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:

$$\delta^{18}O_{sample} = \frac{^{18}O/^{16}O_{sample} - {^{18}O/^{16}O_{standard}}}{^{18}O/^{16}O_{standard}}$$

$$\times\ 1{,}000\ ‰\ \text{VSMOW}.$$

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, $\delta^{18}O$ ($^{18}O/^{16}O$) 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).
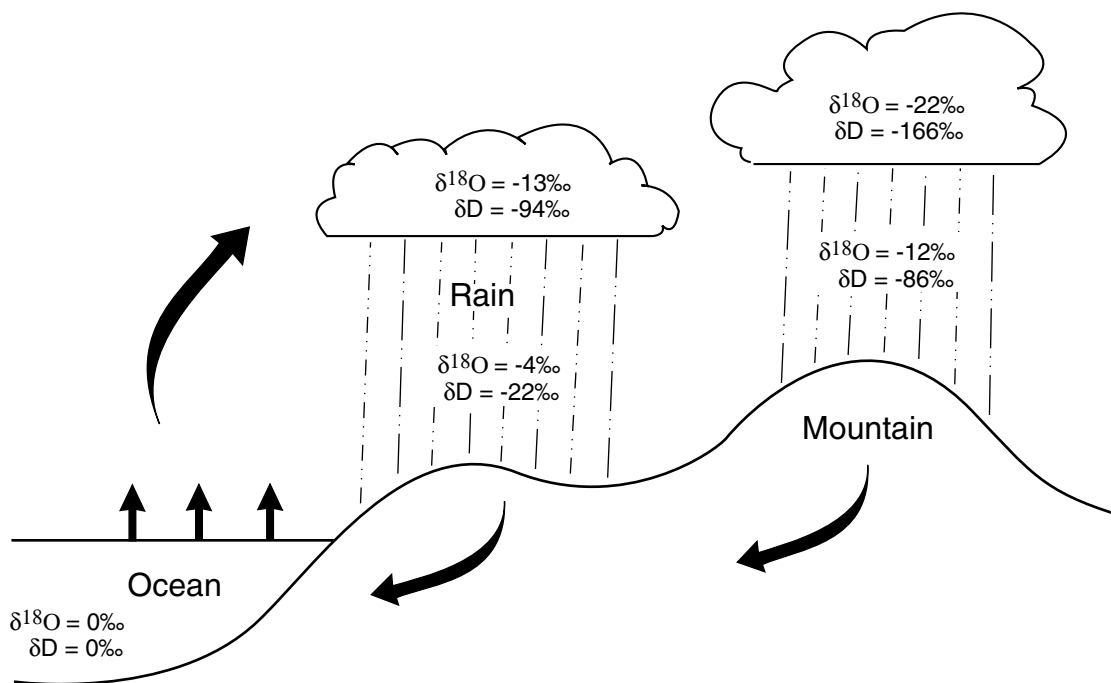

Figure 18. Schematic showing fractionation of stable oxygen and hydrogen isotopes during rainout. Stable isotope values, which compare isotopic ratios relative to ocean water, are expressed in per mil (‰).

Data for Black Hills sites include both $\delta^{18}O$ and δD values (table 7). For sites with more than one set of $\delta^{18}O$ and δD values, a mean value is listed in table 7, and individual values are listed in table 8. A linear relation exists between $\delta^{18}O$ and δD (fig. 19); thus, subsequent discussions and illustrations generally refer only to $\delta^{18}O$ 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 $\delta^{18}O$ 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.
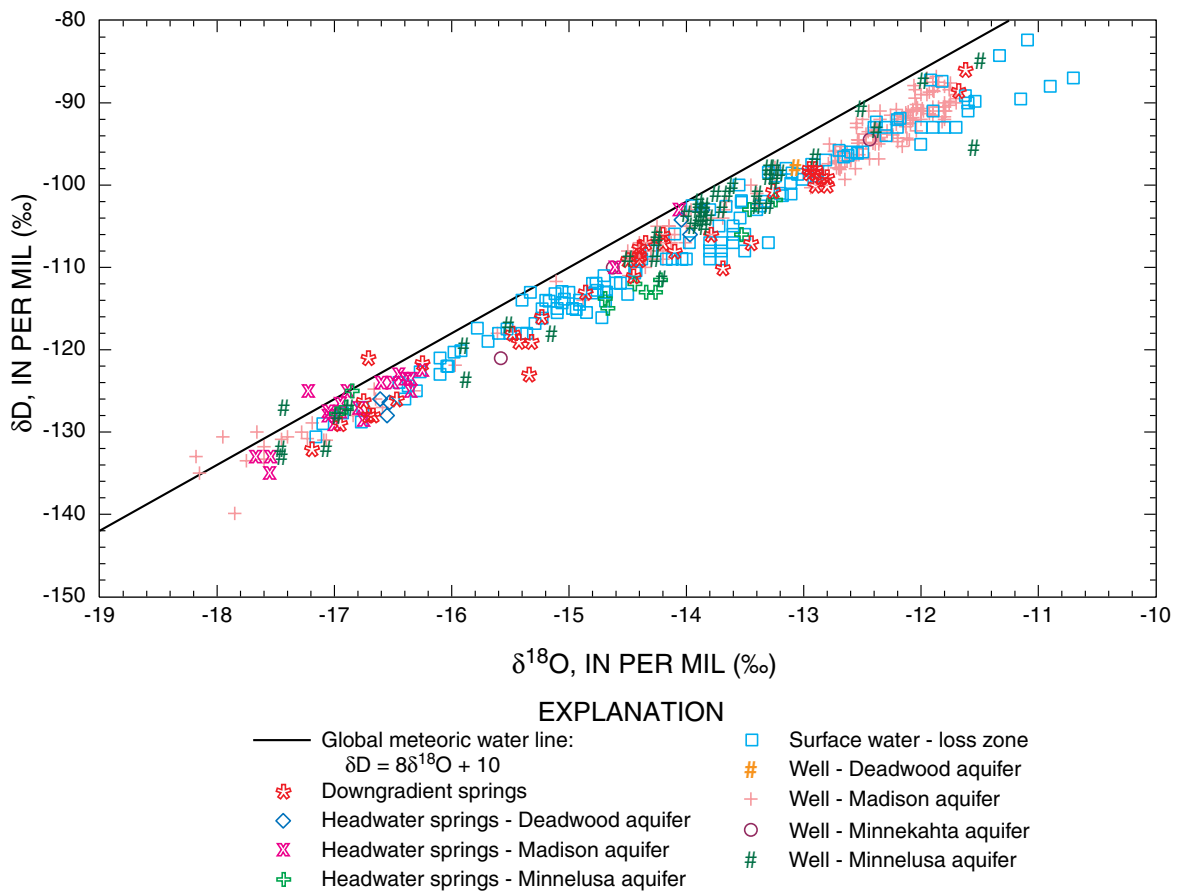

Figure 19. Relation between $\delta^{18}O$ and δD in Black Hills samples in comparison to the global meteoric water line (Craig, 1961).
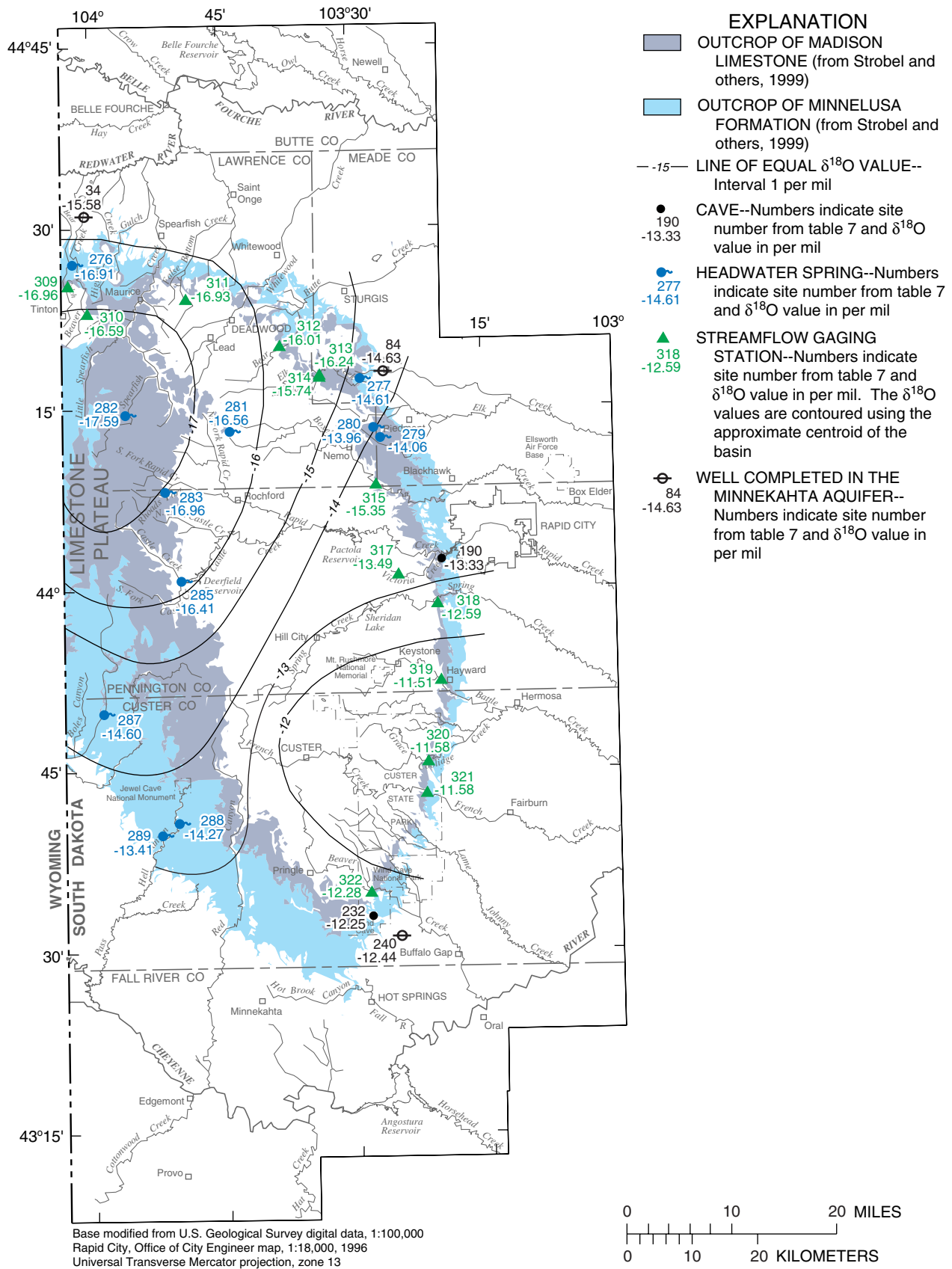
Figure 20. Generalized distribution of δ¹⁸O in surface water and ground water in near-recharge areas.

Many of the data points used to develop figure 20 are ground-water samples, which generally have small temporal variability in $\delta^{18}O$ values relative to surface-water samples. A perspective on temporal variability in precipitation is presented in figure 21A, which shows $\delta^{18}O$ 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 $\delta^{18}O$ is assumed to be small and values are considered representative of average isotopic composition in near-recharge areas.

Temporal variability of $\delta^{18}O$ 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.
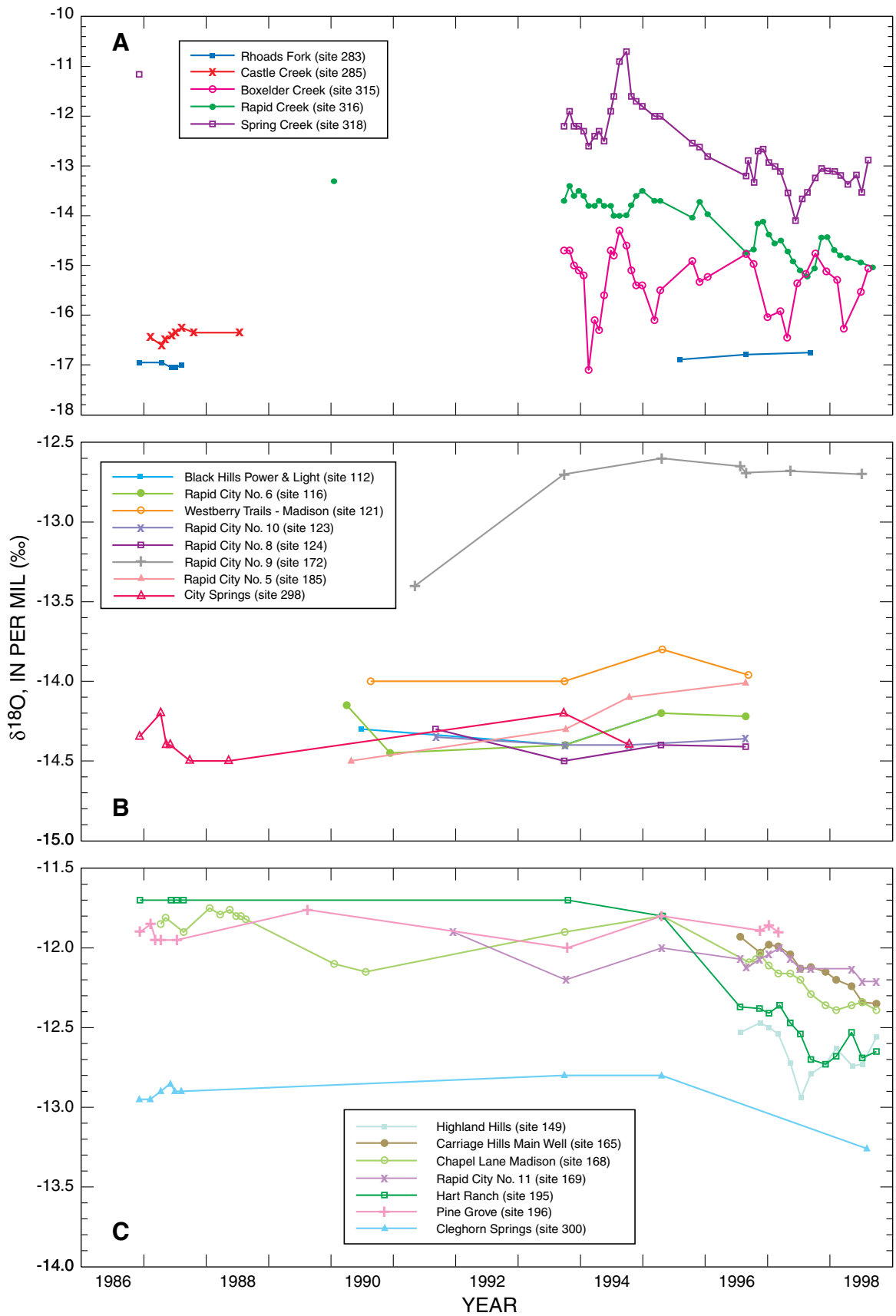
Figure 21. Temporal variation of δ¹⁸O for selected sites. Graph A shows selected loss-zone streams and headwater springs. Graphs B and C show selected wells and artesian springs.
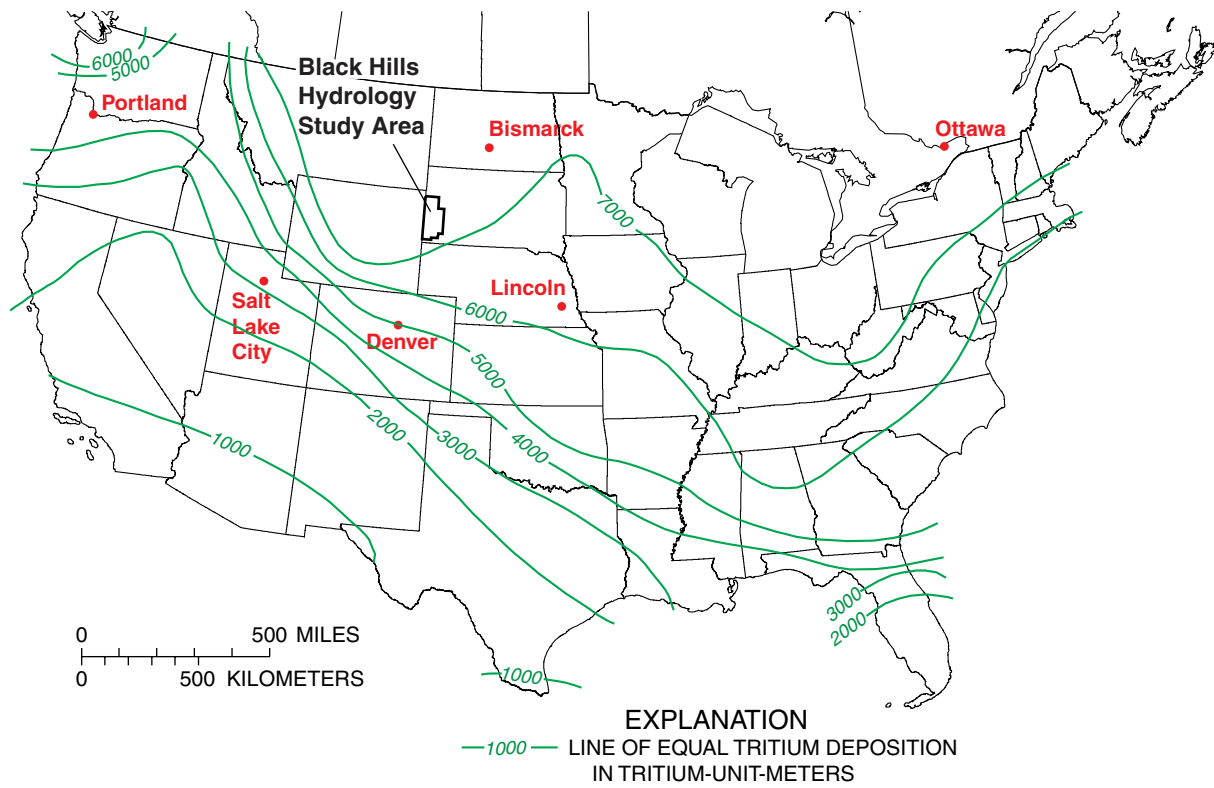
Figure 22. Cumulative tritium deposition on the continental United States, 1953-83, and location of selected collection sites (modified from Michel, 1989).
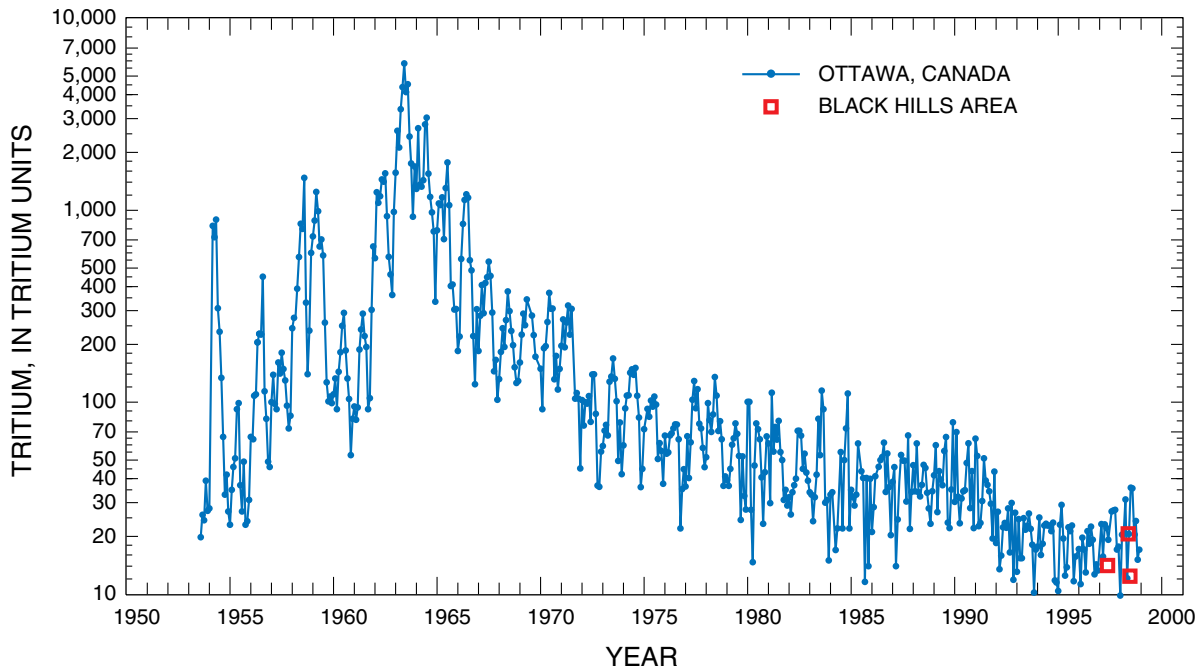

Figure 23. Monthly tritium concentrations in precipitation at Ottawa, Canada. Samples collected in Black Hills area of South Dakota also are shown.
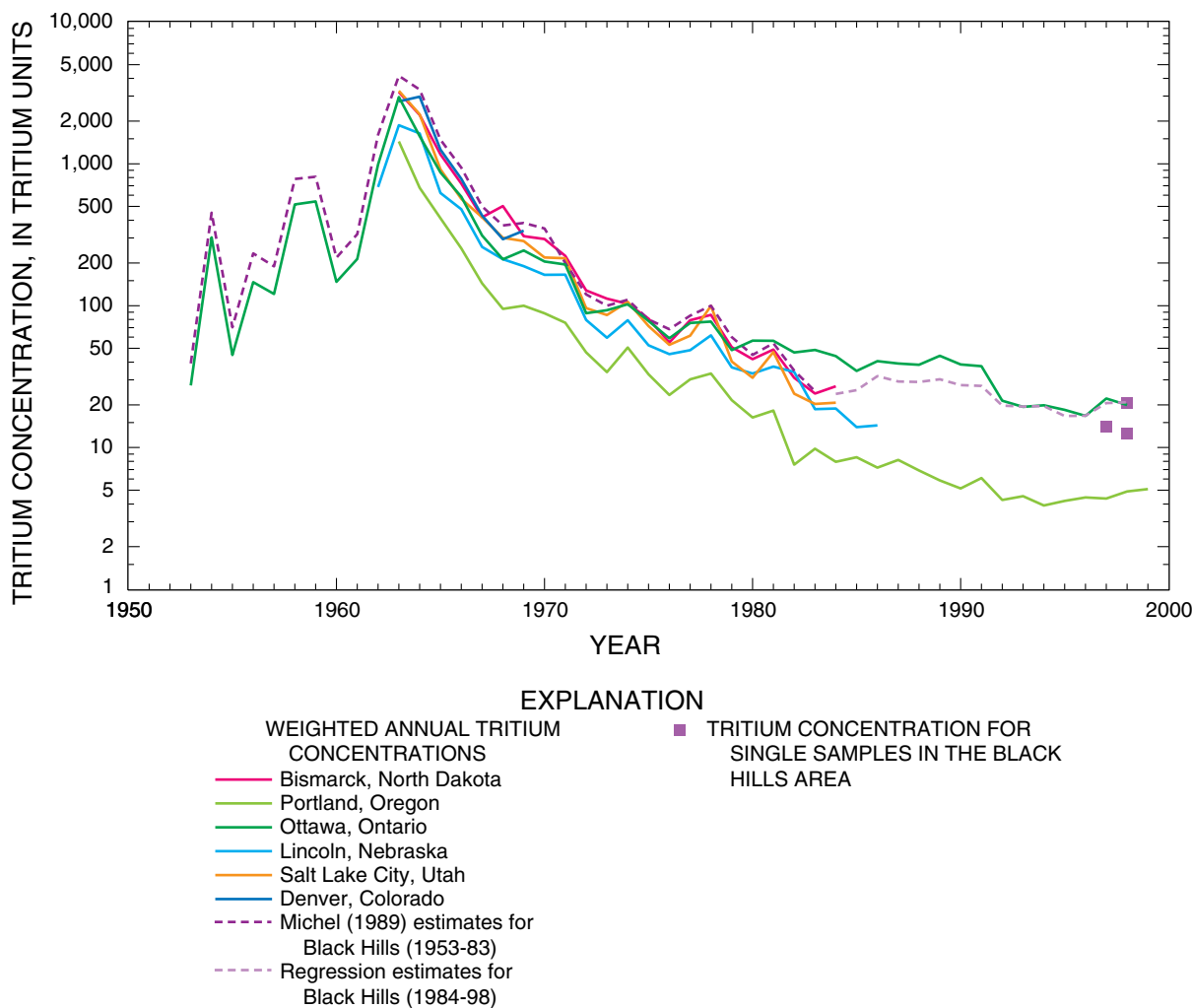
Figure 24. Weighted annual tritium concentrations in precipitation at selected locations. Estimated input and samples for Black Hills area of South Dakota also are shown.

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).

A. Slug flow or pipe flow - negligible mixing with delayed arrival

B. Hypothetical water-table spring with maximum traveltime of 10 years - thorough mixing with immediate arrival

C. Well completed in artesian aquifer at considerable distance from recharge area - thorough mixing with delayed arrival
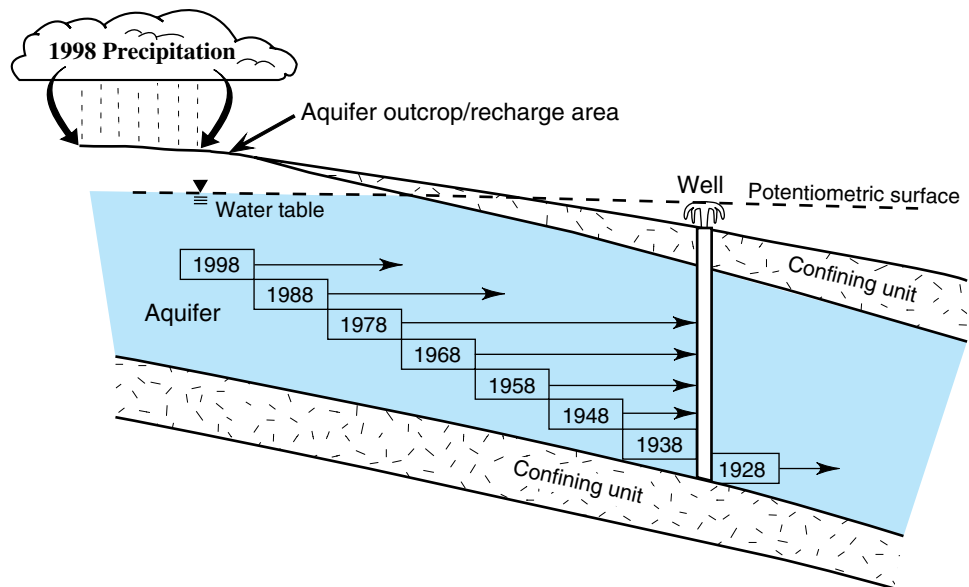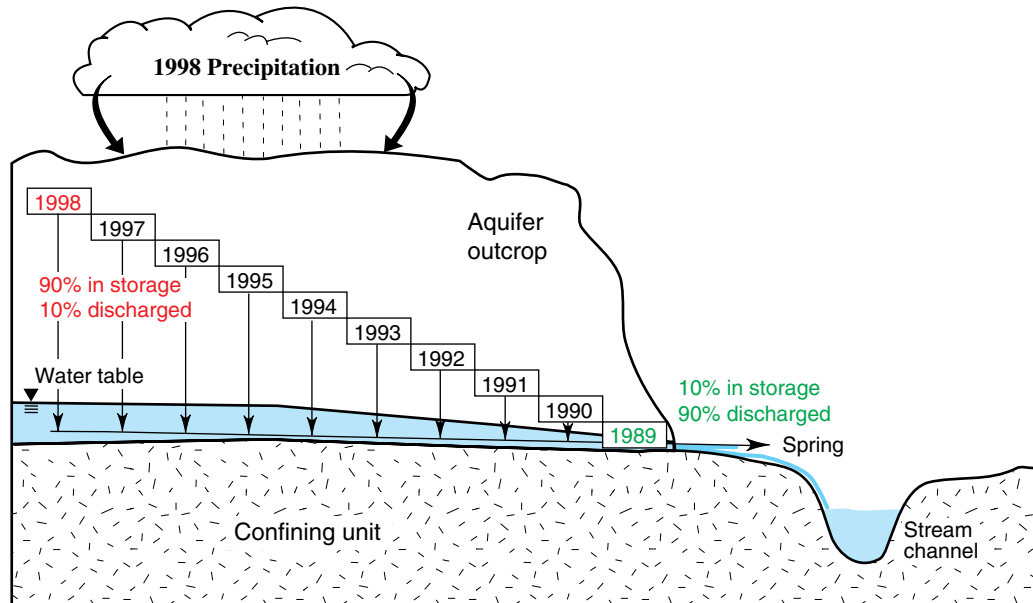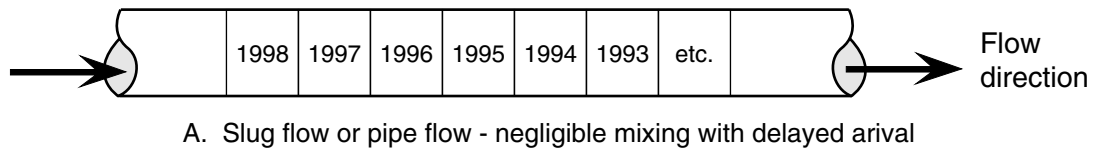
Figure 25. Schematic diagrams illustrating mixing models for age dating for various ground-water flow conditions.

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

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

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 $\mathrm{g}(t')$ 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:

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

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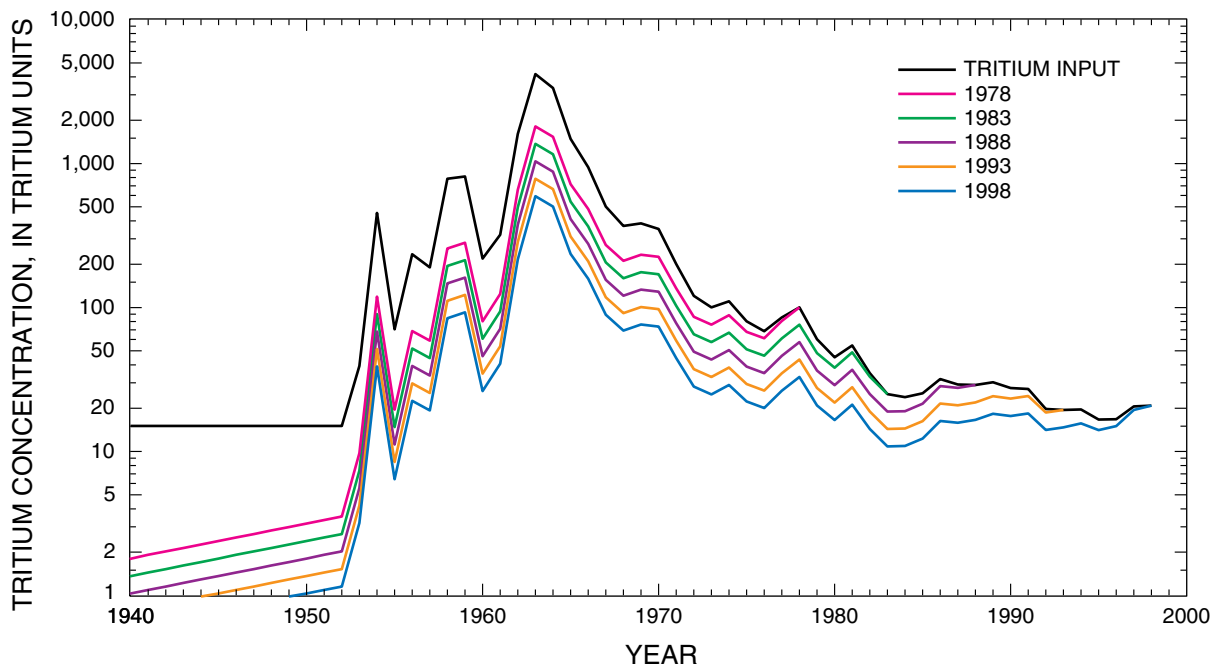
Figure 26. Estimated tritium concentrations in precipitation for Black Hills area and decay curves for selected years. Decay curves depict decayed tritium concentrations for selected sampling years.

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:

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

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

$$\frac{1}{(t'_{max}-t'_{min})} = 10 \text{ percent.}$$

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.
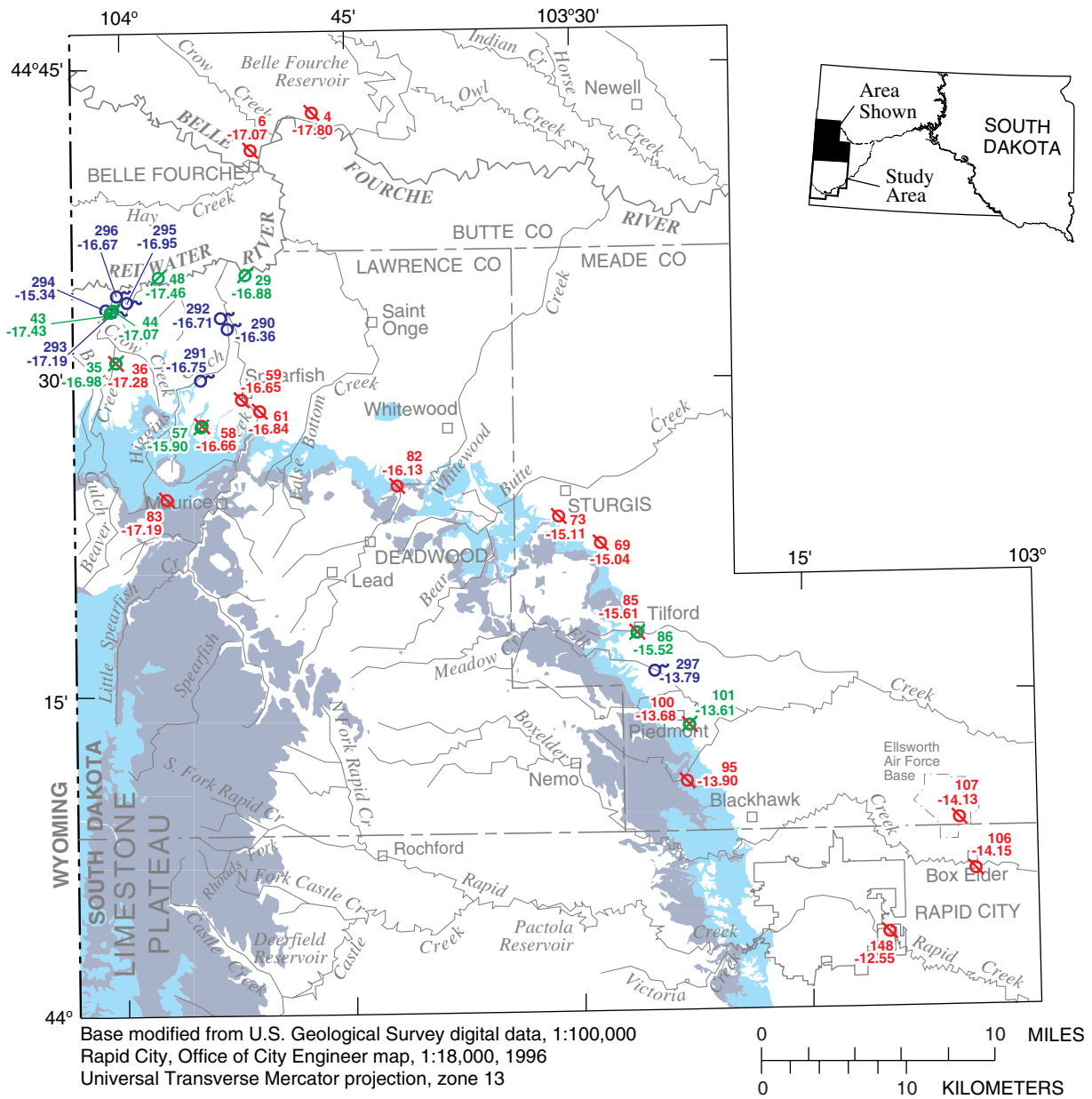
Stable Isotopes

Distributions of $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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.

Figure 27. Distribution of δ^{18}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.

Figure 28. Distribution of $\delta^{18}O$ 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.
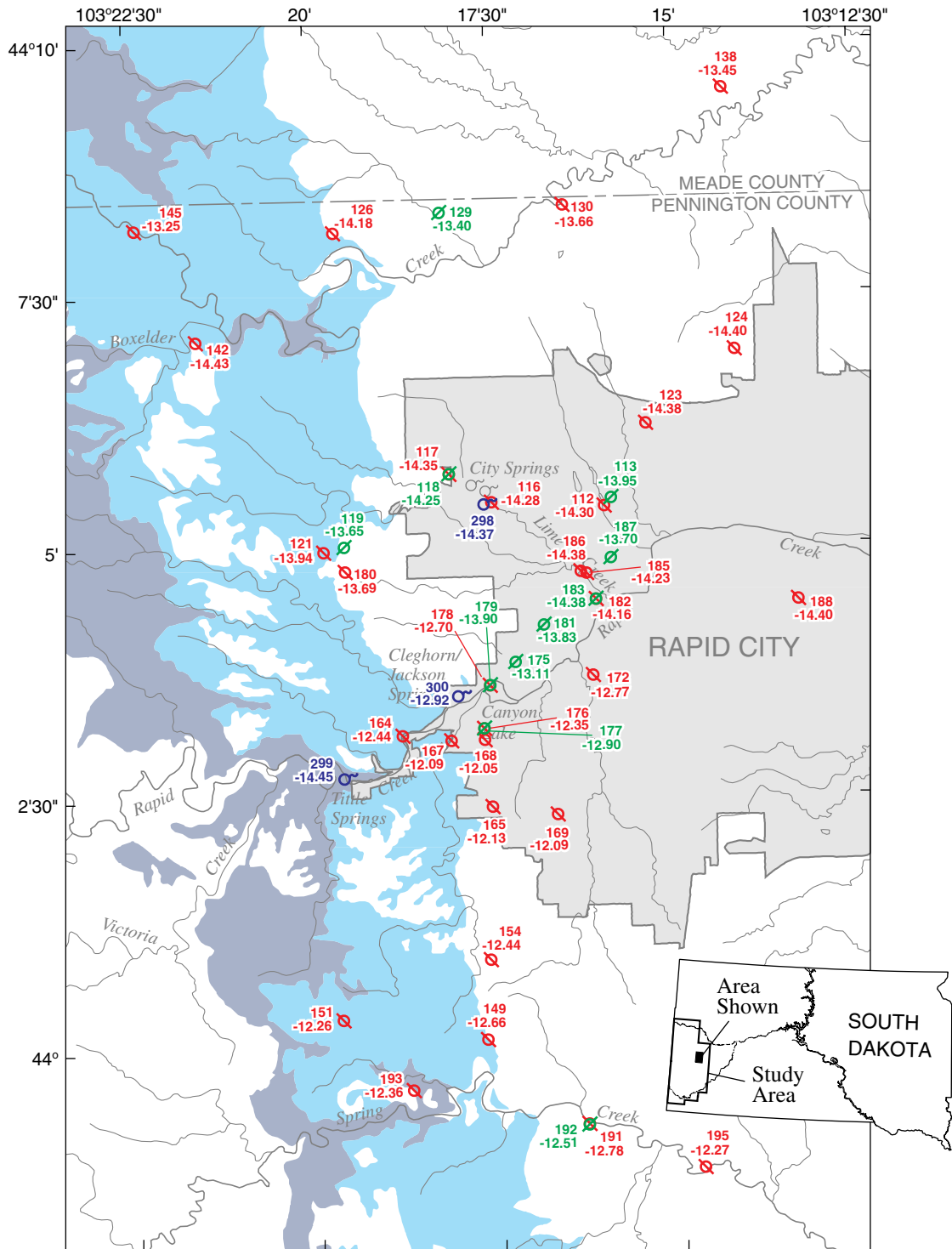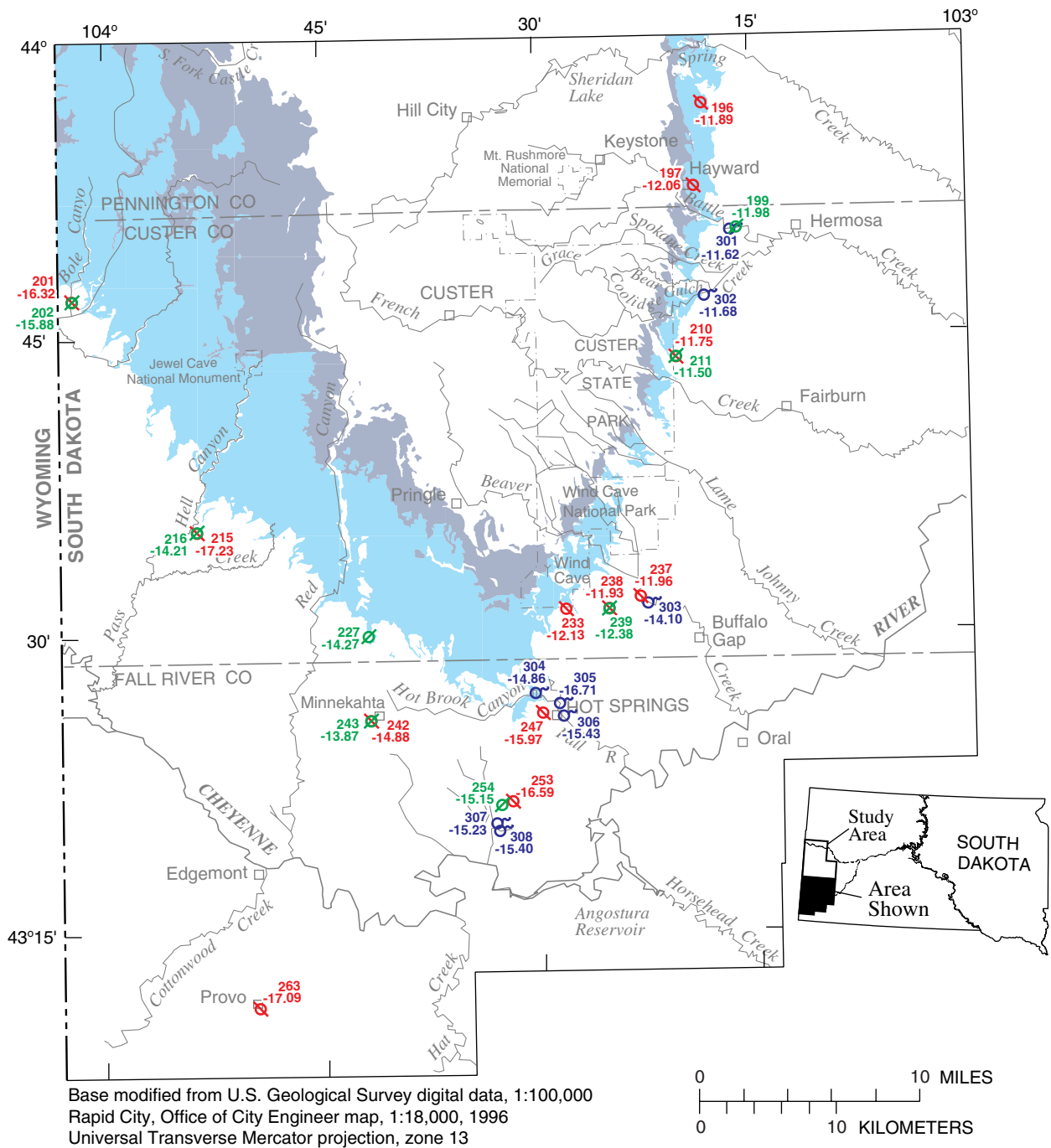
EXPLANATION

OUTCROP OF MADISON LIMESTONE (from Strobel and others, 1999)

OUTCROP OF MINNELUSA FORMATION (from Strobel and others, 1999)

151
-12.26 WELL COMPLETED IN MADISON AQUIFER--Numbers indicate site number and $\delta^{18}O$ value in per mil

192
-12.51 WELL COMPLETED IN MINNELUSA AQUIFER--Numbers indicate site number and $\delta^{18}O$ value in per mil

299
-14.45 DOWNGRADIENT SPRING--Numbers indicate site number and $\delta^{18}O$ value in per mil

Figure 29. Distribution of $\delta^{18}O$ 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	δ¹⁸O Per mil	δ¹⁸O Heavier/lighter	δ¹⁸O S/DS¹	Date	Tritium pCi/L	Tritium TU	Tritium Higher/lower	Hydraulic head S/DS	Hydraulic head Higher/lower	Sulfate (mg/L)	Chloride (mg/L)
36	State Line	Madison	-17.28	L	SS	04-11-94	61.0	19.1	H	DS	H	150	0.7
35	State Line	Minnelusa	-16.98	H	SS	04-11-94	<1.0	<.3	L	DS	L	73	.5
58	Tinton Road	Madison	-16.66	L	DS	09-08-98	30.4	9.5	L	DS	L	58	30
57	Tinton Road	Minnelusa	-15.90	H	DS	09-08-98	78.4	24.6	H	DS	H	3.8	1.2
85	Tilford	Madison	-15.61	L	S	09-03-96	4.0	1.3	L	SS	H	38	.5
86	Tilford	Minnelusa	-15.52	H	S	08-27-96	100.0	31.3	H	SS	L	8.4	.9
100	Piedmont	Madison	-13.68	L	S	09-04-96	<1.0	<.3	L	DS	H	9.3	.7
101	Piedmont	Minnelusa	-13.61	H	S	09-04-96	3.0	.9	H	DS	L	4.2	1.0
117	City Quarry	Madison	-14.35	L	S	05-13-92	96.0	30.1	H	S	H	20	27
118	City Quarry	Minnelusa	-14.25	H	S	05-12-92	2.0	.6	L	S	L	27	6.0
178	Canyon Lake	Madison	²-12.70	H	DS	09-28-93	75.9	23.8	H	DS	H	25	3.2
179	Canyon Lake	Minnelusa	-13.90	L	DS	05-14-92	22.0	6.9	L	DS	L	22	1.4
182	Sioux Park	Madison	²-14.16	H	S	--	--	--	--	DS	H	20	1.6
183	Sioux Park	Minnelusa	²-14.38	L	S	--	--	--	--	DS	L	22	1.7
191	Reptile Gardens	Madison	-12.78	L	SS	07-29-96	15.0	4.7	H	SS	H	20	1.5
192	Reptile Gardens	Minnelusa	-12.51	H	SS	07-30-96	4.0	1.3	L	SS	L	14	1.5
201	Boles Canyon	Madison	-16.32	L	DS	03-22-94	9.0	2.8	H	DS	L	8.3	1.1
202	Boles Canyon	Minnelusa	-15.88	H	DS	12-17-97	3.2	1.0	L	DS	H	26	5.9
210	CSP Airport	Madison	-11.75	L	SS	09-06-95	<1.0	<.3	L	S	Same	22	1.4
211	CSP Airport	Minnelusa	-11.50	H	SS	08-31-95	3.0	.9	H	S	Same	38	2.7
215	Hell Canyon	Madison	-17.23	L	DS	11-05-97	1.9	.6	H	DS	H	230	4.3
216	Hell Canyon	Minnelusa	-14.21	H	DS	11-03-97	<1.0	<.3	L	DS	L	470	4.0
238	7-11 Ranch	Madison	-11.93	H	DS	03-31-94	<1.0	<.3	--	DS	H	24	6.4
239	7-11 Ranch	Minnelusa	-12.38	L	DS	04-05-94	<1.0	<.3	--	DS	L	32	4.3
242	Minnekahta Jnct	Madison	-14.88	L	DS	03-24-94	<1.0	<.3	--	DS	H	37	5.2
243	Minnekahta Jnct	Minnelusa	-13.87	H	DS	09-11-95	<1.0	<.3	--	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 $\delta^{18}O$ 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 $\delta^{18}O$ 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, $\delta^{18}O$ 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.
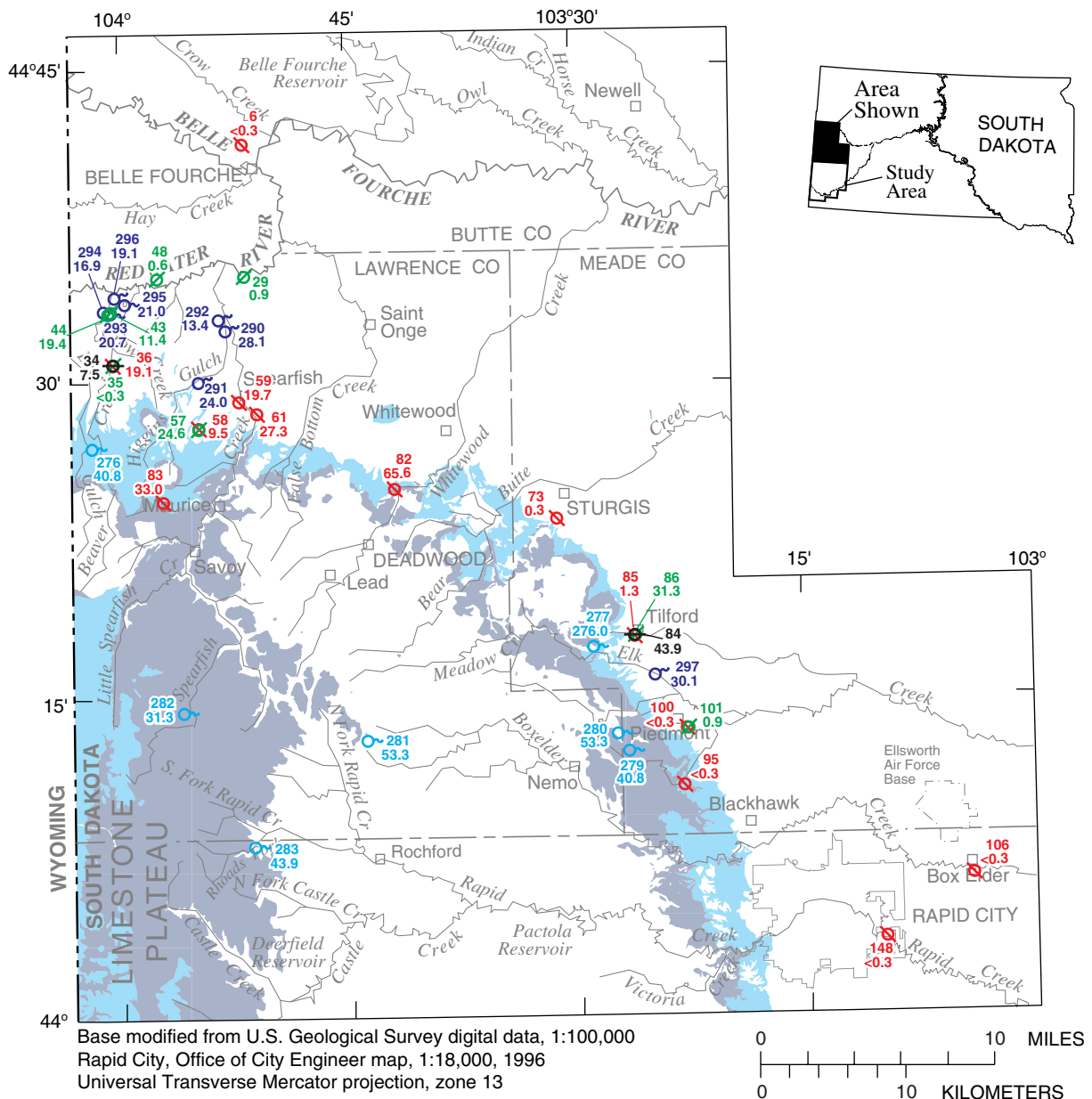
Tritium

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.

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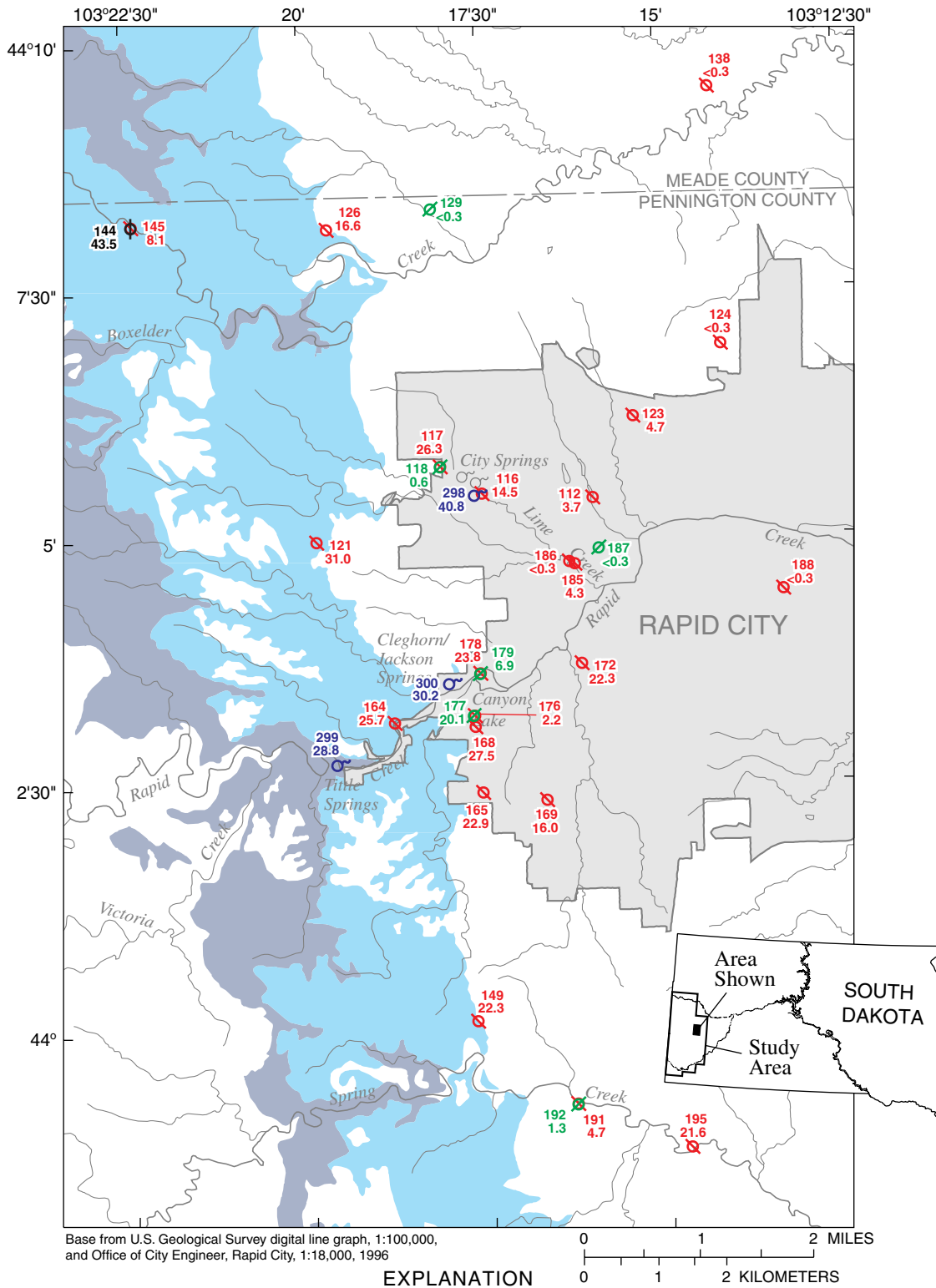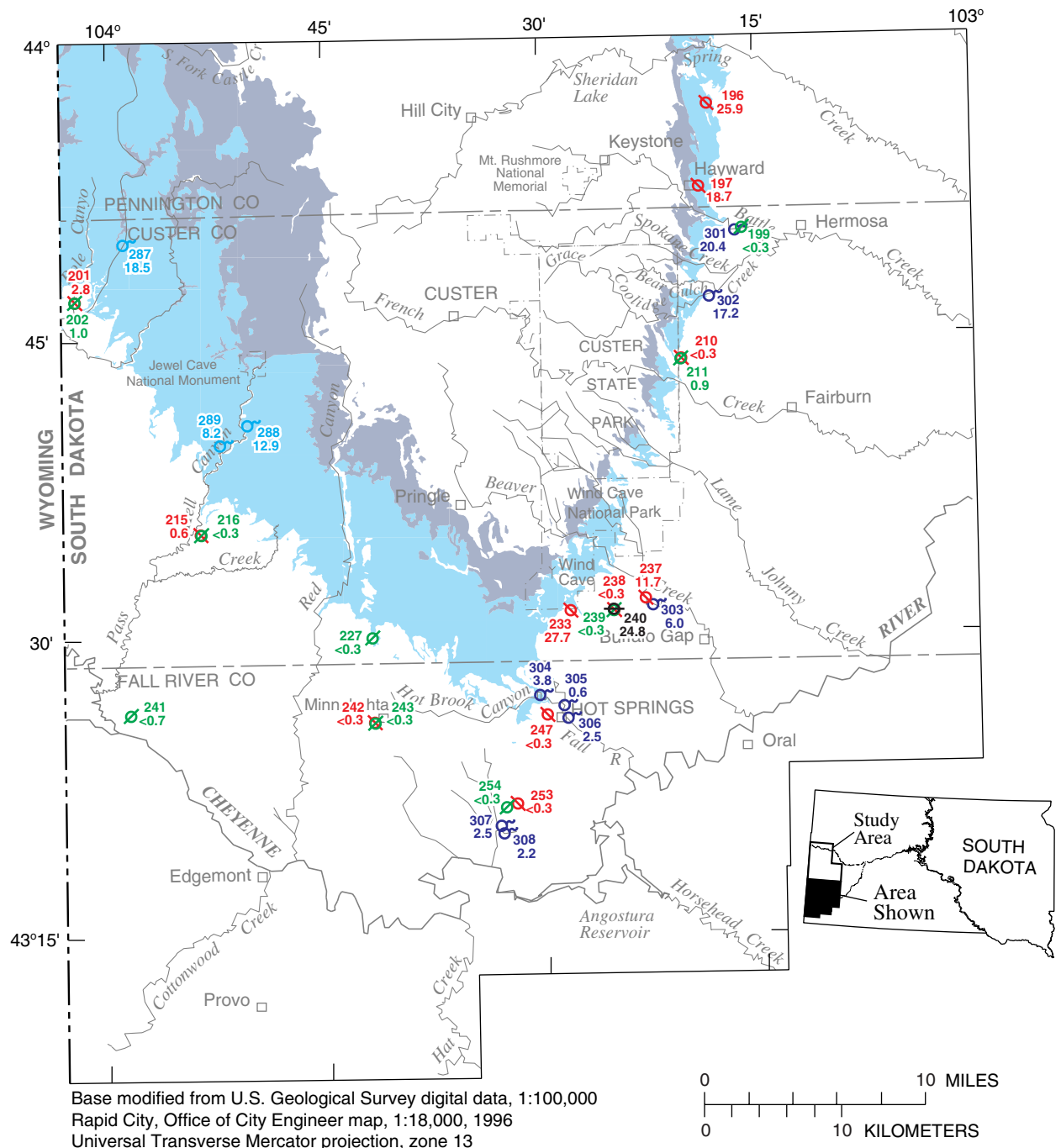
Figure 31. Distribution of tritium for selected sites in the Rapid City area. Sampling dates are through 1998, with the most recent concentration shown for sites with multiple samples.

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).
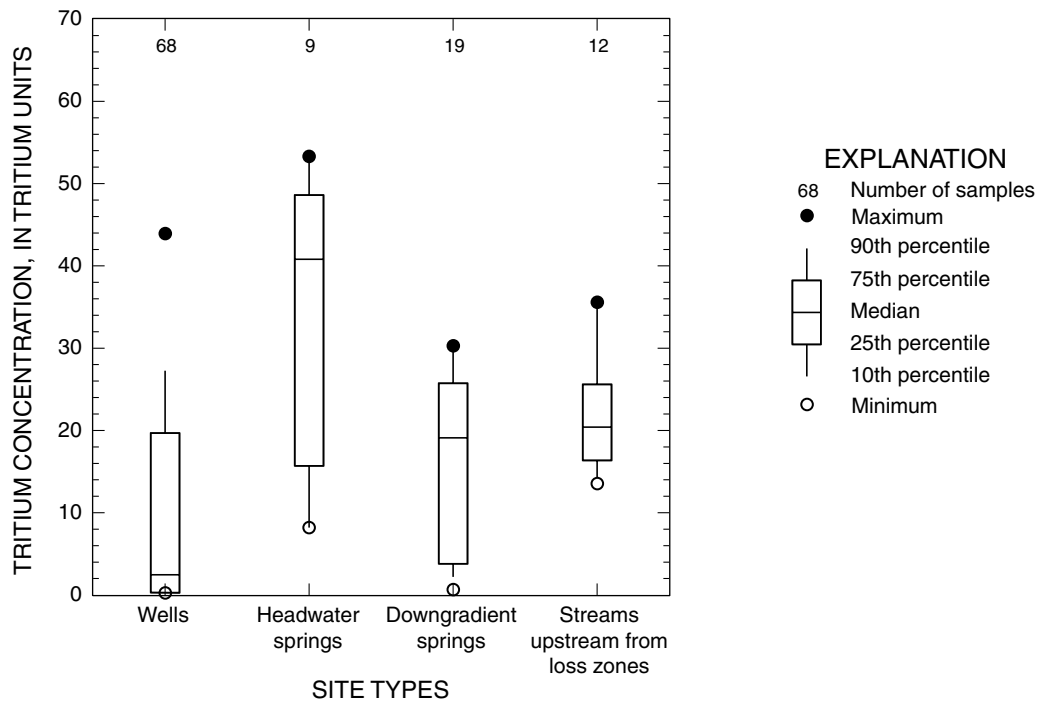

Figure 33. Boxplots of tritium concentrations for selected ground-water and surface-water samples collected during 1990-98 in the Black Hills area.

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 headwater 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ values for the Madison wells south of Rapid Creek probably indicate a northerly flow component for recharge in the Spring Creek area. The $\delta^{18}O$ 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 ft^3/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 $\delta^{18}O$ 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 $\delta^{18}O$ values. This dampened response to relatively large variability in $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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) $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ values. Thus, unequal mixing of recent and pre-bomb water is a likely scenario at this site.

The $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ variability (fig. 21B) and with large distance from the outcrop (fig. 31). The $\delta^{18}O$ values (fig. 21C) for site 149 (Highland Hills) show large variability, which is consistent with relatively high and variable tritium concentrations (table 4). The $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ for the Black Hills area (fig. 20). Temporal variability in $\delta^{18}O$ 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 model[1]

[--, unnamed)

Site number	Spring name	Sample date	Tritium concentration (tritium units)	Minimum traveltime[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

[1]For 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.
[2]Range of years for maximum traveltimes.
[3]Exact sample date unknown (see table 7).
[4]Location 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).
[5]No 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 traveltimes 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 traveltimes dating to the mid 1960's (just subsequent to the tritium peak of 1963). The old estimates for most springs indicate maximum traveltimes 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 groundwater 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 ft^3/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 $\delta^{18}O$ 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 $\delta^{18}O$ values for these springs are very similar, which probably indicates generally thorough mixing conditions associated with large discharges and associated large recharge areas. The $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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.
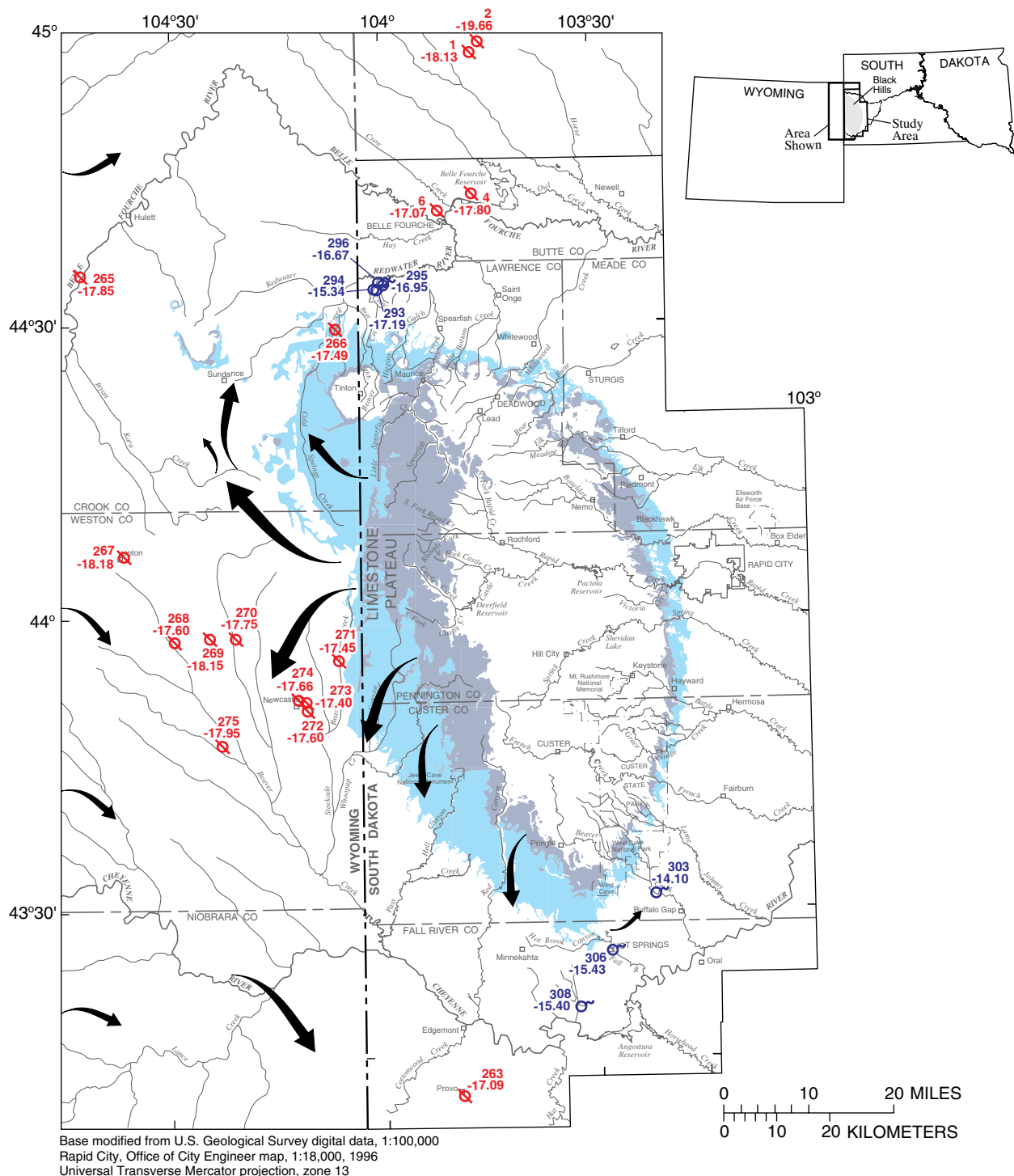
Figure 34. Distribution of $\delta^{18}O$ in selected Madison wells and springs and generalized flowpaths, based on $\delta^{18}O$ values, in the Black Hills of South Dakota and Wyoming.

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 $\delta^{18}O$ value in per mil

308 -15.40 DOWNGRADIENT SPRING--Numbers indicate site number and $\delta^{18}O$ value in per mil

Base modified from U.S. Geological Survey digital data, 1:100,000
Rapid City, Office of City Engineer map, 1:18,000, 1996
Universal Transverse Mercator projection, zone 13

The δ^{18}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 δ^{18}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 δ^{18}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 δ^{18}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 δ^{18}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 δ^{18}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 δ^{18}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 δ^{18}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 traveltimes, but confirm the influence of recharge from within the study area.
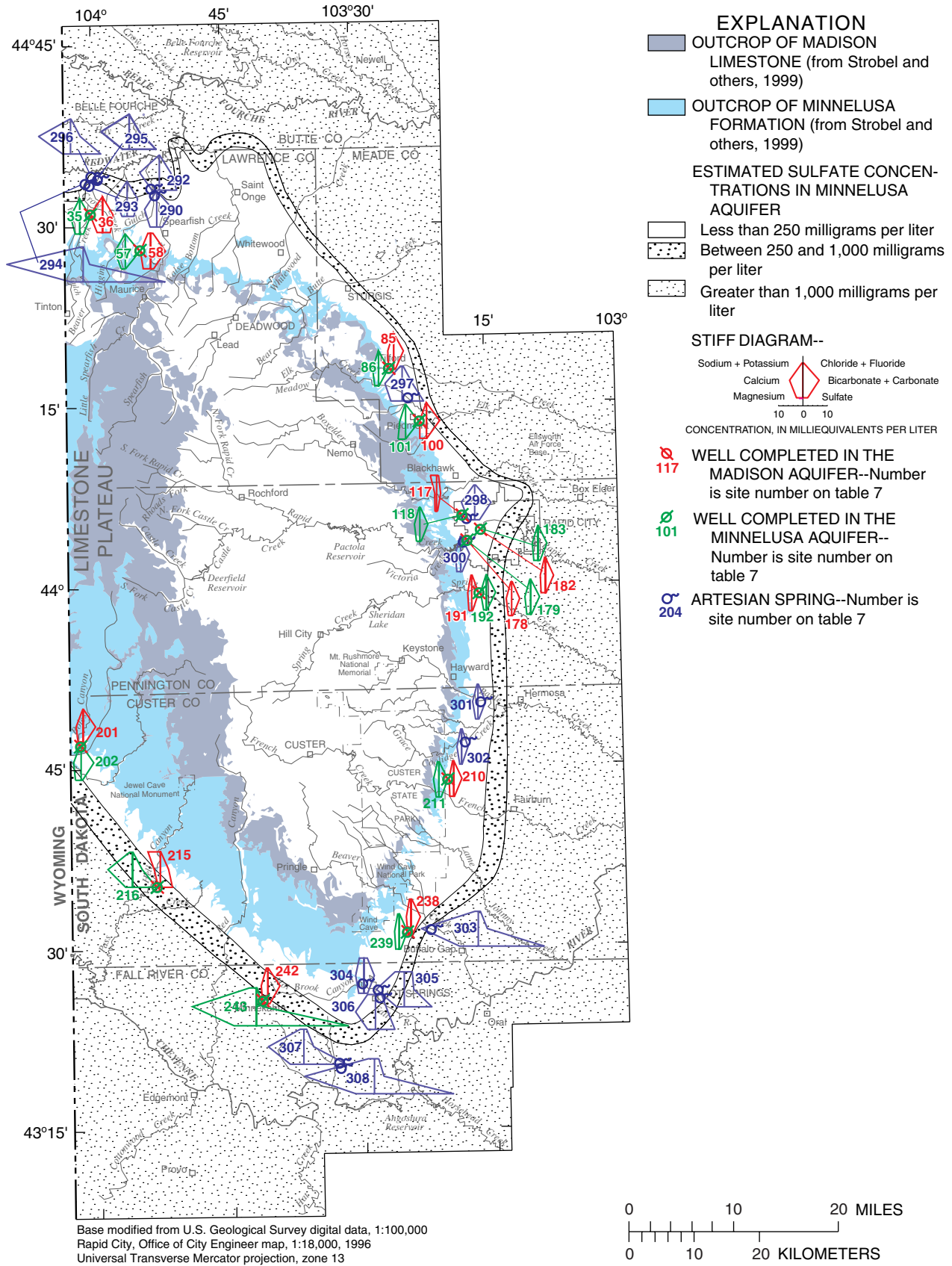
Figure 35. Selected Stiff diagrams showing the distribution of major-ion chemistry in selected well pairs and artesian springs in the Black Hills area.

The $\delta^{18}O$ 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 traveltimes; (2) the areal distribution of $\delta^{18}O$ 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 $\delta^{18}O$ values in the Black Hills area, including well pairs, was presented in figures 27-29. Values for $\delta^{18}O$ 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 $\delta^{18}O$ values, using criteria of less than 0.25 ‰ for similar, greater than 0.30 ‰ for dissimilar, and within this range for somewhat similar. The $\delta^{18}O$ 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 $\delta^{18}O$ values that are similar or somewhat similar (table 3). These similarities are not necessarily indicative of extensive mixing because similarities in $\delta^{18}O$ 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 $\delta^{18}O$ values are quite similar. Furthermore, the $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ value.

The $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 ft^3/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 (ft³/s)	Elevation of land surface (feet above MSL)	Hydraulic head (feet above MSL) Madison aquifer	Hydraulic head (feet above MSL) Minnelusa aquifer	Sulfate (mg/L)	Chloride (mg/L)	Estimated spring source from previous studies	Date	δ¹⁸O (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 / --

[1]Estimated by Klemp (1995).
[2]Estimated by Whalen (1994).
[3]Estimated 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 traveltimes. 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 traveltimes. 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 $\delta^{18}O$ (ratio of $^{18}O/^{16}O$ relative to a reference standard) for recharge areas is developed and used as a tracer for ground-water flowpaths. Distributions of $\delta^{18}O$ in ground water are consistent with spatial patterns in recharge areas, with isotopically lighter $\delta^{18}O$ 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 flowpaths 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ data for these sites showing larger response to temporal variations in Boxelder Creek.

Time-series $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 traveltimes. This is consistent with the $\delta^{18}O$ values, which indicate potential recharge areas extending along the entire southwestern flank of the uplift. The $\delta^{18}O$ 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 traveltimes.

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.