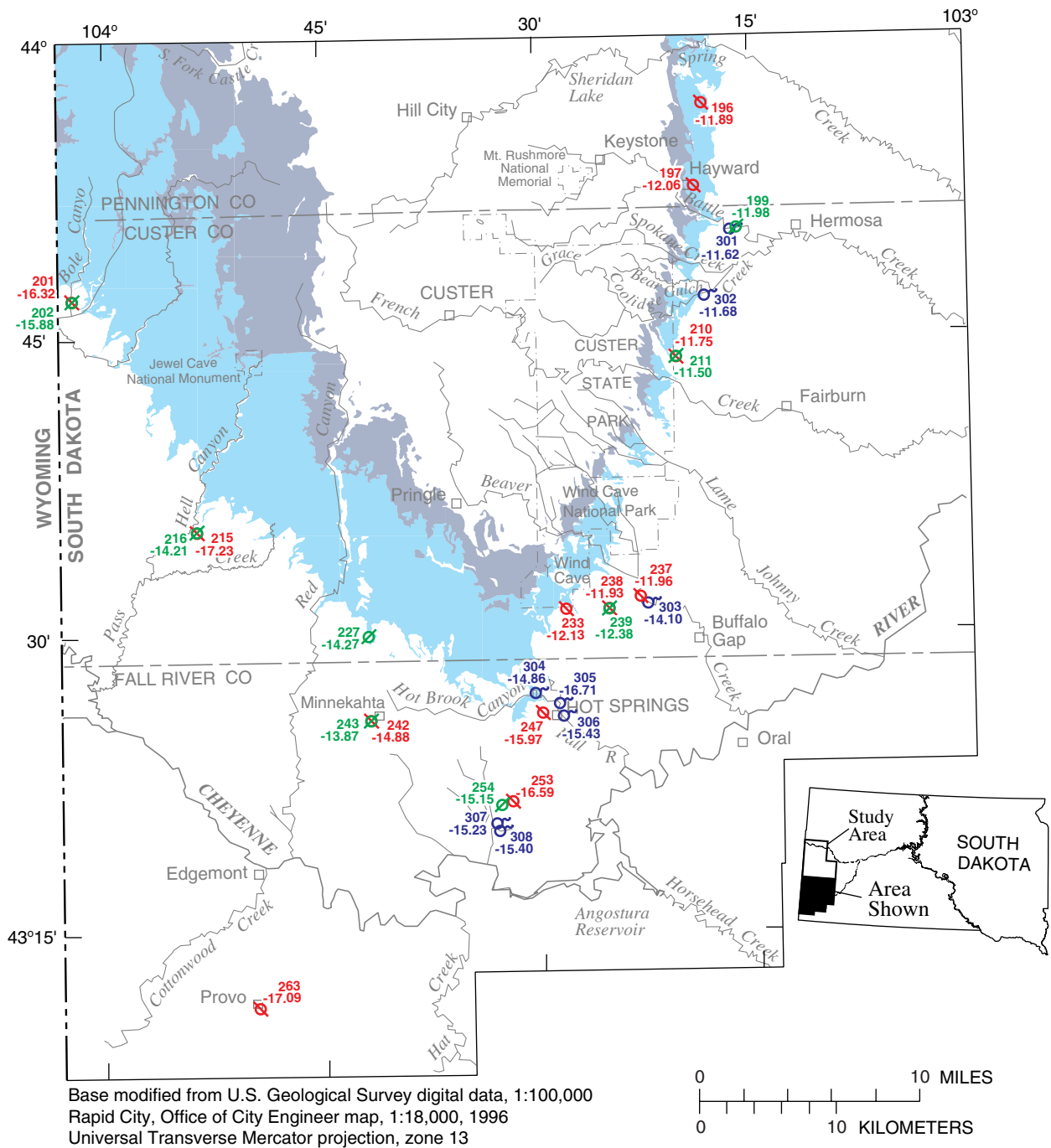
Figure 27. Distribution of $\delta^{18}\text{O}$ in selected Madison and Minnelusa wells and springs in the northern Black Hills area. Sampling dates are through 1998, with mean values shown for sites with multiple samples.



Base from U.S. Geological Survey digital line graph, 1:100,000, Rapid City, Office of City Engineer map, 1:18,000, 1996

- EXPLANATION**
- OUTCROP OF MADISON LIMESTONE (from Strobel and others, 1999)
 - OUTCROP OF MINNELUSA FORMATION (from Strobel and others, 1999)
 - 151 ⊗ -12.26 WELL COMPLETED IN MADISON AQUIFER--Numbers indicate site number and $\delta^{18}\text{O}$ value in per mil
 - 192 ⊗ -12.51 WELL COMPLETED IN MINNELUSA AQUIFER--Numbers indicate site number and $\delta^{18}\text{O}$ value in per mil
 - 299 ⊗ -14.45 DOWNGRADIENT SPRING--Numbers indicate site number and $\delta^{18}\text{O}$ value in per mil

Figure 28. Distribution of $\delta^{18}\text{O}$ in selected Madison and Minnelusa wells and springs in the Rapid City area. Sampling dates are through 1998, with mean values shown for sites with multiple samples.



EXPLANATION

- OUTCROP OF MADISON LIMESTONE (from Strobel and others, 1999)
- OUTCROP OF MINNELUSA FORMATION (from Strobel and others, 1999)
- 148
-12.55 WELL COMPLETED IN MADISON AQUIFER--Numbers indicate site number and $\delta^{18}\text{O}$ value in per mil
- 101
-13.61 WELL COMPLETED IN MINNELUSA AQUIFER--Numbers indicate site number and $\delta^{18}\text{O}$ value in per mil
- 297
-13.79 DOWNGRADIENT SPRING--Numbers indicate site number and $\delta^{18}\text{O}$ value in per mil

Figure 29. Distribution of $\delta^{18}\text{O}$ in selected Madison and Minnelusa wells and springs in the southern Black Hills area. Sampling dates are through 1998, with mean values shown for sites with multiple samples.

Table 3. Selected data for observation well pairs

[S, similar; SS, somewhat similar; DS, dissimilar; H, higher or heavier; L, lower or lighter. mg/L, milligrams per liter; pCi/L, picocuries per liter; TU, tritium units; <, less than; --, no data or not shown]

Site number	Name	Aquifer	δ ¹⁸ O				Tritium				Hydraulic head			Sulfate (mg/L)	Chloride (mg/L)
			Per mil	Heavier/lighter	S/DS ¹	Date	pCi/L	TU	Higher/lower	S/DS	Higher/lower				
36	State Line	Madison	-17.28	L	SS	04-11-94	61.0	19.1	H	DS	H	DS	H	150	0.7
35	State Line	Minnelusa	-16.98	H	SS	04-11-94	<1.0	<.3	L	DS	L	DS	L	73	.5
58	Tinton Road	Madison	-16.66	L	DS	09-08-98	30.4	9.5	L	DS	L	DS	L	58	30
57	Tinton Road	Minnelusa	-15.90	H	DS	09-08-98	78.4	24.6	H	DS	H	DS	H	3.8	1.2
85	Tilford	Madison	-15.61	L	S	09-03-96	4.0	1.3	L	SS	H	SS	H	38	.5
86	Tilford	Minnelusa	-15.52	H	S	08-27-96	100.0	31.3	H	SS	L	SS	L	8.4	.9
100	Piedmont	Madison	-13.68	L	S	09-04-96	<1.0	<.3	L	DS	H	DS	H	9.3	.7
101	Piedmont	Minnelusa	-13.61	H	S	09-04-96	3.0	.9	H	DS	L	DS	L	4.2	1.0
117	City Quarry	Madison	-14.35	L	S	05-13-92	96.0	30.1	H	S	H	S	H	20	27
118	City Quarry	Minnelusa	-14.25	H	S	05-12-92	2.0	.6	L	S	L	S	L	27	6.0
178	Canyon Lake	Madison	-12.70	H	DS	09-28-93	75.9	23.8	H	DS	H	DS	H	25	3.2
179	Canyon Lake	Minnelusa	-13.90	L	DS	05-14-92	22.0	6.9	L	DS	L	DS	L	22	1.4
182	Sioux Park	Madison	-14.16	H	S	--	--	--	--	DS	H	DS	H	20	1.6
183	Sioux Park	Minnelusa	-14.38	L	S	--	--	--	--	DS	L	DS	L	22	1.7
191	Reptile Gardens	Madison	-12.78	L	SS	07-29-96	15.0	4.7	H	SS	H	SS	H	20	1.5
192	Reptile Gardens	Minnelusa	-12.51	H	SS	07-30-96	4.0	1.3	L	SS	L	SS	L	14	1.5
201	Boles Canyon	Madison	-16.32	L	DS	03-22-94	9.0	2.8	H	DS	L	DS	L	8.3	1.1
202	Boles Canyon	Minnelusa	-15.88	H	DS	12-17-97	3.2	1.0	L	DS	H	DS	H	26	5.9
210	CSP Airport	Madison	-11.75	L	SS	09-06-95	<1.0	<.3	L	S	Same	S	Same	22	1.4
211	CSP Airport	Minnelusa	-11.50	H	SS	08-31-95	3.0	.9	H	S	Same	S	Same	38	2.7
215	Hell Canyon	Madison	-17.23	L	DS	11-05-97	1.9	.6	H	DS	H	DS	H	230	4.3
216	Hell Canyon	Minnelusa	-14.21	H	DS	11-03-97	<1.0	<.3	L	DS	L	DS	L	470	4.0
238	7-11 Ranch	Madison	-11.93	H	DS	03-31-94	<1.0	<.3	--	DS	H	DS	H	24	6.4
239	7-11 Ranch	Minnelusa	-12.38	L	DS	04-05-94	<1.0	<.3	--	DS	L	DS	L	32	4.3
242	Minnekahta Jct	Madison	-14.88	L	DS	03-24-94	<1.0	<.3	--	DS	H	DS	H	37	5.2
243	Minnekahta Jct	Minnelusa	-13.87	H	DS	09-11-95	<1.0	<.3	--	DS	L	DS	L	1,800	12

¹Comparison between δ¹⁸O values for each well pair using criteria of <0.25 per mil for similar, between 0.25 and 0.30 per mil for somewhat similar, and >0.30 per mil for dissimilar.

²Mean value for multiple sampling dates.

In the Rapid City area (fig. 28), recharge probably is dominated by large streamflow losses from Boxelder, Rapid, and Spring Creeks, rather than from precipitation on the relatively small outcrop areas. In western Rapid City, a distinct division of lighter $\delta^{18}\text{O}$ values to the north and heavier values to the south is apparent for the Madison aquifer along Rapid Creek. Areas south of Rapid Creek apparently are isotopically similar to Spring Creek (fig. 20) and sites north of Rapid Creek generally reflect isotopically lighter composition similar to that of Rapid Creek and Boxelder Creek.

The $\delta^{18}\text{O}$ values for sites near Battle, Grace Coolidge, and French Creeks (fig. 29) are isotopically heavier than for any other part of the Black Hills area. Values in this area generally are in the range of about -11.5 to -12.0 ‰ and are very similar to values for the nearby streamflow loss zones. These values probably indicate a substantial influence from streamflow recharge; however, information is not available for evaluation of isotopic composition in the outcrop areas. Along the southern and southwestern flanks of the uplift, $\delta^{18}\text{O}$ values for most wells and springs (fig. 29) are much lighter than estimated values for near-recharge areas immediately nearby (fig. 20), indicating either recharge areas to the northwest or possible influence of regional flow from the west, as discussed in subsequent sections of this report.

Tritium

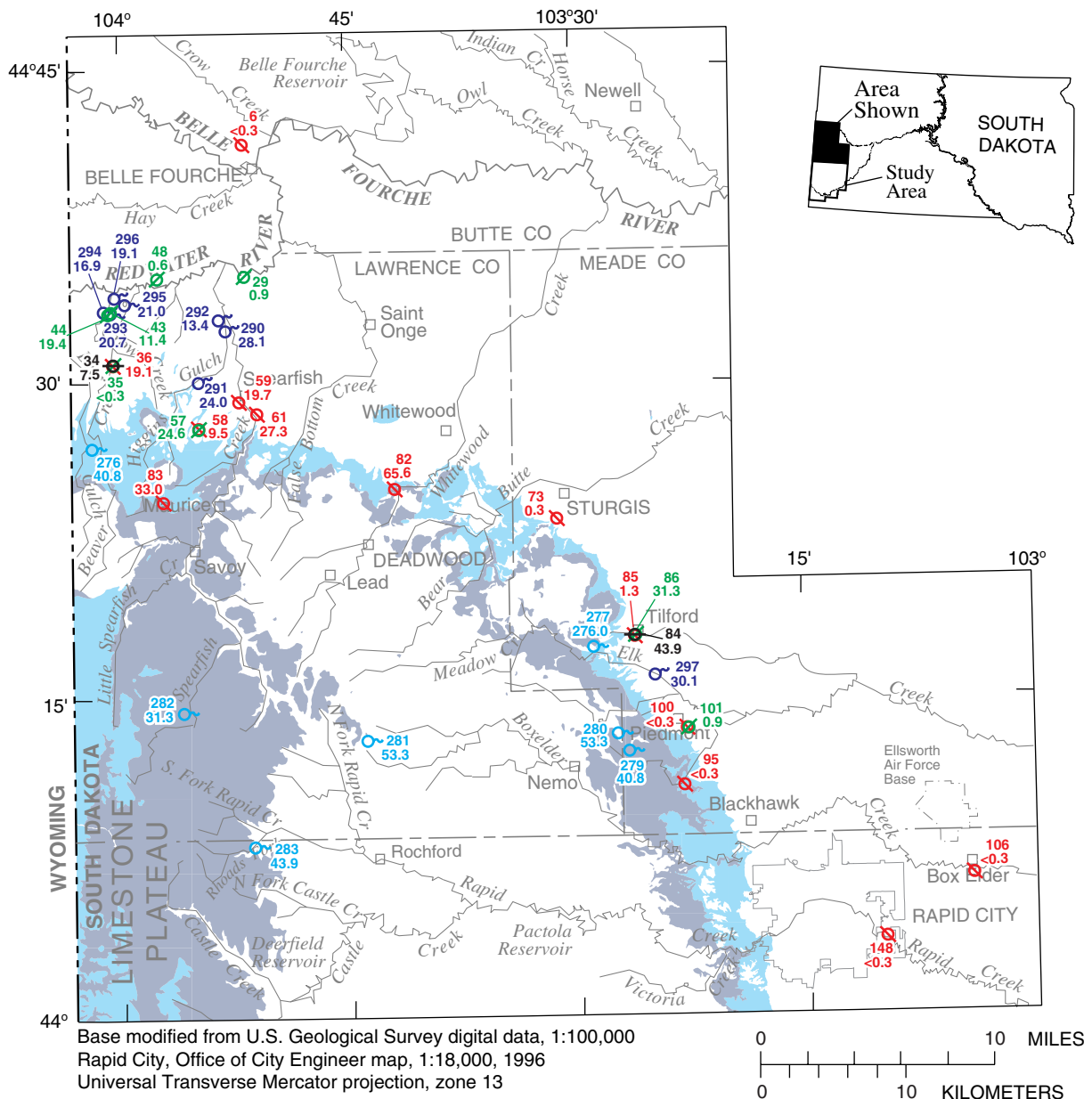
Tritium data for Black Hills sites are presented in table 7. Most sites include data collected only through water year 1998. Additional tritium data collected during water year 2000 are included for six selected sites that are relevant to site-specific discussions of isotope geochemistry for the Rapid City area, which are presented in a subsequent section.

Spatial distributions of tritium concentrations for wells, headwater springs, and downgradient springs in the Black Hills area are shown in figures 30, 31, and 32. The sites shown include a limited number of samples available for the Deadwood and Minnekahta aquifers. For sites with more than one tritium sample, the most recent concentration (through water year 1998) is shown.

Various observations can be made from examination of the tritium distributions (figs. 30-32). Large spatial variability in concentrations occurs near outcrop areas, which reflects large variability in mixing conditions and aquifer characteristics (heterogeneity). Most of the wells that are far removed from outcrop areas have low, or nondetectable (<0.3 TU) tritium concentrations, which generally supports the use of the time-delay mixing model for artesian areas. Concentrations noted as <0.3 TU are equivalent to about <1.0 pCi/L, which is the method reporting limit (MRL) for most of the laboratory analyses that have been performed. The "2 sigma" value is reported as 1.0 pCi/L for most samples with concentrations at or near the MRL (table 7). The true concentration is expected to be within 2 sigma of the reported concentration about 95 percent of the time (Bob Michel, U.S. Geological Survey, oral commun., 2000). Thus, based on estimated tritium concentrations in precipitation (table 11), samples reported as <0.3 TU are assumed to be composed primarily of water recharged prior to initial influence of nuclear testing in 1953 (pre-bomb water), regardless of sampling date or mixing conditions (figs. 26 and 36).

Samples with tritium concentrations that equal or slightly exceed the MRL also are dominated by pre-bomb water, but probably are showing the presence of some proportion of modern tritium (tritium produced during 1953 or later). For concentrations between 0.3 and 1.0 TU, the detection of modern tritium is fairly certain, from an analytical standpoint, and would indicate either: (1) the initial arrival of modern water for slug-flow conditions; or (2) at least some proportion of modern water for all mixing conditions.

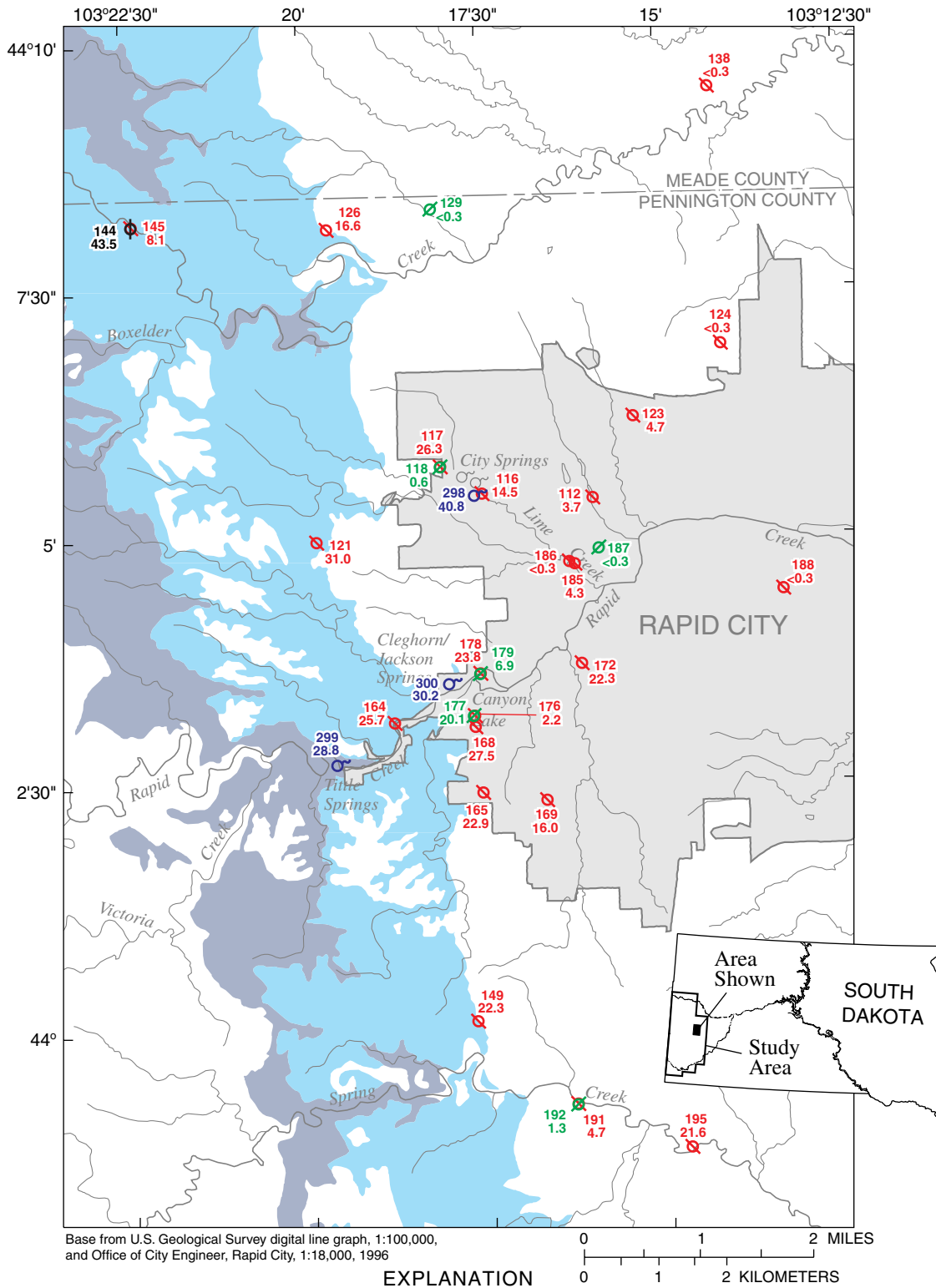
Given the uncertainty in estimation of tritium concentrations in recent precipitation (since about 1992) for the Black Hills area, concentrations as low as 10 TU (fig. 23) may be possible for recently recharged water. Thus, for samples with tritium concentrations between about 1 and 5 TU, dominant proportions of pre-bomb water generally can be assumed. For concentrations greater than about 5 TU, it is difficult to make generalizations because of numerous possible mixing scenarios; however, for all mixing conditions, the probability of dominant proportions of modern water increases with increasing tritium concentrations.



EXPLANATION

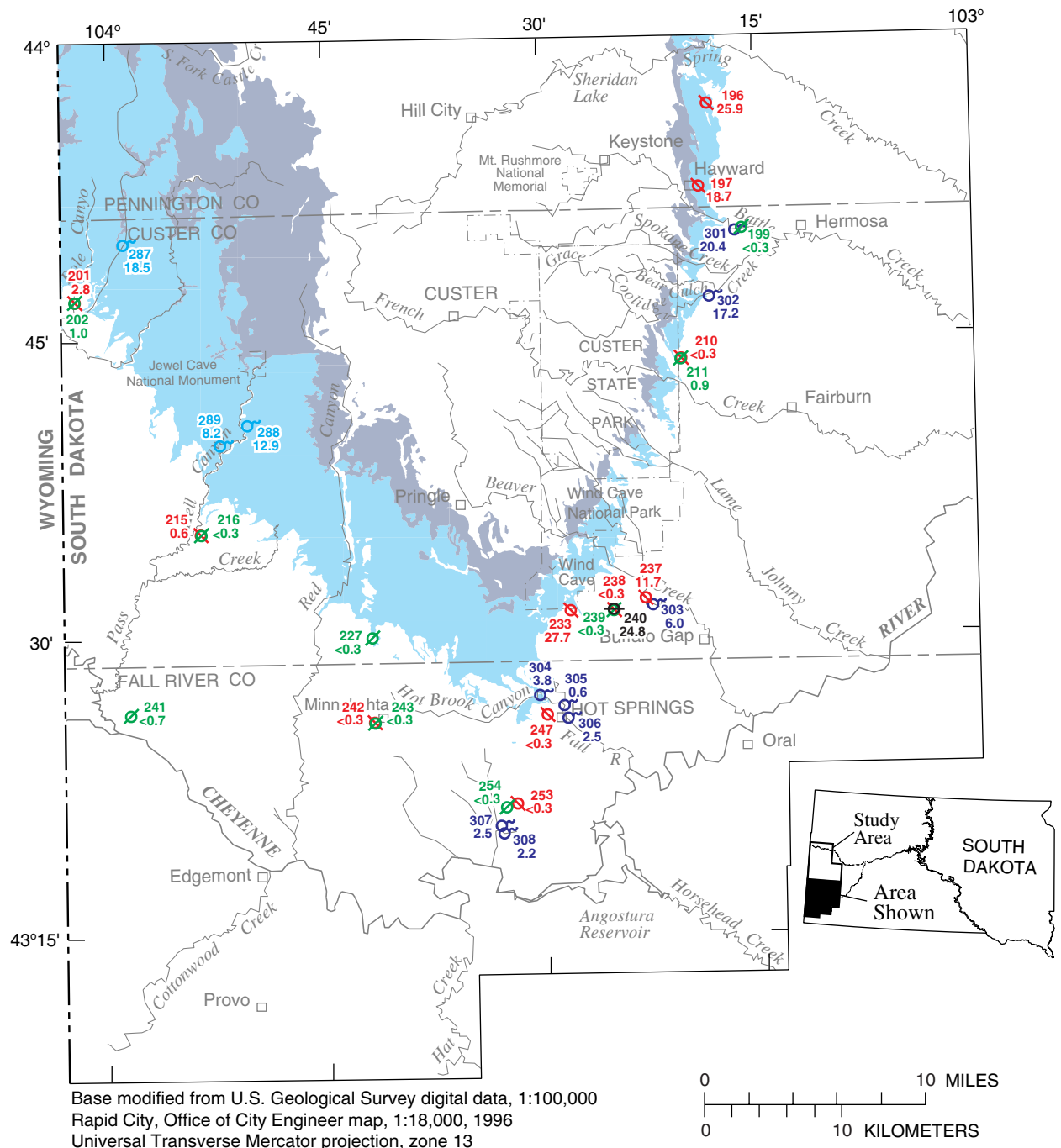
- OUTCROP OF MADISON LIMESTONE (from Strobel and others, 1999)
- OUTCROP OF MINNELUSA FORMATION (from Strobel and others, 1999)
- 106
-0.3 WELL COMPLETED IN MADISON AQUIFER--Numbers indicate site number and tritium concentration in tritium units
- 86
31.3 WELL COMPLETED IN MINNELUSA AQUIFER--Numbers indicate site number and tritium concentration in tritium units
- 84
43.9 WELL COMPLETED IN MINNEKAHTA AQUIFER--Numbers indicate site number and tritium concentration in tritium units
- 281
53.3 HEADWATER SPRING--Numbers indicate site number and tritium concentration in tritium units
- 297
30.1 DOWNGRADIENT SPRING--Numbers indicate site number and tritium concentration in tritium units

Figure 30. Distribution of tritium for selected sites in the northern Black Hills area. Sampling dates are through 1998, with the most recent concentration shown for sites with multiple samples.



- EXPLANATION**
- OUTCROP OF MADISON LIMESTONE (from Strobel and others, 1999)
 - OUTCROP OF MINNELUSA FORMATION (from Strobel and others, 1999)
 - 195
21.6 ⊗ WELL COMPLETED IN MADISON AQUIFER--Numbers indicate site number and tritium concentration in tritium units
 - 192
1.3 ⊗ WELL COMPLETED IN MINNELUSA AQUIFER--Numbers indicate site number and tritium concentration in tritium units
 - 144
43.5 ⊕ WELL COMPLETED IN DEADWOOD AQUIFER--Numbers indicate site number and tritium concentration in tritium units
 - 299
28.8 ⊕ DOWNGRAIDENT SPRING--Numbers indicate site number and tritium concentration in tritium units

Figure 31. Distribution of tritium for selected sites in the Rapid City area. Sampling dates are through 1998, with the most recent concentration shown for sites with multiple samples.



EXPLANATION

- OUTCROP OF MADISON LIMESTONE (from Strobel and others, 1999)
- OUTCROP OF MINNELUSA FORMATION (from Strobel and others, 1999)
- 242 <0.3 ⊗ WELL COMPLETED IN MADISON AQUIFER--Numbers indicate site number and tritium concentration in tritium units
- 254 <0.3 ⊗ WELL COMPLETED IN MINNELUSA AQUIFER--Numbers indicate site number and tritium concentration in tritium units
- 240 24.8 ⊗ WELL COMPLETED IN MINNEKAHTA AQUIFER--Numbers indicate site number and tritium concentration in tritium units
- 288 12.9 ⊕ HEADWATER SPRING--Numbers indicate site number and tritium concentration in tritium units
- 308 2.2 ⊕ DOWNGRAIDENT SPRING--Numbers indicate site number and tritium concentration in tritium units

Figure 32. Distribution of tritium for selected sites in the southern Black Hills area. Sampling dates are through 1998, with the most recent concentration shown for sites with multiple samples.

Boxplots showing the most recent tritium concentrations for 96 ground-water samples collected during 1990-98 from wells, headwater springs, and downgradient springs, and 12 samples from streams upstream from loss zones are presented in figure 33. These plots provide evidence that the mixing models illustrated in figure 25 have general applicability. The lower end of the range of tritium concentrations for headwater springs is much higher than for the wells and downgradient springs, which is consistent with the concept of an immediate-arrival mixing model in outcrop areas for the Madison and Minnelusa aquifers. The lower end of the range of tritium concentrations for both wells and downgradient springs is near zero, which indicates that the time-delay mixing model generally is applicable for artesian conditions, where an upper confining unit is present and recharge water must travel a substantial lateral distance before reaching a discharge point.

Delay times for wells generally are longer than for downgradient springs, which probably tend to develop near preferential flowpaths that may be further enhanced by dissolution activity. This dual-porosity

setting is conceptually inconsistent with the assumption of thorough mixing; however, extensive mixing may be approximated by springs with large discharges, which can capture water from large recharge areas.

It can be demonstrated that effects of dilution from mixing have a major influence on tritium concentrations in the Madison and Minnelusa aquifers. For slug-flow conditions, water recharged between about 1962 and 1970 would have tritium concentrations of about 70 TU to as much as several hundred TU for all sample dates prior to 1998 (fig. 26). Tritium concentrations for the 96 ground-water samples collected since 1990, however, are uniformly less than 70 TU (fig. 33), indicating a conspicuous absence of values reflecting slug-flow conditions for recharge during this period. Concentrations indicative of “pulses” consisting of several consecutive years of recharge during this peak-tritium period also are absent from the sample set. Dual-porosity flow conditions consisting of a combination of near-slug flow scenarios (which may include recently recharged water) and general mixing with older water, however, are entirely plausible and are consistent with the range of sampled values (fig. 33).

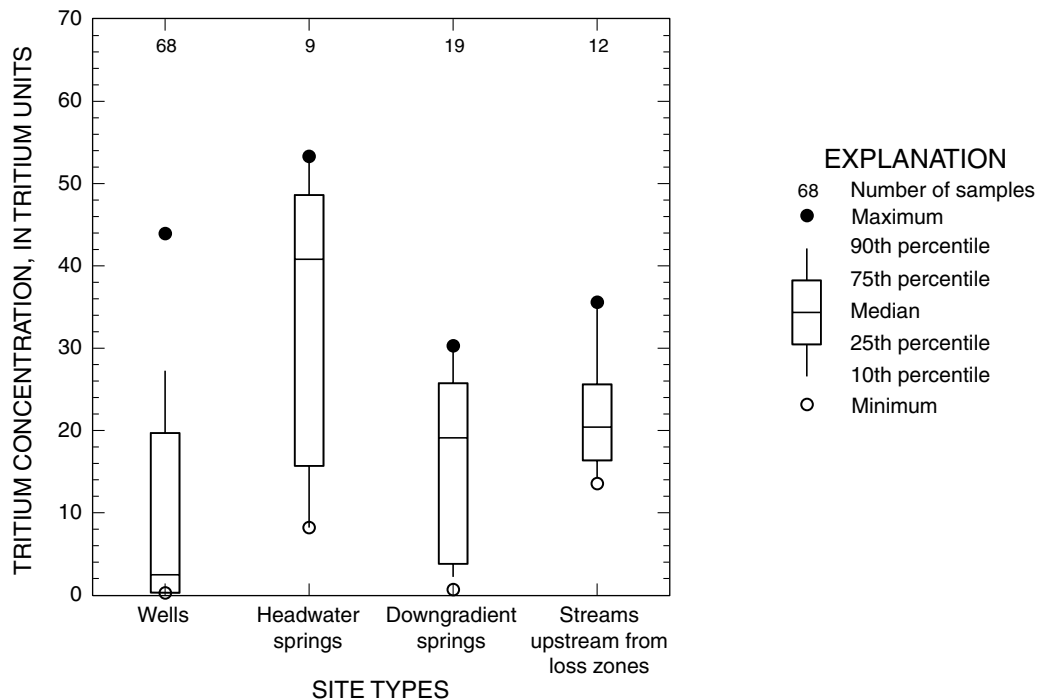


Figure 33. Boxplots of tritium concentrations for selected ground-water and surface-water samples collected during 1990-98 in the Black Hills area.

Sophisticated methods are available to address the numerous mixing possibilities in complex hydrologic settings. Combinations of lumped-parameter models have been used, for example, to represent settings where both slug-flow and mixed-reservoir effects are important (Maloszewski and Zuber, 1982; Zuber, 1986; Richter and others, 1993). Compartmental mixing models (Yurtsever and Payne, 1986) and combinations of environmental tracer techniques with numerical ground-water flow models (Reilly and others, 1994) also have been used to address complicated hydraulic settings. These methods, however, require more extensive data sets than those that are currently available. Future collection of time-series tracer data in the Black Hills area would facilitate more sophisticated evaluations of mixing conditions and ground-water ages. The tritium data and conceptual models presented in this report, in conjunction with stable-isotope and major-ion data, can be used to draw various conclusions about flowpaths and mixing conditions in the Black Hills area, as discussed in subsequent sections.

Site-Specific Considerations

Site-specific discussions of isotopic interpretations regarding areal flowpaths, ages, and mixing conditions for the Madison and Minnelusa aquifers in the Black Hills area are presented in this section. The Rapid City area is discussed first because detailed data sets are available for this area. Discussions of head-water springs and northern and southern Black Hills areas also are included. Previous discussions of general considerations for stable isotopes included various interpretations regarding recharge areas and general flowpaths for several example sites along the northern and northeastern flanks of the uplift; these examples are not repeated herein.

Rapid City Area

A large data set is available for the Rapid City area for stable isotopes (fig. 28) and tritium (fig. 31), with multiple samples available for many sites (tables 7 and 8). Evaluation of flowpaths and mixing conditions for the Rapid City area is especially complicated because: (1) recharge generally is dominated by streamflow losses, rather than precipitation on outcrop areas (Carter, Driscoll, and Hamade, 2001); and (2) large and variable withdrawals from the Madison and Minnelusa aquifers have occurred. Municipal production from the Madison aquifer has increased substantially since about 1990 (Anderson and others, 1999).

As previously discussed, a distinct division of stable isotope values is apparent for the Madison aquifer along Rapid Creek. Areas south of Rapid Creek reflect isotopic composition similar to Spring Creek, which is isotopically heavier than Rapid Creek and Boxelder Creek (fig. 21). Sites north of Rapid Creek generally reflect isotopically lighter composition similar to that of Rapid Creek and Boxelder Creek. Isotopic composition of precipitation on outcrops in the Rapid City area is heavier than in Rapid and Boxelder Creeks and averages about -13 to -14 ‰ (fig. 20). The $\delta^{18}\text{O}$ values for several Madison wells north of Rapid City (sites 130, 138, and 145) reflect this heavier isotopic composition (fig. 28), which probably indicates larger influence from precipitation recharge. The $\delta^{18}\text{O}$ values for Minnelusa wells in the Rapid City area show a general gradation from north to south of lighter to heavier values, with no distinct division, which probably indicates larger influence from precipitation recharge, than for the Madison aquifer in this area.

The $\delta^{18}\text{O}$ values for the Madison wells south of Rapid Creek probably indicate a northerly flow component for recharge in the Spring Creek area. The $\delta^{18}\text{O}$ values for springs along Rapid Creek, however, indicate flow from different sources. Cleghorn (site 300) and Jackson Springs are large springs with combined discharge in excess of 20 ft³/s, which probably are recharged primarily by Spring Creek, Rapid Creek, and precipitation on outcrop areas to the southwest and west (Anderson and others, 1999). Dye testing has confirmed rapid movement of water from a loss zone in Boxelder Creek to City Springs (site 298) and several wells in northwestern Rapid City; however, detectable dye concentrations have not been recovered in Cleghorn Springs (Rahn, 1971; Greene, 1999). The $\delta^{18}\text{O}$ value for Tittle Springs (site 299) is notably lighter than for precipitation in the outcrop area, which probably indicates recharge from Rapid Creek.

Results of dye testing in the Rapid City area (Greene, 1999), in combination with tritium samples, provides relatively definitive age-dating information for several sites. Dye was injected in the loss zone of Boxelder Creek (site 315) during August 1993. A tritium concentration of 58.1 TU was measured in Boxelder Creek one month later (table 7). Greene (1999) reported dye recovery at several sampling locations, including site 112 (Black Hills Power and Light) and site 123 (Rapid City No. 10), with dye arrival times of 41 and 49 days, respectively, and tritium concentrations of 3.7 and 4.7 TU.

The conceptual mixing models, which are based on an assumption of equal annual recharge proportions, are unable to provide age estimates that are compatible with dye results. Using a 0-year delay curve for 1993 (fig. 36F), which is consistent with prompt dye arrival, maximum traveltimes dating back hundreds of years are indicated for the sample concentrations of 3.7 and 4.7 TU. Dye concentrations in the resulting mix would be much lower than reported by Greene (1999) and probably would be undetectable. Unequal mixing of about 5 to 10 percent very recent water (tritium concentration of about 58 TU) with 90 to 95 percent pre-bomb water (0 TU) would produce a viable mix. Intermediate-age water (with high tritium concentrations) probably is not entirely absent; however, the proportion contributed to the mix must be extremely small. This scenario is a noteworthy example of unequal mixing conditions that can occur in a dual-porosity system.

Greene (1999) also reported dye recovery at sites 116 (Rapid City No. 6), 121 (Westberry Trails), and 298 (City Springs), with dye arrival times of 30, 26, and 30 days, respectively, and tritium concentrations of 14.5, 31.0, and 40.8 TU. Dye also was recovered at site 117 (City Quarry Madison), which had a tritium concentration of 26.3 TU; however, an arrival time was not reported. Viable estimates of maximum traveltime can be made for these samples using a 0-year delay mixing model; however, the resulting mixes again are not compatible with reported dye concentra-

tions. Unequal mixes of very recent and older water again provide more plausible explanations.

Subsequent samples collected during 2000 from Boxelder Creek, Rapid City No. 10, and City Springs had tritium concentrations of 15.9, 7.3, and 25.7 TU, respectively (table 4). The increased tritium concentration in the sample from Rapid City No. 10 probably indicates an increased proportion of recent water (perhaps approaching 50 percent), which is attributed primarily to effects of pumping during the interim years. The well was constructed during 1991 and produces about 1,800 gal/min (Anderson and others, 1999). The tritium concentration of the 2000 sample for City Springs is higher than the corresponding Boxelder Creek sample, whereas the concentration of the 1993 sample was lower, which may be indicative of transient flow and mixing conditions associated with changing recharge and discharge conditions.

Additional insights are obtained from examination of temporal variability in stable isotope values for ground-water sites. Data for sites with multiple samples are listed in table 8 and selected sites are shown in figure 21B, which was presented earlier. The four wells in which dye was recovered (Black Hills Power and Light, Rapid City Nos. 6 and 10, and Westberry Trails) and City Springs show only minor variability in $\delta^{18}\text{O}$ values. This dampened response to relatively large variability in $\delta^{18}\text{O}$ values recharged by Boxelder Creek is consistent with the traveltime analysis, which indicates relatively small proportions of recent water.

Table 4. Tritium data for selected sites having data for 2000

[Data are included in table 7; --, no data available]

Site number	Name	Tritium, in tritium units				
		1991	1993	1996	1997	2000
123	Rapid City No. 10	--	4.7	--	--	7.3
169	Rapid City No. 11	10.7	16.6	16.0	--	12.0
172	Rapid City No. 9	21.0	24.3	--	22.3	18.2
195	Hart Ranch	--	23.5	21.6	--	17.7
298	City Springs	--	40.8	--	--	25.7
315	Boxelder Creek near Nemo	--	58.1	--	26.8	15.9

Cleghorn Springs (site 300) provides an example of ground-water flow and mixing conditions that may be reasonably represented by the time-delay mixing model. The $\delta^{18}\text{O}$ values (fig. 21C) for 1986-95 have only minor variability (-12.80 to -12.95 ‰) and values for 11 samples collected between January 1999 and May 2000 range only from -13.09 to -13.19 ‰ (L.D. Putnam, U.S. Geological Survey, written commun., 2000). Thus, a delayed and dampened response to the temporal trends in Spring and Rapid Creeks is indicated (fig. 21A). Tritium concentrations in Cleghorn Springs (table 7) from 1978 (182 TU) and 1993 (30.2 TU) indicate dominant proportions of water recharged within a timeframe of about 10 to 20 years (fig. 36, graphs A and F). Estimates of older age also are possible for each sample, but probably can be discounted because of the response of $\delta^{18}\text{O}$ values to recharge conditions.

Temporal changes in mixing conditions and age characteristics probably have occurred in the vicinity of several high-production wells in the Rapid City area that have been completed since about 1990 (Anderson and others, 1999). Potential changes for site 123 (Rapid City No. 10) were discussed previously. An initial (1991) $\delta^{18}\text{O}$ sample for site 172 (Rapid City No. 9) is notably lighter than later samples, which show negligible variability during subsequent years (table 8, fig. 21B). Tritium concentrations (table 4) increased from 21.0 to 24.3 TU (1991 to 1993), which probably indicates a larger component of more modern water in an altered mix. Steadily decreasing tritium concentrations measured in 1997 and 2000 may be indicative of progressive decay of a relatively long-term mix, which is consistent with stabilized $\delta^{18}\text{O}$ values. The decay-curve families for 1993 and 1997 (fig. 36, graphs F and J) show a variety of plausible age estimates.

Tritium concentrations for site 169 (Rapid City No. 11) also increased between 1991 and 1993 (table 4), which may indicate a response to initial production. Subsequent tritium samples for 1996 and 2000 have smaller concentrations. The $\delta^{18}\text{O}$ values (fig. 21C) trend towards progressively lighter values, which probably reflects a response to the Spring Creek trend. The tritium decay-curve families for 1991, 1993, and 1996 (fig. 36, graphs D, F, and I) generally provide no solutions for mixes involving water recently recharged (within several years), which is indicated by the $\delta^{18}\text{O}$ values. Thus, unequal mixing of recent and pre-bomb water is a likely scenario at this site.

The $\delta^{18}\text{O}$ values for site 185 (Rapid City No. 5) show a trend towards progressively heavier water (fig. 21B), which is opposite to the trend in streamflow recharge. The single available tritium concentration of 4.3 TU in 1993 indicates probable dominance by old water, which would tend to dampen $\delta^{18}\text{O}$ variability. A plausible explanation is increased proportions of isotopically heavier water from the south-southwest or from the overlying Minnelusa aquifer (fig. 28), induced from recent production. Either source would be consistent with aquifer test results (Greene, 1993) that showed strongly directional transmissivities and leaky confinement at this site. Tritium concentrations of <0.3 TU were measured in 1990 and 1993 from the Lime Creek observation well (site 186), which is located about 700 ft away from Rapid City No. 5. Rapid City No. 5 produces about 1,700 gal/min, which indicates that the well is located in a transmissive part of the aquifer. The low tritium concentrations in both wells, however, may indicate that: (1) the matrix is not exchanging much water with preferential flowpaths; or (2) preferential flowpaths are not well connected to modern recharge sources.

Variability in $\delta^{18}\text{O}$ values for site 195 (Hart Ranch) is the largest of any ground-water site for which temporal data are available (fig. 21C). Variability during 1986-95 appears to be small; however, data for 1987-93 are absent. Values for 1996-98 are notably lighter than for previous periods, which again is consistent with the trend for Spring Creek. Tritium concentrations decreased steadily for samples from 1993, 1996, and 2000 (table 4), which can be indicative of long-term mixes. However, this mixing condition contradicts the $\delta^{18}\text{O}$ data, which indicate a relatively large response to recent recharge.

Tritium data for sites 168 and 176 (Chapel Lane Madison wells), which are located within 1,000 ft of each other (fig. 31), provide an example of large differences in ground-water ages and mixing conditions resulting from aquifer heterogeneity. Low tritium concentrations for site 176 for 1991 and 1993 samples (1.9 and 2.2 TU, respectively) indicate production primarily from the aquifer matrix. A much higher tritium concentration from 1993 (27.5 TU) for site 168 indicates production primarily from preferential flowpaths, which is supported by variability in $\delta^{18}\text{O}$ values (fig. 21C). Another example of aquifer heterogeneity is provided by the low tritium concentration for site 191 (Reptile Gardens Madison well) that is located generally upgradient from site 195 (Hart Ranch), which has a much higher tritium concentration.

A low (undetectable) tritium value for site 124 (Rapid City No. 8) is consistent with small $\delta^{18}\text{O}$ variability (fig. 21B) and with large distance from the outcrop (fig. 31). The $\delta^{18}\text{O}$ values (fig. 21C) for site 149 (Highland Hills) show large variability, which is consistent with relatively high and variable tritium concentrations (table 4). The $\delta^{18}\text{O}$ values (fig. 21C) for site 165 (Carriage Hills) show less variability than Highland Hills, but trend more steadily towards lighter values, which may indicate more dampened response to recent recharge. The single tritium sample (22.9 TU) for site 165 provides no information beyond confirming the presence of modern water. For the Pine Grove well (site 196), which is located just south of the Rapid City area (fig. 29), moderate variability in $\delta^{18}\text{O}$ values (fig. 21C) is consistent with the tritium concentration of 25.9 TU (fig. 32).

Headwater Springs

The stable isotope values for headwater springs were used in developing the map of generalized spatial

distribution for $\delta^{18}\text{O}$ for the Black Hills area (fig. 20). Temporal variability in $\delta^{18}\text{O}$ values is small for headwater springs (table 8), which supports the use of the immediate-arrival mixing model (fig. 25B) for general evaluation of ground-water ages in this hydrologic setting. The use of the immediate-arrival model is further supported by the distribution of tritium concentrations for headwater springs, relative to wells and down-gradient springs, as discussed previously (fig. 33). All of the headwater springs are located within or near aquifer outcrops, with some recharge presumably occurring in the immediate proximity of springs. Generalized age estimates for headwater springs are presented in table 5.

The age estimates in table 5 are derived using the 0-year delay curves (fig. 36) for the appropriate date of sample collection. A mix of equal proportions from all years between the minimum (0 years for immediate arrival) and maximum traveltimes is assumed for this mixing model. Two possible estimates for the maximum traveltime exist for most samples; thus, “young” and “old” estimates are provided for each sample.

Table 5. Generalized age estimates for headwater springs, derived using immediate-arrival mixing model¹

[--, unnamed)

Site number	Spring name	Sample date	Tritium concentration (tritium units)	Minimum travel-time ¹ (years)	Maximum traveltimes ¹ (years)			
					Young estimate		Old estimate	
					Year range ²	Average of range	Year range ²	Average of range
276	Knight	08-04-95	40.8	0	1965-67	30	1900-20	80
277	Jones	01-01-78	276.0	0	1963-65	14	1948-54	27
279	--	³ 07-18-96	40.8	0	1964-66	31	1915-25	76
280	--	08-08-95	53.3	0	1964-65	30	1930-40	60
281	JHD	09-13-95	53.3	0	1964-65	30	1930-40	60
282	Intake Gulch	08-03-95	31.3	0	1967-69	27	1875-95	110
283	Rhoads Fork	⁴ 01-01-78	62.2	0	1972-78	3	1840-60	130
		08-07-95	43.9	0	1965-66	30	1910-30	75
287	Barrel	07-25-95	18.5	0	1975-95	0-20	1800-30	160
288	Water Draw	09-14-95	12.9	0	(⁵)	(⁵)	pre 1800	>200
289	McKenna	09-14-95	8.2	0	(⁵)	(⁵)	pre 1700	>300

¹For immediate arrival model, a mix of equal proportions from all years between minimum and maximum traveltimes is assumed. Two solutions for the maximum traveltime are possible for most samples.

²Range of years for maximum traveltimes.

³Exact sample date unknown (see table 7).

⁴Location for the 1978 sample is unknown and probably does not exactly coincide with the 1995 sampling location. Exact sample date also unknown (see table 7).

⁵No mixing solution available for younger estimate using immediate-arrival model; however, plausible solutions for unequal mixing are possible.

Two of the springs (Jones and Rhoads Fork) were sampled during 1978. The tritium concentration for Jones Spring (276 TU) is very high and shows a substantial proportion of water recharged near the 1963 peak (figs. 26 and 36A). The concentration for Rhoads Fork (62.2 TU) is much lower, indicating either: (1) dominance by recharge after 1972; or (2) maximum travel times exceeding about 100 years. In deriving the young estimate, it was necessary to assume a slightly higher tritium concentration (about 80-100 TU) in order to obtain a viable solution. An additional (1995) sample for Rhoads Fork provides a conflicting age estimate; however, the precise location of the 1978 sample is not known and is presumed to be different.

The young estimates for many of the springs indicate maximum travel times dating to the mid 1960's (just subsequent to the tritium peak of 1963). The old estimates for most springs indicate maximum travel times approaching or exceeding 100 years. Notable exceptions are the last three springs listed in table 5, for which old estimates are much older than for other headwater springs. Viable solutions for young estimates for these springs cannot be obtained using the immediate arrival mixing model (fig. 36H); however, unequal mixing conditions involving recently recharged water are plausible.

Continuous records of daily discharge for site 283 (Rhoads Fork) indicate dominance by ground-water discharge, with virtually no short-term variability in streamflow. Annual streamflow, however, correlates strongly with 9-year moving average precipitation (Driscoll and Carter, in press). Flow characteristics are similar for a gaging station downstream from site 282 (Intake Gulch). The thickness of the Madison Limestone near these two sites (Carter and Redden, 1999e) is insufficient to accommodate storage volumes associated with the old estimates. Thus, the old estimates for Rhoads Fork and Intake Gulch are not considered plausible.

Northern Black Hills Area

Several large artesian springs are located along the northern axis of the Black Hills uplift, all of which are presumed to originate primarily from the Madison and/or Minnelusa aquifers, based on the work of Klemp (1995), who evaluated source aquifers using geochemical modeling. These springs are a major discharge area for these aquifers, with cumulative

discharge of all artesian springs along the northern flank estimated as 90 ft³/s for 1987-96 (Carter, Driscoll, Hamade, and Jarrell, 2001). The potentiometric-surface maps for the Madison and Minnelusa aquifers (figs. 7 and 8) indicate primary flow components to these springs from the south and west. The possible contribution of regional flow components from the west (fig. 6) is evaluated in a subsequent section.

A substantial component of recharge from the Black Hills area is indicated for these artesian springs by the $\delta^{18}\text{O}$ values (fig. 27), which are similar to values in large recharge areas to the south and west (fig. 20), which may extend to the Limestone Plateau. With the exception of site 294 (Mirror Lake), the $\delta^{18}\text{O}$ values for these springs are very similar, which probably indicates generally thorough mixing conditions associated with large discharges and associated large recharge areas. The $\delta^{18}\text{O}$ values for springs also are very similar to those for Madison and Minnelusa wells in this area. Values for wells generally grade to slightly heavier values in a southeasterly direction, reflecting more localized flowpaths (figs. 7 and 8) with isotopically heavier composition (fig. 20).

The $\delta^{18}\text{O}$ value for site 294 (Mirror Lake) is similar to that for site 34 (fig. 20, State Line Minnekahta well), which may indicate a recharge contribution from the Minnekahta aquifer or localized recharge from other low-elevation outcrop areas. The tritium concentration for site 294 (fig. 30) also is notably lower than for three other springs in close proximity, which also may indicate a different recharge source. The relatively high tritium concentrations for the artesian springs do not necessarily preclude regional flow contributions, but indicate a substantial recharge contribution from areas within the Black Hills area.

The similarities in isotope values in the vicinity of the large springs probably indicates generally uniform mixing conditions, which is consistent with the physical setting (major discharge area with large recharge area) and supports the general applicability of the time-delay mixing model for general evaluation of ground-water ages. Tritium samples for two wells that are located about one-quarter mile apart along Crow Creek (fig. 30) provide a useful starting point for evaluation of ground-water ages. Site 43 (McNenny well No. 1) was sampled in 1978 (11.4 TU) and site 44 (McNenny well No. 2) was sampled in 1994 (19.4 TU). Applying the time-delay mixing model for the earlier

sample (fig. 36A) indicates viable solutions only for delay times in the range of about 16 to 24 years. Considering both samples, a common solution with a maximum traveltime of about 175 years can be obtained using a delay time of 16 years. Viable solutions with similar delay times and maximum traveltimes exist for site 293 (McNenny Rearing Pond) and site 296, which consists of the cumulative discharge of numerous springs along Crow Creek, as well as for site 295 (Cox Lake), which is located about 1 mi farther east. The theoretical solutions for these samples are relatively insensitive to changes in delay time, for delay times up to about 28 years.

Tritium samples from 1994 and 1997 are available (table 7) for sites 290 (Higgins Gulch) and 292 (Old Spearfish Hatchery) located northwest of Spearfish (fig. 30). For site 290, the tritium concentrations are 31.3 and 28.1 TU, respectively, for which numerous combinations of delay times and residence times provide comparable solutions. Two $\delta^{18}\text{O}$ values for the same years (-16.47 and -16.25 ‰, respectively) may be sufficiently different to indicate relatively short-term response to transient recharge conditions. For site 292, a large difference in tritium concentrations exists between the 1994 sample (26.0 TU) and the 1997 sample (13.4 TU), strongly indicating short-term response to transient recharge conditions.

A single 1978 tritium sample for site 82 (65.6 TU) is nearly identical to estimated concentrations in precipitation for that period (fig. 26). The immediate-arrival mixing model may be applicable because this Madison well is located within the outcrop area. In contrast, tritium was not detected for site 95, which also is located within the Madison outcrop near Blackhawk. Tritium also was not detected for sites 6, 106, and 148, all of which are very remote from outcrop areas. Large variability in traveltimes is apparent for other wells along the northeastern flank. Substantial influence of modern recharge is apparent for springflow along Elk Creek (site 297), which is consistent with general characteristics for artesian springs.

Southern Black Hills Area

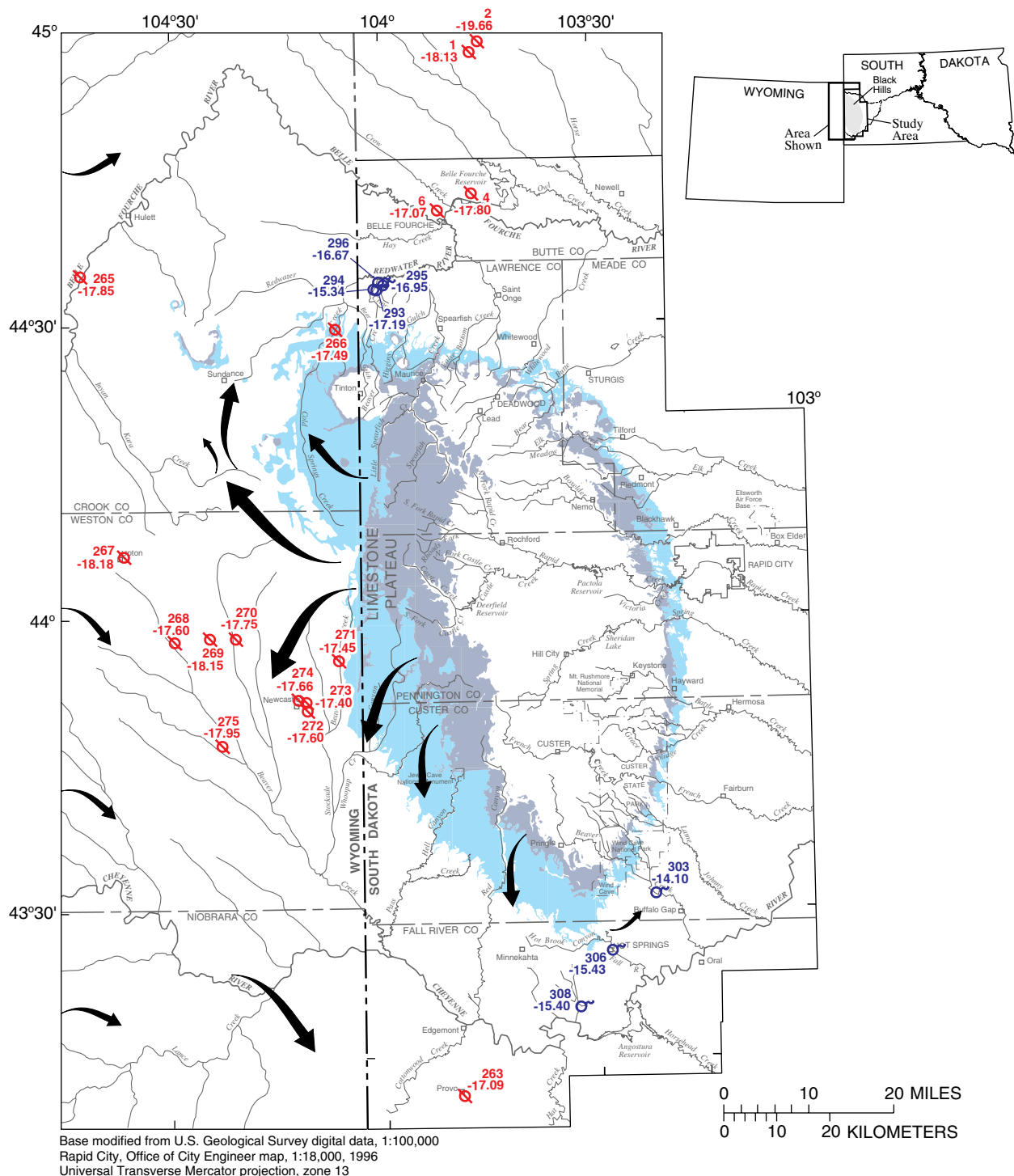
The $\delta^{18}\text{O}$ values for sites near Battle, Grace Coolidge, and French Creeks are in the range of about -11.5 to -12.0 ‰ (fig. 29) and are very similar to values

for the nearby streamflow loss zones (fig. 20). Recharge in this area is dominated by streamflow recharge (Carter, Driscoll, Hamade, and Jarrell, 2001) because of larger drainage areas for contributing streams, relative to outcrop areas of the Madison and Minnelusa Formations. Tritium concentrations for artesian springs along Battle and Grace Coolidge Creeks (sites 301 and 302) indicate younger water than for several nearby wells (fig. 32), which is consistent with mixing conditions associated with the development of artesian springs along preferential flowpaths.

The $\delta^{18}\text{O}$ values for sites in recharge areas (fig. 20) along the southwestern flank of the uplift are isotopically lighter than for sites along the southeastern flank, which probably reflects larger influence from storms of Pacific origin along the western flank. Downgradient sites along the southwestern flank (fig. 29) reflect this lighter isotopic composition, with $\delta^{18}\text{O}$ values that generally are even lighter than those in nearby outcrop areas. This pattern indicates generally southeasterly flowpaths originating in higher elevation areas to the north. This conclusion is supported by tritium concentrations for downgradient wells in this area (fig. 32), which generally are dominated by pre-bomb water, indicating generally long traveltimes and flowpaths. The possible influence of regional flowpaths from the west is discussed in the following section. Complex flowpaths in the southern Black Hills also may be influenced by interactions between the Madison and Minnelusa aquifers, which also are discussed in subsequent sections.

REGIONAL FLOWPATHS

Regional flow characteristics (fig. 6) are an important consideration in evaluating flowpaths, especially near the northern and southern axes of the uplift. Generalized regional flowpaths for the Madison aquifer near the study area, which are based on the following discussions, are presented in figure 34, along with $\delta^{18}\text{O}$ values for samples from selected artesian springs and Madison wells. The artesian springs shown are major discharge points for the Madison and/or Minnelusa aquifers and do not necessarily consist entirely of flow from the Madison aquifer. Information is not available for evaluation of possible regional influences for the Minnelusa aquifer.



EXPLANATION

- OUTCROP OF MADISON LIMESTONE (from Strobel and others, 1999; DeWitt and others, 1989)
- OUTCROP OF MINNELUSA FORMATION (from Strobel and others, 1999; DeWitt and others, 1989)
- GENERALIZED FLOWPATH
- 263
-17.09 WELL COMPLETED IN MADISON AQUIFER--Numbers indicate site number and $\delta^{18}\text{O}$ value in per mil
- 308
-15.40 DOWNGRADIENT SPRING--Numbers indicate site number and $\delta^{18}\text{O}$ value in per mil

Figure 34. Distribution of $\delta^{18}\text{O}$ in selected Madison wells and springs and generalized flowpaths, based on $\delta^{18}\text{O}$ values, in the Black Hills of South Dakota and Wyoming.

The $\delta^{18}\text{O}$ values for sites 1 and 2 (north of the study area) are -18.13‰ and -19.66‰ , respectively (fig. 34), which are much lighter than any of the values in Black Hills recharge areas (fig. 20). Busby and others (1983) and Plummer and others (1990) note Madison wells near recharge areas in Wyoming near the Bighorn Mountains with $\delta^{18}\text{O}$ values as light as -18.5‰ and near the Laramie Mountains as light as -19.25‰ . In addition, concentrations of sodium (45 and 36 mg/L, respectively), chloride (67 and 25 mg/L), and sulfate (1,700 and 1,600 mg/L) for sites 1 and 2 (Busby and others, 1991) are approximately an order of magnitude higher than for wells along the northwestern flank of the Black Hills (fig. 10) and are consistent with a regional flowpath trending northeasterly from the Bighorn Mountains in Wyoming. This information provides strong evidence of a regional flow component from the west, just north of the study area.

The $\delta^{18}\text{O}$ values for sites 4 and 6 (near Belle Fourche) and large artesian springs on the northwestern flank of the uplift (sites 293- 296) are consistent with values in Black Hills recharge areas (fig. 20). Major-ion concentrations for site 6 (fig. 10) also are consistent with values near the uplift and show no influence from regional flowpaths. Major-ion concentrations for site 4 are slightly higher than site 6, and the $\delta^{18}\text{O}$ value is more similar to site 1 than site 6, indicating more evolved ground water at this well and perhaps a slight regional influence. However, south of site 4, the Madison aquifer probably is not influenced by regional flow from the west. Relatively high calcium and sulfate concentrations for some of the springs (fig. 35) are similar to many Minnelusa wells (fig. 11) and probably are influenced by dissolution of anhydrite in the Minnelusa aquifer, as discussed later. Relatively high tritium concentrations for the springs (fig. 30) indicate substantial influence from modern recharge and support the conclusion that flow near the northern flank of the uplift is dominated by Black Hills recharge.

The $\delta^{18}\text{O}$ values for sites 271- 274, just west of the South Dakota/Wyoming border (fig. 34) are similar to, but slightly lighter than, the estimated isotopic composition in nearby recharge areas (fig. 20). The $\delta^{18}\text{O}$ values for sites farther west are somewhat lighter and provide an indication of possible influence from regional flow from the west. Busby and others (1991) reported sodium, chloride, and sulfate concentrations for site 275 of 11.0, 7.6, and 200 mg/L, respectively,

which also could indicate influence from regional flow. The reported sulfate concentration for site 265 (210 mg/L) is similar; however, sodium (3.7 mg/L) and chloride (2.6 mg/L) concentrations show little, if any, influence of regional flow. Reported major-ion concentrations for all other sites in Wyoming are much lower and essentially preclude possible influence from regional flow.

For site 263 near Provo, sodium (200 mg/L) and chloride (270 mg/L) concentrations are high and may indicate influence of regional flow or the presence of evaporites. The sulfate concentration (310 mg/L) is similar to some regional values reported by Busby and others (1991), but is lower than values for sites 1 and 2 north of the study area, which are influenced by regional flow. Thus, increasing constituent concentrations resulting from basinward evolutionary processes cannot be distinguished from a potential regional flow component. The $\delta^{18}\text{O}$ value of -17.09‰ for site 263 (fig. 34) does not preclude a regional flow component, but probably does preclude recharge originating south of about Pennington County (fig. 20).

Sodium and chloride concentrations for large springs near the southern axis of the uplift (fig. 35) are sufficiently high to indicate possible influence of regional flow. Anomalously high sodium and chloride concentrations in this area (Whalen, 1994) are indicated by Stiff diagrams for various Madison and Minnelusa wells (figs. 10 and 11). Chloride concentrations also are comparable with those for several other wells (table 3) that have no possible influence from regional flow. Examples include the Tinton Road (site 36) and City Quarry (site 117) Madison wells. High calcium and sulfate concentrations for sites 307 (Cool Spring), 308 (Cascade Springs), and other springs in this area probably are influenced by dissolution of anhydrite in the Minnelusa aquifer, as discussed in a subsequent section. The $\delta^{18}\text{O}$ values for large springs northeast of Provo (fig. 34) are much heavier than for site 263 and for sites in Wyoming, which indicates dominant recharge from within the study area, including influence of isotopically heavy recharge along the southwestern flank of the uplift, within Custer County (fig. 20). Low, but detectable, tritium concentrations in these springs (fig. 32) indicate relatively long travel times, but confirm the influence of recharge from within the study area.

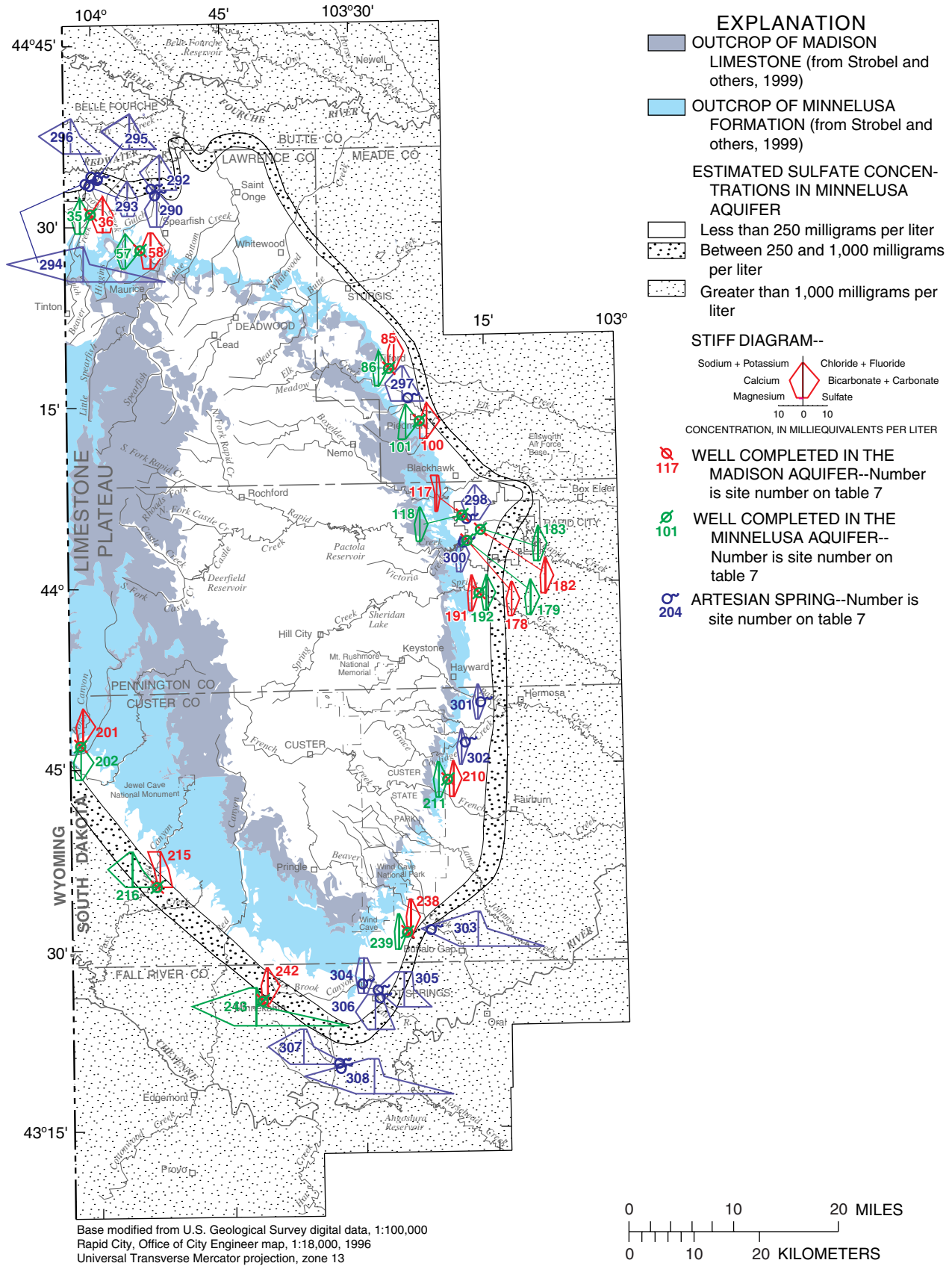


Figure 35. Selected Stiff diagrams showing the distribution of major-ion chemistry in selected well pairs and artesian springs in the Black Hills area.

The $\delta^{18}\text{O}$ value of -14.10 ‰ for Beaver Creek Spring (site 303) is much lighter than estimated values for nearby outcrop areas (fig. 20) and nearby wells (fig. 29), which indicates a possible flowpath extending from the general Hot Springs area. Such a flowpath would include a substantial component of isotopically light water recharged west of the uplift axis and would require ground-water flow nearly parallel to mapped potentiometric contours (figs. 7 and 8) in some areas. This hypothesis is possible, given the hydraulic characteristics of the Madison and Minnelusa aquifers (Long, 2000), a hydraulic gradient in that direction, and the accuracy of potentiometric-surface mapping, which is limited by sparsity of data points in the area (Strobel and others, 2000a, 2000b). A flowpath from the Hot Springs area to Beaver Creek Spring is supported by three general factors, including: (1) a low tritium concentration for site 303 (fig. 32) indicating generally long travel times; (2) the areal distribution of $\delta^{18}\text{O}$ values (fig. 29) relative to recharge areas (fig. 20), indicating generally southeasterly (nonorthogonal) flowpaths along the southwestern flank; and (3) results of a water-budget analysis (Carter, Driscoll, Hamade, and Jarrell, 2001), which indicates a substantial flow component to Beaver Creek Springs from west of the uplift axis.

Evaluation of all available geochemical information indicates that regional flowpaths for the Madison aquifer are essentially deflected around the study area, with the possible exception of the southwestern and northwestern corners. Sites 1 and 2 (fig. 34) north of the study area show definite influence from regional flowpaths; however, areas south of site 4 are dominated by local recharge and probably have negligible regional influence. Major-ion chemistry for sites in the southwestern corner of the study area (fig. 10) indicate possible regional influence; however, north of this area regional influence probably is minor or negligible. The potentiometric-surface map for the Madison aquifer (fig. 7) neither confirms nor precludes a regional influence in these areas.

INTERACTIONS BETWEEN MADISON AND MINNELUSA AQUIFERS

Hydrographs for numerous well pairs indicate distinct hydraulic separation between the Madison and Minnelusa aquifers in many areas (Driscoll, Bradford, and Moran, 2000); however, possible hydraulic

connection is indicated in other areas. Hydraulic connection probably occurs at various artesian springs around the periphery of the Black Hills, many of which are stratigraphically located within or slightly above the Minnelusa Formation. Previous investigators (Rahn, 1971; Whalen, 1994; Klemp, 1995; Hayes, 1999) have identified the Madison and Minnelusa aquifers as potential sources for many artesian springs.

Geologic conditions facilitate hydraulic connection between the two aquifers. Confining layers in the lower portion of the Minnelusa Formation probably are influenced by paleo-karst features such as caverns and sinkholes in the upper Madison Limestone. Extensive fracturing and solution activity have contributed to extensive secondary porosity in both formations and decreased competency of the confining layers. Potential exists for downward leakage (from Minnelusa to Madison) in recharge areas where the aquifers are unconfined (water-table conditions), and for leakage in either direction, depending on direction of hydraulic gradient, where artesian conditions exist. In this section, potential interactions are evaluated through analysis of hydraulic and geochemical information for well pairs and artesian springs.

Interactions at Well Pairs

Potential interactions between the Madison and Minnelusa aquifers are evaluated through examination of hydraulic and geochemical information for well pairs. This section primarily addresses the potential for general, areal leakage between the aquifers.

Hydraulic Considerations

Hydrographs for 13 well pairs (26 wells), for which geochemical information is available, are presented as figure 37 in the Supplemental Information section. Locations of well pairs are shown in figure 35. A summary of hydraulic comparisons for these well pairs is included in table 3, which was presented previously.

Hydrographs for 9 of the 13 well pairs are fairly well separated and do not indicate direct hydraulic connection. Hydrographs are nearly identical in hydraulic head and shape for the City Quarry wells (fig. 37E) and the CSP Airport wells (fig. 37J). Hydrograph shapes for the Tilford wells (fig. 37C) are similar; however, hydraulic heads are slightly different. Hydrographs for the Reptile Gardens wells (fig. 37H)

have some similarities; however, the period of record is insufficient to be definitive.

Similar hydrographs could result from similar hydraulic characteristics and recharge/discharge characteristics, rather than hydraulic connection. Of the four well pairs with similar hydrographs (table 3), hydraulic connection has been confirmed by aquifer testing (Greene, 1993) only for the City Quarry wells (fig. 37E). These wells are located about one-half mile from City Springs, which emerge through the Minnelusa Formation, but have been shown through dye testing to originate from the Madison aquifer (Greene, 1997, 1999). Absence of effective hydraulic connection at some wells in the Rapid City area has been indicated by aquifer testing (Greene, 1993), as exemplified by the lack of response for the Sioux Park Minnelusa well (fig. 37G). Aquifer testing for two production wells in the Spearfish area also indicated no measurable hydraulic connection between the Madison and Minnelusa aquifers for the wells tested (Greene and others, 1999). Given the wide variety of hydrograph shapes, the striking similarities for the CSP Airport wells (fig. 37J) and Tilford wells (fig. 37C) probably result from hydraulic connection.

Conversely, hydraulic connection does not necessarily mean hydrographs will be similar. The Madison and Minnelusa aquifers probably are hydraulically connected at Cleghorn and Jackson Springs, which emerge through the Minnelusa Formation, but probably originate primarily from the Madison aquifer, as discussed later. The Canyon Lake wells (fig. 37F), which are located about one-fourth mile away, show no indication of connection, however.

Hydraulic head is higher in the Madison aquifer than in the Minnelusa aquifer for 10 of the 13 wells pairs considered (table 3, fig. 37). One exception is the CSP Airport wells (fig. 37J), where heads are nearly identical. The other exceptions are the Tinton Road wells (fig. 37B) and the Boles Canyon wells (fig. 37I), where water-table conditions occur in both aquifers. Paired wells are measured in five other locations where artesian conditions exist (Driscoll, Bradford, and Moran, 2000); however, paired geochemical data are not available. Hydraulic head in the Minnelusa aquifer consistently exceeds that of the Madison aquifer at only one of these locations. Thus, for areas near the outcrops with artesian conditions, the greatest leakage potential generally is from the Madison aquifer to the Minnelusa aquifer.

Geochemical Considerations

In this section, geochemical information for Madison/Minnelusa well pairs is examined for evidence of leakage between the two aquifers. Geochemical interpretations may be influenced by effects of well construction, especially for the Minnelusa aquifer, in which observation wells typically are completed only in the top of the aquifer (Driscoll, Bradford, and Moran, 2000).

Stiff diagrams (fig. 35) indicate major-ion chemistry is very similar for many well pairs, especially near outcrop areas. The most notable differences are in concentrations of sulfate, which increase with increasing distance from recharge areas in the Minnelusa aquifer. Comparisons of sulfate concentrations for well pairs are provided in table 3.

The distribution of $\delta^{18}\text{O}$ values in the Black Hills area, including well pairs, was presented in figures 27-29. Values for $\delta^{18}\text{O}$ for well pairs are summarized in table 3, with lighter values in the Madison aquifer for 10 of the 13 well pairs, which reflects generally higher recharge elevations than for the Minnelusa aquifer. Paired values also are categorized as similar, somewhat similar, or dissimilar, based on the difference in $\delta^{18}\text{O}$ values, using criteria of less than 0.25 ‰ for similar, greater than 0.30 ‰ for dissimilar, and within this range for somewhat similar. The $\delta^{18}\text{O}$ values are categorized as dissimilar for six pairs (table 3), all of which also have dissimilar hydrographs.

All of the four pairs with similar or somewhat similar hydrographs (sites 85/86, 117/118, 191/192, and 210/211) have $\delta^{18}\text{O}$ values that are similar or somewhat similar (table 3). These similarities are not necessarily indicative of extensive mixing because similarities in $\delta^{18}\text{O}$ values may result from similarities in recharge characteristics. Hydraulic connection between the Madison and Minnelusa aquifers has been confirmed at the City Quarry wells (sites 117/118), however, by aquifer testing (Greene, 1993) and by dye testing (Greene, 1999). Although hydraulic connection has been confirmed at the City Quarry wells, tritium values indicate much longer traveltimes for the Minnelusa aquifer.

Hydrographs are dissimilar (table 3) for the Sioux Park wells (sites 182/183); however, the $\delta^{18}\text{O}$ values are quite similar. Furthermore, the $\delta^{18}\text{O}$ value for the Minnelusa well (-14.38 ‰) is notably lighter than for several nearby Minnelusa wells (fig. 28) and closely resembles values for Madison wells to the northwest. Hydraulic head in the Madison aquifer

generally exceeds that in the Minnelusa aquifer at the Sioux Park wells (fig. 37G); however, aquifer testing has indicated that direct hydraulic connection does not occur at this location. Thus, if the $\delta^{18}\text{O}$ value for the Sioux Park Minnelusa well (site 183) is influenced by upward leakage from the Madison aquifer, the leakage probably occurs to the northwest, near where confirmed leakage occurs in the vicinity of the City Quarry wells (sites 117/118) and City Springs (site 298).

Geochemical comparisons for wells along the southwestern flank of the Black Hills provide useful information regarding complex flowpaths in this area. The $\delta^{18}\text{O}$ value of -16.32 ‰ for the Boles Canyon Madison well (site 201) is somewhat heavier than for site 215 (fig. 29) and for wells to the northwest in Wyoming (fig. 34). The Madison aquifer is not fully saturated at site 201 and may be influenced by downward leakage from the overlying Minnelusa aquifer, where hydraulic head is about 500 ft higher (fig. 36I). The sulfate concentrations for sites 201 and 202 (table 3) do not preclude this possibility.

The sulfate concentration for the Hell Canyon Madison well (site 215) is higher than for most other Madison wells (table 3, fig. 10), which could indicate downward leakage from the Minnelusa aquifer. The hydraulic gradient between aquifers is adverse (upward) at the well site (fig. 37K), but may be favorable at upgradient locations (such as Boles Canyon). The $\delta^{18}\text{O}$ value for the Madison well (-17.23 ‰) is much lighter than for the Minnelusa well (site 216), however, which essentially precludes substantial influence from Minnelusa aquifer leakage. The $\delta^{18}\text{O}$ value also is lighter than for nearby recharge areas (fig. 20), which could indicate a regional flow component. Overall major-ion chemistry (sodium sulfate) at this site is somewhat distinct (fig. 10), however, and a chloride deficiency (table 3) is not indicative of a regional flow component. The high sodium and sulfate concentrations probably are explained by generally increasing ion concentrations resulting from basinward evolutionary processes, which is consistent with the long flowpath indicated by the light $\delta^{18}\text{O}$ value.

The $\delta^{18}\text{O}$ values for both Minnekahta Junction wells (site 242 and 243) are notably heavier than for other nearby sites (fig. 29) and probably reflect recharge primarily near the southern end of the uplift. The relatively heavy $\delta^{18}\text{O}$ values essentially preclude the influence of regional flow from the west at this location. The hydraulic head difference between the Madison and Minnelusa aquifers at this site is only

about 5 to 15 ft (fig. 37M); thus, leakage in either direction might be possible in upgradient locations, depending on the hydraulic gradient. The large difference in sulfate concentrations (table 3) probably precludes substantial leakage from the Minnelusa to the Madison aquifer, however.

Tritium concentrations for well pairs also are summarized in table 3. Sample collection dates were comparable for most well pairs (table 7), with the exception of the Boles Canyon wells (sites 201/202), which were collected several years apart. Tritium concentrations cannot necessarily provide conclusive information regarding aquifer mixing. An example is the City Quarry wells (sites 117 and 118), where hydraulic connection between the aquifers has been confirmed by aquifer testing, and similar $\delta^{18}\text{O}$ values indicate probable mixing. Without other information, the low tritium concentration for the Minnelusa well (0.6 TU), relative to the Madison well (30.1 TU), would indicate minimal mixing. With other information, the tritium concentrations indicate that a substantial traveltime occurs in the Minnelusa aquifer before arrival of any water originating as leakage from the Madison aquifer.

The greatest potential for extensive mixing probably exists near the other three well pairs with similar hydrographs. Tritium concentrations, however, do not provide additional insights regarding mixing at these sites. For the Reptile Gardens wells (sites 191 and 192) and the CSP Airport wells (sites 210 and 211), tritium concentrations are low and do not provide useful information. For the Tilford wells (sites 85 and 86), the hydraulic gradient is upward (Madison to Minnelusa) and small (fig. 37C). Tritium concentrations do not provide additional insights because the concentration for the Madison well (1.3 TU) is much lower than for the Minnelusa well (31.3 TU); thus, the only possible effect from upward leakage would be undiscernible dilution of concentrations in the Minnelusa aquifer. Tritium concentrations for the State Line Madison (19.1 TU) and Minnelusa (<0.3 TU) wells (sites 35 and 36) indicate extensive mixing can be ruled out, in spite of a large hydraulic gradient from Madison to Minnelusa. Of the four well pairs with similar hydrographs, two pairs have notably different tritium concentrations (Tilford pair and City Quarry pair). Thus, extensive mixing near these two pairs probably does not occur. Tritium concentrations for the other two pairs (Reptile Gardens and CSP Airport) are very low and do not provide conclusive information.

The overall conclusion from comparison of hydraulic and geochemical information for well pairs is that general leakage between the Madison and Minnelusa aquifers probably does not result in areally extensive mixing in most locations. Comparisons of hydrographs for well pairs indicates the possibility of hydraulic connection in 4 of 13 locations. Geochemical information provides indications of mixing only in the general vicinity of City Springs in northwest Rapid City. Geochemical information for other areas is largely inconclusive and provides no definitive indications of extensive mixing. Interactions between the two aquifers in the vicinity of artesian springs are examined in the following section.

Interactions at Artesian Springs

Extensive interactions between the Madison and Minnelusa aquifers may occur at artesian springs, many of which have large discharges. Combined discharge of all artesian springs within the Black Hills area is estimated as 189 ft³/s for 1987-96, which represents about 48 percent of average recharge to the Madison and Minnelusa aquifers (Carter, Driscoll, Hamade, and Jarrell, 2001). Numerous investigators have identified the Madison and Minnelusa aquifers as probable sources for artesian springs in the Black Hills, based on hydraulic properties and geochemical characteristics. Extensive cavern development within the Madison aquifer creates potential for focused movement of large quantities of water. Breccia pipes within the Minnelusa Formation (Bowles and Braddock, 1963) were identified by Hayes (1999) as a pathway for vertical movement of water from the Madison aquifer. The Minnekahta aquifer also may be a contributing source in locations where the Minnekahta Limestone is present. The underlying Deadwood aquifer also cannot be discounted as a possible source.

Precise quantification of relative contributions from source aquifers to individual springs is not necessarily possible; however, geochemical information is useful for evaluating interactions between the Madison and Minnelusa aquifers at artesian springs. Hydraulic information also must be considered before geochemical information is addressed.

Hydraulic Considerations

Locations of artesian springs are shown on potentiometric-surface maps of the Madison and

Minnelusa aquifers (figs. 7 and 8). Hydraulic head in the Madison and Minnelusa aquifers at major spring locations is estimated from potentiometric-surface maps and is summarized in table 6, along with approximate land-surface elevations near the springs. Some of the springs considered in table 6 consist of a series of springs along stream reaches. For these cases, the elevations listed generally are for locations downstream from the individual discrete springs (sites 290, 292, 296, 297, 301, 302, and 306).

Several hydraulic possibilities exist for interactions between the Madison and Minnelusa aquifers at spring locations, including: (1) water originates only from the Minnelusa aquifer, with no contribution from the underlying Madison aquifer; (2) water originates entirely from the Madison aquifer and passes through the Minnelusa Formation, with little interaction; (3) water originates entirely from the Madison aquifer, part of which discharges at the surface and part of which recharges the Minnelusa aquifer; and (4) water originating from both aquifers contributes to springflow. For cases where the Madison aquifer contributes to springflow, leakage to the Minnelusa aquifer could consist of either focused leakage in the immediate vicinity of the spring-discharge point or general leakage in upgradient directions.

The Minnelusa aquifer probably can be discounted as a primary source for springs located where the Minnelusa Formation is exposed, which generally precludes artesian conditions in the Minnelusa aquifer. One example is Cleghorn Springs (site 300) and Jackson Springs, which comprise a large spring complex in western Rapid City (fig. 35) adjacent to an outcrop section of the Minnelusa Formation, where several hundred feet of outcrop occurs in a cliff above the springs. Hydraulic head in the Madison aquifer is considerably above land surface at this location (table 6); however, hydraulic head in the Minnelusa aquifer is approximately at land surface, as indicated by water levels in a pair of observation wells (fig. 37F, sites 178 and 179) located about one-quarter mile east of the springs. The large and steady discharge of the springs (Anderson and others, 1999) also indicates a dominant contribution from the Madison aquifer. The spring complex probably serves as a relief mechanism for controlling hydraulic head in the Minnelusa aquifer; thus, a contribution to springflow from the Minnelusa aquifer cannot necessarily be excluded.

Table 6. Selected hydraulic and geochemical information for major artesian springs

[ft³/s, cubic feet per second; MSL, mean sea level; mg/L, milligrams per liter; TU, tritium units; -- no information; %, percent; <, less than; ≈, approximately equal]

Site number	Name	Approximate discharge (ft ³ /s)	Elevation of land surface (feet above MSL)	Hydraulic head (feet above MSL)		Sulfate (mg/L)	Chloride (mg/L)	Estimated spring source from previous studies	Isotopes		
				Madison aquifer	Minnelusa aquifer				Date	δ ¹⁸ O (per mil)	Tritium (TU)
290	Higgins Gulch	5-10	3,405	3,490	3,550	110	12	Mostly Madison ¹	09-26-94 10-10-97 mean	-- -- -16.36	31.3 28.1 --
292	Old Spearfish Hatchery	≈5	3,405	3,500	3,550	340	2.3	70% Madison, 30% Minnelusa ¹	09-26-94 08-21-97	-16.71 --	26.0 13.4
293	NcNenny Rearing Pond	≈1	3,400	3,720	3,580	130	.8	Mostly Madison ¹	09-28-94	-17.19	20.7
294	Mirror Lake	≈1	3,410	3,720	3,580	1,600	2.7	50% Madison, 50% Minnelusa ¹	09-28-94	-15.34	16.9
295	Cox Lake	≈5	3,415	3,705	3,580	545	.7	Mostly Madison ¹	09-27-94	-16.95	21.0
296	Crow Creek	30-50	3,355	3,710	3,560	580	6.3	--	08-30-96	-16.67	19.1
297	Elk Creek	0-20	3,450	3,450	3,450	420	15	--	09-05-96	-13.79	30.1
298	City Springs	0-5	3,440	3,450	3,450	98	14	--	06-26-93 mean	-- -14.37	40.8 --
300	Cleghorn Springs	20-25	3,380	3,420	3,380	25	6.5	--	01-01-78 09-27-93 mean	-- -- -13.02	182.0 30.2 --
301	Battle Creek	1-10	3,540	3,540	3,540	19	5.4	--	09-06-96	-11.62	20.4
302	Grace Coolidge Creek	0-20	3,650	3,650	3,650	11	5.3	--	09-10-96	-11.68	17.2
303	Beaver Creek Spring	10-15	3,460	3,480	3,480	1,300	33	Mostly Madison with dissolved Minnelusa minerals ²	04-25-94 mean	-- -14.10	6.0 --
304	Hot Brook Spring	<5	3,625	3,700	3,625	76	51	Mostly Madison ²	04-21-94 10-03-94	-- -14.86	4.1 3.8
305	Evans Plunge Spring	<5	3,465	3,610	3,420	540	110	Mostly Madison ²	01-01-78 04-21-94	-16.71 --	-- 0.6
306	Fall River	20-30	3,415	3,580	3,360	400	89	--	09-11-96	-15.43	2.5
307	Cool Spring	≈2	3,450	3,505	3,450	830	38	--	09-12-96	-15.23	2.5
308	Cascade Spring	18-22	3,440	3,495	3,450	1,500	47	Mostly Madison with dissolved Minnelusa minerals ³	10-19-95 09-12-96 mean	-- -- -15.40	2.2 2.2 --

¹Estimated by Klemp (1995).

²Estimated by Whalen (1994).

³Estimated by Hayes (1999).

A similar setting exists for Hot Brook Spring (site 304) located just northwest of Hot Springs (fig. 35). This spring also is located within an outcrop section of the Minnelusa Formation, in an area where hydraulic head in the Madison aquifer is much higher than in the Minnelusa aquifer (table 6), as indicated by water levels in a pair of observation wells in Hot Springs (Driscoll, Bradford, and Moran, 2000). These wells are not included in figure 37 because geochemical data are not available for both wells.

All of the other artesian springs listed in table 6 occur in locations where the Minnelusa Formation is confined by overlying units and artesian conditions are assumed for both the Madison and Minnelusa aquifers. Mapped hydraulic heads at other artesian spring locations generally are higher in the Madison aquifer than the Minnelusa aquifer (table 6, figs. 7 and 8), with the exception of sites 290 and 292 (just northwest of Spearfish) where mapped hydraulic heads may not be definitive because control points are sparse (Strobel and others, 2000a, 2000b). Hydraulic head is much higher in the Madison aquifer, relative to the Minnelusa aquifer, for spring areas along and near Crow Creek (sites 293-296) and in the Hot Springs area (sites 304-306). Hydraulic head in the Madison aquifer is only slightly higher than in the Minnelusa aquifer in the vicinity of Cool Spring (site 307) and Cascade Springs (site 308).

The Madison aquifer generally has larger potential for higher hydraulic head because recharge areas occur at higher elevation than for the Minnelusa aquifer. Higher hydraulic head in the Madison aquifer could indicate higher potential for contributions to springflow, relative to contributions from the Minnelusa aquifer. An alternative line of reasoning may be plausible, however. Higher hydraulic head in the Madison aquifer also indicates relatively competent confinement by the overlying Minnelusa Formation, which could imply larger contributions from the Minnelusa aquifer. Thus, generalities regarding dominant contributions to artesian springflow cannot be inferred from comparisons of hydraulic head.

Discharge rates for artesian springs (table 6) also provide insights regarding hydraulic considerations. Flow variability is minimal for many artesian springs (Miller and Driscoll, 1998; Anderson and others, 1999; U.S. Geological Survey, 2000), including McNenny Rearing Pond, Cox Lake, Crow Creek, Cleghorn Springs, Beaver Creek Springs, Fall River, and

Cascade Springs (sites 293, 295, 296, 300, 303, 306, 308, respectively). Hydraulic heads at these sites generally are substantially above land surface for one or both of the two aquifers.

In contrast, discharge is much more variable for Elk Creek, City Springs, Battle Creek, and Grace Coolidge Creek (sites 297, 298, 301, and 302, respectively). At these sites, mapped hydraulic heads in both aquifers are approximately coincident with land-surface elevation; however, to some extent, land-surface elevations have been used to infer hydraulic heads for the two aquifers. This inference generally is validated, however, by hydrographs for observation wells in the vicinity of these springs (Driscoll, Bradford, and Moran, 2000). An example is City Springs (fig. 35, site 298), which is located about one-half mile downgradient from the City Quarry wells (sites 117 and 118). The discharge of City Springs correlates strongly with hydraulic head, with flow occurring only when hydraulic head exceeds about 3,440 ft (fig. 37E).

The previous discussion supports a general conclusion that artesian springs are a relief mechanism that provide somewhat of an upper limit for hydraulic head in the Madison and Minnelusa aquifers. Artesian springflow increases in response to increasing recharge and increasing water levels. Springflow responds relatively slowly in locations where hydraulic head is substantially above land surface, with faster response in locations where hydraulic head is near land surface.

Geochemical Considerations

Previous investigators (Whalen, 1994; Klemp, 1995; and Hayes, 1999) used geochemical modeling to estimate contributions of the Madison and Minnelusa aquifers to selected springs. Their methods considered major-ion chemistry and several isotopes that are influenced by rock/water interactions, including carbon, sulfur, and strontium isotopes. Results are not necessarily definitive because of: (1) uncertainties in selecting representative source and end-point waters along assumed flowpaths; (2) spatial variability in mineralogical characteristics within the two formations; and (3) potential geochemical influences from interactions with other aquifers or confining units. Generalized results of previous modeling efforts for selected artesian springs are summarized in table 6. The Madison aquifer generally was identified as the primary source, with variable contributions from the Minnelusa aquifer, or chemical influences resulting from residence time within the Minnelusa Formation.

Stiff diagrams for artesian springs were presented in figure 35. Sulfate concentrations, which can be distinctly different for the Madison and Minnelusa aquifers, are listed in table 6 for large artesian springs. Springs with high sulfate concentrations have major-ion chemistry similar to that of many Minnelusa wells (fig. 11), which generally indicates chemical influence from the Minnelusa aquifer (or from anhydrite dissolution in overlying confining units). High sulfate concentrations, however, may result from dissolution of Minnelusa minerals by water from the Madison aquifer and do not necessarily indicate a contribution of water from the Minnelusa aquifer. Springs with low sulfate concentrations have major-ion chemistry similar to that of many Madison and Minnelusa wells (figs. 10 and 11) and are not necessarily indicative of a Madison aquifer source.

Large spatial variability in sulfate concentrations occurs in the major artesian spring areas along the northern and southern axes of the Black Hills, which probably results from differences in availability of anhydrite within the Minnelusa Formation. Sulfate also could be derived from other potential sources, such as gypsum within the Spearfish Formation; however, many springs with low sulfate concentrations issue from the Spearfish Formation. Source aquifers cannot be determined from other major-ion constituents. High calcium and magnesium concentrations could be contributed by either aquifer (figs. 10 and 11). High concentrations of sodium/potassium occur only in several Madison wells in the southwestern corner of the study area (fig. 10); however, concentrations in downgradient springs are much smaller (fig. 35).

The large springs in the northwestern part of the study area have large spatial variability in major-ion chemistry (fig. 35). Sulfate concentrations among site 293 (McNenny Rearing Pond), site 294 (Mirror Lake), site 295 (Cox Lake), and site 296 (Crow Creek) range from 130 to 1,600 mg/L. The Madison aquifer was identified by Klemp (1995) as the primary source of McNenny Rearing Pond and Cox Lake (table 6), both of which had low sulfate concentrations. A mix of water from the Madison and Minnelusa aquifers was estimated for Mirror Lake (Klemp, 1995), which had the highest sulfate concentration. The large discharge of Crow Creek (table 6), which has an intermediate sulfate concentration (580 mg/L), is comprised of the cumulative flow of many artesian springs, including sites 293 and 294.

The $\delta^{18}\text{O}$ value of -16.67 ‰ for Crow Creek (fig. 27) reflects the general isotopic composition for the Madison and Minnelusa aquifers in this large discharge area. Values for many other area springs are similar; however, the value for Mirror Lake (site 294) is notably heavier, as previously discussed. Modern tritium values for all springs in this large discharge area support the conclusion of small or negligible influence of regional flow from the west in this area, as previously discussed.

Three large spring discharge areas are located near the southern axis of the uplift (fig. 35), two of which consist of multiple springs. The discharge of Cascade Springs (site 308) is much larger than Cool Spring (site 307), and sulfate concentrations (1,500 and 830 mg/L, respectively) are much different (table 6). The high sulfate concentrations resemble ion chemistry for Minnelusa wells and reflect influence from the sulfate dissolution front (fig. 35). Geochemical modeling of Cascade Springs water by Hayes (1999) indicated a primary component of relatively fresh water from the Madison aquifer as a dissolution agent for anhydrite within the Minnelusa Formation.

The $\delta^{18}\text{O}$ values for Cascade (site 307) and Cool Springs (site 308) are notably lighter than for Madison and Minnelusa wells near the southern tip of the uplift and notably heavier than values further north (figs. 29 and 34). This isotopic composition reflects a general mix from a large potential recharge area all along the western and southwestern flanks of the uplift, which may include contributions from the Minnelusa aquifer. This is consistent with tritium concentrations (fig. 32), which indicate a small proportion of modern water mixed with a dominant proportion of pre-bomb water, indicating generally long travel times. Upgradient wells all have even lower tritium concentrations, which illustrates the enhancement of preferential flowpaths near artesian springs. The combination of geochemical information generally excludes substantial contribution from regional flow from the west, as previously discussed.

Three closely spaced springs in the Hot Springs area (sites 304, 305, and 306) have large spatial variability in major-ion chemistry. The large flow (table 6) of Fall River (site 306) includes the discharge of sites 304 and 305, as well as various other individual springs (not shown), which have large spatial variability in ion chemistry (Alexander and others, 1989). Sulfate concentrations for the three sites considered range from 76 mg/L for site 304 (Hot Brook Spring) to

540 mg/L for site 305 (Evans Plunge Spring). The Madison aquifer is the likely source of Hot Brook Spring, based on hydraulic head (table 6) and physical setting, as previously discussed; this conclusion is consistent with Whalen's (1994) determination. Based on hydraulic head, the Madison aquifer also is the source of Evans Plunge Spring, but both aquifers could contribute to other springs along the Fall River. All three springs have relatively high sodium and chloride concentrations, which is consistent with localized conditions in the Madison and Minnelusa aquifers (Whalen, 1994).

Springs that consist predominantly of pre-bomb water comprise the flow of Fall River (site 306), which has a tritium concentration of 2.5 TU. The youngest water is contributed by Hot Brook Spring (site 304, 3.8 TU), with Evans Plunge Spring (site 305) contributing older water (0.6 TU). Water from the nearby Vets Home Madison well (site 247) is even older, with no detectable tritium.

As previously discussed, the recharge area for Beaver Creek Springs (site 303, fig. 34) probably extends to the west side of the uplift axis, based on the $\delta^{18}\text{O}$ value, which is notably lighter than estimated values for nearby outcrop areas (fig. 20) and nearby wells (fig. 29). Relative contributions from the Madison and Minnelusa aquifers cannot be determined from the $\delta^{18}\text{O}$ values; however, high sulfate concentrations (table 6, fig. 35) indicate substantial influence from the Minnelusa Formation (either flow contributions or rock/water interactions).

The tritium concentration (6.0 TU) for Beaver Creek Spring (fig. 32) is discernibly higher than for other artesian springs to the southwest, presumably from the influence of a localized recharge component from along the southeastern flank of the uplift. Tritium concentrations for wells near the spring indicate a wide range of travel times. Tritium was not detected in the 7-11 Ranch Madison and Minnelusa wells (sites 238 and 239, respectively); however, some proportion of modern water is apparent for other wells. A 1978 sample (27.7 TU) for site 233 (Kaiser well) indicates some modern water, presumably mixed with pre-bomb water (fig. 36A). Site 237 (Streeter Ranch) has samples of 10.6 TU from 1977 and 11.7 TU from 1997 (table 7). The time-delay mixing curves (fig. 36) generally indicate theoretical delay times of 10 or more years and mixing with substantial proportions of pre-bomb water. Unequal mixing conditions probably are

more plausible, given the probable influence of preferential flowpaths associated with the nearby spring.

Synopsis of Interaction Processes

Consideration of both hydraulic and geochemical information is necessary to interpret complex interaction processes between the Madison and Minnelusa aquifers. A synopsis of interaction processes is provided in this section.

As previously discussed, various hydrogeologic factors such as paleo-karst features, fracturing, and solution activity facilitate hydraulic connections between the Madison and Minnelusa aquifers. The Madison aquifer has potential for higher hydraulic head than the Minnelusa aquifer because of higher elevation recharge areas. Hydrographs for paired observation wells indicate that higher hydraulic head in the Madison aquifer is maintained in most near-outcrop areas where artesian conditions exist, which indicates general competency of the confining layer between the two aquifers. This is consistent with a previous conclusion that general leakage between the Madison and Minnelusa aquifers probably does not result in areally extensive mixing.

Saturation indices indicate that the Madison aquifer is undersaturated with respect to gypsum, even at the highest sulfate concentrations. Thus, ongoing dissolution of Minnelusa Formation minerals probably occurs where the hydraulic gradient is favorable for upward leakage from the Madison aquifer, especially in areas where the competency of the confining layer has been substantially decreased.

Hayes (1999) hypothesized that upward leakage from the Madison aquifer was contributing to ongoing development of breccia pipes at Cascade Springs. Hayes (1999) noted that breccia pipes commonly occur in the upper Minnelusa Formation, but very few have been observed in the lower part of the formation. Networks of interbedded breccia layers and short, vertical breccia dikes do occur in the lower Minnelusa Formation, however, as schematically illustrated in figure 5. Paleo-karst features in the upper Madison Limestone have influenced the depositional environment of the overlying Minnelusa Formation. Deformation and fracturing associated with the subsequent uplift (Laramide Orogeny) also have contributed to decreased competency of the confining layer between the two aquifers.

Hayes (1999) further hypothesized that many exposed breccia pipes of the upper Minnelusa Formation probably are the throats of abandoned artesian springs. An outward (downgradient) migration of artesian springs probably has occurred as upgradient spring-discharge points are abandoned and new ones are occupied, keeping pace with regional erosion over geologic time (Hayes, 1999). In response, hydraulic heads in the Madison and Minnelusa aquifers have declined over geologic time, as indicated by exposed breccia pipes located upgradient from Cascade Springs (Hayes, 1999). Further supporting evidence is provided by Ford and others (1993), who concluded that water-level declines of more than 300 ft have occurred in the Madison aquifer during the last 350,000 years, based on geochemical data for Wind Cave.

Ground water discharging from the Madison aquifer at artesian springs was referred to as “rejected recharge” by Huntoon (1985), who hypothesized that recharge is rejected as transmissivity decreases with distance from upgradient recharge areas. This hypothesis is consistent with decreasing potential for large secondary porosity with increasing distance from the uplift, which results from: (1) decreased deformation and associated fracturing of rocks; and (2) decreasing potential for dissolution enhancement associated with increasing basinward concentrations of dissolved constituents.

Artesian springflow, which represents about 48 percent of average recharge to the Madison and Minnelusa aquifers (Carter, Driscoll, Hamade, and Jarrell, 2001), is an important factor in controlling water levels in these aquifers. Artesian springs are essentially a relief mechanism that provide an upper limit for hydraulic head. Springs located where hydraulic head is substantially above land surface generally have relatively stable discharge. In locations where hydraulic head is near land surface, however, discharge characteristics generally are more variable, with springflow increasing in response to increasing water levels.

The Madison aquifer is identified as the primary source for several large artesian springs located within outcrop sections of the Minnelusa Formation, which generally precludes artesian conditions within the Minnelusa aquifer. Precise quantification of relative contributions from the Madison and Minnelusa aquifers to artesian springs is complicated by numerous factors; however, geochemical modeling by various

investigators has identified the Madison aquifer as the primary potential source for many springs.

Upward leakage from the Madison aquifer is concluded to be an important factor in development of artesian springs and probably contributes flow to most springs. This process is driven by the dissolution potential of water from the Madison aquifer, which is undersaturated with respect to gypsum. Upward leakage at artesian springs probably is a major factor in dissolution and transport of anhydrite cements, associated with ongoing development of the anhydrite dissolution front in the Minnelusa aquifer. Although conclusive geochemical evidence of extensive mixing is not apparent, general leakage from the Madison aquifer probably contributes to ongoing dissolution of anhydrite within the Minnelusa Formation.

Artesian spring development is further hypothesized to be a self-perpetuating process, with springs initially developing in locations with large secondary porosity and associated high hydraulic conductivity. Development of preferential flowpaths in these areas contributes to increased dissolution activity, which continually contributes to increased enhancement of hydraulic conductivity. Similar development of preferential flowpaths also can occur in locations without artesian springs.

Considering all available information, it is concluded that interactions between the Madison and Minnelusa aquifers are an important factor governing the hydraulic behavior of the two aquifers. The exchange of water resulting from general, areal leakage probably is small, relative to that which occurs near artesian springs; however, both processes probably contribute to the control of hydraulic heads in the Black Hills area.

SUMMARY AND CONCLUSIONS

The Madison and Minnelusa aquifers are two of the most important aquifers in the Black Hills area because of utilization for water supplies and important influences on surface-water resources resulting from large springs and streamflow-loss zones. Examination of geochemical information provides a better understanding of the complex flow systems within these aquifers and interactions between the aquifers.

Two main types of water exist within the Madison aquifer—calcium magnesium bicarbonate type, which is expected in a carbonate aquifer; and calcium sodium chloride sulfate type, which is present mainly in the southwestern part of the study area. This

chemistry probably reflects the presence of more evolved ground water and regional flow, or greater amounts of evaporite minerals available for dissolution.

Three main types of water exist within the Minnelusa aquifer—calcium magnesium bicarbonate type, calcium magnesium sulfate type, and calcium magnesium bicarbonate sulfate chloride type. Water in the Minnelusa aquifer generally evolves downgradient from a calcium magnesium bicarbonate type to a calcium magnesium sulfate type, due to dissolution of anhydrite. In the southern part of the study area, ground water in the Minnelusa aquifer is characterized by higher concentrations of sodium and chloride. The high chloride concentrations in this area could reflect leakage between the aquifers, the dissolution of evaporite minerals, or the presence of more evolved ground water contributed by regional flow.

The most notable differences in major-ion chemistry between the Madison and Minnelusa aquifers are in concentrations of sulfate. Sulfate concentrations in the Minnelusa aquifer are dependent on the amount of anhydrite present in the Minnelusa Formation. A transition zone where dissolution of anhydrite is actively occurring was inferred from lines of equal sulfate concentrations in the range of 250 to 1,000 mg/L (milligrams per liter). Upgradient from this zone, the anhydrite generally is not present because of earlier removal from the formation by dissolution. Downgradient from this zone, thick anhydrite beds remain in the formation.

Water chemistry for the Madison and Minnelusa aquifers is controlled by reactions among calcite, dolomite, and anhydrite. Saturation indices for gypsum, calcite, and dolomite for most samples in both the Madison and Minnelusa aquifers are indicative of the occurrence of dedolomitization. Because water in the Madison aquifer remains undersaturated with respect to gypsum, even at the highest sulfate concentrations, upward leakage has potential to drive increased dissolution of anhydrite in the Minnelusa Formation, especially where Minnelusa aquifer water is nearly saturated with respect to gypsum.

Forward geochemical modeling is used to illustrate trends in pH and calcium and magnesium concentrations with increasing dissolution of anhydrite. Comparison of actual calcium and magnesium concentrations to model results indicates that if dedolomitization is occurring in both the Madison and Minnelusa aquifers, conditions in the aquifers (temperature, K_{dolomite}) are similar but not identical to modeled values. In

the Minnelusa aquifer, pH generally is lower at high sulfate concentrations, which supports the occurrence of the dedolomitization reaction. In the Madison aquifer, the data are consistent with dedolomitization, but pH trends are limited by the extent of anhydrite dissolution.

Ground water in both aquifers generally is well oxygenated at considerable distances from the outcrop areas because little organic material or reduced inorganic minerals are available for oxidation reactions. Reduction of sulfate, nitrate, and ferric iron minerals, methane fermentation, and anaerobic decay of organic matter are therefore not likely in the Madison and Minnelusa aquifers in the study area.

Isotopic information is used to evaluate ground-water flowpaths, ages, and mixing conditions for the Madison and Minnelusa aquifers. Distinctive patterns exist in the distribution of stable isotopes of oxygen and hydrogen in precipitation for the Black Hills area, with isotopically lighter precipitation generally occurring at higher elevations and latitudes. A generalized distribution of $\delta^{18}\text{O}$ (ratio of $^{18}\text{O}/^{16}\text{O}$ relative to a reference standard) for recharge areas is developed and used as a tracer for ground-water flowpaths. Distributions of $\delta^{18}\text{O}$ in ground water are consistent with spatial patterns in recharge areas, with isotopically lighter $\delta^{18}\text{O}$ values in the Madison aquifer resulting from generally higher elevation recharge sources, relative to the Minnelusa aquifer. For some areas, dominant proportions of isotopically light streamflow recharge are identified, relative to recharge from infiltration of precipitation on lower elevation outcrop areas. Both sources are important recharge mechanisms for the two aquifers.

The radioisotope tritium is used to evaluate mixing conditions and general ground-water ages. Estimates of annual tritium concentrations in precipitation for the Black Hills are based on long-term records for Ottawa, Canada, and shorter records for Bismarck, North Dakota, and Lincoln, Nebraska.

Three conceptual models, which are simplifications of lumped-parameter models, are considered for evaluation of ground-water flow and mixing conditions. For a simple slug-flow model, which assumes no mixing, tritium concentrations in ground water can be related through a first-order decay equation to estimated concentrations at the time of recharge. Two simplified mixing models that assume equal proportions of annual recharge over a range of years also are considered. An “immediate-arrival” model is used to

conceptually represent conditions in outcrop areas and a “time-delay” model is used for locations removed from outcrops, where delay times for earliest arrival of ground water generally would be expected. Decay curve families with incremental delay times are used for evaluating approximate age ranges for these conceptual mixing applications.

Limitations for use of the simplified, conceptual models include uncertainties in estimated tritium input (which may include precipitation and streamflow recharge) and gross assumptions regarding equal annual recharge and thorough mixing conditions. A major limitation results from highly heterogeneous aquifer properties that commonly may be dominated by dual-porosity hydraulic characteristics, consisting of high-porosity secondary openings within a low-porosity aquifer matrix. For this setting, a wide variety of mixing conditions could occur, including relatively old water from the aquifer matrix mixing with various and transient proportions of modern water flowing in near slug-flow conditions. Because of these limitations, the conceptual models are used only for general evaluation of mixing conditions and approximation of age ranges.

Despite limitations, the general applicability of arrival times associated with the conceptual models is demonstrated by the distribution of tritium concentrations for several groupings of hydrogeologic situations. Headwater springs, which are located in or near outcrop areas, have the highest tritium concentrations, which is consistent with the immediate-arrival mixing model. Tritium concentrations for many wells are very low, or nondetectable, indicating general applicability of the time-delay conceptual model for locations beyond outcrop areas, where artesian conditions generally occur. Concentrations for artesian springs generally are higher than for wells, which indicates generally shorter delay times resulting from preferential flow-paths that typically are associated with artesian springs. The general applicability of mixing models is supported by the absence of extremely high tritium values, which would be indicative of near slug-flow conditions, with recharge centered around periods of high tritium concentrations that occurred near the 1963 tritium peak. Exceptions to this generality cannot be discounted, however.

Extensive isotopic data sets are available for evaluation of mixing conditions and general ground-water ages in the Rapid City area, where large recharge

occurs from streamflow losses along Boxelder, Rapid, and Spring Creeks, which have distinctively different $\delta^{18}\text{O}$ signatures. A distinct division of lighter isotopic values to the north and heavier values to the south occurs in the Madison aquifer along Rapid Creek. A less distinctive gradation occurs for the Minnelusa aquifer, which probably reflects larger influence from precipitation recharge.

Dye testing has confirmed rapid ground-water flow (timeframe of weeks) from a loss zone in Boxelder Creek to City Springs and several wells located several miles downgradient in northwestern Rapid City. Tritium concentrations were very low (about 4 to 5 tritium units) for two sites with prompt dye arrival, dramatically demonstrating the limitations of the conceptual mixing models, which were unable to provide compatible age estimates. The combination of tritium and dye data indicated unequal mixing of about 5 to 10 percent very recent water and 90 to 95 percent pre-bomb water, which illustrates the complex mixing conditions that can occur in a dual-porosity system. Limited time-series $\delta^{18}\text{O}$ data for these sites showed minimal response to temporal variations in Boxelder Creek, which is consistent with a dominant proportion of pre-bomb water. Several other sites with dye recovery had higher tritium concentrations, reflecting larger proportions of modern water, with $\delta^{18}\text{O}$ data for these sites showing larger response to temporal variations in Boxelder Creek.

Time-series $\delta^{18}\text{O}$ and tritium data provide useful information regarding mixing conditions and general ages for numerous other sampling sites in the Rapid City area. Sites with minimal variability in $\delta^{18}\text{O}$ values generally have tritium data indicative of dominant proportions of pre-bomb water, reflecting generally thorough mixing conditions. A number of sites, however, showed response to temporal $\delta^{18}\text{O}$ trends in streamflow recharge, with associated tritium data generally indicating relatively large proportions of modern recharge. Several large Madison production wells located near the Rapid Creek transition zone had changes in $\delta^{18}\text{O}$ values indicative of changes in capture zones associated with recent production.

Evaluation of major-ion and isotope data indicates that regional flowpaths for the Madison aquifer are essentially deflected around the study area, with the possible exception of the southwestern and northwestern corners. Two wells just north of the study area clearly show influence of regional flow and a well just within the study area shows possible influence. Large

artesian springs near the northern axis of the uplift show no regional influence and are concluded to be recharged within the uplift area.

Major-ion concentrations for wells just west of the study area in Wyoming indicate deflection of regional flowpaths; however, minor influence may be possible for the most westerly wells considered. High ion concentrations for several wells in the southwestern corner of the study area indicate possible regional influence, but cannot necessarily be distinguished from basinward increases in constituent concentrations. North of this area, regional influence probably is minor or negligible. The $\delta^{18}\text{O}$ values for large springs along the southern axis of the uplift essentially preclude regional influence, which is supported by ion chemistry. Low, but detectable, tritium concentrations in these springs confirm the influence of recharge from within the study area, but indicate relatively long travel times. This is consistent with the $\delta^{18}\text{O}$ values, which indicate potential recharge areas extending along the entire southwestern flank of the uplift. The $\delta^{18}\text{O}$ value for Beaver Creek Spring is much lighter than estimated values for nearby outcrop areas and nearby wells, which indicates a possible flowpath extending from the general Hot Springs area. This flowpath to Beaver Creek Spring also is supported by a low tritium value indicating generally long travel times.

Potential interactions between the Madison and Minnelusa aquifer are examined using hydraulic and geochemical information for well pairs and artesian springs. Hydrographs for 9 of 13 well pairs are fairly well separated and do not indicate direct hydraulic connection between the aquifers. Although some exchange of water must occur in locations where hydraulic head differences occur, conclusive geochemical evidence of extensive mixing resulting from general, areal leakage between the aquifers is not apparent.

The Madison aquifer has been positively identified from dye testing/recovery as a source for City Springs and is concluded to be a primary source for several artesian springs (Cleghorn/Jackson and Hot Brook Springs) where artesian conditions in the Minnelusa aquifer are precluded by nearby outcrop sections. Contributions from these aquifers cannot necessarily be quantified for other artesian springs because of geochemical similarities between the Madison and Minnelusa aquifers. For some springs, high sulfate concentrations indicate Minnelusa influence, but may result from dissolution of Minnelusa

minerals by water from the Madison aquifer. Various investigators have hypothesized that the Madison aquifer is the primary source for many artesian springs, based on geochemical modeling, which is consistent with generally higher hydraulic head in the Madison aquifer, relative to the Minnelusa aquifer.

Generally higher hydraulic head in the Madison aquifer, in combination with gypsum undersaturation, is concluded to be a primary mechanism driving interactions with the Minnelusa aquifer, in areas where artesian conditions exist. Upward leakage from the Madison aquifer probably contributes to general dissolution of anhydrite deposits and development of breccia pipes in the Minnelusa aquifer. Breccia development may be especially prevalent in locations where the competency of intervening confining layers has been decreased by fracturing or by depositional influences in the Minnelusa Formation resulting from paleo-karstification of the Madison Limestone.

Development of breccia pipes probably contributes to enhanced vertical hydraulic conductivity in the Minnelusa aquifer. Breccia pipes are a likely mechanism for upward movement of large quantities of water through the Minnelusa aquifer at artesian spring locations and many exposed breccia pipes of the upper Minnelusa Formation probably are the throats of abandoned artesian springs. Dissolution processes are an important factor in a self-perpetuating process associated with development of preferential flowpaths and artesian springs. Preferential flowpaths initially develop in locations with large secondary porosity and associated hydraulic conductivity, with ongoing enhancement resulting from dissolution activity.

Outward (downgradient) migration of the artesian springs probably occurs as upgradient spring-discharge points are abandoned and new ones are occupied, keeping pace with regional erosion over geologic time. In response to this outward migration, hydraulic heads in the Madison and Minnelusa aquifers also have declined over geologic time.

Artesian springflow and general leakage are concluded to be important factors in governing hydraulic characteristics and water levels in the Madison and Minnelusa aquifers. Artesian springflow, which represents about one-half of average recharge to the Madison and Minnelusa aquifers, is especially important. Artesian springs act as a relief mechanism that provide an upper limit for hydraulic head, with springflow increasing in response to increasing water levels.

REFERENCES

- Alexander, E.C., Davis, M.A., and Alexander, S.C., 1989, Hydrologic study of Jewel Cave/Wind Cave, Final Report: University of Minnesota, unpublished report, contract CX-1200-S-A047, 149 p.
- Alexander, E.C., Davis, M.A., Alexander, S.C., and Lively, R.S., 1988, Thermal springs of the southern Black Hills, *in* Schilberg and Springhetti, eds., Caves and associated features of the Black Hills: Guidebook 45th Annual Convention National Speleological Society, p. 14-26.
- Anderson, M.T., Driscoll, D.G., and Williamson, J.E., 1999, Ground-water and surface-water interactions along Rapid Creek near Rapid City, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 98-4214, 99 p.
- Back, William, Hanshaw, B.B., Plummer, L.N., Rahn, P.H., Rightmire, C.T., and Rubin, Meyer, 1983, Process and rate of dedolomitization; mass transfer and ¹⁴C dating in a regional carbonate aquifer: Geological Society of America Bulletin, v. 94, p. 1415-1429.
- Bowles, C.G., and Braddock, W.A., 1963, Solution breccias of the Minnelusa Formation in the Black Hills, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 475-C, p. C91-C95.
- Braddock, W.A., 1963, Geology of the Jewel Cave SW quadrangle, Custer County, South Dakota: U.S. Geological Survey Bulletin 1063-G, p. 217-268.
- Braddock, W.A., and Bowles, C.G., 1963, Calcitization of dolomite by calcium sulfate solutions in the Minnelusa Formation, Black Hills, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 475-C, p. 96-99.
- Brobst, D.A., and Epstein, J.B., 1963, Geology of the Fanny Peak quadrangle, Wyoming-South Dakota: U.S. Geological Survey Bulletin 1063-I, p. 323-377.
- Browne, G.S., 1992, Water quality characteristics and geochemical differentiation of the Minnelusa and Madison aquifers in the vicinity of Rapid City, South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished M.S. thesis, 84 p.
- Busby, J.F., Kimball, B.A., Downey, J.S., and Peter, K.D., 1995, Geochemistry of water in aquifers and confining units of the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402-F, 146 p.
- Busby, J.F., Lee, R., and Hanshaw, B.B., 1983, Major geochemical processes related to the hydrology of the Madison aquifer system and associated rocks in parts of Montana, South Dakota, and Wyoming: U.S. Geological Survey Water-Resources Investigation Report 83-4093, 180 p.
- Busby, J.F., Plummer, L.N., Lee, R.W., and Hanshaw, B.B., 1991, Geochemical evolution of ground water in the Madison aquifer system in parts of Montana, Wyoming, and South Dakota: U.S. Geological Survey Professional Paper 1273-F, 89 p.
- Carter, J.M., Driscoll, D.G., and Hamade, G.R., 2001, Estimated recharge to the Madison and Minnelusa aquifers in the Black Hills area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 00-4278, 66 p.
- Carter, J.M., Driscoll, D.G., Hamade, G.R., and Jarrell, G.J., 2001, Hydrologic budgets for the Madison and Minnelusa aquifers, Black Hills of South Dakota and Wyoming, water years 1987-96: U.S. Geological Survey Water-Resources Investigations Report 01-4119, 53 p.
- Carter, J.M., and Redden, J.A., 1999a, Altitude of the top of the Inyan Kara Group, Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigation Atlas HA-744-A, 2 sheets, scale 1:100,000.
- 1999b, Altitude of the top of the Minnekahta Limestone, Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigation Atlas HA-744-B, 2 sheets, scale 1:100,000.
- 1999c, Altitude of the top of the Minnelusa Formation, Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigation Atlas HA-744-C, 2 sheets, scale 1:100,000.
- 1999d, Altitude of the top of the Madison Limestone, Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigation Atlas HA-744-D, 2 sheets, scale 1:100,000.
- 1999e, Altitude of the top of the Deadwood Formation, Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigation Atlas HA-744-E, 2 sheets, scale 1:100,000.
- Clark, I.D., and Fritz, P., 1997, Environmental isotopes in hydrogeology: Boca Raton, Fla., CRC Press/Lewis Publishers, 328 p.
- Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-1703.
- 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, 1 sheet, scale 1:250,000.
- DeWitt, Ed, Redden, J.A., Wilson, A.B., and Buscher, David, 1986, Mineral resource potential and geology of the Black Hills National Forest, South Dakota and Wyoming: U.S. Geological Survey Bulletin 1580, 135 p.
- Downey, J.S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.

- Downey, J.S., and Dinwiddie, G.A., 1988, The regional aquifer system underlying the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming—Summary: U.S. Geological Survey Professional Paper 1402-A, 64 p.
- Driscoll, D.G., 1992, Plan of study for the Black Hills Hydrology Study, South Dakota: U.S. Geological Survey Open-File Report 92-84, 10 p.
- Driscoll, D.G., Bradford, W.L., and Moran, M.J., 2000, Selected hydrologic data, through water year 1998, Black Hills Hydrology Study, South Dakota: U.S. Geological Survey Open-File Report 00-70, 284 p.
- Driscoll, D.G., and Carter, J.M., in press, Hydrologic conditions and budgets for the Black Hills of South Dakota, through water year 1998: U.S. Geological Survey Water-Resources Investigations Report 01-4226.
- Driscoll, D.G., Hamade, G.R., and Kenner, S.J., 2000, Summary of precipitation data for the Black Hills area of South Dakota, water years 1931-98: U.S. Geological Survey Open-File Report 00-329, 151 p.
- Epstein, J.B., 2000, Gypsum karst and hydrologic evolution in the northern Black Hills, South Dakota, *in* Strobel, M.L., Davis, A.D., Sawyer, J.F., Webb, C.J., Naus, C.A., and Rahn, P.H., eds., Proceedings of the 1999 Conference on the Hydrology of the Black Hills: Rapid City, South Dakota School of Mines and Technology Bulletin 20, p. 73-79.
- Fahrenbach, M.D., 1995, Sedimentation, paleontology, and paleoecology of the Late Devonian-Early Mississippian Englewood Formation, Black Hills, South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished Ph.D. dissertation, 615 p.
- Feldman, R.M., and Heimlich, R.A., 1980, The Black Hills: Kent, Ohio, Kent State University, Kendall/Hunt Publishing Company, K/H Geology Field Guide Series, 190 p.
- Ford, D.C., Lundberg, J., Palmer, A.N., Palmer, M.V., Dreybrodt, W., and Schwarcz, H.P., 1993, Uranium-series dating of the draining of an aquifer—the example of Wind Cave, Black Hills, South Dakota: Geological Society of America Bulletin, v. 105, p. 241-250.
- Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.
- Gonfiantini, R., Frohlich, K., Araguas-Araguas, L., and Rozanski, K., 1998, Isotopes in groundwater hydrology, *in* Kendall, C., and McDonnell, J., eds., Isotope tracers in catchment hydrology: New York, Elsevier Publishing Company, p. 203-246.
- Gott, G.B., Wolcott, D.E., and Bowles, C.G., 1974, Stratigraphy of the Inyan Kara Group and localization of uranium deposits, southern Black Hills, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 763, 57 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.
- 1997, Tracing recharge from sinking streams over spatial dimensions of kilometers in a karst aquifer: Ground Water, v. 35, no. 5, p. 898-904.
- 1999, Characterizing recharge to wells in carbonate aquifers using environmental and artificially recharged tracers, *in* Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999—Volume 3 of 3—Subsurface Contamination from Point Sources: U.S. Geological Survey Water-Resources Investigations Report 99-4018C, p. 803-808.
- Greene, E.A., Shapiro, A.M., and Carter, J.M., 1999, 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., 1975, Mineral and water resources of South Dakota: U.S. Congress, 94th, 1st Session, Interior and Insular Affairs Committee Print, 313 p.
- 1996, Roadside geology of South Dakota: Missoula, Mont., Mountain Press Publishing Company, 358 p.
- Hayes, T.S., 1999, Episodic sediment-discharge events in Cascade Springs, southern Black Hills, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 99-4168, 34 p.
- Hem, J.D., 1992, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 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.
- Huntoon, P.W., 1985, Rejection of recharge water from Madison aquifer along eastern perimeter of Bighorn Artesian Basin, Wyoming: Ground Water, v. 23, no. 3, p. 345-353.
- International Atomic Energy Agency, 1981, Statistical treatment of environmental isotope data in precipitation: Technical Report Series No. 206, 256 p.
- 1999, Global Network for Isotopes in Precipitation—The GNIP Database, Release 3, October 1999: accessed December 9, 1999, at URL <http://www.iaea.org/programs/ri/gnip/gnipmain.html>
- Johnson, B.N., 1933, A climatological review of the Black Hills: The Black Hills Engineer, Rapid City, South Dakota School of Mines and Technology, 71 p.

- Katz, B.G., Hornsby, H.D., Bohlke, J.F., and Mokray, M.F., 1999, Sources and chronology of nitrate contamination in spring waters, Suwannee River Basin, Florida: U.S. Geological Survey Water-Resources Investigations Report 99-4252, 54 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.
- Krauskopf, K.B., and Bird, D.K., 1995, Introduction to geochemistry (3d ed.): New York, McGraw-Hill, 647 p.
- 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.
- Langmuir, Donald, 1997, Aqueous environmental geochemistry: Upper Saddle River, N.J., Prentice-Hall, 600 p.
- Long, A.J., 2000, Modeling techniques for karst aquifers—anisotropy, dual porosity, and linear systems analysis: Rapid City, South Dakota School of Mines and Technology, unpublished Ph.D. dissertation, 59 p.
- Long, A.J., and Putnam, L.D., 2000, Conceptual model of the Minnelusa and Madison aquifers near Rapid City, South Dakota, *in* Strobel, M.L., Davis, A.D., Sawyer, J.F., Webb, C.J., Naus, C.A., and Rahn, P.H., eds., Proceedings of the 1999 Conference on the Hydrology of the Black Hills: Rapid City, South Dakota School of Mines and Technology Bulletin no. 20, p. 98-104.
- Long, A.J., Strobel, M.L., and Hamade, G.H., 1999, Localized leakage between the Madison and Minnelusa aquifers in the eastern part of the Black Hills, South Dakota [abs.]: Geological Society of America Abstracts with Programs, October 25-28, 1999, p. 412.
- Maloszewski, P., and Zuber, A., 1982, Determining the turnover time of groundwater systems with the aid of environmental tracers, 1. Models and their applicability: *Journal of Hydrology*, v. 57, p. 207-231.
- Manga, M., 1999, On the timescales characterizing groundwater discharge at springs: *Journal of Hydrology*, v. 219, p. 56-69.
- Michel, R.L., 1989, Tritium deposition in the continental United States, 1953-83: U.S. Geological Survey Water-Resources Investigations Report 89-4072, 46 p.
- 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.
- National Atmospheric Deposition Program/National Trends Network, 1999, National Atmospheric Deposition Program/National Trends Network monitoring location WY99: accessed February 12, 1999, at URL <http://nadp.sws.uiuc.edu/nadpdata>
- Naus, C.A., 1999, Geochemistry of ground water in the Madison and Minnelusa aquifers in the Black Hills of South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished M.S. thesis, 142 p.
- Parkhurst, D.L., 1995, User's guide to PHREEQC—a computer program for speciation, reaction-path, advective-transport, and inverse geochemical calculations: U.S. Geological Survey Water-Resources Investigations Report 95-4227, 143 p.
- Parkhurst, D.L., and Appelo, C.A.J., 1999, User's guide to PHREEQC (version 2)—A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Water-Resources Investigations Report 99-4259, 312 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.
- Plummer, L.N., Busby, J.F., Lee, R.W., and Hanshaw, B.B., 1990, Geochemical modeling of the Madison aquifer in parts of Montana, Wyoming, and South Dakota: *Water Resources Research*, v. 26, no. 9, p. 1981-2014.
- Rahn, P.H., 1971, The hydrologic significance of the November 1968 dye test on Boxelder Creek, Black Hills, South Dakota: *Proceedings of the South Dakota Academy of Science*, v. 50, p. 52-56.
- 1985, Ground water stored in the rocks of western South Dakota, *in* Rich, F.J., ed., *Geology of the Black Hills, South Dakota and Wyoming* (2d ed.): Geological Society of America, Field Trip Guidebook, American Geological Institute, p. 154-174.
- 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.
- Reilly, T.E., Plummer, L.N., Phillips, P.J., and Busenberg, E., 1994, The use of simulation and multiple environmental tracers to quantify groundwater flow in a shallow aquifer: *Water Resources Research*, v. 30, no. 2, p. 421-434.
- Richter, J., Szymczak, P., Abraham, T., and Jordan, H., 1993, Use of combinations of lumped-parameter models to interpret groundwater isotope data: *Journal of Contaminant Hydrology*, v. 14, p. 1-13.
- Rose, S., 1993, Environmental tritium systematics of baseflow in Piedmont Province watersheds, Georgia: *Journal of Hydrology*, v. 143, p. 191-216.
- Stiff, H.A., Jr., 1951, The interpretation of chemical water analysis by means of patterns: *Journal of Petroleum Technology*, v. 3, no. 10, p. 15-17.
- Strobel, M.L., Galloway, J.M., Hamade, G.R., and Jarrell, G.J., 2000a, Potentiometric surface of the Madison aquifer, Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigation Atlas HA-745-D, 2 sheets, scale 1:100,000.

- 2000b, Potentiometric surface of the Minnelusa aquifer, Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigation Atlas HA-745-C, 2 sheets, scale 1:100,000.
- 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.
- Swenson, F.A., 1968, New theory of recharge to the artesian basin of the Dakotas: Geological Society of America Bulletin 1081-B, p. 163-182.
- U.S. Department of Commerce, 1999, Climatological data for South Dakota, annual summary: Asheville, N.C.
- U.S. Geological Survey, 2000, Water resources data, South Dakota, water year 1999: U.S. Geological Survey Water-Data Report SD-99-1, 501 p.
- von Morlot, A., 1847, Veber Dolomit und seine kunstliche Darstellung aus kalkstein: Naturwissenschaftliche Abhandlungenm, gesammelt und durch Subscription lursg, von Wilhelm Haidinger, v. 1, p. 305-315.
- Wenker, G.A., 1997, Geological setting and water quality of headwater springs in the Black Hills of South Dakota: Rapid City, South Dakota School of Mines and Technology, M.S. thesis, 101 p.
- Whalen, P.J., 1994, Source aquifers for Cascade Springs, Hot Springs, and Beaver Creek Springs in the southern Black Hills of South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished M.S. thesis, 299 p.
- Whitehead, R.L., 1996, Ground water atlas of the United States—segment 8, Montana, North Dakota, South Dakota, Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas 730-I, 24 p.
- Yurtsever, Y., and Payne, B.R., 1986, Mathematical models based on compartmental simulation approach for quantitative interpretation of tracer data in hydrological systems: Proceedings of the 5th International Symposium on Underground Water Tracing, v. 5, p. 341-353.
- Zuber, 1986, Mathematical models for the interpretation of environmental radioisotopes in groundwater systems, *in* Fritz, P., and Fontes, J.C., eds., Handbook of Environmental Geochemistry, v. 2, The terrestrial environment: New York, Elsevier Publishing Company, p. 1-59.

SUPPLEMENTAL INFORMATION

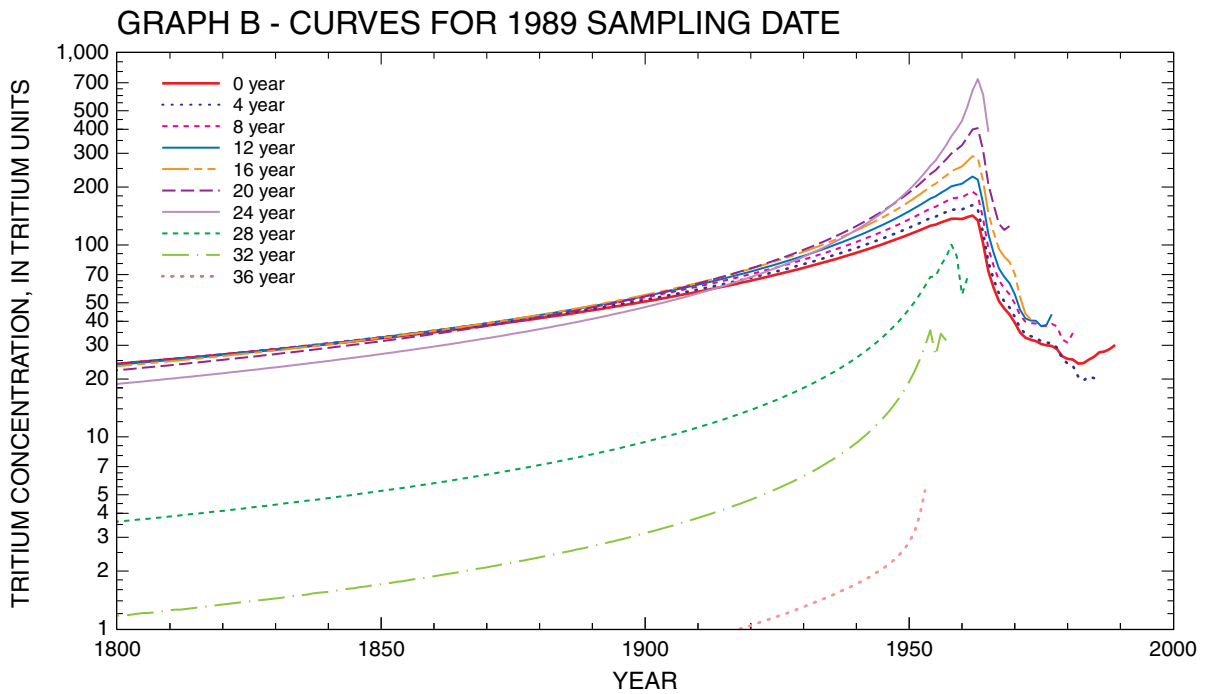
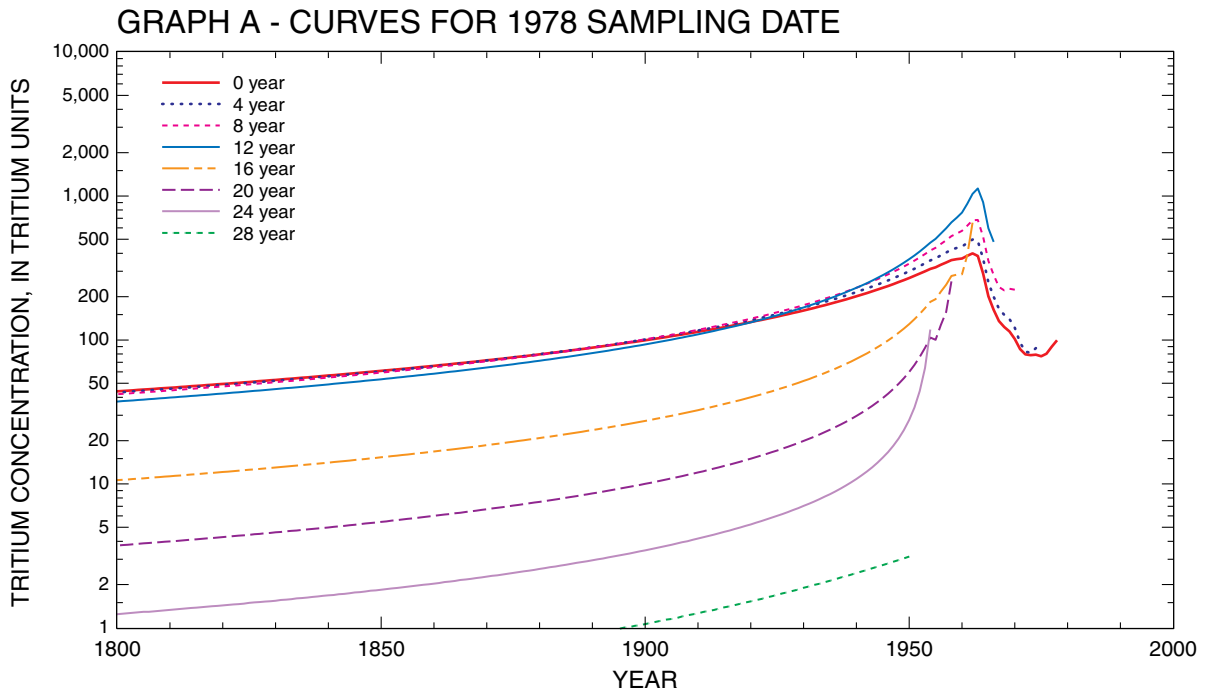


Figure 36. Decay-curve families for time-delay mixing model. Each graph shows a family of curves for a given sampling year. Each curve shows average decayed tritium concentrations, for hypothetical mixes over time, for specified delay times that are provided in 4-year increments.

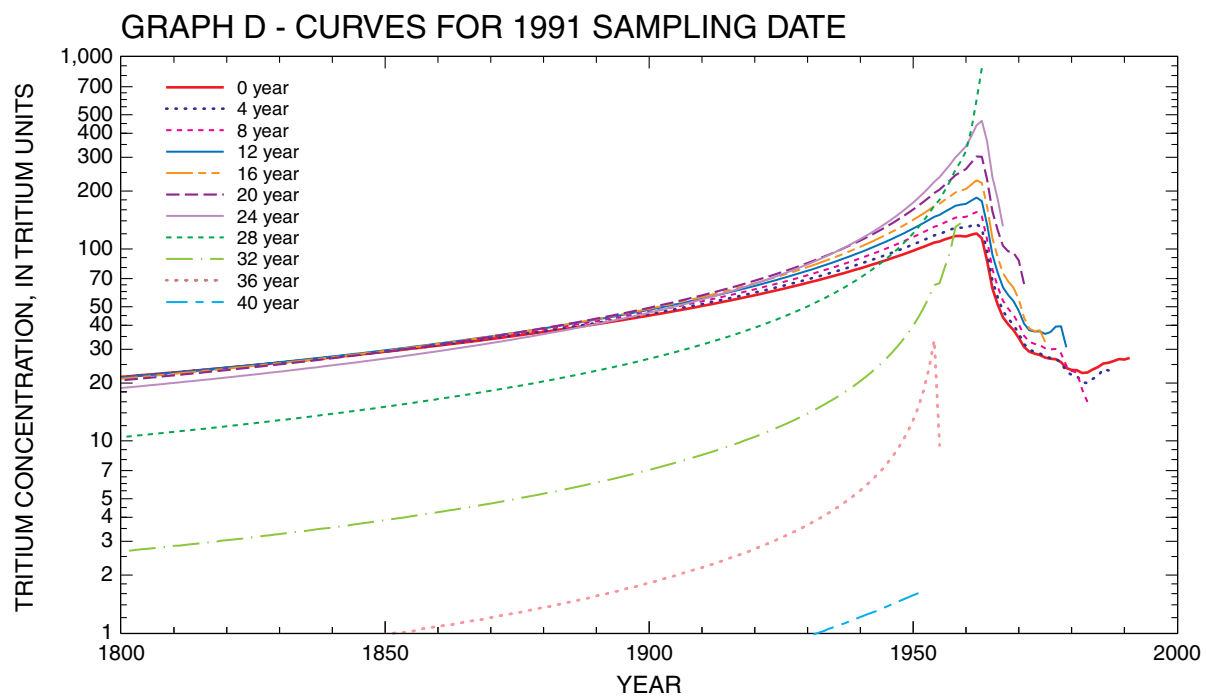
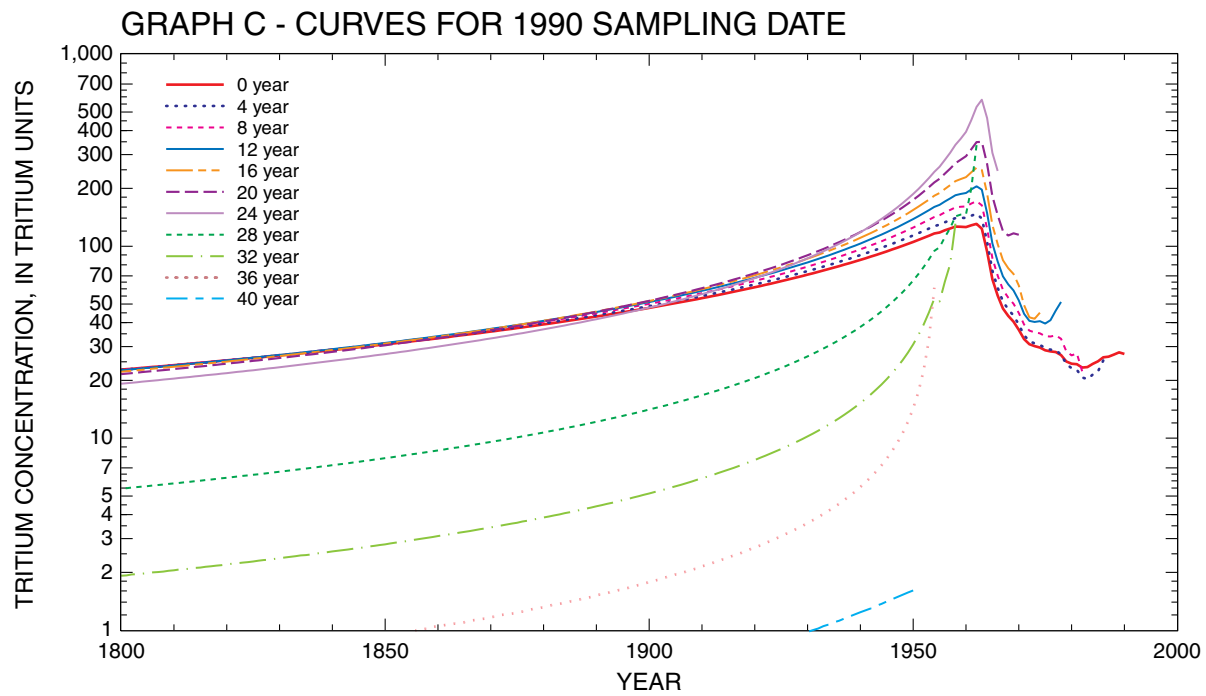


Figure 36. Decay-curve families for time-delay mixing model. Each graph shows a family of curves for a given sampling year. Each curve shows average decayed tritium concentrations, for hypothetical mixes over time, for specified delay times that are provided in 4-year increments.--Continued

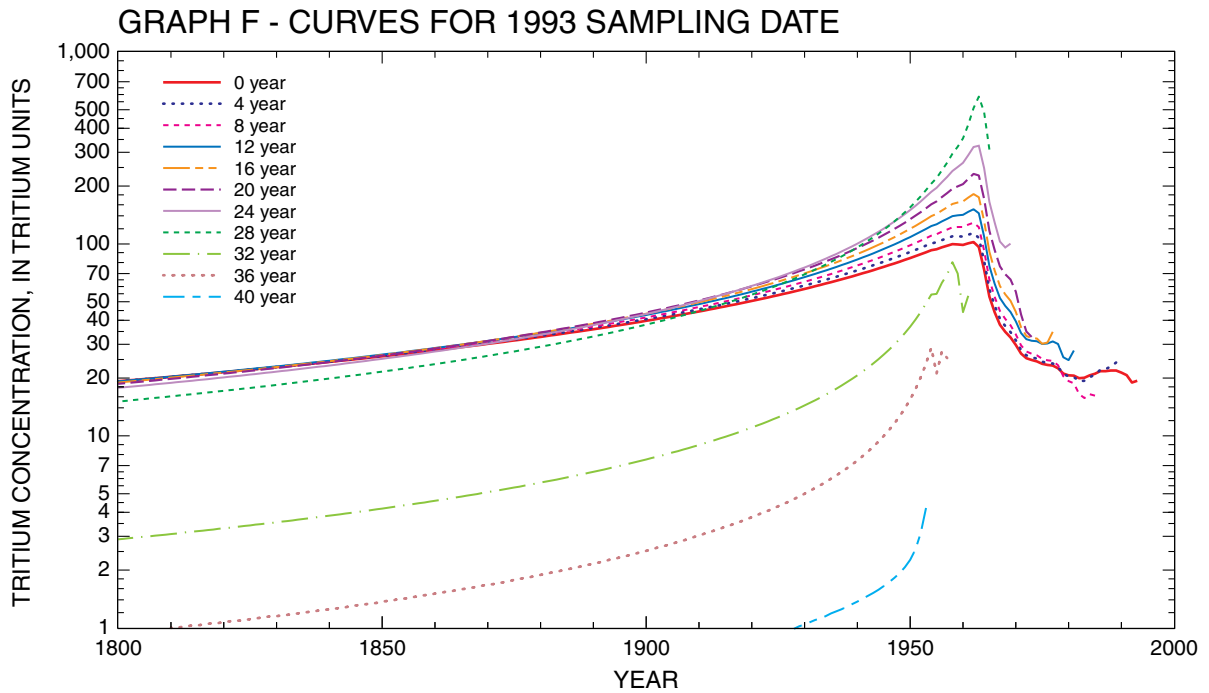
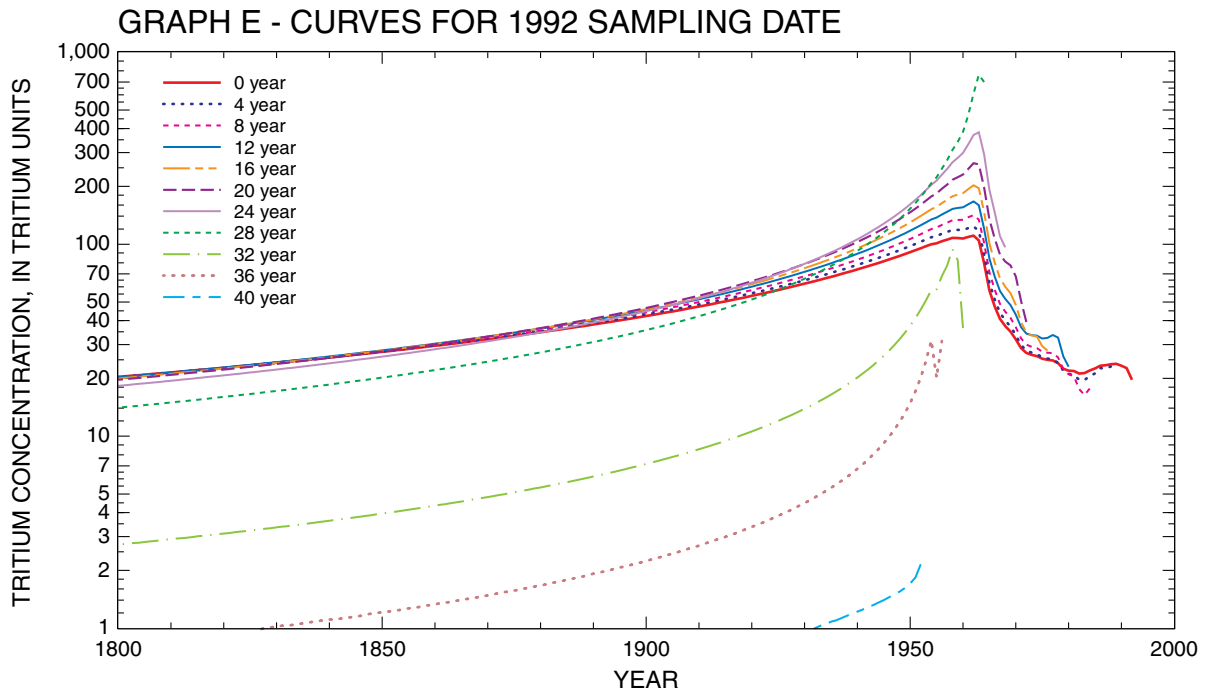


Figure 36. Decay-curve families for time-delay mixing model. Each graph shows a family of curves for a given sampling year. Each curve shows average decayed tritium concentrations, for hypothetical mixes over time, for specified delay times that are provided in 4-year increments.--Continued

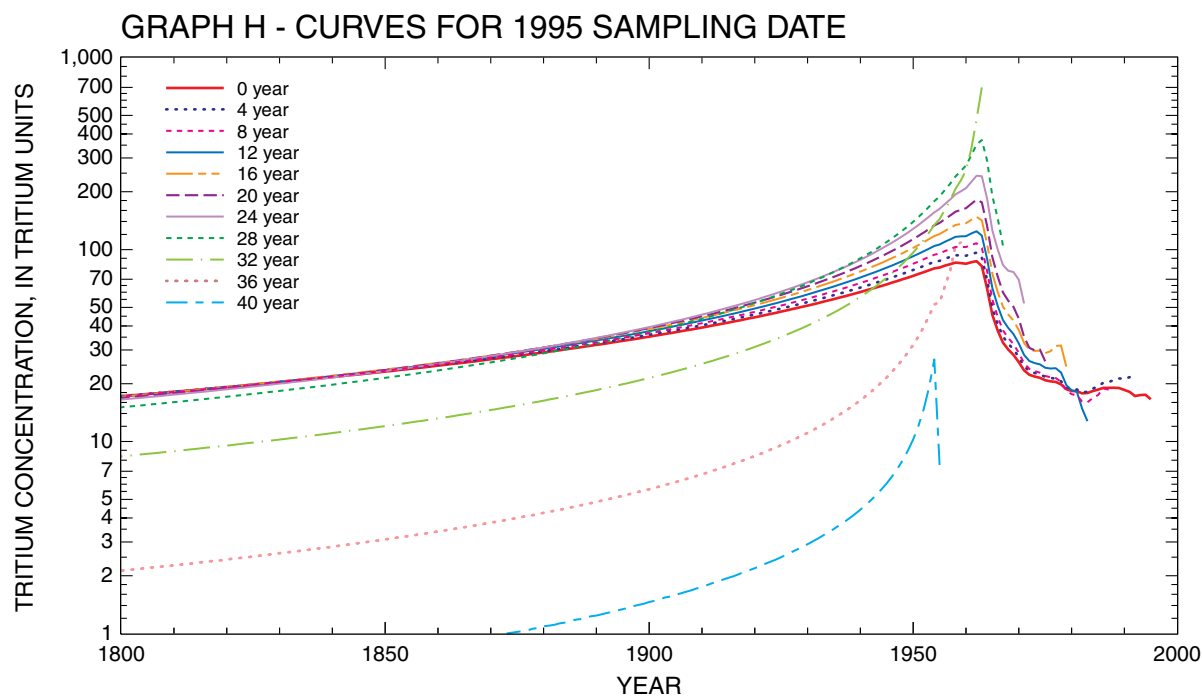
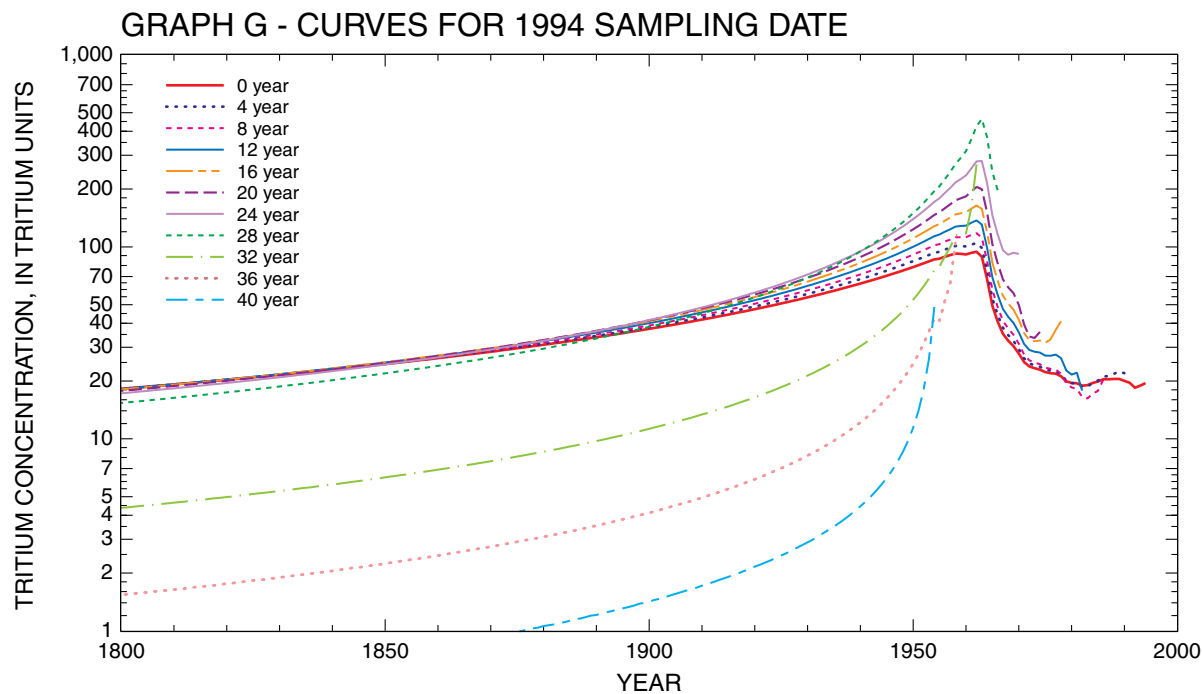


Figure 36. Decay-curve families for time-delay mixing model. Each graph shows a family of curves for a given sampling year. Each curve shows average decayed tritium concentrations, for hypothetical mixes over time, for specified delay times that are provided in 4-year increments.--Continued

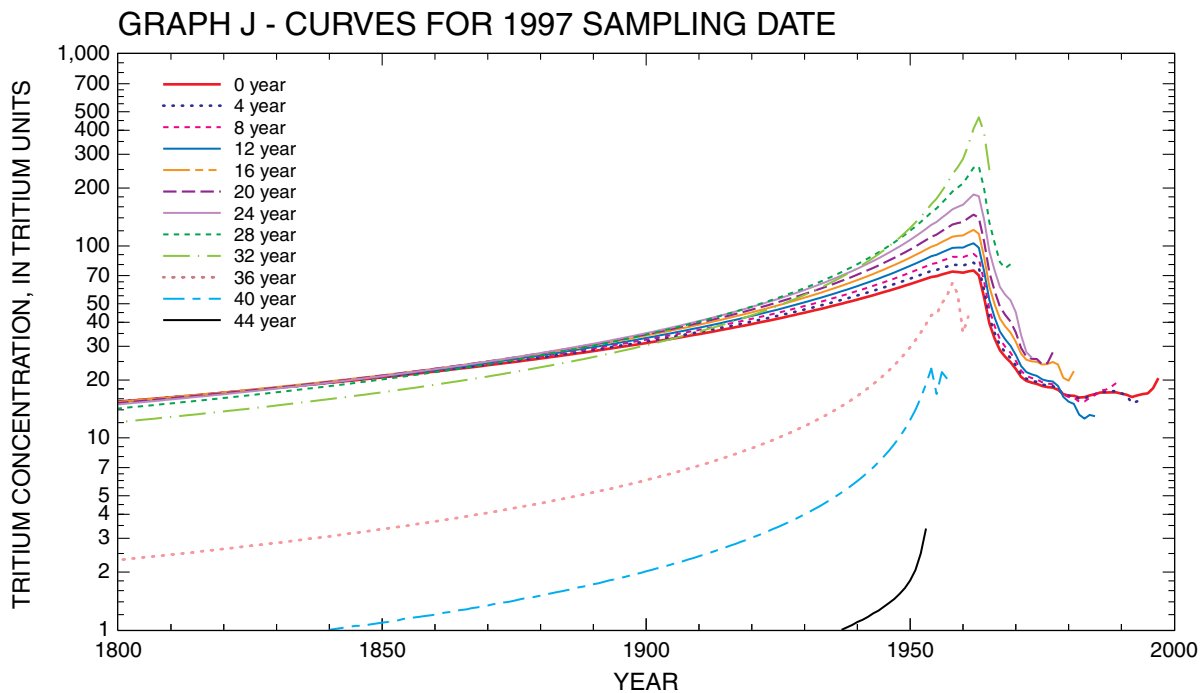
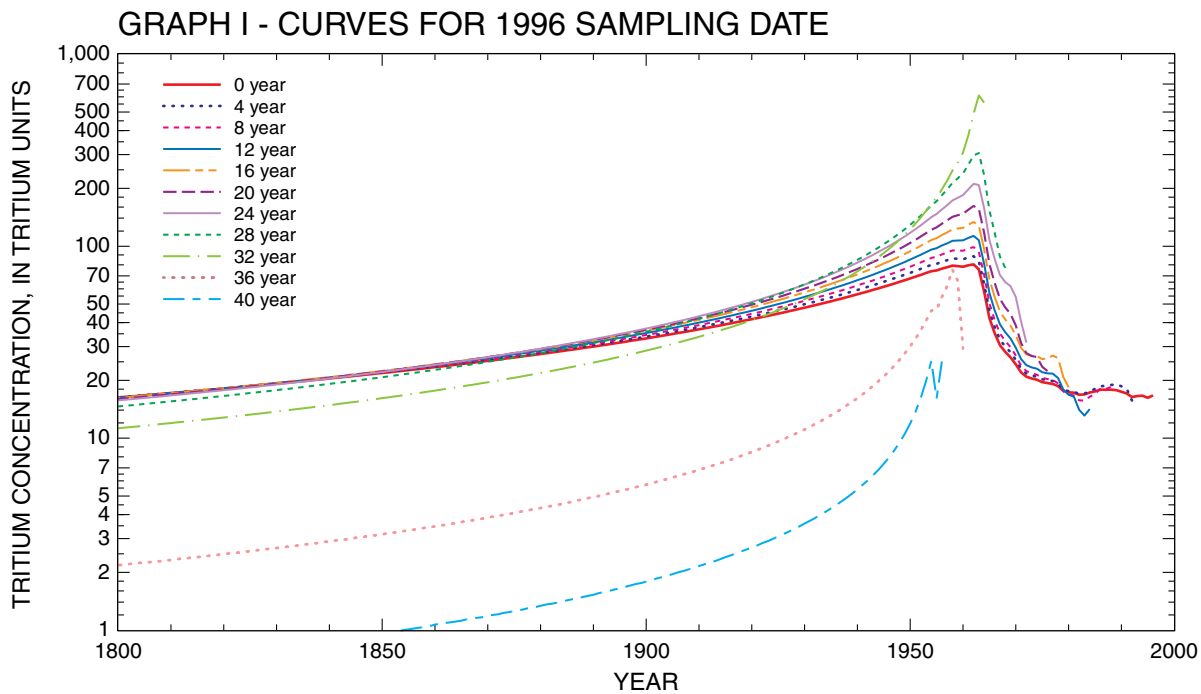


Figure 36. Decay-curve families for time-delay mixing model. Each graph shows a family of curves for a given sampling year. Each curve shows average decayed tritium concentrations, for hypothetical mixes over time, for specified delay times that are provided in 4-year increments.--Continued

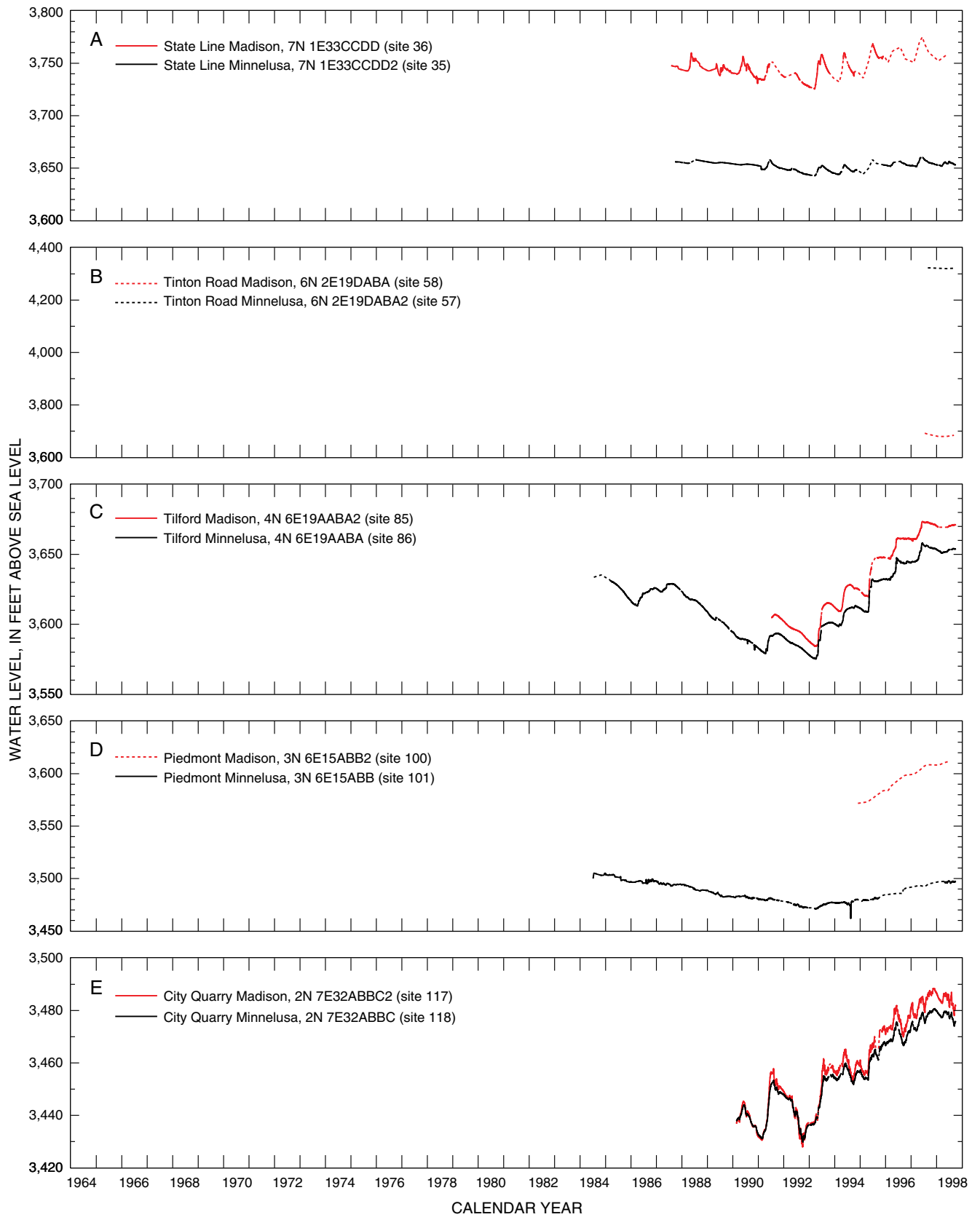


Figure 37. Hydrographs of selected well pairs.

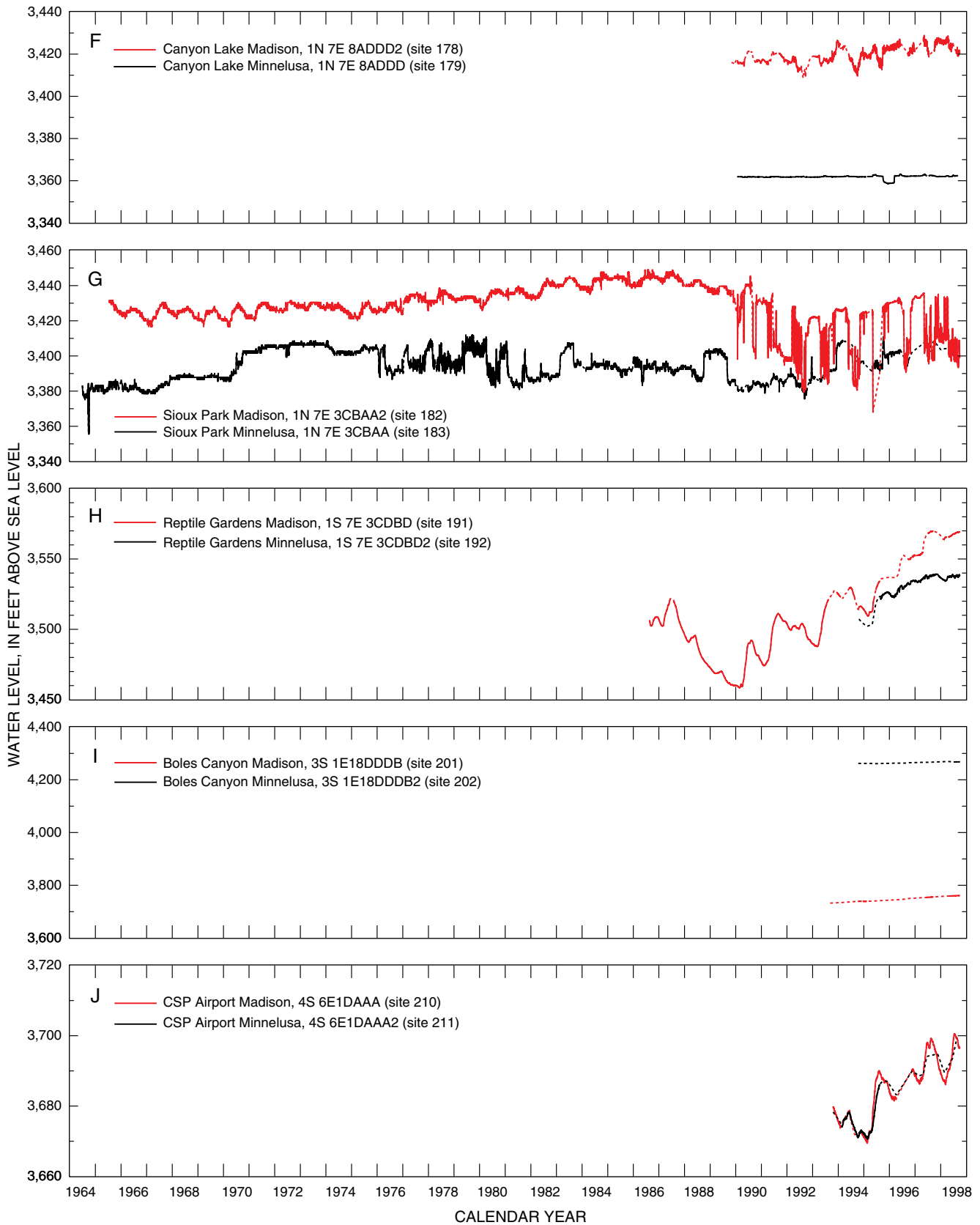


Figure 37. Hydrographs of selected well pairs.--Continued

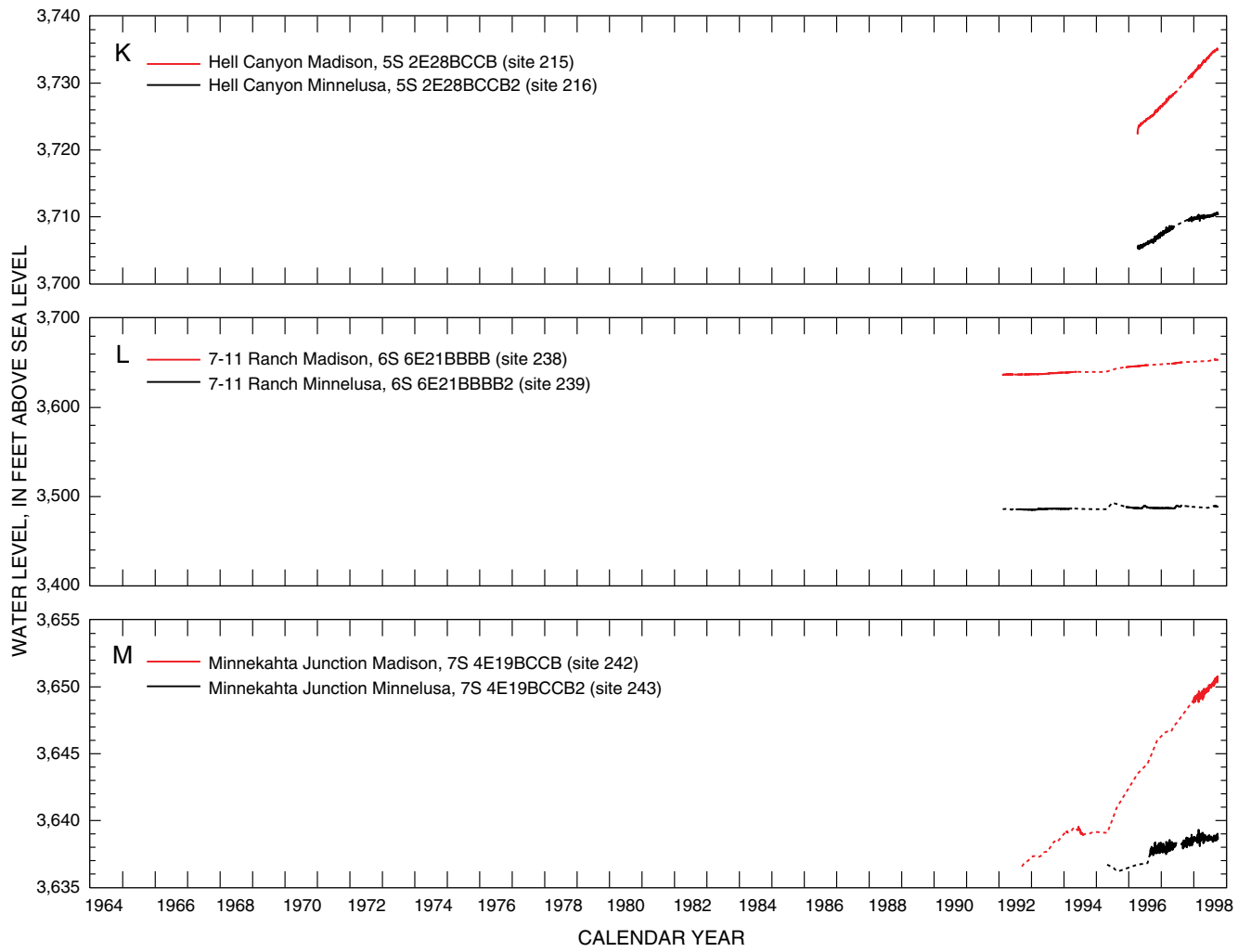


Figure 37. Hydrographs of selected well pairs.--Continued

Table 7. Selected site information and isotope data for sites used in report

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnl, Minnelusa; Mnkt, Minnekahta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves													
1	445739103465301	12N 3E32ACBC	Delzer #2	445739	1034653	Mdsn	NA	² 07-21-78	-18.13	--	<1.0	--	<0.3
2	445842103454301	12N 3E28ACBB2	Delzer #1	445842	1034543	Mdsn	NA	² 08-11-78	-19.66	--	<1.0	--	<.3
3	444253103440001	9N 3E27ADBD	NA	444253	1034359	Mnl	NA	--	--	--	--	--	--
4	444312103465901	9N 3E20CDDD	Bean	444313	1034653	Mdsn	NA	² 08-23-78	-17.80	--	--	--	--
5	444320103471801	9N 3E20CC	NA	444320	1034718	Mdsn	NA	--	--	--	--	--	--
6	444129103514801	9N 2E34CDDCA	Belle Fourche Municipal	444129	1035148	Mdsn	NA	08-17-94	-17.07	-131.0	<1.0	1	<.3
7	444128103514701	9N 2E34CDD	NA	444128	1035147	Mdsn	NA	--	--	--	--	--	--
8	444114103323901	8N 5E 5BCAB	NA	444114	1033239	Mdsn	NA	--	--	--	--	--	--
9	443627103460301	8N 3E33CCB	NA	443625	1034555	Mnl	NA	--	--	--	--	--	--
10	443655103482001	8N 3E31ACA	NA	443650	1034744	Mnl	NA	--	--	--	--	--	--
11	444108103432201	8N 3E 2BDBC	NA	444108	1034322	Mnl	NA	--	--	--	--	--	--
12	443716103522501	8N 2E28DDCB	NA	443716	1035225	Mdsn	NA	--	--	--	--	--	--
13	443124103433401	7N 3E35CB	NA	443124	1034334	Mnl	NA	--	--	--	--	--	--
14	443515103473001	7N 3E 7AABA	NA	443525	1034732	Mnl	NA	--	--	--	--	--	--
15	443124103531601	7N 2E33CBCD2	NA	443124	1035316	Mnl	NA	--	--	--	--	--	--
16	443117103541301	7N 2E32BAC	NA	443147	1035413	Mnl	NA	--	--	--	--	--	--
17	443148103534001	7N 2E32AAC	NA	443148	1035340	Mdsn	NA	--	--	--	--	--	--
18	443215103533001	7N 2E29D	NA	443215	1035330	Mnl	NA	--	--	--	--	--	--
19	443240103531002	7N 2E29AA2	NA	443240	1035310	Mnl	NA	--	--	--	--	--	--
20	443227103503401	7N 2E26BDB	NA	443227	1035034	Mdsn	NA	--	--	--	--	--	--
21	443230103504101	7N 2E26BCDA	NA	443230	1035041	Mnl	NA	--	--	--	--	--	--
22	443255103502501	7N 2E23CDAB	NA	443300	1035028	Mnl	NA	--	--	--	--	--	--
23	443323103515501	7N 2E22BCA	NA	443324	1035158	Mnl	NA	--	--	--	--	--	--
24	443318103532701	7N 2E20ADD	NA	443318	1035327	Mnl	NA	--	--	--	--	--	--
25	443420103551001	7N 2E19CAAA	NA	443315	1035514	Mnl	NA	--	--	--	--	--	--

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Minnelusa; Mnl, Minnekahta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves—Continued													
26	443355103553001	7N 2E18CA	NA	443359	1035532	Mnls	NA	--	--	--	--	--	--
27	443330103520301	7N 2E15CC	NA	443348	1035203	Mnls	NA	--	--	--	--	--	--
28	443423103510801	7N 2E15AADC	NA	443423	1035108	Mnls	NA	--	--	--	--	--	--
29	443515103513901	7N 2E10BADC	LA-62A Redwater	443513	1035143	Mnls	Obs	04-12-94	-16.88	-127.0	3.0	1	0.9
30	443010103523001	7N 2E 9ABAB	NA	443010	1035230	Mnls	NA	--	--	--	--	--	--
31	443108103530601	7N 2E 4BD	NA	443108	1035306	Mnls	NA	--	--	--	--	--	--
32	443553103502101	7N 2E 2CACA	NA	443553	1035021	Mnls	NA	--	--	--	--	--	--
33	443603103494001	7N 2E 1BBC	NA	443603	1034940	Mnls	NA	--	--	--	--	--	--
34	443100104002003	7N 1E33CCDD3	LA-94A State Line Minnekahta	443104	1040025	Mnkt	Pair	08-18-94	-15.58	-121.0	24.0	2	7.5
35	443100104002002	7N 1E33CCDD2	LA-87B State Line Minnelusa	443104	1040025	Mnls	Pair	04-11-94	-16.98	-128.0	<1.0	1	<.3
36	443100104002001	7N 1E33CCDD	LA-87A State Line Madison	443104	1040025	Mdsn	Pair	04-11-94	-17.28	-130.0	61.0	5	19.1
37	443153104015101	7N 1E32BBBB	NA	443153	1040151	Mnls	NA	--	--	--	--	--	--
38	443150104020001	7N 1E30DDDC	NA	443156	1040205	Mnls	NA	--	--	--	--	--	--
39	443210104021601	7N 1E30DDAB	NA	443210	1040216	Mdsn	NA	--	--	--	--	--	--
40	443330104024501	7N 1E30CADD	NA	443230	1040241	Mnls	NA	--	--	--	--	--	--
41	443240104024001	7N 1E30AAAD	NA	443240	1040155	Mnls	NA	--	--	--	--	--	--
42	443215103573001	7N 1E26ACD	NA	443215	1035730	Mnls	NA	--	--	--	--	--	--
43	443320104003501	7N 1E21BBC	McNenny Well No. 1	443334	1040035	Mnls ³	NA	² 01-01-78	-17.43	-127.0	36.4	--	11.4
44	443320104004501	7N 1E20AAD	McNenny Well No. 2	443328	1040045	Mnls ³	NA	08-17-94	-17.07	-132.0	62.0	4	19.4
45	443355103574501	7N 1E14CCDD	NA	443343	1035802	Mnls	NA	--	--	--	--	--	--
46	443339103575701	7N 1E14CCD	NA	443339	1035757	Mnls	NA	--	--	--	--	--	--
47	443511103575801	7N 1E11BCAD	NA	443511	1035758	Mdsn	NA	--	--	--	--	--	--
48	443515103572501	7N 1E11ACAC	Swanson Well	443508	1035730	Mnls	NA	08-16-94	--	--	2.0	1	.6
48	443515103572501	7N 1E11ACAC	Swanson Well	443508	1035730	Mnls	NA	mean ⁴	-17.46	-132.5	--	--	--
49	442754103220801	6N 6E22DABD	NA	442754	1032208	Mnls	NA	--	--	--	--	--	--
50	442901103281601	6N 5E14ADBD	NA	442901	1032816	Mnls	NA	--	--	--	--	--	--

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnls, Minnelusa; Mnkt, Minnekakhta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves—Continued													
51	442749103381401	6N 4E21DBCD	NA	442749	1033814	Mnls	NA	--	--	--	--	--	--
52	442917103462901	6N 3E17ABAA	NA	442917	1034629	Mnls	NA	--	--	--	--	--	--
53	442721103493701	6N 2E25BBCB	NA	442721	1034937	Mnls	NA	--	--	--	--	--	--
54	442820103503501	6N 2E23BBBA	NA	442820	1035035	Mnls	NA	--	--	--	--	--	--
55	442857103513401	6N 2E22ABBB	NA	442827	1035132	Mnls	NA	--	--	--	--	--	--
56	442822103534501	6N 2E20ABAB2	NA	442822	1035345	Mdsn	NA	--	--	--	--	--	--
57	442802103544602	6N 2E19DABA2	LA-96C Tinton Road Minnelusa	442759	1035449	Mnls	Pair	09-08-98	-15.90	-119.5	78.4	5.1	24.6
58	442802103544601	6N 2E19DABA	LA-96B Tinton Road Madison	442802	1035446	Mdsn	Pair	09-08-98	-16.66	-124.8	30.4	2.6	9.5
59	442919103511601	6N 2E15BBBB	City of Spearfish - Dickey Well	442917	1035206	Mdsn	NA	08-06-96	-16.65	-126.0	63.0	4	19.7
60	442906103510501	6N 2E15AADC	NA	442906	1035105	Mnls	NA	--	--	--	--	--	--
61	442842103505501	6N 2E14CBCC	City of Spearfish - Nevin Well	442842	1035055	Mdsn	NA	08-06-96	-16.84	-128.0	87.0	5	27.3
62	442906103504201	6N 2E14BBCC	NA	442906	1035042	Mnls	NA	--	--	--	--	--	--
63	442937103511201	6N 2E10DACB	NA	442937	1035112	Mnls	NA	--	--	--	--	--	--
64	442930103522001	6N 2E 9D	NA	442930	1035220	Mnls	NA	--	--	--	--	--	--
65	443100103543001	6N 2E 5BBBB	NA	443104	1035437	Mnls	NA	--	--	--	--	--	--
66	443019103523101	6N 2E 4DCAD	NA	443019	1035231	Mnls	NA	--	--	--	--	--	--
67	443032103575001	6N 1E 2CABC	NA	443032	1035750	Mnls	NA	--	--	--	--	--	--
68	442111103265701	5N 5E36ADDA	NA	442111	1032657	Mnls	NA	--	--	--	--	--	--
69	442217103272201	5N 5E26ABDA	Black Hills National Cemetery	442215	1032829	Mdsn	NA	² 08-10-78	-15.04	--	--	--	--
70	442148103273801	5N 5E25CADB2	NA	442148	1032738	Mnls	NA	--	--	--	--	--	--
71	442311103303501	5N 5E21AAAA	NA	442311	1033035	Mnls	NA	--	--	--	--	--	--
72	442337103303501	5N 5E16DAA	NA	442337	1033035	Mnls	NA	--	--	--	--	--	--
73	442335103311001	5N 5E16CAAD	MD-86A Sturgis	442336	1033111	Mdsn	Obs	12-02-97	-15.11	-111.7	1.0	1	.3
74	442431103314101	5N 5E 9CBCC	NA	442431	1033141	Mnls	NA	--	--	--	--	--	--
75	442443103312701	5N 5E 9BCAA	NA	442443	1033127	Mnls	NA	--	--	--	--	--	--
76	442435103320301	5N 5E 8ACDD	NA	442435	1033203	Mnls	NA	--	--	--	--	--	--

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Minnelusa; Mnl, Minnekahta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves—Continued													
77	442502103325401	5N 5E 5CC	NA	442511	1033238	Mnls	NA	--	--	--	--	--	--
78	442533103324801	5N 5E 5BBCB	NA	442533	1033248	Mnls	NA	--	--	--	--	--	--
79	442306103352001	5N 4E23AAAD	NA	442306	1033520	Mnls	NA	--	--	--	--	--	--
80	442515103340401	5N 4E 1DAAD	NA	442515	1033404	Mnls	NA	--	--	--	--	--	--
81	442545103343701	5N 4E 1ABBD	LA-86C Whitewood Minnelusa	442544	1033437	Mnls	NA	--	--	--	--	--	--
82	442504103415301	5N 3E 1DCCB	Fuhs	442504	1034153	Mdsn	NA	207-21-78	-16.13	--	209.3	--	65.6
83	4424351033571101	5N 1E11DABA	LA-95C Big Hill Madison	442434	1035710	Mdsn	Obs	10-29-97	-17.19	-128.9	105.3	6.4	33.0
84	441759103261203	4N 6E19AABA3	MD-95A Tilford Minnekahta	441759	1032612	Mnkt	Pair	09-19-96	-14.63	-110.0	140.0	8	43.9
85	441759103261202	4N 6E19AABA2	MD-90A Tilford Madison	441759	1032612	Mdsn	Pair	09-03-96	-15.61	-118.0	4.0	1	1.3
86	441759103261201	4N 6E19AABA	MD-84B Tilford Minnelusa	441800	1032612	Mnls	Pair	08-27-96	-15.52	-117.0	100.0	6	31.3
87	441812103230501	4N 6E16DCB	NA	441812	1032405	Mnls	NA	--	--	--	--	--	--
88	441807103235601	4N 6E16DCAC	NA	441807	1032356	Mnls	NA	--	--	--	--	--	--
89	441749103515701	4N 2E22BACB	NA	441749	1035157	Mdsn	NA	--	--	--	--	--	--
90	442024103545701	4N 2E 6AACD	NA	442024	1035457	Mdsn	NA	--	--	--	--	--	--
91	441023103194401	3N 7E31CBDD	NA	441023	1031944	Mnls	NA	--	--	--	--	--	--
92	441033103193001	3N 7E31CAA	NA	441033	1031930	Mnls	NA	--	--	--	--	--	--
93	441028103200401	3N 6E36DA	NA	441028	1032004	Mnls	NA	--	--	--	--	--	--
94	441033103210301	3N 6E35ADDA	NA	441040	1032107	Mdsn	NA	--	--	--	--	--	--
95	441055103230501	3N 6E34BA	High Meadows	441055	1032305	Mdsn	NA	12-18-91	-13.90	-103.0	<1.0	1	<.3
96	441130103205601	3N 6E25BCDC	NA	441130	1032056	Mnls	NA	--	--	--	--	--	--
97	441127103195801	3N 6E25ADDC	NA	441127	1031958	Mnls	NA	--	--	--	--	--	--
98	441318103221301	3N 6E24CADD	NA	441207	1032033	Mnls	NA	--	--	--	--	--	--
99	441208103205001	3N 6E24C	NA	441208	1032050	Mnls	NA	--	--	--	--	--	--
100	441337103225002	3N 6E15ABB2	MD-94A Piedmont Madison	441335	1032250	Mdsn	Pair	09-04-96	-13.68	-103.0	<1.0	1	<.3
101	441337103225001	3N 6E15ABB	MD-84A Piedmont Minnelusa	441335	1032250	Mnls	Pair	09-04-96	-13.61	-100.0	3.0	1	.9
102	441247103220701	3N 6E14CCDD	NA	441247	1032207	Mnls	NA	--	--	--	--	--	--

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnls, Minnelusa; Mnkt, Minnekakhta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves—Continued													
103	441311103220801	3N 6E14CBAB	NA	441311	1032208	Mnls	NA	--	--	--	--	--	--
104	441355103230901	3N 6E10CDBB	NA	441355	1032309	Mdsn	NA	--	--	--	--	--	--
105	441303103232601	3N 6E10CBBA	NA	441303	1032326	Mnls	NA	--	--	--	--	--	--
106	440629103040901	2N 9E29BBCC	City of Box Elder	440629	1030409	Mdsn	NA	10-14-92	-14.15	-105.0	<1.0	1	<0.3
106	440629103040901	2N 9E29BBCC	City of Box Elder	440629	1030409	Mdsn	NA	10-22-93	--	--	<1.0	--	<.3
107	440851103044801	2N 9E 7CDCC	Ellsworth AFB	440855	1030510	Mdsn	NA	² 01-01-78	-14.13	-107.0	--	--	--
108	440650103110001	2N 8E20CCDD	NA	440641	1031120	Mdsn	NA	--	--	--	--	--	--
109	440730103112001	2N 8E17CCDD	NA	440730	1031120	Mnls	NA	--	--	--	--	--	--
110	440850103045001	2N 8E13BDC	NA	440801	1030616	Mdsn	NA	--	--	--	--	--	--
111	440504103161501	2N 7E34CCBC	NA	440504	1031615	Mnls	NA	--	--	--	--	--	--
112	440519103160701	2N 7E34CBAA	Black Hills Power & Light	440523	1031557	Mdsn	NA	mean ⁴	-14.30	-108.3	--	--	--
112	440519103160701	2N 7E34CBAA	Black Hills Power & Light	440523	1031557	Mdsn	NA	09-30-93	--	--	11.7	--	3.7
113	440528103155201	2N 7E34BDAD	Timberline	440528	1031552	Mnls	NA	06-22-90	-13.95	-105.0	--	--	--
114	440528103161001	2N 7E34BCCA	NA	440528	1031610	Mnls	NA	--	--	--	--	--	--
115	440538103161201	2N 7E34BBBC	NA	440538	1031612	Mnls	NA	--	--	--	--	--	--
116	440526103173001	2N 7E32ADDD	Rapid City No. 6	440526	1031730	Mdsn	NA	10-04-93	--	--	46.3	--	14.5
116	440526103173001	2N 7E32ADDD	Rapid City No. 6	440526	1031730	Mdsn	NA	mean ⁴	-14.28	-107.2	--	--	--
117	440544103180002	2N 7E32ABBD2	PE-89C City Quarry Madison	440543	1031805	Mdsn	Pair	05-13-92	-14.35	-108.0	96.0	6	30.1
117	440544103180002	2N 7E32ABBD2	PE-89C City Quarry Madison	440543	1031805	Mdsn	Pair	10-13-93	--	--	83.9	--	26.3
118	440544103180001	2N 7E32ABBD	PE-89D City Quarry Minnelusa	440543	1031805	Mnls	Pair	05-12-92	-14.25	-107.0	2.0	1	.6
119	440516103194001	2N 7E31CDCB	Westberry Trails - Minnelusa	440501	1031933	Mnls	NA	08-15-90	-13.65	-101.0	--	--	--
120	440500103195001	2N 7E31CCCCA2	NA	440500	1031950	Mdsn	NA	--	--	--	--	--	--
121	440500103193601	2N 7E31CCCCA	Westberry Trails - Madison	440458	1031950	Mdsn	NA	09-30-93	--	--	98.9	--	31.0
121	440500103193601	2N 7E31CCCCA	Westberry Trails - Madison	440458	1031950	Mdsn	NA	mean ⁴	-13.94	-104.3	--	--	--
122	440541103192301	2N 7E31BADA	NA	440541	1031923	Mdsn	NA	--	--	--	--	--	--
123	440612103152001	2N 7E27DABB	Rapid City No. 10	440612	1031522	Mdsn	NA	10-01-93	--	--	14.9	--	4.7

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnls, Minnelusa; Mnkt, Minnekahta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves—Continued													
123	440612103152001	2N 7E27DABB	Rapid City No. 10	440612	1031522	Mdsn	NA	⁵ 07-19-00	--	--	23.4	1.6	7.3
123	440612103152001	2N 7E27DABB	Rapid City No. 10	440612	1031522	Mdsn	NA	mean ⁴	-14.38	-108.8	--	--	--
124	440655103140501	2N 7E23DADC	Rapid City No. 8	440655	1031407	Mdsn	NA	09-28-93	--	--	<1.0	--	<.3
124	440655103140501	2N 7E23DADC	Rapid City No. 8	440655	1031407	Mdsn	NA	mean ⁴	-14.40	-108.5	--	--	--
125	440647103183201	2N 7E20CCDB	NA	440647	1031832	Mnls	NA	--	--	--	--	--	--
126	440808103193701	2N 7E18BCA	Lien	440808	1031937	Mdsn	NA	² 07-20-78	--	--	53.0	--	16.6
126	440808103193701	2N 7E18BCA	Lien	440808	1031937	Mdsn	NA	mean ⁴	-14.18	-106.0	--	--	--
127	440738103173601	2N 7E17DDDB	NA	440738	1031736	Mnls	NA	--	--	--	--	--	--
128	440817103181701	2N 7E17BACA2	NA	440817	1031817	Mnls	NA	--	--	--	--	--	--
129	440818103180801	2N 7E17BAAD	PE-84B - Dog Track	440819	1031809	Mnls	Obs	05-19-92	-13.40	-101.0	<1.0	1	<.3
130	440823103162701	2N 7E16AAB	Fischer Sand and Gravel	440823	1031627	Mdsn	NA	09-18-96	-13.66	-102.0	--	--	--
131	440832103160901	2N 7E10CDCA	NA	440837	1031609	Mnls	NA	--	--	--	--	--	--
132	440824103160401	2N 7E10CCDC	NA	440824	1031604	Mnls	NA	--	--	--	--	--	--
133	440826103174701	2N 7E 8DDCC2	NA	440826	1031747	Mnls	NA	--	--	--	--	--	--
134	440833103184101	2N 7E 8CCBC	NA	440833	1031841	Mnls	NA	--	--	--	--	--	--
135	440907103183501	2N 7E 8BBCD	NA	440907	1031835	Mnls	NA	--	--	--	--	--	--
136	440901103184801	2N 7E 7ADAB	NA	440901	1031848	Mnls	NA	--	--	--	--	--	--
137	440919103170501	2N 7E 4CDCE	NA	440920	1031658	Mnls	NA	--	--	--	--	--	--
138	440931103141401	2N 7E 2DBDDC	Weston Development	440931	1031414	Mdsn	NA	10-08-92	-13.45	-100.0	<1.0	1	<.3
138	440931103141401	2N 7E 2DBDDC	Weston Development	440931	1031414	Mdsn	NA	10-14-93	--	--	<1.0	--	<.3
139	440939103142001	2N 7E 2DBDD	NA	440939	1031420	Mnls	NA	--	--	--	--	--	--
140	440527103220401	2N 6E35BCAB	NA	440527	1032204	Mdsn	NA	--	--	--	--	--	--
141	440541103211401	2N 6E35AADA	NA	440541	1032114	Mdsn	NA	--	--	--	--	--	--
142	44058103213001	2N 6E23DBAB	Stanley	440704	1032132	Mdsn	NA	mean ⁴	-14.43	-110.0	--	--	--
143	440708103214301	2N 6E23BDD	NA	440708	1032143	Mdsn	NA	--	--	--	--	--	--
144	440811103222202	2N 6E15ADAA2	PE-96B Doty Deadwood	440811	1032221	Ddwd	Pair	10-21-97	-13.07	-98.0	138.9	8.3	43.5

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnls, Mammelusa; Mnkt, Minnekakhta; Dtdwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves—Continued													
145	440811103222201	2N 6E15ADAA	PE-95C Doty Madison	440811	10322221	Mdsn	Pair	10-22-97	-13.25	-98.7	25.9	1.9	8.1
146	440919103210201	2N 6E 1CCCD2	NA	440919	1032102	Mnls	NA	--	--	--	--	--	--
147	440920103210401	2N 6E 1CCCD	NA	440920	1032104	Mnls	NA	--	--	--	--	--	--
148	440334103095601	IN 8E 9CAB2	Rapid Valley	440334	1030956	Mdsn	NA	10-13-92	-12.55	-92.5	<1.0	1	<.3
149	440004103174001	IN 7E32DABA	Highland Hills	440006	1031742	Mdsn	NA	07-25-96	--	--	71.0	5	22.3
149	440004103174001	IN 7E32DABA	Highland Hills	440006	1031742	Mdsn	NA	mean ⁴	-12.66	-96.7	--	--	--
150	440002103173901	IN 7E32DA2	NA	440002	1031739	Mdsn	NA	--	--	--	--	--	--
151	440523103194201	IN 7E31BCAD	Beardsley	440019	1031941	Mdsn	NA	09-17-96	-12.26	-91.5	--	--	--
152	440026103194001	IN 7E31BBDA	NA	440026	1031940	Mdsn	NA	--	--	--	--	--	--
153	440032103184601	IN 7E30DDDC	NA	440032	1031846	Mdsn	NA	--	--	--	--	--	--
154	440054103173801	IN 7E29DAAC	Hamm's Well A	440054	1031738	Mdsn	NA	mean ⁴	-12.44	-92.8	--	--	--
155	440148103150001	IN 7E23CBBA	NA	440148	1031500	Mnls	NA	--	--	--	--	--	--
156	440203103143601	IN 7E23BDAB	NA	440203	1031436	Mnls	NA	--	--	--	--	--	--
157	440140103152601	IN 7E22D	NA	440140	1031526	Mnls	NA	--	--	--	--	--	--
158	440213103153401	IN 7E22AB	NA	440213	1031534	Mnls	NA	--	--	--	--	--	--
159	440130103163401	IN 7E21DDC	NA	440130	1031634	Mnls	NA	--	--	--	--	--	--
160	440142103164301	IN 7E21DBDB	NA	440142	1031643	Mnls	NA	--	--	--	--	--	--
161	440223103173201	IN 7E21BCAB	Carriage Hills	440205	1031720	Mdsn	NA	--	--	--	--	--	--
162	440202103164101	IN 7E21ACA	NA	440202	1031641	Mnls	NA	--	--	--	--	--	--
163	440307103193001	IN 7E18BABB	NA	440307	1031930	Mnls	NA	--	--	--	--	--	--
164	440308103184601	IN 7E18AAAD	Cleghorn Well	440308	1031847	Mdsn	NA	11-13-96	-12.44	-96.8	82.0	5	25.7
165	440223103173201	IN 7E17DDDA	Carriage Hills Main Well	440225	1031734	Mdsn	NA	07-24-96	--	--	73.0	5	22.9
165	440223103173201	IN 7E17DDDA	Carriage Hills Main Well	440225	1031734	Mdsn	NA	mean ⁴	-12.13	-92.8	--	--	--
166	440237103173401	IN 7E17DADA	NA	440237	1031734	Mnls	NA	--	--	--	--	--	--
167	440308103180701	IN 7E17ABCC	Steuerwald	440304	1031807	Mdsn	NA	09-13-96	-12.09	-91.9	--	--	--
168	440300103173501	IN 7E17AAAC2	Chapel Lane Madison (CHPLN-2)	440305	1031739	Mdsn	NA	09-30-93	--	--	87.7	--	27.5

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnls, Minnelusa; Mnkt, Minnekahta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves—Continued													
168	440300103173501	IN 7E17AAAAC2	Chapel Lane Madison (CHPLN-2)	440305	1031739	Mdsn	NA	mean ⁴	-12.05	-92.3	--	--	--
169	440220103164001	IN 7E16DCDC	Rapid City No. 11 (Corral Drive)	440220	1031640	Mdsn	NA	12-17-91	--	--	34.0	3	10.7
169	440220103164001	IN 7E16DCDC	Rapid City No. 11 (Corral Drive)	440220	1031640	Mdsn	NA	10-05-93	--	--	53.0	--	16.6
169	440220103164001	IN 7E16DCDC	Rapid City No. 11 (Corral Drive)	440220	1031640	Mdsn	NA	07-24-96	--	--	51.0	3	16.0
169	440220103164001	IN 7E16DCDC	Rapid City No. 11 (Corral Drive)	440220	1031640	Mdsn	NA	⁵ 07-19-00	--	--	38.4	2.6	12.0
169	440220103164001	IN 7E16DCDC	Rapid City No. 11 (Corral Drive)	440220	1031640	Mdsn	NA	mean ⁴	-12.09	-91.5	--	--	--
170	440300103165801	IN 7E16BADB	NA	440300	1031658	Mnls	NA	--	--	--	--	--	--
171	440225103160801	IN 7E15CC	NA	440225	1031608	Mnls	NA	--	--	--	--	--	--
172	440342103160701	IN 7E10BCDB	Rapid City No. 9 (Meadowbrook)	440342	1031609	Mdsn	NA	05-08-91	--	--	67.0	5	21.0
172	440342103160701	IN 7E10BCDB	Rapid City No. 9 (Meadowbrook)	440342	1031609	Mdsn	NA	09-29-93	--	--	77.5	--	24.3
172	440342103160701	IN 7E10BCDB	Rapid City No. 9 (Meadowbrook)	440342	1031609	Mdsn	NA	05-13-97	--	--	71.0	4.5	22.3
172	440342103160701	IN 7E10BCDB	Rapid City No. 9 (Meadowbrook)	440342	1031609	Mdsn	NA	⁵ 07-19-00	--	--	58.2	3.2	18.2
172	440342103160701	IN 7E10BCDB	Rapid City No. 9 (Meadowbrook)	440342	1031609	Mdsn	NA	mean ⁴	-12.77	-98.3	--	--	--
173	440331103171601	IN 7E9CBAC	NA	440331	1031716	Mnls	NA	--	--	--	--	--	--
174	440338103171601	IN 7E9BCDC	NA	440338	1031716	Mnls	NA	--	--	--	--	--	--
175	440351103171301	IN 7E9BBCA	Rapid City No. 3	440351	1031713	Mnls	NA	mean ⁴	-13.11	-98.7	--	--	--
176	440310103173802	IN 7E8DDCD2	Chapel Lane-Madison (CHPLN-3)	440312	1031740	Mdsn	Pair	12-11-91	-12.35	-92.0	6.0	1	1.9
176	440310103173802	IN 7E8DDCD2	Chapel Lane-Madison (CHPLN-3)	440312	1031740	Mdsn	Pair	09-30-93	--	--	6.9	--	2.2
177	440310103173801	IN 7E8DDCD	Chapel Lane-Minnelusa (CHPLN-1)	440312	1031741	Mnls	Pair	05-20-92	-12.90	-96.5	64.0	4	20.1
178	440338103173302	IN 7E8ADDD2	PE-89A Canyon Lake Madison	440337	1031734	Mdsn	Pair	09-28-93	--	--	75.9	--	23.8
178	440338103173302	IN 7E8ADDD2	PE-89A Canyon Lake Madison	440337	1031734	Mdsn	Pair	mean ⁴	-12.70	-98.0	--	--	--
179	440338103173301	IN 7E8ADDD	PE-89B Canyon Lake Minnelusa	440337	1031735	Mnls	Pair	05-14-92	-13.90	-103.0	22.0	2	6.9
180	440446103193201	IN 7E6BACB	Crosswaite	440446	1031932	Mdsn	NA	09-16-96	-13.69	-104.0	--	--	--
181	440414103164601	IN 7E4DCBA	Rapid City No. 4	440413	1031649	Mnls	NA	mean ⁴	-13.83	-103.0	--	--	--
182	440430103160202	IN 7E3CBAA2	PE-65A Sioux Park 2 Madison	440427	1031605	Mdsn	Pair	mean ⁴	-14.16	-105.7	--	--	--
183	440430103160201	IN 7E3CBAA	PE-64B Sioux Park 1 Minnelusa	440427	1031605	Mnls	Pair	mean ⁴	-14.38	-107.5	--	--	--

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnls, Minnelusa; Mnkt, Minnekakhta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves—Continued													
184	440436103161201	IN 7E 3BCBC	NA	440436	1031612	Mnls	NA	--	--	--	--	--	--
185	440443103161301	IN 7E 3BBBCD	Rapid City No. 5	440443	1031613	Mdsn	NA	10-07-93	--	--	13.7	--	4.3
185	440443103161301	IN 7E 3BBBCD	Rapid City No. 5	440443	1031613	Mdsn	NA	mean ⁴	-14.23	-107.0	--	--	--
186	440446103161701	IN 7E 3BBCC	PE-89E Lime Creek	440444	1031618	Mdsn	NA	06-20-90	--	--	<1.0	1	<.3
186	440446103161701	IN 7E 3BBCC	PE-89E Lime Creek	440444	1031618	Mdsn	NA	09-25-93	--	--	<1.0	--	<.3
186	440446103161701	IN 7E 3BBCC	PE-89E Lime Creek	440444	1031618	Mdsn	NA	mean ⁴	-14.38	-109.0	--	--	--
187	440452103155301	IN 7E 3BABD	Camp Rapid	440452	1031553	Mnls	NA	07-16-90	-13.70	-103.0	<1.0	1	<.3
188	440427103131701	IN 7E 1DBBB	Rapid City No. 7 (Star Village)	440426	1031318	Mdsn	Obs	02-07-91	-14.40	-108.0	2.0	1	.6
188	440427103131701	IN 7E 1DBBB	Rapid City No. 7 (Star Village)	440426	1031318	Mdsn	Obs	10-31-93	--	--	<1.0	--	<.3
189	440032103195901	IN 6E36AAAB	NA	440032	1031959	Mdsn	NA	--	--	--	--	--	--
190	440224103195401	IN 6E13DDDD	Brooks Cave	440224	1031954	Mdsn	Cave	03-06-87	-13.40	-102.5	--	--	--
191	435916103161801	IS 7E 3CDBD	PE-86A Reptile Gardens Madison	435915	1031620	Mdsn	Pair	10-30-93	--	--	9.5	--	3.0
191	435916103161801	IS 7E 3CDBD	PE-86A Reptile Gardens Madison	435915	1031620	Mdsn	Pair	07-29-96	-12.78	-95.0	15.0	1	4.7
192	435916103161802	IS 7E 3CDBD2	PE-94B Reptile Gardens Minnelusa	435915	1031620	Mnls	Pair	07-30-96	-12.51	-90.7	4.0	1	1.3
193	435937103184401	IS 7E 5BDCA	Spring Canyon (Main Well) No. 1	435937	1031844	Mdsn	NA	08-28-96	-12.36	-96.8	--	--	--
194	435845103163401	IS 7E10BCAC	NA	435845	1031634	Mnls	NA	--	--	--	--	--	--
195	435851103143501	IS 7E11ACAB	Hart Ranch	435848	1031445	Mdsn	NA	10-19-93	--	--	75.0	--	23.5
195	435851103143501	IS 7E11ACAB	Hart Ranch	435848	1031445	Mdsn	NA	07-23-96	--	--	69.0	4	21.6
195	435851103143501	IS 7E11ACAB	Hart Ranch	435848	1031445	Mdsn	NA	⁵ 07-19-00	--	--	56.6	3.2	17.7
195	435851103143501	IS 7E11ACAB	Hart Ranch	435848	1031445	Mdsn	NA	mean ⁴	-12.27	-93.3	--	--	--
196	435635103181401	IS 7E20CAD	Pine Grove	435635	1031814	Mdsn	NA	10-15-93	--	--	82.6	--	25.9
196	435635103181401	IS 7E20CAD	Pine Grove	435635	1031814	Mdsn	NA	mean ⁴	-11.89	-88.1	--	--	--
197	435227103185301	2S 7E17CCAA	PE-95A Hayward	435227	1031852	Mdsn	Obs	11-20-97	-12.06	-87.9	59.8	3.8	18.7
198	435042103171101	2S 7E28DB	NA	435042	1031711	Mnls	NA	--	--	--	--	--	--
199	435018103155801	2S 7E34ABBA	CU-83A Hermosa West	435020	1031600	Mnls	Obs	10-28-97	-11.98	-87.3	<1.0	1	<.3
200	435004103161301	2S 7E34BD	NA	435004	1031613	Mnls	NA	--	--	--	--	--	--

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnls, Minnelusa; Mnkt, Minnekahta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves—Continued													
201	434700104021401	3S 1E18DDDB	CU-93C Boles Canyon Madison	434701	1040215	Mdsn	Pair	03-22-94	-16.32	-125.0	9.0	1	2.8
202	434700104021402	3S 1E18DDDB2	CU-93D Boles Canyon Minnelusa	434701	1040215	Mnls	Pair	12-17-97	-15.88	-123.6	3.2	1	1.0
203	434846103481801	3S 3E 6DCBB	NA	434846	1034818	Mdsn	NA	--	--	--	--	--	--
204	434503103183601	3S 7E32BABA	NA	434503	1031836	Mnls	NA	--	--	--	--	--	--
205	434502103165801	3S 7E33AACB	NA	434502	1031658	Mnls	NA	--	--	--	--	--	--
206	434402103502301	4S 2E 2ADB	NA	434402	1035023	Mdsn	NA	--	--	--	--	--	--
207	434326103555101	4S 2E 6CCDC	NA	434326	1035551	Mnls	NA	--	--	--	--	--	--
208	434351103461501	4S 3E 4BCDA	NA	434351	1034615	Mnls	NA	--	--	--	--	--	--
209	434218103463701	4S 3E17ADAB	NA	434218	1034637	Mnls	NA	--	--	--	--	--	--
210	434350103201901	4S 6E 1DAAA	CU-93A CSP Airport Madison	434350	1032020	Mdsn	Pair	09-06-95	-11.75	-87.6	<1.0	1	<.3
211	434350103201902	4S 6E 1DAAA2	CU-93A CSP Airport Minnelusa	434350	1032020	Mnls	Pair	08-31-95	-11.50	-84.9	3.0	1	.9
212	434236103201601	4S 6E12DDAD	NA	434236	1032016	Mnls	NA	--	--	--	--	--	--
213	434001103131301	4S 7E25DDDB	NA	434001	1031313	Mnls	NA	--	--	--	--	--	--
214	433545103502701	5S 2E23DCAB	NA	433545	1035027	Mnls	NA	--	--	--	--	--	--
215	433517103534201	5S 2E28BCCB	CU-95A Hell Canyon Madison	433517	1035342	Mdsn	Pair	11-05-97	-17.23	-130.8	1.9	1	.6
216	433517103534202	5S 2E28BCCB2	CU-95B Hell Canyon Minnelusa	433517	1035342	Mnls	Pair	11-03-97	-14.21	-111.4	<1.0	1	<.3
217	433849103442701	5S 3E 3ADBB	NA	433849	1034427	Mdsn	NA	--	--	--	--	--	--
218	433831103475201	5S 3E 6DAAC	NA	433831	1034752	Mnls	NA	--	--	--	--	--	--
219	433440103465501	5S 3E32ABAB	NA	433440	1034655	Mnls	NA	--	--	--	--	--	--
220	433852103384901	5S 4E 4ABCB	NA	433852	1033849	Mdsn	NA	--	--	--	--	--	--
221	433607103383401	5S 4E21ACAD	NA	433607	1033834	Mdsn	NA	--	--	--	--	--	--
222	433506103344001	5S 4E25DAAA	NA	433510	1033445	Mdsn	NA	--	--	--	--	--	--
223	433628103173801	5S 7E16CDCA	NA	433628	1031738	Mnls	NA	--	--	--	--	--	--
224	432927103520401	6S 2E34BA	NA	432927	1035204	Mnls	NA	--	--	--	--	--	--
225	432927103521001	6S 2E34BABC	NA	432927	1035210	Mnls	NA	--	--	--	--	--	--
226	432917103522101	6S 2E34BC	NA	432917	1035221	Mnls	NA	--	--	--	--	--	--

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnls, Minnelusa; Mnkt, Minnekahta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves—Continued													
227	433003103420701	6S 3E25ADDC	Myrvik	433000	1034158	Mnls	NA	05-04-94	-14.27	-109.0	<1.0	1	<0.3
228	433347103385101	6S 4E 4BADA	NA	433343	1033857	Mnls	NA	--	--	--	--	--	--
229	433339103385601	6S 4E 4BADD	NA	433339	1033856	Mnls	NA	--	--	--	--	--	--
230	433119103360001	6S 4E14DDAC	NA	433119	1033600	Mnls	NA	--	--	--	--	--	--
231	433000103393901	6S 4E29ADCA	NA	433000	1033939	Mdsn	NA	--	--	--	--	--	--
232	433302103281501	6S 5E12DBAB	Windy City Lake	433255	1032827	Mdsn	Cave	mean ⁴	-12.25	-90.3	--	--	--
233	433114103281601	6S 5E24BAAA	Kaiser	433114	1032816	Mdsn	NA	² 07-19-78	-12.13	--	88.4	--	27.7
234	433021103273601	6S 5E24DDDD	NA	433021	1032736	Mnls	NA	--	--	--	--	--	--
235	432945103323801	6S 5E29DBDA	NA	432945	1033238	Mnls	NA	--	--	--	--	--	--
236	433303103225801	6S 6E 3DDCA	NA	433303	1032258	Mnls	NA	--	--	--	--	--	--
237	433150103230501	6S 6E15ABDD	Streeter Ranch	433150	1032305	Mdsn	NA	² 11-01-77	--	--	33.8	--	10.6
237	433150103230501	6S 6E15ABDD	Streeter Ranch	433150	1032305	Mdsn	NA	03-11-97	--	--	37.4	2.6	11.7
237	433150103230501	6S 6E15ABDD	Streeter Ranch	433150	1032305	Mdsn	NA	mean ⁴	-11.96	-87.6	--	--	--
238	433115103251401	6S 6E21BBBB	CU-91A (7-11 Ranch 1) Madison	433115	1032516	Mdsn	Pair	03-31-94	-11.93	-88.7	<1.0	1	<.3
239	433115103251402	6S 6E21BBBB2	CU-91B (7-11 Ranch 2) Minnelusa	433115	1032516	Mnls	Pair	04-05-94	-12.38	-93.3	<1.0	1	<.3
240	433115103251403	6S 6E21BBBB3	CU-96A (7-11 Ranch 3) Minnekahta	433115	1032516	Mnkt	Pair	11-13-97	-12.44	-94.5	79.0	4.5	24.8
241	432613103584001	7S 1E15DD	Superior #1 Peterson	432613	1035840	Mnls	NA	10-04-68	--	--	<2.3	--	<.7
242	432548103414801	7S 4E19BCCB	FR-92A Minnekahta Jnct Madison	432545	1034151	Mdsn	Pair	03-24-94	-14.88	-114.0	<1.0	1	<.3
243	432548103414802	7S 4E19BCCB2	FR-94A Minnekahta Jnct Minnelusa	432545	1034151	Mnls	Pair	09-11-95	-13.87	-104.0	<1.0	1	<.3
244	432808103294901	7S 5E 2CBAB	NA	432808	1032949	Mnls	NA	--	--	--	--	--	--
245	432616103294701	7S 5E14CBDD	NA	432616	1032947	Mnls	NA	--	--	--	--	--	--
246	432616103294702	7S 5E14CBDD2	NA	432616	1032947	Mnls	NA	--	--	--	--	--	--
247	432603103295901	7S 5E14CCCC	FR-95A Vets Home Madison	432602	1032958	Mdsn	Obs	11-18-97	-15.97	-121.9	<1.0	1	<.3
248	432622103291501	7S 5E14DBC	NA	432622	1032915	Mnls	NA	--	--	--	--	--	--
249	432537103301401	7S 5E22ADBC	NA	432537	1033014	Mnls	NA	--	--	--	--	--	--
250	432523103305401	7S 5E22CDCB	NA	432523	1033054	Mnls	NA	--	--	--	--	--	--

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnl, Minnelusa; Mnkt, Minnekahta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Wells or Caves—Continued													
251	432510103304801	7S 5E22CDCD	NA	432510	1033048	Mnls	NA	--	--	--	--	--	--
252	432459103290101	7S 5E26AACA	NA	432459	1032901	Mnls	NA	--	--	--	--	--	--
253	432136103321001	8S 5E16BBAD	Fetters	432136	1033210	Mdsn	NA	05-12-94	-16.59	-127.0	<1.0	1	<0.3
254	432127103325601	8S 5E17ACBB	Chiller	432127	1033256	Mnls	NA	05-11-94	-15.15	-118.0	<1.0	1	<.3
255	431810103491701	9S 2E 1AABC	NA	431810	1034917	Mdsn	NA	--	--	--	--	--	--
256	431804103492101	9S 2E 1ABDD	NA	431804	1034921	Mdsn	NA	--	--	--	--	--	--
257	431753103492601	9S 2E 1ACDB	NA	431753	1034926	Mdsn	NA	--	--	--	--	--	--
258	431750103500301	9S 2E 1BCDC	NA	431750	1035003	Mdsn	NA	--	--	--	--	--	--
259	431743103501501	9S 2E 2DAAA	NA	431743	1035015	Mdsn	NA	--	--	--	--	--	--
260	431232103513501	10S 2E 3DAAA	NA	431232	1035135	Mdsn	NA	--	--	--	--	--	--
261	431218103512501	10S 2E 3DADD	NA	431218	1035125	Mdsn	NA	--	--	--	--	--	--
262	431220103514001	10S 2E 3DDAA	NA	431220	1035140	Mdsn	NA	--	--	--	--	--	--
263	431246103515901	10S 2E13ACBA	Black Hills Army Depot #2 (Provo)	431105	1034935	Mdsn	NA	2 ⁰¹ -01-78	-17.09	-131.0	--	--	--
264	445546104382701	57N 65W15DA - Wyo	HTH No. 1	445546	1043827	Mdsn	NA	2 ⁰¹ -01-78	--	--	17.2	--	5.4
265	443458104425801	53N 65W18BBD - Wyo	Devils Tower	443458	1044258	Mdsn	NA	2 ⁰¹ -01-78	-17.85	-139.9	4.8	--	1.5
266	442930104063501	52N 60W18C - Wyo	Ranch A	442930	1040635	Mdsn	NA	2 ⁰¹ -01-78	-17.49	--	132.7	--	41.6
267	440621104364301	48N 65W25CC - Wyo	Upton	440621	1043643	Mdsn	NA	2 ⁰¹ -01-78	-18.18	-133.0	--	--	--
268	435740104294002	46N 64W13CC - Wyo	Coronado No. 2	435740	1042940	Mdsn	NA	2 ⁰¹ -01-78	-17.60	-133.3	<1.0	--	<.3
269	435800104244001	46N 63W15BD - Wyo	Osage	435800	1042440	Mdsn	NA	2 ⁰¹ -01-78	-18.15	-135.0	1.6	--	.5
270	435800104210001	46N 62W18BDC - Wyo	Seeley	435800	1042100	Mdsn	NA	2 ⁰¹ -01-78	-17.75	-133.5	2.6	--	.8
271	435540104063001	46N 60W31BA - Wyo	Martens	435540	1040630	Mdsn	NA	2 ⁰¹ -01-78	-17.45	-130.9	--	--	--
272	435030104110001	45N 61W33AB - Wyo	Self	435030	1041100	Mdsn	NA	2 ⁰¹ -01-78	-17.60	-131.8	<1.0	--	<.3
273	435125104110502	45N 61W28AB - Wyo	Voss	435125	1041105	Mdsn	NA	2 ⁰¹ -01-78	-17.40	-130.6	7.3	--	2.3
274	435138104121101	45N 61W20DCA - Wyo	Newcastle	435138	1041211	Mdsn	NA	2 ⁰¹ -01-78	-17.66	-130.0	<1.0	--	<.3
275	434700104230001	44N 63W26CAC - Wyo	JBJ	434700	1042300	Mdsn	NA	2 ⁰¹ -01-78	-17.95	-130.6	<1.0	--	<.3

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnl, Minnelusa; Mnkt, Minnekakhta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Springs													
276	442706104015401	6N 1E30DAAD	Knight Spring	442706	1040154	Mnl	HW	08-04-95	--	--	130.0	7	40.8
276	442706104015401	6N 1E30DAAD	Knight Spring	442706	1040154	Mnl	HW	mean ⁴	-16.91	-126.6	--	--	--
277	441726103285801	4N 5E23DBC	Jones Spring	441726	1032858	Mdsn	HW	² 01-01-78	-14.61	-110.0	880.4	--	276.0
278	441949103583201	4N 1E 3DD	NA	441950	1035830	Mdsn	HW	--	--	--	--	--	--
279	441232103264301	3N 6E19BDBA	NA	441232	1032643	Mdsn	HW	07-18-96	-14.06	-103.0	130.0	8	40.8
280	441322103272801	3N 5E13ACAA	NA	441322	1032728	Ddwd	HW	08-08-95	--	--	170.0	9	53.3
280	441322103272801	3N 5E13ACAA	NA	441322	1032728	Ddwd	HW	mean ⁴	-13.96	-104.4	--	--	--
281	441310103435901	3N 3E14CBBB	JHD Spring	441310	1034359	Ddwd	HW	09-13-95	--	--	170.0	9	53.3
281	441310103435901	3N 3E14CBBB	JHD Spring	441310	1034359	Ddwd	HW	mean ⁴	-16.56	-126.8	--	--	--
282	441434103560001	3N 2E 6CCCD	Intake Gulch	441434	1035600	Mdsn	HW	08-03-95	--	--	100.0	6	31.3
282	441434103560001	3N 2E 6CCCD	Intake Gulch	441434	1035600	Mdsn	HW	mean ⁴	-17.59	-133.7	--	--	--
283	06408700	2N 2E15ADB	Rhoads Fork near Rochford	440812	1035129	Mdsn	HW	² 01-01-78	--	--	198.4	--	62.2
283	06408700	2N 2E15ADB	Rhoads Fork near Rochford	440812	1035129	Mdsn	HW	08-07-95	--	--	140.0	8	43.9
283	06408700	2N 2E15ADB	Rhoads Fork near Rochford	440812	1035129	Mdsn	HW	mean ⁴	-16.96	-127.1	--	--	--
284	440820104004000	2N 1E16BBD	Cold Creek Springs	440820	1040040	Mdsn	HW	--	--	--	--	--	--
285	06409000	1N 2E25CCA	Castle Creek above Deerfield	440049	1034948	Mdsn	HW	mean ⁴	-16.41	-123.7	--	--	--
286	440415104014000	1N 1E 5CCA	Beaver Creek Springs	440415	1040140	Mdsn	HW	--	--	--	--	--	--
287	434953103585201	2S 1E34DBAC	Barrel Spring	434953	1035852	Mnl	HW	07-25-95	--	--	59.0	4	18.5
287	434953103585201	2S 1E34DBAC	Barrel Spring	434953	1035852	Mnl	HW	mean ⁴	-14.60	-113.6	--	--	--
288	434045103502301	4S 2E26AABC	Water Draw Spring	434045	1035023	Mnl	HW	09-14-95	--	--	41.0	3	12.9
288	434045103502301	4S 2E26AABC	Water Draw Spring	434045	1035023	Mnl	HW	mean ⁴	-14.27	-112.5	--	--	--
289	433944103521801	4S 2E34BCAB	Mckenna Spring	433944	1035218	Mnl	HW	09-14-95	--	--	26.0	2	8.2
289	433944103521801	4S 2E34BCAB	Mckenna Spring	433944	1035218	Mnl	HW	mean ⁴	-13.41	-103.6	--	--	--
290	443237103525801	7N2E28BACD	Higgins Gulch below I-90	443237	1035258	Mnl	DG	09-26-94	--	--	100.0	6	31.3
290	443237103525801	7N2E28BACD	Higgins Gulch below I-90	443237	1035258	Mnl	DG	10-10-97	--	--	89.6	5.1	28.1
290	443237103525801	7N2E28BACD	Higgins Gulch below I-90	443237	1035258	Mnl	DG	mean ⁴	-16.36	-123.8	--	--	--

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnl, Minnelusa; Mnt, Minnekahta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Springs—Continued													
291	443012103544700		Higgins Gulch above Spearfish	443012	1035447		DG	08-21-97	-16.75	-126.2	76.5	4.5	24.0
292	443309103532401	7N 2E20DAAD	Old Spearfish Hatchery	443309	1035324		DG	09-26-94	-16.71	-128.0	83.0	5	26.0
292	443309103532401	7N 2E20DAAD	Old Spearfish Hatchery	443309	1035324		DG	08-21-97	--	--	42.9	2.6	13.4
293	443330104003401	7N 1E21BBBCD	McNenny Rearing Pond	443330	1040034		DG	09-28-94	-17.19	-132.0	66.0	4	20.7
294	443335104010001	7N 1E20AABC	Mirror Lake	443335	1040100		DG	09-28-94	-15.34	-123.0	54.0	3	16.9
295	443356103593701	7N 1E16DADC	Cox Lake	443356	1035937		DG	09-27-94	-16.95	-129.0	67.0	4	21.0
296	06430532	7N 1E16BDB	Crow Creek near Beulah, WY	443414	1040019		DG	08-30-96	-16.67	-128.0	61.0	4	19.1
297	06425100	3N 8E 9AA	Elk Creek near Rapid City	441425	1030903		DG	09-05-96	-13.79	-106.0	96.0	6	30.1
298	440525103173701	2N 7E32ADDA2	City Springs	440525	1031737		DG	09-26-93	--	--	130.2	--	40.8
298	440525103173701	2N 7E32ADDA2	City Springs	440525	1031737		DG	⁵ 06-06-00	--	--	81.9	4.8	25.7
298	440525103173701	2N 7E32ADDA2	City Springs	440525	1031737		DG	mean ⁴	-14.37	-107.9	--	--	--
299	440243103193701	1N 7E18CBAA	Tittle Spring	440243	1031937		DG	07-22-96	-14.45	-111.0	92.0	5	28.8
300	440327103180503	1N 7E 8DBBD	Cleghorn Springs	440331	1031801		DG	² 01-01-78	--	--	580.6	--	182.0
300	440327103180503	1N 7E 8DBBD	Cleghorn Springs	440331	1031801		DG	09-27-93	--	--	96.3	--	30.2
300	440327103180503	1N 7E 8DBBD	Cleghorn Springs	440331	1031801		DG	mean ⁴	-12.92	-99.1	--	--	--
301	435013103162600	2S 7E34BBB	Battle Creek bel. Minnelusa outcrop	435013	1031626		DG	09-06-96	-11.62	-85.9	65.0	4	20.4
302	434655103181701	3S 7E17DCDD	Grace Coolidge Creek	434655	1031817		DG	09-10-96	-11.68	-88.5	55.0	3	17.2
303	433128103223401	6S 6E14CDB	Beaver Creek Spring	433128	1032234		DG	04-25-94	--	--	19.0	2	6.0
303	433128103223401	6S 6E14CDB	Beaver Creek Spring	433128	1032234		DG	10-03-94	-14.10	-108.0	--	--	--
304	432703103302801	7S 5E10DCBA	Hot Brook Spring	432703	1033028		DG	04-21-94	--	--	13.0	1	4.1
304	432703103302801	7S 5E10DCBA	Hot Brook Spring	432703	1033028		DG	10-03-94	-14.86	-113.0	12.0	1	3.8
305	432630103284701	7S 5E13BCCC	Evans Plunge Spring	432630	1032847		DG	² 01-01-78	-16.71	-121.0	--	--	--
305	432630103284701	7S 5E13BCCC	Evans Plunge Spring	432630	1032847		DG	04-21-94	--	--	2.0	1	.6
306	06402000	7S 5E24BB	Fall River at Hot Springs	432550	1032833		DG	09-11-96	-15.43	-119.0	8.0	1	2.5
307	432028103331601	8S 5E20BDCB	Cool Spring	432028	1033316		DG	09-12-96	-15.23	-116.0	8.0	1	2.5
308	432006103330501	8S 5E20CDAB	Cascade Springs	432006	1033305		DG	10-19-95	--	--	7.0	1	2.2

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnl, Minnelusa; Mnkt, Minnekahta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Springs—Continued													
308	432006103330501	8S 5E20CDAB	Cascade Springs	432006	1033305		DG	09-12-96	--	--	7.0	1	2.2
308	432006103330501	8S 5E20CDAB	Cascade Springs	432006	1033305		DG	mean ⁴	-15.40	-118.5	--	--	--
Surface Water													
309	06429920		Bear Gulch near Maurice	442514	1040226	NA	LZ	10-10-96	--	--	42.0	3	13.2
309	06429920		Bear Gulch near Maurice	442514	1040226	NA	LZ	09-11-97	--	--	59.2	3.8	18.6
309	06429920		Bear Gulch near Maurice	442514	1040226	NA	LZ	mean ⁴	-16.96	-128.8	--	--	--
310	06430520		Beaver Creek near Maurice	442257	1040013	NA	LZ	10-09-96	--	--	75.0	5	23.5
310	06430520		Beaver Creek near Maurice	442257	1040013	NA	LZ	09-11-97	--	--	68.8	4.5	21.6
310	06430520		Beaver Creek near Maurice	442257	1040013	NA	LZ	mean ⁴	-16.59	-127.4	--	--	--
311	442405103485100		False Bottom Cr ab Madison outcrop	442405	1034851	NA	LZ	08-21-97	-16.93	-127.7	43.5	2.6	13.6
312	06437020		Bear Butte Creek near Deadwood	442008	1033806	NA	LZ	10-09-96	--	--	99.0	6	31.0
312	06437020		Bear Butte Creek near Deadwood	442008	1033806	NA	LZ	10-10-97	--	--	81.9	5.1	25.7
312	06437020		Bear Butte Creek near Deadwood	442008	1033806	NA	LZ	mean ⁴	-16.01	-121.2	--	--	--
313	441742103333300		Elk Creek above Meadow Creek	441742	1033333	NA	LZ	09-20-96	--	--	100.0	6	31.3
313	441742103333300		Elk Creek above Meadow Creek	441742	1033333	NA	LZ	10-09-97	--	--	81.0	4.5	25.4
313	441742103333300		Elk Creek above Meadow Creek	441742	1033333	NA	LZ	mean ⁴	-16.24	-123.7	--	--	--
314	441738103333400		Meadow Creek above Elk Creek	441738	1033334	NA	LZ	09-20-96	--	--	120.0	7	37.6
314	441738103333400		Meadow Creek above Elk Creek	441738	1033334	NA	LZ	10-09-97	--	--	113.6	6.4	35.6
314	441738103333400		Meadow Creek above Elk Creek	441738	1033334	NA	LZ	mean ⁴	-15.74	-118.2	--	--	--
315	06422500		Boxelder Creek near Nemo	440838	1032716	NA	LZ	09-27-93	--	--	185.3	--	58.1
315	06422500		Boxelder Creek near Nemo	440838	1032716	NA	LZ	10-08-97	--	--	85.4	5.1	26.8
315	06422500		Boxelder Creek near Nemo	440838	1032716	NA	LZ	⁵ 06-06-00	--	--	50.6	3.2	15.9
315	06422500		Boxelder Creek near Nemo	440838	1032716	NA	LZ	mean ⁴	-15.35	-116.3	--	--	--
316	06412200		Rapid Creek above Victoria Creek	440248	1032106	NA	LZ	09-27-93	--	--	110.7	--	34.7
316	06412200		Rapid Creek above Victoria Creek	440248	1032106	NA	LZ	mean ⁴	-14.18	-109.9	--	--	--
317	440110103245101		Victoria Creek	440110	1032451	NA	LZ	mean ⁴	-13.49	-99.7	--	--	--

Table 7. Selected site information and isotope data for sites used in report—Continued

[pCi/L, picocuries per liter; TU, tritium unit; Mdsn, Madison; Mnl, Minnelusa; Mnkt, Minnekahta; Ddwd, Deadwood; <, less than; NA, not applicable; Obs, observation; LZ, loss zone; --, no data. Site types: Obs, observation well; Pair, observation well pair; HW, headwater spring; DG, downgradient spring; LZ, stream above loss zone]

Site number	Station identification number	Local number	Name	Latitude	Longitude	Aquifer	Site type	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)	Tritium (pCi/L)	Tritium 2-sigma (pCi/L)	Tritium (TU) ¹
Surface Water—Continued													
318	06407500		Spring Creek near Keystone	435845	1032025	NA	LZ	09-27-93	--	--	94.7	--	29.7
318	06407500		Spring Creek near Keystone	435845	1032025	NA	LZ	09-09-96	--	--	80.0	5	25.1
318	06407500		Spring Creek near Keystone	435845	1032025	NA	LZ	mean ⁴	-12.59	-96.5	--	--	--
319	06404000		Battle Creek near Keystone	435221	1032010	NA	LZ	09-06-96	--	--	61.0	4	19.1
319	06404000		Battle Creek near Keystone	435221	1032010	NA	LZ	09-12-97	--	--	61.1	3.8	19.2
319	6404000		Battle Creek near Keystone	435221	1032010	NA	LZ	mean ⁴	-11.51	-84.8	--	--	--
320	06404998		Grace Coolidge Cr nr Game Lodge	434540	1032149	NA	LZ	09-10-96	--	--	51.0	3	16.0
320	06404998		Grace Coolidge Cr nr Game Lodge	434540	1032149	NA	LZ	09-12-97	--	--	50.6	3.2	15.9
320	06404998		Grace Coolidge Cr nr Game Lodge	434540	1032149	NA	LZ	mean ⁴	-11.58	-85.8	--	--	--
321	06403300		French Creek above Fairburn	434302	1032203	NA	LZ	10-07-96	--	--	65.0	4	20.4
321	06403300		French Creek above Fairburn	434302	1032203	NA	LZ	09-11-97	--	--	57.6	3.8	18.1
321	06403300		French Creek above Fairburn	434302	1032203	NA	LZ	mean ⁴	-11.58	-89.5	--	--	--
322	06402430		Beaver Creek near Pringle	433453	1032834	NA	LZ	10-01-96	--	--	83.0	5	26.0
322	06402430		Beaver Creek near Pringle	433453	1032834	NA	LZ	09-10-97	--	--	73.3	4.5	23.0
322	06402430		Beaver Creek near Pringle	433453	1032834	NA	LZ	mean ⁴	-12.28	-92.2	--	--	--
Meteorological													
323	441852103594800		Precip at Little Spearfish Cr	441852	1035948	NA	NA	06-20-98	--	--	40.3	2.6	12.6
324	440415103151500		Precip at USGS at Rapid City	440415	1031515	NA	NA	05-22-97	--	--	45.8	3.2	14.4
324	440415103151500		Precip at USGS at Rapid City	440415	1031515	NA	NA	05-21-98	--	--	66.9	3.8	21.0

¹ 1 TU = 3.19 pCi/L.

² Data from Busby and others (1983, 1991). In some cases, exact sample dates are unknown but are listed as 01-01-78.

³ Recent drilling in the vicinity indicates that these may be Opeche or Minnekahta.

⁴ Mean values for individual samples listed in table 8.

⁵ Table includes only data collected through water year 1998, with exception of tritium data for six selected sites collected during water year 2000.

Table 8. Stable isotope data for sites with multiple samples

[--, no data]

Site number	Name	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)
48	Swanson Well	08-16-94	-17.45	-133.0
48	Swanson Well	08-30-96	-17.46	-132.0
112	Black Hills Power & Light	06-26-90	-14.30	-108.0
112	Black Hills Power & Light	09-30-93	-14.40	-108.0
112	Black Hills Power & Light	04-20-95	-14.20	-109.0
116	Rapid City No. 6	04-03-90	-14.15	-105.0
116	Rapid City No. 6	12-13-90	-14.45	-109.0
116	Rapid City No. 6	10-04-93	-14.40	-107.0
116	Rapid City No. 6	04-20-95	-14.20	-108.0
116	Rapid City No. 6	08-26-96	-14.22	-107.0
121	Westberry Trails - Madison	08-21-90	-14.00	-103.0
121	Westberry Trails - Madison	09-30-93	-14.00	-105.0
121	Westberry Trails - Madison	04-26-95	-13.80	-106.0
121	Westberry Trails - Madison	09-11-96	-13.96	-103.0
123	Rapid City No. 10	09-06-91	-14.35	-110.0
123	Rapid City No. 10	10-01-93	-14.40	-108.0
123	Rapid City No. 10	10-14-94	-14.40	-109.0
123	Rapid City No. 10	08-26-96	-14.36	-108.0
124	Rapid City No. 8	09-05-91	-14.30	-108.0
124	Rapid City No. 8	09-28-93	-14.50	-109.0
124	Rapid City No. 8	04-18-95	-14.40	-109.0
124	Rapid City No. 8	08-26-96	-14.41	-108.0
126	Lien	¹ 07-20-78	-14.19	--
126	Lien	09-10-96	-14.17	-106.0
142	Stanley	08-23-89	-14.36	-109.0
142	Stanley	09-10-96	-14.49	-111.0
149	Highland Hills	07-25-96	-12.53	-96.3
149	Highland Hills	11-18-96	-12.47	-94.8
149	Highland Hills	01-09-97	-12.50	-95.6
149	Highland Hills	03-03-97	-12.54	-94.9
149	Highland Hills	05-13-97	-12.72	-97.9
149	Highland Hills	07-14-97	-12.94	-100.3
149	Highland Hills	09-10-97	-12.79	-97.4
149	Highland Hills	12-05-97	-12.73	-96.4
149	Highland Hills	02-06-98	-12.63	-96.1

Table 8. Stable isotope data for sites with multiple samples—Continued

[-, no data]

Site number	Name	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)
149	Highland Hills	05-11-98	-12.74	-95.9
149	Highland Hills	07-08-98	-12.73	-97.2
149	Highland Hills	09-30-98	-12.56	-98.0
154	Hamms Well A	12-04-86	-12.55	-93.0
154	Hamms Well A	02-06-87	-12.40	-93.0
154	Hamms Well A	04-09-87	-12.50	-92.0
154	Hamms Well A	06-04-87	-12.40	-94.0
154	Hamms Well A	07-02-87	-12.35	-91.0
154	Hamms Well A	08-11-87	-12.45	-93.5
165	Carriage Hills Main Well	07-24-96	-11.93	-91.3
165	Carriage Hills Main Well	11-18-96	-12.03	-90.6
165	Carriage Hills Main Well	01-07-97	-11.98	-91.0
165	Carriage Hills Main Well	03-03-97	-11.99	-90.7
165	Carriage Hills Main Well	05-13-97	-12.04	-93.4
165	Carriage Hills Main Well	07-11-97	-12.13	-92.9
165	Carriage Hills Main Well	09-10-97	-12.12	-94.3
165	Carriage Hills Main Well	12-05-97	-12.15	-91.8
165	Carriage Hills Main Well	02-06-98	-12.20	-94.7
165	Carriage Hills Main Well	05-07-98	-12.24	-93.9
165	Carriage Hills Main Well	07-08-98	-12.34	-94.6
165	Carriage Hills Main Well	09-29-98	-12.35	-93.8
168	Chapel Lane Madison (CHPLN-2)	04-09-87	-11.85	-90.5
168	Chapel Lane Madison (CHPLN-2)	05-07-87	-11.81	-90.5
168	Chapel Lane Madison (CHPLN-2)	08-21-87	-11.90	-91.5
168	Chapel Lane Madison (CHPLN-2)	01-21-88	-11.75	-89.8
168	Chapel Lane Madison (CHPLN-2)	03-22-88	-11.79	-91.0
168	Chapel Lane Madison (CHPLN-2)	05-17-88	-11.76	-90.3
168	Chapel Lane Madison (CHPLN-2)	06-24-88	-11.80	-90.0
168	Chapel Lane Madison (CHPLN-2)	07-22-88	-11.80	-91.7
168	Chapel Lane Madison (CHPLN-2)	08-19-88	-11.82	-92.3
168	Chapel Lane Madison (CHPLN-2)	01-19-90	-12.10	-94.5
168	Chapel Lane Madison (CHPLN-2)	07-23-90	-12.15	-92.5
168	Chapel Lane Madison (CHPLN-2)	09-30-93	-11.90	-91.0
168	Chapel Lane Madison (CHPLN-2)	04-25-95	-11.80	-92.0
168	Chapel Lane Madison (CHPLN-2)	09-13-96	-12.09	-92.5

Table 8. Stable isotope data for sites with multiple samples—Continued

[--, no data]

Site number	Name	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)
168	Chapel Lane Madison (CHPLN-2)	10-24-96	-12.07	-91.8
168	Chapel Lane Madison (CHPLN-2)	11-18-96	-12.04	-90.2
168	Chapel Lane Madison (CHPLN-2)	01-07-97	-12.11	-91.1
168	Chapel Lane Madison (CHPLN-2)	03-03-97	-12.16	-91.6
168	Chapel Lane Madison (CHPLN-2)	05-13-97	-12.16	-95.3
168	Chapel Lane Madison (CHPLN-2)	07-11-97	-12.20	-94.3
168	Chapel Lane Madison (CHPLN-2)	09-10-97	-12.29	-93.4
168	Chapel Lane Madison (CHPLN-2)	12-05-97	-12.36	-94.6
168	Chapel Lane Madison (CHPLN-2)	02-06-98	-12.39	-93.3
168	Chapel Lane Madison (CHPLN-2)	05-07-98	-12.36	-94.4
168	Chapel Lane Madison (CHPLN-2)	07-08-98	-12.34	-94.2
168	Chapel Lane Madison (CHPLN-2)	09-29-98	-12.39	-95.0
169	Rapid City No. 11 (Corral Drive)	12-17-91	-11.90	-90.5
169	Rapid City No. 11 (Corral Drive)	10-05-93	-12.20	-92.0
169	Rapid City No. 11 (Corral Drive)	04-21-95	-12.00	-91.0
169	Rapid City No. 11 (Corral Drive)	07-24-96	-12.07	-90.8
169	Rapid City No. 11 (Corral Drive)	08-26-96	-12.13	-92.5
169	Rapid City No. 11 (Corral Drive)	11-14-96	-12.07	-91.0
169	Rapid City No. 11 (Corral Drive)	01-07-97	-12.04	-90.8
169	Rapid City No. 11 (Corral Drive)	03-11-97	-12.00	-92.0
169	Rapid City No. 11 (Corral Drive)	05-13-97	-12.07	-92.1
169	Rapid City No. 11 (Corral Drive)	07-11-97	-12.13	-91.5
169	Rapid City No. 11 (Corral Drive)	09-10-97	-12.13	-92.6
169	Rapid City No. 11 (Corral Drive)	05-07-98	-12.13	-91.2
169	Rapid City No. 11 (Corral Drive)	07-08-98	-12.21	-90.8
169	Rapid City No. 11 (Corral Drive)	09-29-98	-12.21	-92.6
172	Rapid City No. 9 (Meadowbrook)	05-08-91	-13.40	-101.0
172	Rapid City No. 9 (Meadowbrook)	09-26-93	-12.70	-97.0
172	Rapid City No. 9 (Meadowbrook)	04-24-95	-12.60	-97.0
172	Rapid City No. 9 (Meadowbrook)	07-26-96	-12.65	-99.3
172	Rapid City No. 9 (Meadowbrook)	08-26-96	-12.69	-98.1
172	Rapid City No. 9 (Meadowbrook)	05-13-97	-12.68	-97.8
172	Rapid City No. 9 (Meadowbrook)	07-08-98	-12.70	-97.9
175	Rapid City No. 3	12-05-86	-13.30	-99.0
175	Rapid City No. 3	02-06-87	-13.25	-98.0

Table 8. Stable isotope data for sites with multiple samples—Continued

[--, no data]

Site number	Name	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)
175	Rapid City No. 3	03-10-87	-13.10	--
175	Rapid City No. 3	04-10-87	-13.30	-98.5
175	Rapid City No. 3	06-16-87	-13.30	-99.0
175	Rapid City No. 3	07-02-87	-11.55	-95.5
175	Rapid City No. 3	08-20-87	-13.30	-97.9
175	Rapid City No. 3	09-01-87	-13.25	-98.5
175	Rapid City No. 3	03-17-88	-13.25	-99.5
175	Rapid City No. 3	05-17-88	-13.20	-98.5
175	Rapid City No. 3	07-19-88	-13.40	-102.5
178	PE-89A Canyon Lake Madison	12-06-89	-12.85	-100.0
178	PE-89A Canyon Lake Madison	09-28-93	-12.70	-98.0
178	PE-89A Canyon Lake Madison	04-19-95	-12.60	-97.0
178	PE-89A Canyon Lake Madison	10-10-96	-12.63	-97.1
181	Rapid City No. 4	12-05-86	-13.90	-104.5
181	Rapid City No. 4	02-06-87	-13.90	-102.0
181	Rapid City No. 4	03-10-87	-13.90	-102.0
181	Rapid City No. 4	04-10-87	-13.85	-102.5
181	Rapid City No. 4	06-16-87	-13.85	-105.0
181	Rapid City No. 4	07-02-87	-13.30	-102.5
181	Rapid City No. 4	08-07-87	-13.90	-103.0
181	Rapid City No. 4	09-01-87	-14.00	-103.5
181	Rapid City No. 4	03-22-88	-13.85	-102.5
181	Rapid City No. 4	05-17-88	-13.85	-103.0
181	Rapid City No. 4	07-15-88	-13.90	-103.0
181	Rapid City No. 4	07-18-90	-13.75	-101.0
181	Rapid City No. 4	08-26-96	-13.81	-104.0
182	PE-65A Sioux Park 2 Madison	03-14-90	-14.25	-105.0
182	PE-65A Sioux Park 2 Madison	08-30-90	-14.45	-108.0
182	PE-65A Sioux Park 2 Madison	10-10-96	-13.79	-104.0
183	PE-64B Sioux Park 1 Minnelusa	03-14-90	-14.50	-109.0
183	PE-64B Sioux Park 1 Minnelusa	08-29-90	-14.25	-106.0
185	Rapid City No. 5	04-25-90	-14.50	-108.0
185	Rapid City No. 5	10-07-93	-14.30	-107.0
185	Rapid City No. 5	10-13-94	-14.10	-106.0
185	Rapid City No. 5	08-26-96	-14.01	-107.0

Table 8. Stable isotope data for sites with multiple samples—Continued

[--, no data]

Site number	Name	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)
186	PE-89E Lime Creek	11-21-89	-14.45	-109.0
186	PE-89E Lime Creek	06-20-90	-14.30	-109.0
195	Hart Ranch	12-08-86	-11.70	-89.0
195	Hart Ranch	06-08-87	-11.70	-90.0
195	Hart Ranch	07-12-87	-11.70	-89.5
195	Hart Ranch	08-20-87	-11.70	-90.0
195	Hart Ranch	10-19-93	-11.70	-90.0
195	Hart Ranch	04-26-95	-11.80	-91.0
195	Hart Ranch	07-23-96	-12.37	-93.3
195	Hart Ranch	11-14-96	-12.38	-93.0
195	Hart Ranch	01-08-97	-12.41	-94.9
195	Hart Ranch	03-11-97	-12.36	-95.0
195	Hart Ranch	05-13-97	-12.47	-93.8
195	Hart Ranch	07-11-97	-12.54	-94.5
195	Hart Ranch	09-10-97	-12.70	-97.1
195	Hart Ranch	12-05-97	-12.73	-95.8
195	Hart Ranch	02-06-98	-12.68	-95.3
195	Hart Ranch	05-07-98	-12.53	-94.5
195	Hart Ranch	07-08-98	-12.69	-96.0
195	Hart Ranch	09-29-98	-12.65	-97.2
196	Pine Grove	12-09-86	-11.90	-87.5
196	Pine Grove	02-10-87	-11.85	-87.5
196	Pine Grove	03-10-87	-11.95	-87.0
196	Pine Grove	04-10-87	-11.95	-89.0
196	Pine Grove	07-13-87	-11.95	-87.0
196	Pine Grove	08-16-89	-11.76	-88.4
196	Pine Grove	10-15-93	-12.00	-89.0
196	Pine Grove	04-21-95	-11.80	-88.0
196	Pine Grove	11-18-96	-11.89	-88.6
196	Pine Grove	01-09-97	-11.86	-88.0
196	Pine Grove	03-05-97	-11.90	-88.5
232	Windy City Lake	03-10-87	-12.45	-91.0
232	Windy City Lake	05-17-88	-12.05	-89.5
237	Streeter Ranch	¹ 11-01-77	-12.05	-88.4
237	Streeter Ranch	03-11-97	-11.87	-86.8

Table 8. Stable isotope data for sites with multiple samples—Continued

[--, no data]

Site number	Name	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)
276	Knight Spring	08-04-95	-16.85	-125.0
276	Knight Spring	08-28-96	-16.90	-127.0
276	Knight Spring	09-11-97	-16.98	-127.8
280		08-08-95	-13.86	-103.0
280		09-09-96	-13.97	-106.0
280		09-09-97	-14.04	-104.2
281	JHD Spring	09-13-95	-16.55	-128.0
281	JHD Spring	09-06-96	-16.61	-126.0
281	JHD Spring	09-09-97	-16.53	-126.4
282	Intake Gulch	08-03-95	-17.55	-135.0
282	Intake Gulch	08-28-96	-17.67	-133.0
282	Intake Gulch	09-09-97	-17.54	-133.0
283	Rhoads Fork near Rochford	¹ 01-01-78	-17.22	-125.0
283	Rhoads Fork near Rochford	12-05-86	-16.95	-126.5
283	Rhoads Fork near Rochford	04-14-87	-16.95	-127.5
283	Rhoads Fork near Rochford	06-12-87	-17.05	-128.0
283	Rhoads Fork near Rochford	07-06-87	-17.05	-127.5
283	Rhoads Fork near Rochford	08-11-87	-17.00	-129.0
283	Rhoads Fork near Rochford	08-07-95	-16.89	-125.0
283	Rhoads Fork near Rochford	08-28-96	-16.79	-127.0
283	Rhoads Fork near Rochford	09-09-97	-16.75	-128.5
285	Castle Creek above Deerfield	02-09-87	-16.45	-123.0
285	Castle Creek above Deerfield	04-14-87	-16.60	-124.0
285	Castle Creek above Deerfield	05-05-87	-16.50	-124.0
285	Castle Creek above Deerfield	06-12-87	-16.40	-123.5
285	Castle Creek above Deerfield	07-06-87	-16.35	-125.0
285	Castle Creek above Deerfield	08-11-87	-16.25	-122.5
285	Castle Creek above Deerfield	10-20-87	-16.35	-124.0
285	Castle Creek above Deerfield	07-14-88	-16.35	-123.5
287	Barrel Spring	07-25-95	-14.67	-115.0
287	Barrel Spring	09-13-96	-14.44	-112.0
287	Barrel Spring	09-08-97	-14.69	-113.8
288	Water Draw Spring	09-14-95	-14.34	-113.0
288	Water Draw Spring	09-13-96	-14.26	-113.0
288	Water Draw Spring	09-08-97	-14.22	-111.5

Table 8. Stable isotope data for sites with multiple samples—Continued

[--, no data]

Site number	Name	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)
289	Mckenna Spring	09-14-95	-13.46	-103.0
289	Mckenna Spring	09-13-96	-13.53	-106.0
289	Mckenna Spring	09-08-97	-13.24	-101.8
290	Higgins Gulch below I-90	09-26-94	-16.47	-126.0
290	Higgins Gulch below I-90	10-10-97	-16.25	-121.6
298	City Springs	12-04-86	-14.35	-107.0
298	City Springs	04-09-87	-14.20	-107.0
298	City Springs	05-12-87	-14.40	-107.5
298	City Springs	06-04-87	-14.40	-108.5
298	City Springs	09-29-87	-14.50	-109.0
298	City Springs	05-12-88	-14.50	-109.0
298	City Springs	09-26-93	-14.20	-106.0
298	City Springs	10-15-94	-14.40	-109.0
300	Cleghorn Springs	12-05-86	-12.95	-98.5
300	Cleghorn Springs	02-06-87	-12.95	-98.0
300	Cleghorn Springs	04-10-87	-12.90	-98.0
300	Cleghorn Springs	06-04-87	-12.85	-99.0
300	Cleghorn Springs	07-02-87	-12.90	-100.0
300	Cleghorn Springs	08-07-87	-12.90	-98.5
300	Cleghorn Springs	09-27-93	-12.80	-99.0
300	Cleghorn Springs	04-20-95	-12.80	-100.0
300	Cleghorn Springs	08-05-98	-13.26	-100.7
308	Cascade Spring	¹ 01-01-78	-15.48	-118.0
308	Cascade Spring	09-12-96	-15.32	-119.0
309	Bear Gulch near Maurice	10-10-96	-16.76	-127.0
309	Bear Gulch near Maurice	09-11-97	-17.16	-130.6
310	Beaver Creek near Maurice	10-09-96	-16.40	-126.0
310	Beaver Creek near Maurice	09-11-97	-16.77	-128.8
312	Bear Butte Creek near Deadwood	10-09-96	-16.03	-122.0
312	Bear Butte Creek near Deadwood	10-10-97	-15.98	-120.3
313	Elk Creek above Meadow Creek	09-20-96	-16.10	-123.0
313	Elk Creek above Meadow Creek	10-09-97	-16.37	-124.4
314	Meadow Creek above Elk Creek	09-20-96	-15.69	-119.0
314	Meadow Creek above Elk Creek	10-09-97	-15.78	-117.4
315	Boxelder Creek near Nemo	09-27-93	-14.70	-111.0

Table 8. Stable isotope data for sites with multiple samples—Continued

[-, no data]

Site number	Name	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)
315	Boxelder Creek near Nemo	10-29-93	-14.70	-113.0
315	Boxelder Creek near Nemo	11-24-93	-15.00	-113.0
315	Boxelder Creek near Nemo	12-22-93	-15.10	-114.0
315	Boxelder Creek near Nemo	01-20-94	-15.20	-114.0
315	Boxelder Creek near Nemo	02-18-94	-17.10	-129.0
315	Boxelder Creek near Nemo	03-25-94	-16.10	-121.0
315	Boxelder Creek near Nemo	04-20-94	-16.30	-125.0
315	Boxelder Creek near Nemo	05-19-94	-15.60	-118.0
315	Boxelder Creek near Nemo	06-27-94	-14.70	-112.0
315	Boxelder Creek near Nemo	07-15-94	-14.80	-112.0
315	Boxelder Creek near Nemo	08-17-94	-14.30	-108.0
315	Boxelder Creek near Nemo	09-27-94	-14.60	-112.0
315	Boxelder Creek near Nemo	10-26-94	-15.10	-115.0
315	Boxelder Creek near Nemo	11-23-94	-15.40	-118.0
315	Boxelder Creek near Nemo	12-29-94	-15.40	-114.0
315	Boxelder Creek near Nemo	03-10-95	-16.10	-123.0
315	Boxelder Creek near Nemo	04-13-95	-15.50	-118.0
315	Boxelder Creek near Nemo	10-18-95	-14.91	-114.0
315	Boxelder Creek near Nemo	11-29-95	-15.33	-113.0
315	Boxelder Creek near Nemo	01-16-96	-15.23	-115.0
315	Boxelder Creek near Nemo	08-28-96	-14.77	-112.0
315	Boxelder Creek near Nemo	10-11-96	-14.97	-115.0
315	Boxelder Creek near Nemo	12-31-96	-16.04	-122.0
315	Boxelder Creek near Nemo	03-17-97	-15.92	-120.1
315	Boxelder Creek near Nemo	04-25-97	-16.45	-124.0
315	Boxelder Creek near Nemo	06-23-97	-15.36	-118.0
315	Boxelder Creek near Nemo	08-12-97	-15.17	-114.1
315	Boxelder Creek near Nemo	10-08-97	-14.76	-112.8
315	Boxelder Creek near Nemo	12-11-97	-15.12	-113.2
315	Boxelder Creek near Nemo	02-12-98	-15.29	-116.8
315	Boxelder Creek near Nemo	03-23-98	-16.27	-122.7
315	Boxelder Creek near Nemo	07-01-98	-15.53	-117.5
315	Boxelder Creek near Nemo	08-14-98	-15.06	-112.9
316	Rapid Creek above Victoria Creek	01-19-90	-13.30	-107.0
316	Rapid Creek above Victoria Creek	09-27-93	-13.70	-108.0

Table 8. Stable isotope data for sites with multiple samples—Continued

[--, no data]

Site number	Name	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)
316	Rapid Creek above Victoria Creek	10-29-93	-13.40	-103.0
316	Rapid Creek above Victoria Creek	11-24-93	-13.60	-106.0
316	Rapid Creek above Victoria Creek	12-22-93	-13.50	-106.0
316	Rapid Creek above Victoria Creek	01-20-94	-13.60	-105.0
316	Rapid Creek above Victoria Creek	02-18-94	-13.80	-108.0
316	Rapid Creek above Victoria Creek	03-25-94	-13.80	-103.0
316	Rapid Creek above Victoria Creek	04-20-94	-13.70	-108.0
316	Rapid Creek above Victoria Creek	05-19-94	-13.80	-107.0
316	Rapid Creek above Victoria Creek	06-27-94	-13.80	-109.0
316	Rapid Creek above Victoria Creek	07-15-94	-14.00	-109.0
316	Rapid Creek above Victoria Creek	08-17-94	-14.00	-109.0
316	Rapid Creek above Victoria Creek	09-27-94	-14.00	-109.0
316	Rapid Creek above Victoria Creek	10-26-94	-13.80	-108.0
316	Rapid Creek above Victoria Creek	11-23-94	-13.60	-107.0
316	Rapid Creek above Victoria Creek	12-29-94	-13.50	-108.0
316	Rapid Creek above Victoria Creek	03-10-95	-13.70	-109.0
316	Rapid Creek above Victoria Creek	04-13-95	-13.70	-107.0
316	Rapid Creek above Victoria Creek	10-18-95	-14.04	-109.0
316	Rapid Creek above Victoria Creek	11-30-95	-13.72	-105.0
316	Rapid Creek above Victoria Creek	01-16-96	-13.97	-107.0
316	Rapid Creek above Victoria Creek	08-28-96	-14.74	-113.0
316	Rapid Creek above Victoria Creek	10-11-96	-14.68	-113.0
316	Rapid Creek above Victoria Creek	11-04-96	-14.16	-109.0
316	Rapid Creek above Victoria Creek	12-05-96	-14.12	-109.0
316	Rapid Creek above Victoria Creek	01-08-97	-14.38	-109.0
316	Rapid Creek above Victoria Creek	02-13-97	-14.56	-111.9
316	Rapid Creek above Victoria Creek	03-20-97	-14.50	-113.3
316	Rapid Creek above Victoria Creek	04-29-97	-14.72	-116.1
316	Rapid Creek above Victoria Creek	05-29-97	-14.91	-114.5
316	Rapid Creek above Victoria Creek	07-10-97	-15.10	-115.5
316	Rapid Creek above Victoria Creek	08-21-97	-15.23	-116.2
316	Rapid Creek above Victoria Creek	10-03-97	-15.06	-114.3
316	Rapid Creek above Victoria Creek	11-12-97	-14.44	-110.7
316	Rapid Creek above Victoria Creek	12-16-97	-14.43	-110.4
316	Rapid Creek above Victoria Creek	01-26-98	-14.69	-114.1

Table 8. Stable isotope data for sites with multiple samples—Continued

[-, no data]

Site number	Name	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)
316	Rapid Creek above Victoria Creek	03-02-98	-14.80	-113.1
316	Rapid Creek above Victoria Creek	04-14-98	-14.85	-115.5
316	Rapid Creek above Victoria Creek	06-30-98	-14.94	-115.1
316	Rapid Creek above Victoria Creek	09-08-98	-15.04	-113.9
317	Victoria Creek	04-09-87	-13.95	-102.5
317	Victoria Creek	06-09-87	-13.55	-100.0
317	Victoria Creek	07-06-87	-13.30	-98.4
317	Victoria Creek	08-13-87	-13.15	-98.0
318	Spring Creek near Keystone	12-04-86	-11.15	-89.5
318	Spring Creek near Keystone	09-27-93	-12.20	-93.0
318	Spring Creek near Keystone	10-29-93	-11.90	-91.0
318	Spring Creek near Keystone	11-24-93	-12.20	-93.0
318	Spring Creek near Keystone	12-22-93	-12.20	-92.0
318	Spring Creek near Keystone	01-20-94	-12.30	-94.0
318	Spring Creek near Keystone	02-18-94	-12.60	-96.0
318	Spring Creek near Keystone	03-25-94	-12.40	-93.0
318	Spring Creek near Keystone	04-20-94	-12.30	-93.0
318	Spring Creek near Keystone	05-19-94	-12.50	-96.0
318	Spring Creek near Keystone	06-27-94	-11.90	-93.0
318	Spring Creek near Keystone	07-15-94	-11.60	-90.0
318	Spring Creek near Keystone	08-17-94	-10.90	-88.0
318	Spring Creek near Keystone	09-27-94	-10.70	-87.0
318	Spring Creek near Keystone	10-26-94	-11.60	-91.0
318	Spring Creek near Keystone	11-23-94	-11.70	-93.0
318	Spring Creek near Keystone	12-29-94	-11.80	-93.0
318	Spring Creek near Keystone	03-10-95	-12.00	-93.0
318	Spring Creek near Keystone	04-13-95	-12.00	-95.0
318	Spring Creek near Keystone	10-18-95	-12.54	-96.1
318	Spring Creek near Keystone	11-29-95	-12.62	-96.4
318	Spring Creek near Keystone	01-16-96	-12.81	-96.9
318	Spring Creek near Keystone	08-28-96	-13.20	-101.0
318	Spring Creek near Keystone	09-09-96	-12.89	-98.9
318	Spring Creek near Keystone	10-14-96	-13.33	-102.0
318	Spring Creek near Keystone	11-06-96	-12.70	-95.8
318	Spring Creek near Keystone	12-06-96	-12.66	-96.6

Table 8. Stable isotope data for sites with multiple samples—Continued

[--, no data]

Site number	Name	Date	$\delta^{18}\text{O}$ (per mil)	δD (per mil)
318	Spring Creek near Keystone	01-08-97	-12.93	-97.5
318	Spring Creek near Keystone	02-14-97	-13.01	-99.3
318	Spring Creek near Keystone	03-17-97	-13.11	-101.1
318	Spring Creek near Keystone	04-30-97	-13.54	-104.0
318	Spring Creek near Keystone	06-13-97	-14.10	-106.0
318	Spring Creek near Keystone	07-23-97	-13.66	-102.6
318	Spring Creek near Keystone	08-22-97	-13.53	-102.1
318	Spring Creek near Keystone	10-07-97	-13.24	-98.9
318	Spring Creek near Keystone	11-13-97	-13.05	-98.7
318	Spring Creek near Keystone	12-18-97	-13.10	-98.5
318	Spring Creek near Keystone	01-29-98	-13.11	-99.8
318	Spring Creek near Keystone	03-05-98	-13.19	-100.3
318	Spring Creek near Keystone	04-16-98	-13.37	-102.6
318	Spring Creek near Keystone	06-05-98	-13.18	-101.3
318	Spring Creek near Keystone	07-06-98	-13.53	-101.9
318	Spring Creek near Keystone	08-13-98	-12.88	-98.3
319	Battle Creek near Keystone	09-06-96	-11.09	-82.4
319	Battle Creek near Keystone	09-12-97	-11.92	-87.2
320	Grace Coolidge Cr nr Game Lodge	09-10-96	-11.33	-84.2
320	Grace Coolidge Cr nr Game Lodge	09-12-97	-11.82	-87.4
321	French Creek above Fairburn	10-07-96	-11.54	-89.8
321	French Creek above Fairburn	09-11-97	-11.62	-89.1
322	Beaver Creek near Pringle	10-01-96	-12.38	-92.4
322	Beaver Creek near Pringle	09-10-97	-12.18	-91.9

¹Data from Busby and others (1983, 1991). Sites for which exact sample date is unknown are listed as 01-01-78.

Table 9. Weighted annual tritium concentrations in precipitation for Black Hills area

[TU-m, tritium-unit-meters; TU, tritium units; mm, millimeters; --, no data]

Year	Deposition (TU-m)	Precipitation (mm)	Weighted tritium concentration (TU)
Assumed Values			
1952 and prior	--	--	15.00
Data from Michel (1989)			
1953	18	460	39.13
1954	190	420	452.38
1955	26	370	70.27
1956	77	330	233.33
1957	87	460	189.13
1958	320	410	780.49
1959	300	370	810.81
1960	85	390	217.95
1961	99	310	319.35
1962	960	600	1,600.00
1963	2,000	480	4,166.67
1964	1,200	360	3,333.33
1965	680	460	1,478.26
1966	470	500	940.00
1967	240	480	500.00
1968	180	490	367.35
1969	130	340	382.35
1970	140	400	350.00
1971	93.8	469	200.00
1972	53.4	445	120.00
1973	48.8	488	100.00
1974	27.4	249	110.04
1975	35.4	443	79.91
1976	27.0	396	68.18
1977	56.2	661	85.02
1978	39.5	395	100.00
1979	21.3	355	60.00
1980	19.6	436	44.95
1981	19.4	357	54.34
1982	23.0	660	34.85
1983	9.8	393	24.94
Regression Estimates from Table 10			
1984	--	--	23.75
1985	--	--	25.31
1986	--	--	31.72
1987	--	--	29.14
1988	--	--	28.83
1989	--	--	30.14
1990	--	--	27.46
1991	--	--	27.07
1992	--	--	19.66
1993	--	--	19.37
1994	--	--	19.52
1995	--	--	16.61
1996	--	--	16.72
1997	--	--	20.48
1998	--	--	20.76

Table 10. Monthly estimated tritium concentrations in precipitation, monthly precipitation, and weighted annual tritium concentrations in precipitation for Black Hills area

[Estimated tritium input based on average of extended records for Bismarck, North Dakota, and Lincoln, Nebraska. TU, tritium unit; mm, millimeter; --, no data]

Month	1984		1985		1986		1987		1988		1989		1990		1991	
	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)
January	33.35	7	27.22	9	19.58	12	29.00	5	33.14	10	30.54	3	24.76	6	41.13	12
February	--	--	25.66	5	23.73	26	32.62	41	26.92	11	38.97	14	43.42	15	35.71	26
March	24.15	23	24.06	29	30.34	19	15.10	44	39.54	31	22.85	29	25.77	33	20.47	21
April	--	--	26.19	28	--	--	21.56	9	26.71	20	31.61	58	20.93	53	20.99	81
May	--	--	39.54	31	32.71	44	29.05	104	25.82	81	29.50	49	25.40	100	24.92	144
June	21.55	116	--	--	34.55	124	35.98	22	28.30	57	28.25	45	26.92	35	35.02	94
July	26.35	69	31.56	43	35.39	49	34.41	34	33.23	29	37.17	49	27.12	83	29.30	40
August	--	--	29.90	28	39.81	32	34.36	57	32.42	51	41.69	44	33.75	31	28.30	32
September	--	--	13.43	50	26.76	111	24.81	22	26.60	27	21.04	82	39.59	30	26.92	19
October	--	--	29.90	19	36.44	54	42.26	13	23.51	16	20.17	37	23.57	21	24.38	29
November	--	--	15.10	43	27.79	30	20.05	13	20.87	23	27.28	21	31.61	17	18.62	30
December	--	--	29.70	23	19.10	3	26.76	13	26.92	11	47.08	26	20.17	16	31.46	2
Weighted annual tritium input	23.75		25.31		31.72		29.14		28.83		30.14		27.46		27.07	

Table 10. Monthly estimated tritium input concentrations, monthly precipitation, and weighted annual tritium input concentrations for Black Hills area—Continued
 [Estimated tritium input based on average of extended records for Bismarck, North Dakota, and Lincoln, Nebraska. TU, tritium unit; mm, millimeter; --, no data]

Month	1992		1993		1994		1995		1996		1997		1998	
	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)	Tritium input (TU)	Precipitation (mm)
January	18.00	7	14.48	20	17.50	24	12.55	8	17.19	30	--	--	12.10	14
February	22.91	12	21.62	25	21.90	19	20.70	19	13.21	6	20.81	22	19.22	31
March	14.76	47	16.03	27	16.42	19	24.17	26	18.74	41	16.23	15	19.22	48
April	16.36	37	16.03	66	17.88	52	18.62	56	17.13	60	20.76	75	25.19	20
May	20.29	71	21.79	90	20.58	40	14.07	175	14.42	147	20.17	104	13.79	71
June	20.99	82	19.94	147	20.87	38	14.96	118	19.70	46	18.43	70	18.98	148
July	20.23	86	20.52	98	20.64	46	20.29	72	17.88	41	20.47	134	27.74	82
August	23.51	34	22.57	54	20.58	31	19.70	26	20.41	77	22.96	51	27.48	83
September	16.74	13	20.05	34	19.70	16	20.58	43	18.43	53	23.13	32	19.16	55
October	24.55	16	17.75	36	21.04	117	13.50	71	14.21	90	23.24	27	21.33	129
November	13.64	22	12.41	21	13.57	21	16.23	21	15.30	16	17.13	11	15.83	35
December	22.74	27	17.13	25	13.36	14			14.62	34	17.50	12	17.19	8
Weighted annual tritium input	19.66		19.37		19.52		16.61		16.72		20.48		20.76	

Table 11. Estimated tritium concentrations in precipitation for Black Hills area, adjusted for decay

[TU, tritium units; --, not computed]

Recharge year	Tritium input (TU)	Sample collection date																											
		1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998							
1951 and prior	15	4	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1
1952	15	4	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1
1953	39	10	9	9	8	8	7	7	7	6	6	6	5	5	5	4	4	4	4	4	4	4	3	3	3	3	3	3	3
1954	452	119	112	106	100	95	90	85	80	76	72	68	64	61	57	54	51	49	46	43	41	39	39	39	39	39	39	39	39
1955	70	19	18	17	16	16	15	14	13	12	12	11	11	10	9	9	8	8	8	7	7	7	6	6	6	6	6	6	6
1956	233	68	65	61	58	55	52	49	46	44	41	39	37	35	33	31	30	28	26	25	24	22	22	22	22	22	22	22	22
1957	189	59	55	52	50	47	44	42	40	38	35	34	32	30	28	27	25	24	23	21	20	19	19	19	19	19	19	19	19
1958	780	256	242	229	216	205	194	183	173	164	155	146	138	131	124	117	111	105	99	94	89	84	84	84	84	84	84	84	84
1959	811	281	266	251	238	225	213	201	190	180	170	161	152	144	136	129	122	115	109	103	97	92	92	92	92	92	92	92	92
1960	218	80	76	71	68	64	60	57	54	51	48	46	43	41	39	37	35	33	31	29	28	26	26	26	26	26	26	26	26
1961	319	124	117	111	105	99	94	88	84	79	75	71	67	63	60	57	54	51	48	45	43	41	41	41	41	41	41	41	41
1962	1,600	656	620	586	555	525	496	469	444	420	397	375	355	336	318	300	284	269	254	240	227	215	215	215	215	215	215	215	215
1963	4,167	1,805	1,708	1,615	1,527	1,444	1,366	1,292	1,222	1,156	1,093	1,034	978	925	875	827	782	740	700	662	626	592	592	592	592	592	592	592	592
1964	3,333	1,527	1,444	1,366	1,292	1,222	1,155	1,093	1,033	977	924	874	827	782	740	699	662	626	592	560	529	501	501	501	501	501	501	501	501
1965	1,478	716	677	640	606	573	542	512	485	458	433	410	388	367	347	328	310	293	277	262	248	235	235	235	235	235	235	235	235
1966	940	481	455	431	407	385	364	345	326	308	291	276	261	247	233	221	209	197	187	176	167	158	158	158	158	158	158	158	158
1967	500	271	256	242	229	217	205	194	183	173	164	155	147	139	131	124	117	111	105	99	94	89	89	89	89	89	89	89	89
1968	367	210	199	188	178	168	159	150	142	135	127	120	114	108	102	96	91	86	81	77	73	69	69	69	69	69	69	69	69
1969	382	231	219	207	196	185	175	166	157	148	140	132	125	118	112	106	100	95	90	85	80	76	76	76	76	76	76	76	76
1970	350	224	212	200	190	179	170	160	152	143	136	128	121	115	109	103	97	92	87	82	78	73	73	73	73	73	73	73	73
1971	200	135	128	121	115	108	102	97	92	87	82	78	73	69	66	62	59	55	52	50	47	44	44	44	44	44	44	44	44
1972	120	86	81	77	73	69	65	61	58	55	52	49	47	44	42	39	37	35	33	31	30	28	28	28	28	28	28	28	28
1973	100	76	72	68	64	61	57	54	51	48	46	43	41	39	37	35	33	31	29	28	26	25	25	25	25	25	25	25	25
1974	110	88	83	79	74	70	67	63	60	56	53	50	48	45	43	40	38	36	34	32	31	29	29	29	29	29	29	29	29

Table 11. Estimated tritium concentrations in precipitation for Black Hills area, adjusted for decay—Continued
 [TU, tritium units; --, not computed]

Recharge year	Tritium input (TU)	Sample collection date																										
		1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998						
1975	80	68	64	61	57	54	51	48	46	43	41	39	37	35	33	31	29	28	26	25	23	22						
1976	68	61	58	54	51	49	46	44	41	39	37	35	33	31	29	28	26	25	24	22	21	20						
1977	85	80	76	72	68	64	61	58	54	51	49	46	44	41	39	37	35	33	31	29	28	26						
1978	100	100	95	89	85	80	76	72	68	64	61	57	54	51	48	46	43	41	39	37	35	33						
1979	60	--	60	57	54	51	48	45	43	41	38	36	34	32	31	29	27	26	25	23	22	21						
1980	45	--	--	45	43	40	38	36	34	32	30	29	27	26	24	23	22	21	19	18	17	16						
1981	54	--	--	--	54	51	48	46	43	41	39	37	35	33	31	29	28	26	25	23	22	21						
1982	35	--	--	--	--	35	33	31	30	28	26	25	24	22	21	20	19	18	17	16	15	14						
1983	25	--	--	--	--	--	25	24	22	21	20	19	18	17	16	15	14	14	13	12	11	11						
1984	24	--	--	--	--	--	--	24	23	21	20	19	18	17	16	15	15	14	13	12	12	11						
1985	25	--	--	--	--	--	--	--	25	24	22	21	20	19	18	17	16	15	14	14	13	12						
1986	32	--	--	--	--	--	--	--	--	32	30	29	27	26	24	23	22	20	19	18	17	16						
1987	29	--	--	--	--	--	--	--	--	--	29	27	26	25	23	22	21	20	19	18	17	16						
1988	29	--	--	--	--	--	--	--	--	--	--	29	27	26	25	23	22	21	20	19	18	17						
1989	30	--	--	--	--	--	--	--	--	--	--	--	30	28	27	25	24	23	21	20	19	18						
1990	27	--	--	--	--	--	--	--	--	--	--	--	--	27	26	24	23	22	20	19	18	17						
1991	27	--	--	--	--	--	--	--	--	--	--	--	--	--	27	26	24	23	22	20	19	18						
1992	20	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	19	18	17	16	15	14						
1993	19	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	19	18	17	16	15	14						
1994	20	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	19	18	17	16						
1995	17	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	17	16	15	14						
1996	17	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	17	16	15						
1997	20	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	19						
1998	21	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	21						