Madison and Minnelusa Flow System

Isotopes are important tools in hydrologic studies because they provide a "fingerprint" for water, much like DNA provides a genetic fingerprint for humans. Stable isotopes are natural tracers and can be used in determining flowpaths. Radioactive isotopes are used in estimating ground-water ages.

Geochemical data and water-balance analyses indicate that regional flowpaths in the Madison and Minnelusa aquifers are largely deflected around the study area. The dominant proportion of water in these aquifers within the study area is recharged within the Black Hills area.

A major focus of the Black Hills Hydrology Study has been to obtain a better understanding of the complex flow system within the Madison and Minnelusa aquifers. These aquifers are used extensively within the Black Hills area and have large potential for further development. These aquifers also have an important influence on the surface-water hydrology of the area because of large streamflow losses that provide recharge to these aquifers and because of numerous springs that originate from these aquifers, providing base flow to many area streams. This section of the report presents information regarding flowpaths within the Madison and Minnelusa aquifers and springs that originate from these aquifers.

Flowpaths

Various isotopes (chemical variations of an element) have been used extensively in investigating flowpaths within the Madison and Minnelusa aquifers. Isotopes are atoms of the same element that differ in mass because of a difference in the number of neutrons in the nucleus. Isotopes are useful tools in hydrologic studies because they can provide a "fingerprint" (known as the isotopic **signature**) for water, much like DNA provides a genetic fingerprint for humans.

There are two types of isotopes—stable isotopes and unstable (radioactive) isotopes. The **stable isotopes** of oxygen and hydrogen are stable parts of water molecules and are ideal hydrologic **tracers**. The isotopic signatures of these stable isotopes are affected by meteorological processes but generally are not affected by contact with minerals in soil and rock. Because the isotopic signatures of stable isotopes generally do not change as the water flows underground, these isotopes are natural tracers and can be used in determining flowpaths. Radioactive isotopes, which are subject to decay over time, can be used in estimating the age (since recharge) for water samples.

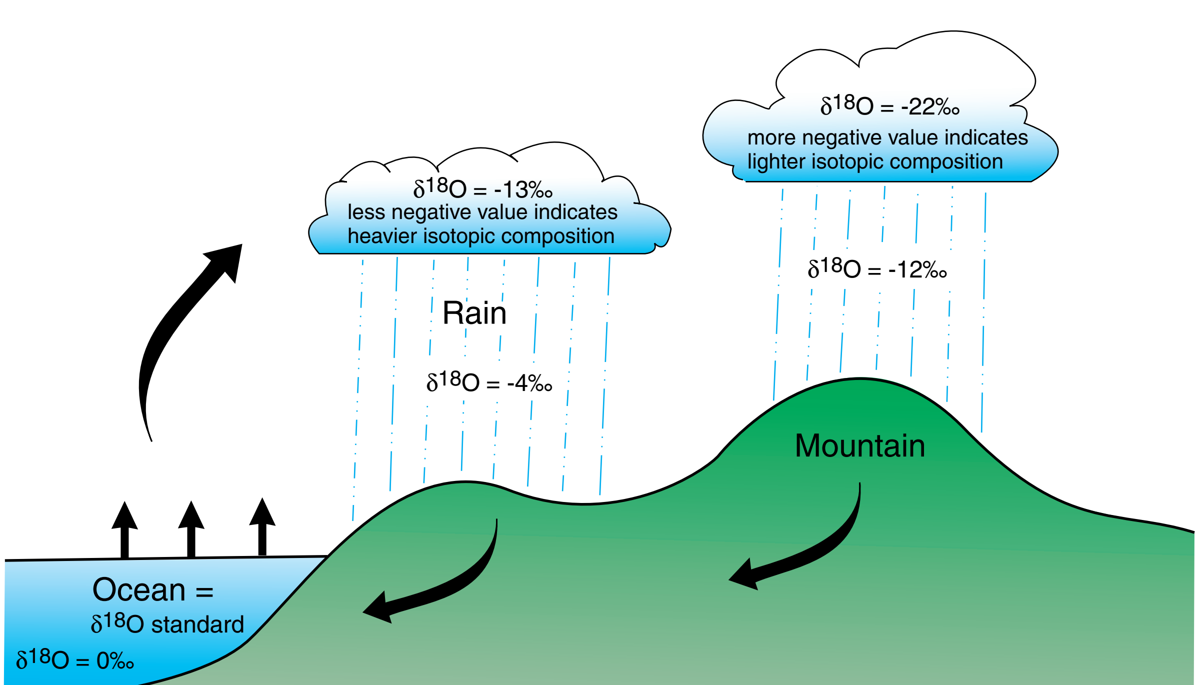

Figure 113 . Schematic diagram showing fractionation of stable oxygen isotopes (modified from Naus and others, 2001). The $\delta^{18}O$ values, which compare $^{18}O/^{16}O$ ratios, relative to ocran water, are expressed in per mil (‰).

Stable isotopes of oxygen have been used in evaluating ground-water flowpaths. Isotopic composition is reported relative to a reference standard as δ (pronounced delta) values in units of parts per thousand (per mil; written ‰). The δ values for oxygen compare the ratio between the heavier isotope oxygen-18 (^{18}O) and the lighter isotope oxygen-16 (^{16}O) of a water sample, relative to ocean water, which is the reference standard and has an isotopic composition ($\delta^{18}O$) of 0 ‰ (fig. 113). The isotopic composition of water vapor in clouds is lighter (more negative values) than the ocean from which it is evaporated. Precipitation is isotopically heavier (less negative values) than the clouds from which it originates. The isotopic composition of clouds and precipitation becomes progressively lighter (more negative values) as air masses move inland, especially in crossing high-altitude areas such as mountain ranges.

Distinctive patterns in the distribution of $\delta^{18}O$ for the Black Hills area (fig. 114) were identified by Naus and others (2001) and were used for interpretation of ground-water flowpaths in the Black Hills area. The lines of equal $\delta^{18}O$ shown in figure 114 indicate the generalized isotopic composition of precipitation in and near recharge areas for the Madison and Minnelusa aquifers. Isotopic composition of precipitation is not constant and varies with individual storm patterns. Relatively consistent patterns over time have been inferred, however, by consistent temporal and spatial trends for ground-water samples, which are indicative of integrated isotopic composition because of generally long residence times.

Isotope values in the Black Hills area become progressively lighter from south to north, and with increasing altitude (fig. 114). The lightest values occur in the highest altitudes of the northern Black Hills, where influences of storms originating from the Pacific Ocean are prevalent. The isotopic composition of Pacific storms becomes lighter in crossing the Rocky Mountains. The heaviest values occur along the southeastern flank of the uplift, where influences of storms originating from the south-southeast are prevalent.

The unique signatures of $\delta^{18}O$ for the Black Hills area were used by Naus and others (2001) for evaluating the possible influence of regional ground-water flowpaths in the Madison aquifer (fig. 114). The $\delta^{18}O$ values for samples from two wells located just north of the study area (-18.13 and -19.66 ‰) are lighter than the lightest values in the high-altitude areas of the northern Black Hills. Values for these two samples are comparable with values for recharge areas west of the Black Hills in Wyoming (fig. 45) reported by Busby and others (1983) and Plummer and others (1990). Thus, water from these wells was concluded to be influenced by regional flow patterns and not by recharge originating in the Black Hills area. The $\delta^{18}O$ values for a group of large artesian springs along the northern axis of the uplift are notably heavier and range from -15.34 to -17.19 ‰. These values are comparable with estimated values in the recharge areas of the northwestern Black Hills and indicate that influence from regional flowpaths is minor or negligible. Similarly, $\delta^{18}O$ values of -17.07 and -17.80 ‰ for samples from two wells located near Belle Fourche are indicative of recharge in the Black Hills area.

In the southern Black Hills, a $\delta^{18}O$ value of -17.09 ‰ for a sample from a well near Provo (fig. 114) does not provide definitive information. Values for three large springs (-15.40 ‰ for Cascade Springs, -15.43 ‰ for Fall River, and -14.10 ‰ for Beaver Creek) show the influence of Black Hills recharge, however, and generally reflect a mix of water recharged along the western and southwestern flanks of the uplift.

The $\delta^{18}O$ data, in combination with other geochemical information, were used by Naus and others (2001) as the basis of a conclusion that regional flowpaths in the Madison aquifer are largely deflected around the study area. Results of water-balance analyses for the Madison and Minnelusa aquifers by Carter, Driscoll, Hamade, and Jarrell (2001) supported this conclusion.

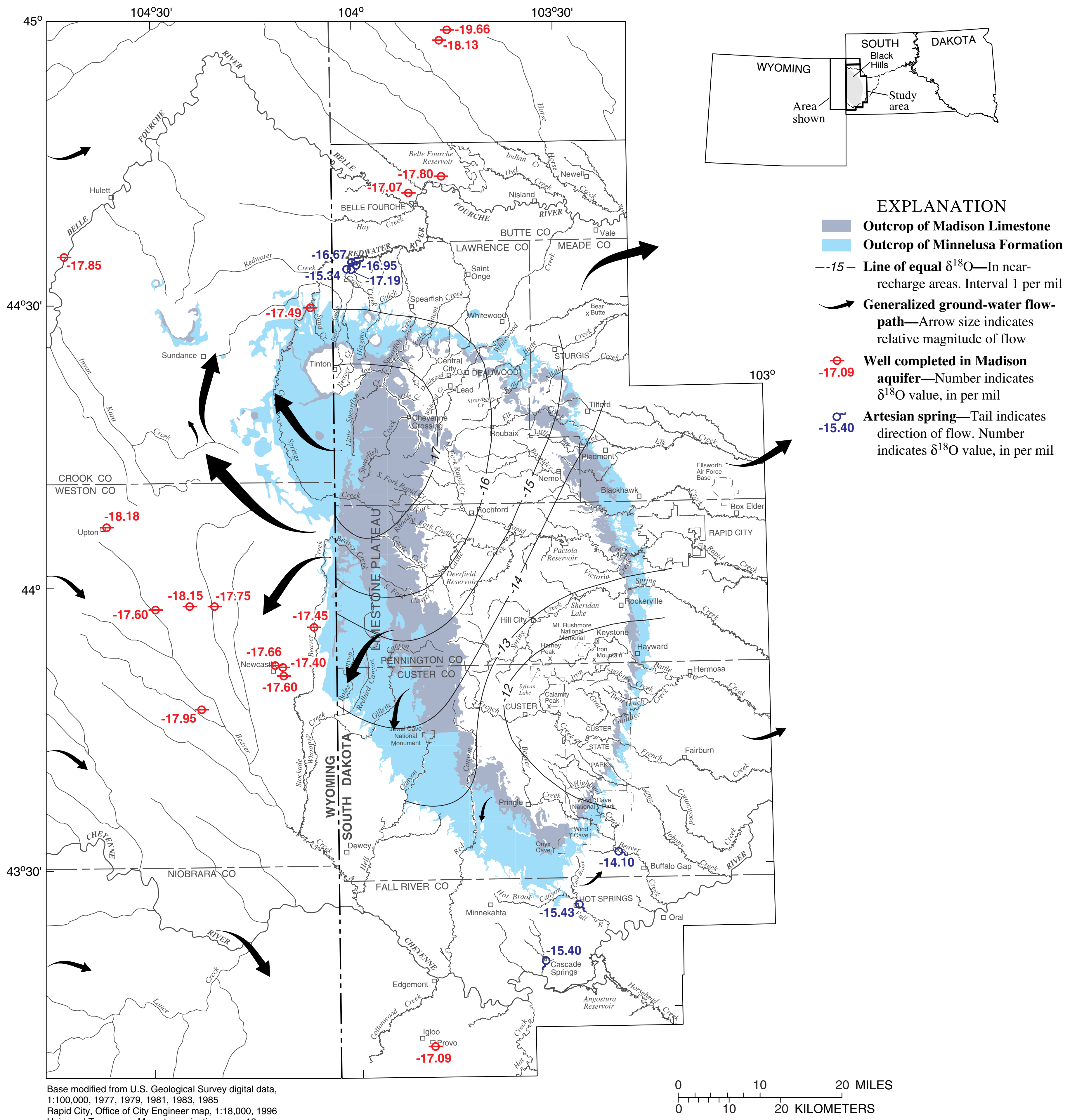

Figure 114. Generalized flowpaths in the Madison aquifer in the Black Hills area of South Dakota and Wyoming (modified from Naus and others, 2001). Lines of equal $\delta^{18}O$ values in near-recharge areas also are shown. Recharge water retains the isotopic composition ($\delta^{18}O$ value) of the rain or streamflow, which is indicated by the lines of equal $\delta^{18}O$ values in near-recharge areas. Thus, $\delta^{18}O$ values have been used for interpreting flowpaths to selected wells and springs.

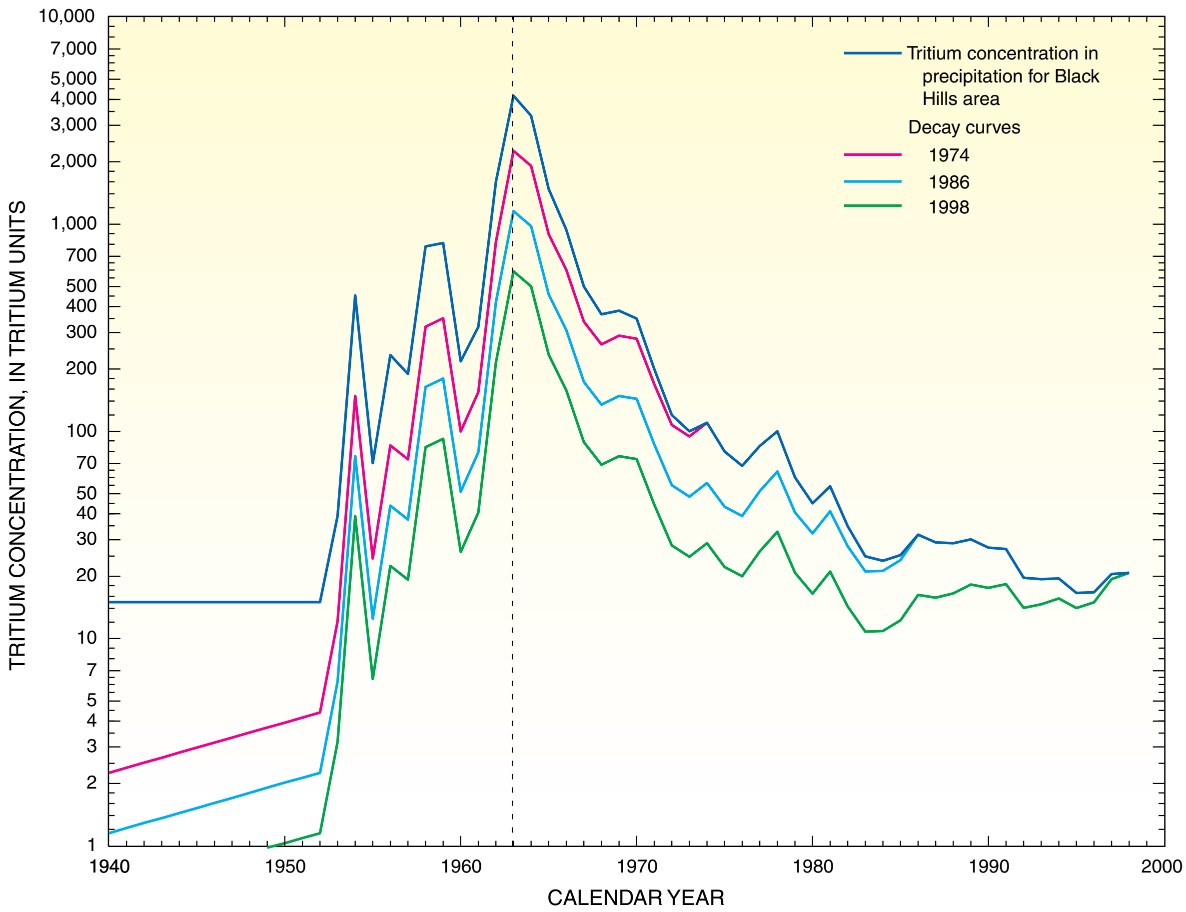

Figure 115. Estimated tritium concentrations in precipitation for the Black Hills area and decay curves for selected years. Decay curves depict decayed tritium concentrations for selected sampling years. Maximum tritium concentrations of about 4,200 tritium units occurred in about 1963. Tritium has a half-life of about 12.43 years and decay curves are presented for selected 12-year increments that approximate this half-life. Using 1963 as an example, the tritium concentration in a sample collected in 1974 containing water recharged in 1963 would be equal to about 2,200 tritium units. The tritium concentration would have decayed by almost one-half to 1,100 tritium units for a sample collected 12 years later in 1986, and again by about one-half to about 600 tritium units for a sample collected in 1998.

Approximate dates of ground-water recharge can be estimated by adjusting for radioactive decay of tritium, which has a half-life of 12.43 years. Three decay curves for selected 12-year increments are presented in figure 115 that approximate the half-life decay of tritium. An example is provided for 1963, during which tritium concentrations in precipitation are estimated as about 4,200 TU. If a sample with this concentration was collected during 1963, the concentration in that sample in 1998 would be about one-eighth of the original concentration, resulting from decay over nearly 3 half-lives (1/2 x 1/2 x 1/2).

Modern water is considered to be water recharged since initiation of nuclear testing in the early 1950's; thus, it is less than 50 years old.

Tritium is an unstable (radioactive) isotope of hydrogen (^3H) that occurs naturally in only trace amounts. Tritium is useful for evaluation of ground-water ages because large quantities of tritium were introduced into the atmosphere during the worldwide nuclear test age (bomb era) that began in the early 1950's, and large variations in tritium concentrations in precipitation have occurred since then.

Naus and others (2001) estimated concentrations of tritium in precipitation for the Black Hills area (fig. 115), which were derived primarily from data by Michel (1989). Prior to nuclear testing, tritium concentrations in precipitation for the area were assumed to be about 15 tritium units (TU). During the 1950's and 1960's, tritium concentrations in precipitation increased sharply from atmospheric testing of thermonuclear bombs, after which tritium concentrations have declined to levels similar to pre-bomb conditions.

Estimation of recharge dates also requires the use of various assumptions regarding ground-water flow conditions. The decay curves presented in figure 115 would be appropriate only for a condition known as slug flow, or pipe flow, whereby a given water front advances with uniform velocity and negligible mixing, such as a slug of water in a pipe. In evaluating ground-water ages for the Madison and Minnelusa aquifers in the Black Hills area, Naus and others (2001) considered other conceptual models that assumed mixing of water recharged over a range of years.

Boxplots showing the distribution of tritium in samples collected in the Black Hills area during 1990-98 are presented in figure 116. A map showing the spatial distribution of ground-water sampling sites is presented as figure 117, which uses various symbol types to indicate ranges of measured tritium concentrations. Water recharged since initiation of nuclear testing in the early 1950's is considered modern. Thus, modern water is less than 50 years old. Samples with detectable tritium concentrations (greater than 0.3 TU) contain at least some modern water, with increasing proportions of modern water indicated by increasing tritium concentrations. Samples with detectable tritium concentrations predominantly contain water that is younger than 50 years.

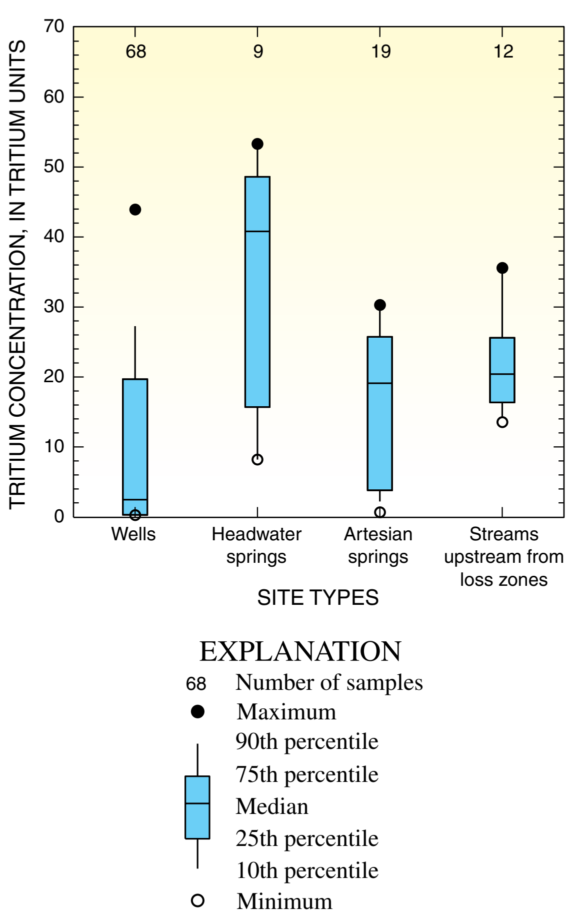

Figure 116. Tritium concentrations for selected ground-water and surface-water samples collected during 1990-98 in the Black Hills area (from Naus and others, 2001).

Tritium is a radioactive isotope of hydrogen (^3H) that can be used to evaluate ground-water ages because large quantities of tritium were introduced into the atmosphere during the nuclear test age (bomb era) that began in the early 1950's. Maximum tritium concentrations in precipitation occurred in about 1963.

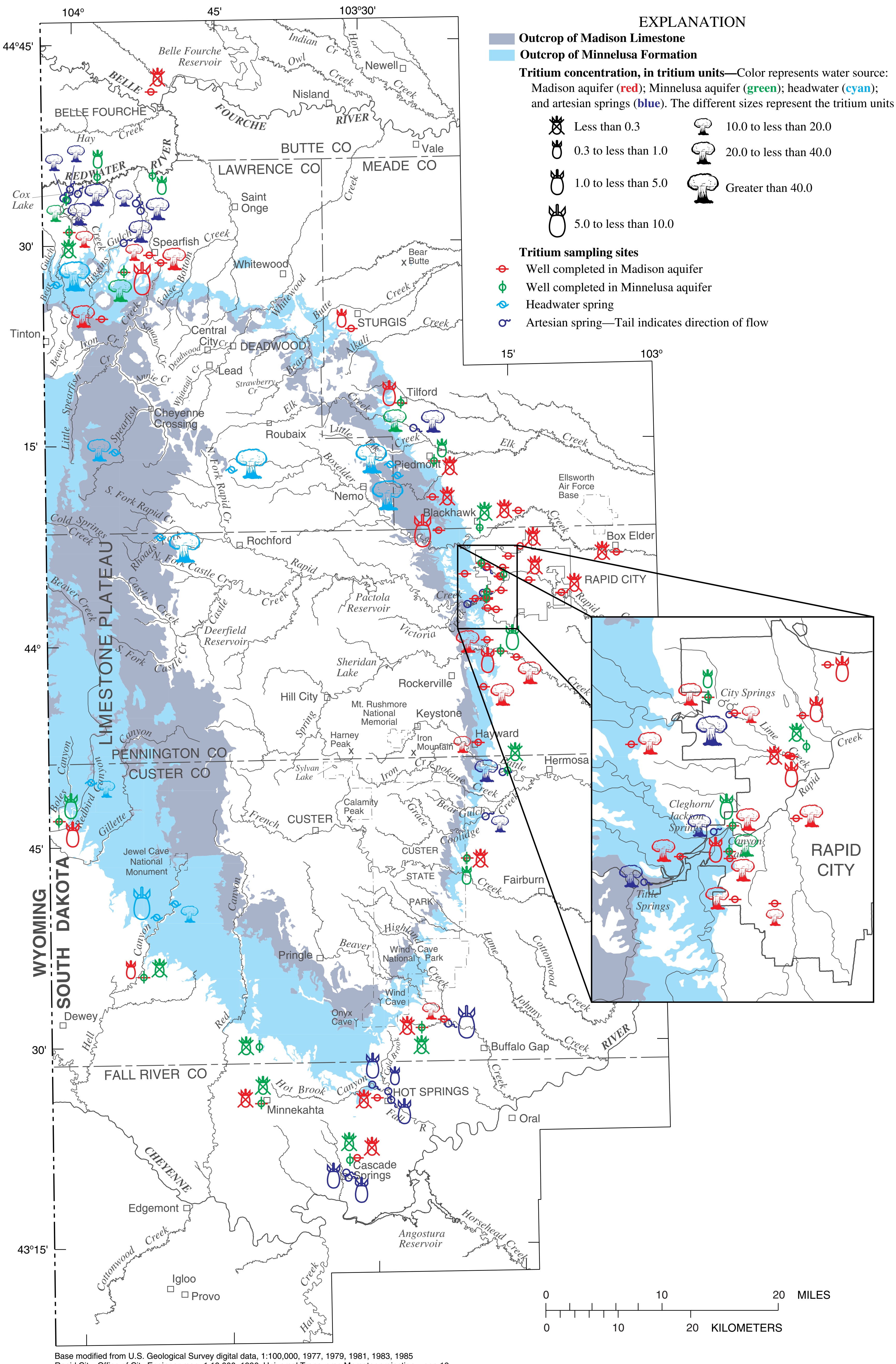

Figure 117. Tritium occurrence for selected sample sites in the Black Hills area. Sites considered include only those sampled during the 1990's. Higher tritium concentrations indicate larger proportions of modern water.

Large variations in traveltimes can occur within very short distances within the Madison and Minnelusa aquifers. A low tritium concentration at any given location does not imply that low tritium concentrations are likely in nearby locations.

As a group, samples from headwater springs have the highest tritium concentrations (fig. 116), which generally indicates relatively high proportions of modern water. The headwater spring sites are within or near outcrops of the Madison Limestone or Minnelusa Formation. Two of these sites are along the northeastern flank of the Black Hills (fig. 117), but are included as headwater springs because they are upgradient from potential effects of streamflow loss zones. Concentrations for samples collected from streams upstream of loss zones generally are comparable with estimated concentrations for precipitation since about 1985. The upper end of the distribution for these streams is much smaller than for headwater springs, many of which may include substantial proportions of water recharged during approximately 1955-80 (fig. 115).

Proportions of water recharged during the peak-tritium period (about 1963) apparently are small for most wells and artesian springs (fig. 115). Tritium concentrations for 50 percent of the wells sampled are less than about 2 to 3 TU (fig. 116), indicating relatively small proportions of modern water for these wells. Thus, it is apparent that traveltimes within the aquifers are relatively long for some locations, which is consistent with relatively long distances from recharge areas to many wells (fig. 117). Increasing distances from outcrop areas do not necessarily indicate longer traveltimes, as shown by tritium concentrations for several wells. An example is provided by a group of sites just northwest of Buffalo Gap, where an upgradient well in the Madison aquifer has a tritium concentration less than 0.3 TU (indicating water older than 50 years); however, a concentration exceeding 10 TU (indicating modern water) was measured farther downgradient.

The preceding discussion provides an example of the large variability in traveltimes that can occur within short distances.

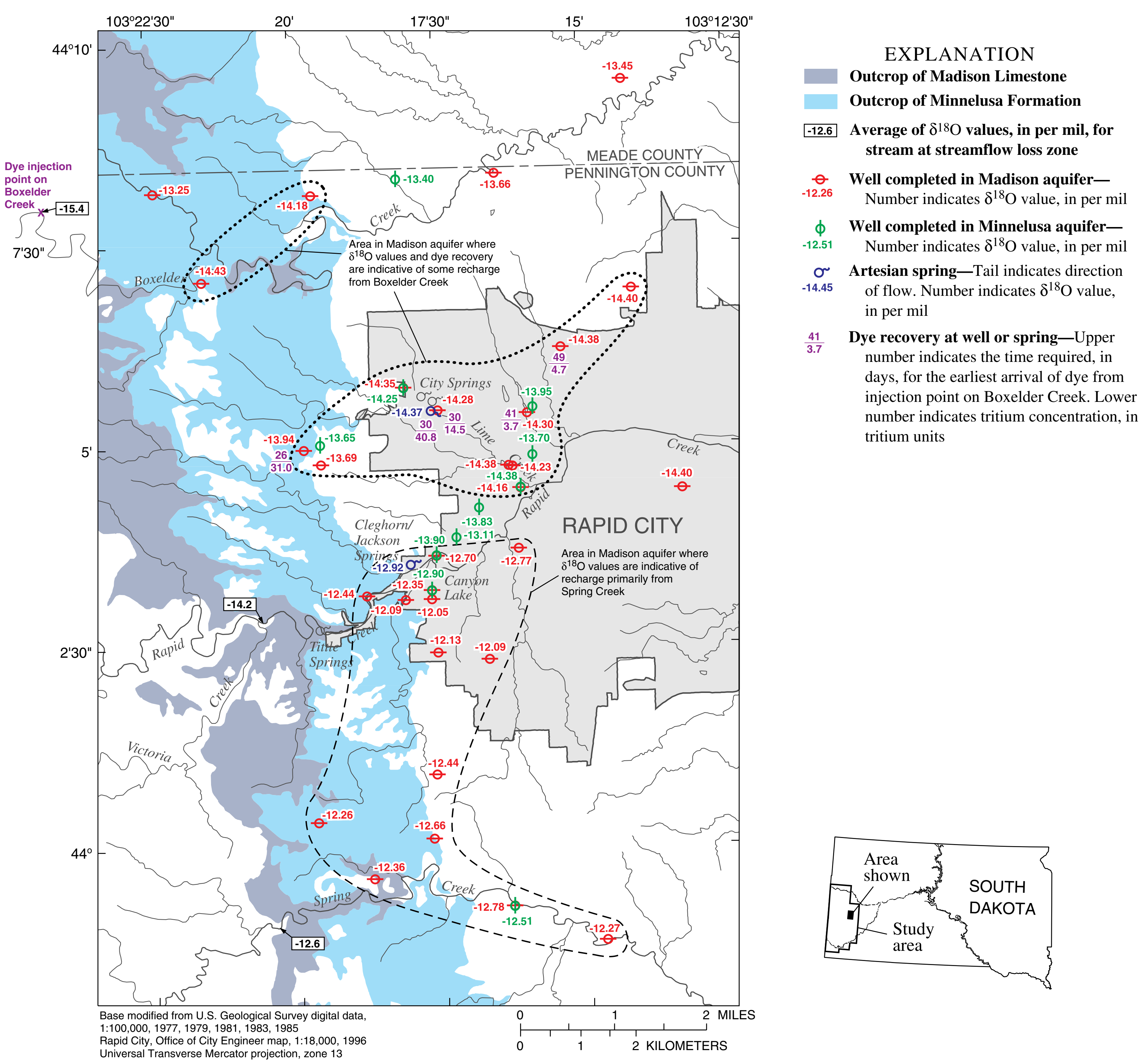

Figure 118. Concentrations of $\delta^{18}O$ in Madison and Minnelusa aquifers in the Rapid City area. Average $\delta^{18}O$ values for streamflow loss zones also are shown. In addition, traveltimes and tritium concentrations for sites at which dye recovery was reported by Greene (1999) are shown.

This also illustrates the complex flowpaths that commonly can occur near artesian springs. In this case, the tritium concentration of the spring northwest of Buffalo Gap is intermediate between upgradient wells in the Madison and Minnelusa aquifers, any of which may be on flowpaths contributing to springflow. In general, the artesian springs have higher tritium concentrations than water from wells (fig. 116). Artesian springs tend to preferentially occur along high-permeability flowpaths, which result in relatively fast traveltimes.

Detailed information regarding flowpaths is available for the Rapid City area because of various site-specific studies that have been conducted in this area. Dye testing performed in this area (Greene, 1999; Strobel, Sawyer, and Rahn, 2000) has contributed to better understanding of complex flow conditions in the Rapid City area. Dye testing consisted of dye injection at a sinkhole in the loss zone of Boxelder Creek, with dye recovery documented at locations indicated in figure 118, many of which are located in the Rapid Creek drainage basin. The time required (in days) for the earliest arrival of dye from the injection point on Boxelder Creek to reach the various locations is shown in figure 118. Ground-water velocities as high as 0.4 mile per hour have been documented for flow to springs along Boxelder Creek (fig. 119).

In the Rapid City area, stable isotope ($\delta^{18}O$) values have indicated an area in the Madison aquifer dominated by recharge from streamflow losses along Spring Creek, as shown by the outlined area in figure 118. In areas north of Rapid Creek, the $\delta^{18}O$ values generally are intermediate between values for Rapid and Boxelder Creeks, indicating a combination of recharge from these areas. Areas that probably have had some influence from water recharged in Boxelder Creek also are shown in figure 118.

Ground-water velocities as high as 0.4 mile per hour for springs along Boxelder Creek have been documented through dye testing. Dye recovery within about 30 to 50 days after injection has been documented for wells in the Rapid City area.

As a group, headwater springs have the highest tritium concentrations, which generally indicates relatively high proportions of modern water. Samples from wells, as a group, have the lowest tritium concentrations, which generally indicates long traveltimes to wells, although there can be large variability in traveltimes within short distances. Artesian springs have higher tritium concentrations than water from wells, which indicates that artesian springs preferentially occur along high-permeability flowpaths, which have relatively fast traveltimes.

Photographs by Derric L. Iles, South Dakota Department of Environment and Natural Resources

Figure 119. Dye testing has been performed in Boxelder Creek, which can lose up to 50 cubic feet per second of flow to the bedrock aquifers. In the upper left photograph, nontoxic, red dye is poured into Boxelder Creek upstream of a major loss zone. In the upper right photograph, dye in the stream can be seen disappearing into a sinkhole in the Madison Limestone. In the bottom photograph, dye in the stream emerges downstream at Gravel Spring, which is about 2,200 feet (linear distance) from the major loss zone. The length of time for the first arrival of dye to travel this distance is variable depending on flow conditions but generally is about 1 to 2 hours (Strobel, Sawyer, and Rahn, 2000). Thus, the ground-water velocity is about 0.2 to 0.4 mile per hour, which is a very fast rate for ground water. Dye also has been recovered at City Springs, which is in the Rapid Creek Basin, about 30 days after injection. This demonstrates that ground-water flowpaths are not necessarily restricted by surface-water drainage basins.

Dye testing has confirmed leakage from the Madison aquifer to the Minnelusa aquifer in the Rapid City area.

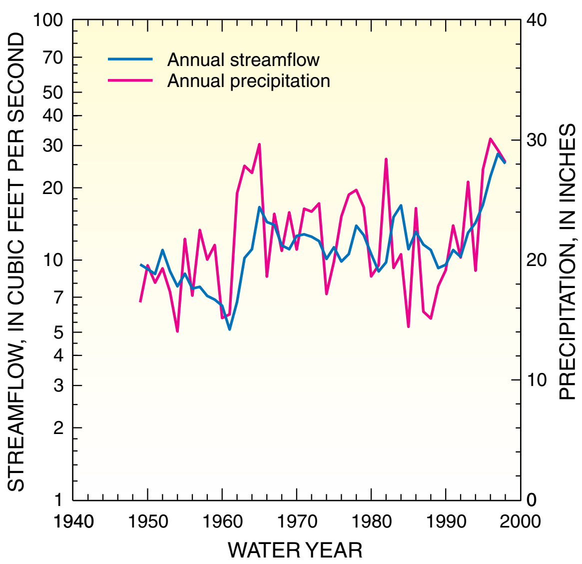

Figure 120. Long-term streamflow and precipitation trends for gaging station 06409000, Castle Creek above Deerfield Reservoir. This is the only streamflow-gaging station representative of the limestone headwater hydrogeologic setting for which long-term streamflow records are available. In this setting, the response of annual streamflow to climatic conditions is dampened by the dominant influence of ground-water discharge. The delayed response of streamflow following increased precipitation during 1962-65 provides an example.

The unique "plumbing system" of the Madison and Minnelusa aquifers is especially valuable in providing a consistent source of base flow to some area streams during dry climatic conditions that are common in the Black Hills area.

Dye testing also has provided valuable insights regarding tritium data. Two of the wells with dye recovery had detectable, but low, tritium values (3.7 and 4.7 TU; fig. 118), which generally would be considered indicative of large proportions of pre-bomb water. This inference is reasonable, but somewhat misleading because the small proportions of modern water in the mix consist of extremely modern water (timeframe of days). Results of dye tests dramatically illustrate the potential for rapid ground-water movement and the associated potential for contamination that exists, even in locations where age-dating information may be indicative of relatively old ground water.

Results of dye testing also provide insights regarding leakage between the Madison and Minnelusa aquifers, which is discussed in more detail in the following section of the report. Two wells in Rapid City in the Minnelusa aquifer (fig. 118) have $\delta^{18}O$ values that are similar to those for colocated wells in the Madison aquifer. For one of these pairs of colocated wells, leakage from the Madison aquifer to the Minnelusa aquifer has been confirmed by a dye test (where dye was recovered at City Springs, which discharges through the Minnelusa aquifer) and by aquifer testing.

Springs

The Madison and Minnelusa aquifers have an important influence on the surface-water hydrology of the Black Hills area. Headwater springs in the Limestone Plateau area provide a reliable source of base flow in some streams, especially within the Spearfish Creek and Rapid Creek (including Castle Creek) Basins. The flows of most area streams are diminished as they cross outcrops of these aquifers, however, these streamflow losses are an important source of ground-water recharge. Farther downgradient, ground water is discharged by artesian springs, again providing a reliable source of base flow in some streams. Streams without artesian springs tend to flow only intermittently, however. This unique "plumbing system" dampens effects of short-term dry conditions, which occur annually in the semiarid climate common to the Black Hills area. This unique system is particularly valuable in providing reliable water supplies during prolonged dry conditions, which also are a common occurrence.

Various information regarding headwater and artesian springs has been presented in previous sections of this report, and locations of selected springs were shown in figure 34. Additional information regarding springs is presented within this section of the report, with an emphasis on artesian springs, where complex interactions between the Madison and Minnelusa aquifers can occur.

The largest headwater springs occur within the Spearfish Creek and Rapid Creek Basins (fig. 34), with numerous smaller springs located within other basins. The approximate location of a ground-water divide in the Limestone Plateau area was identified in figure 83. Recharge that occurs east of this divide generally contributes to headwater springs located near the eastern edge of the Limestone Plateau near the base of the Madison Limestone. The Madison aquifer is the primary source of flow to these springs, with additional contributions from the Deadwood aquifer, which has small outcrop areas (fig. 19) but may receive additional recharge from leakage from the overlying Madison aquifer.

West of the ground-water divide, infiltration of precipitation results in ground-water recharge that is assumed to flow to the west, contributing to regional flowpaths in the Madison and Minnelusa aquifers that wrap around the northern or southern flanks of the uplift (fig. 45). Numerous springs also occur in this area (fig. 34), especially in outcrops of the Minnelusa Formation; however, sustained streamflow west of the ground-water divide is uncommon.

The Madison aquifer is the primary source of flow to headwater springs that occur along the eastern edge of the Limestone Plateau. In this area, saturated thicknesses in the Madison aquifer are limited by spring discharge and by relatively rapid ground-water flow to the west.

Although the Limestone Plateau area is a large recharge area for the Madison and Minnelusa aquifers, saturated thicknesses generally are small within these aquifers in this area. Very few wells have been successfully completed in this area, especially within the Madison Limestone, where saturated conditions generally occur only near the bottom of the formation. Saturated thicknesses are limited by the discharge of springs along the eastern edge of the Plateau and by relatively rapid ground-water flow to the west. Fluctuations in ground-water levels in this area generally are smaller than other areas.

Gaged streams in and near the Limestone Plateau area (fig. 34) were previously shown to have generally stable daily (fig. 80) and monthly (fig. 81) flow characteristics, relative to other hydrogeologic settings. Similarly, streamflow does not respond quickly to annual precipitation patterns because of the dominant influence of ground-water discharge, as shown by the comparison between annual streamflow and precipitation (fig. 120) for gaging station 06409000, Castle Creek above Deerfield Reservoir.

Artesian springs occur in many locations around the periphery of the Black Hills (fig. 34). Many artesian springs are located within or near outcrops of the Spearfish Formation, which is the upper confining unit for the underlying aquifers. The Madison and/or Minnelusa aquifers, which have large secondary porosity, probably are the primary source for most of the artesian springs. The Minnekahta aquifer also may contribute flow to some springs.

A summary of hydraulic and chemical information for the major artesian springs in the Black Hills area is presented in table 13. Most of the artesian springs have very stable daily (fig. 80) and monthly (fig. 81) flow characteristics; however, larger variability in annual flow can occur for some springs. The flow of the Fall River originates almost entirely from artesian springflow, including flows from Hot Brook Spring, Evans Plunge Spring, and various other springs. Variability in annual flow of the Fall River is very small, as shown by the hydrograph presented in figure 121. Flow of the Fall River decreased gradually from about 1940-70; however, a definitive explanation for this decrease is not available (Peterlin, 1990). The largest measured flows occurred during the early 1940’s, immediately following the prolonged drought of the 1930’s (fig. 14). Flows have increased recently, in response to the extremely wet conditions that occurred during the 1990’s.

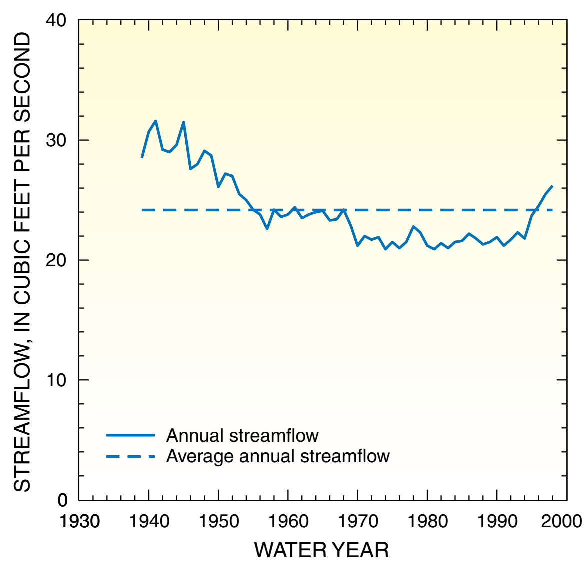

Figure 121. Long-term streamflow trends for gaging station 06402000, Fall River at Hot Springs. The flow of the Fall River originates almost entirely from artesian springflow, including flows from Hot Brook Spring, Evans Plunge Spring, and various other springs.

Along the eastern edge of Limestone Plateau area, the response of streamflow to climatic conditions is dampened by the dominant influence of ground-water discharge. Large reductions in annual flow generally result only from prolonged drought conditions. Conversely, prolonged wet conditions may be necessary to substantially increase annual flows.

Table 13. Selected hydraulic and chemical information for large artesian springs

[Modified from Naus and others (2001). ft^3/s, cubic feet per second; mg/L, milligrams per liter; ≈, approximately equal to; < less than]

Name	Approximate discharge (ft^3/s)	Altitude of land surface (feet above sea level)	Hydraulic head (feet above sea level)		Sulfate (mg/L)	Estimated spring source from previous studies
			Madison aquifer	Minnelusa aquifer		
Higgins Gulch	5-10	3,405	3,490	3,550	110	Mostly Madison[1]
Old Spearfish Hatchery	≈5	3,405	3,500	3,550	340	70 percent Madison, 30 percent Minnelusa[1]
McNenny Rearing Pond	≈1	3,400	3,720	3,580	130	Mostly Madison[1]
Mirror Lake	≈1	3,410	3,720	3,580	1,600	50 percent Madison, 50 percent Minnelusa[1]
Cox Lake	≈5	3,415	3,705	3,580	545	Mostly Madison[1]
Crow Creek	30-50	3,355	3,710	3,560	580	--
Elk Creek	0-20	3,450	3,450	3,450	420	--
City Springs	0-5	3,440	3,450	3,450	98	--
Cleghorn/Jackson Springs	20-25	3,380	3,420	3,380	25	--
Battle Creek	1-10	3,540	3,540	3,540	19	--
Grace Coolidge Creek	0-20	3,650	3,650	3,650	11	--
Beaver Creek Spring	10-15	3,460	3,480	3,480	1,300	Mostly Madison with dissolved Minnelusa minerals[2]
Hot Brook Spring	<5	3,625	3,700	3,625	76	Mostly Madison[2]
Evans Plunge Spring	<5	3,465	3,610	3,420	540	Mostly Madison[2]
Fall River	20-30	3,415	3,580	3,360	400	--
Cool Spring	≈2	3,450	3,505	3,450	830	--
Cascade Springs	18-22	3,440	3,495	3,450	1,500	Mostly Madison with dissolved Minnelusa minerals[3]

[1]Estimated by Klemp (1995).
[2]Estimated by Whalen (1994).
[3]Estimated by Hayes (1999).

Photograph by Timothy S. Hayes

Figure 122. Water-quality measurements were taken during 1992 when a large discharge of red, suspended sediment occurred at Cascade Springs. Similar events during 1906-07 and 1969 were documented by local residents and newspaper accounts. The red sediment probably results from episodic collapses in the Minnelusa Formation when anhydrite beds below land surface are dissolved.

Many large artesian springs have very stable discharges and respond very slowly to changes in long-term climatic conditions (wet and dry cycles). Springs that respond more quickly to short-term recharge conditions generally are located where hydraulic head in the Madison and Minnelusa aquifers is similar to land-surface altitude at the springs.

Annual flow variability is much larger for several springs along the eastern flank of the Black Hills, including City Springs (located in Rapid City) and springs along Elk, Battle, and Grace Coolidge Creeks. For these springs, hydraulic heads in the Madison and Minnelusa aquifers are similar to land-surface altitudes (table 13). The flow of City Springs ceased during the late 1980's and early 1990's, corresponding with decreased water-level altitudes at the nearby City Quarry wells (fig. 67D). Low-flow conditions in the springs along Elk, Battle, and Grace Coolidge Creeks also were recorded during this period due to dry climatic conditions. Flows of these springs increased substantially during the middle to late 1990's due to relatively wet conditions.

Precise determination of contributions to springflow is not possible; however, previous investigators have estimated flow contributions for several artesian springs (table 13), with the Madison aquifer generally identified as the dominant source. Dye testing has confirmed a contribution from the Madison aquifer at City Springs, which discharges through the Minnelusa Formation before emerging at the land surface. For many springs, high concentrations of dissolved sulfate (table 13) indicate substantial influence from dissolution of anhydrite in the Minnelusa Formation; however, this mineralogical influence can result from dissolution of anhydrite by water originating from the Madison aquifer.

Interactions between the Madison and Minnelusa aquifers have been identified as a probable factor in the development of artesian springs (Hayes, 1999; Naus and others, 2001). Higher hydraulic head in the Madison aquifer relative to the Minnelusa aquifer (table 13) creates potential for upward leakage in many artesian spring locations. Water from the Madison aquifer generally has low dissolved sulfate concentrations, which creates potential for further dissolution of anhydrite in the overlying Minnelusa Formation.

Upward leakage of water from the Madison aquifer and associated anhydrite dissolution have been identified as a mechanism leading to the formation of breccia pipes (fig. 25) within the Minnelusa Formation. These breccia pipes have been hypothesized to be throats of abandoned artesian springs in some locations (Hayes, 1999). Artesian springs probably develop preferentially in locations with large secondary porosity and permeability. Development of preferential flowpaths contributes to increased dissolution activity, which further enhances secondary porosity and permeability, in somewhat of a self-perpetuating process.

Upward leakage of water from the Madison aquifer and associated dissolution of anhydrite in the Minnelusa aquifer are instrumental in the formation of breccia pipes within the Minnelusa Formation. These breccia pipes are believed to be throats of abandoned artesian springs in some locations.

Minor leakage between the Madison and Minnelusa aquifers probably occurs at many locations where a hydraulic gradient occurs between the two aquifers. Naus and others (2001) concluded, however, that artesian springflow probably accounts for the largest percentage of leakage that occurs.

The Madison aquifer probably is the dominant source of flow for most artesian springs. For many springs, high concentrations of dissolved sulfate indicate substantial influence from dissolution of anhydrite in the Minnelusa Formation; however, this mineralogical influence can result from dissolution of anhydrite by water originating from the Madison aquifer.

Cascade Springs is a group of artesian springs originating primarily from the Madison aquifer. Water from Cascade Springs normally is quite clear (fig. 41); however, periodic discharges of red, suspended sediment (fig. 122) have occurred. Such reddening events at Cascade Springs were documented in 1906-07, 1969, and 1992. A local newspaper published the following account (reprinted in Twomey and Magee, 1983) of the event that occurred sometime between December 14, 1906, and January 11, 1907:

Cascade Runs Red

"The big geyser at Cascade got stirred up somehow Tuesday night and belched up red gypsum and all sorts of hot looking stuff, turning Cascade Creek to blood red. It continued throwing out red stuff all Wednesday morning, up to the time of this writing, and we believe also is throwing out more water than usual."

The red suspended sediment discharged at Cascade Springs probably results from episodic collapse brecciation in the upper Minnelusa Formation (Hayes, 1999). This collapse brecciation is caused by the subsurface dissolution of anhydrite beds and cements in the Minnelusa Formation.

Several breccia pipes (fig. 25) are located upgradient from Cascade Springs, and were hypothesized by Hayes (1999) to be throats of abandoned spring vents. This observation provides evidence of outward migration of artesian springs over geologic time, in response to declining water levels in the Madison and Minnelusa aquifers. Further supporting evidence is provided by Ford and others (1993), who inferred water-level declines of more than 300 feet in the Madison aquifer during the last 350,000 years using data from Wind Cave. The Mammoth Site at Hot Springs provides an example of an abandoned artesian spring location (fig. 123).

Artesian springs have migrated outward over geologic time in response to declining water levels in the Madison and Minnelusa aquifers. The water level in the Madison aquifer has declined more than 300 feet during the last 350,000 years.

Illustrations and related information courtesy of the Mammoth Site of Hot Spring

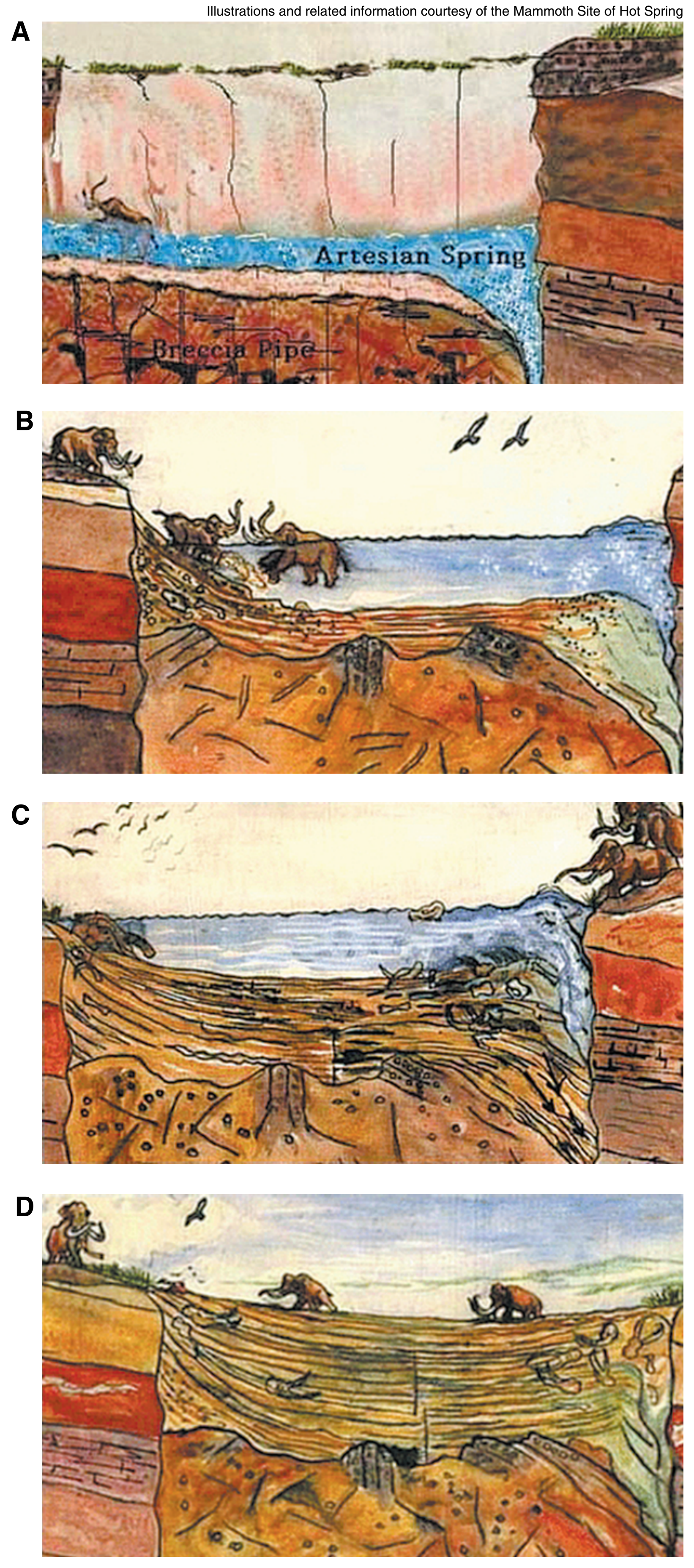

Figure 123. The Mammoth Site of Hot Springs provides an example of an abandoned artesian spring. At this location, a sinkhole formed approximately 26,000 years ago when a cavern in the Minnelusa Formation collapsed. This collapse caused a breccia pipe to form. The overlying Spearfish Formation at land surface also collapsed forming a sinkhole that was approximately 65 feet deep. The breccia pipe provided an opening for a warm artesian spring to percolate up through the rocks to create a steeply sided pond (Illustration A). Enticed by the warm water, mammoths entered the pond to drink and bathe, and then could not escape (Illustration B). Trapped in the sinkhole, the mammoths ultimately died along with other trapped animals. The watering hole was active for about 700 years, and slowly filled with layers of drying silt, sediments, and dying mammoths (Illustration C). Eventually the sinkhole filled, and the artesian spring dried up (Illustration D). The mud, which aided in trapping the mammoths, entombed and preserved the mammoths until their discovery in 1974.

Artesian springs act as a "relief valve" for the Madison and Minnelusa aquifers. Large-scale development of these aquifers could diminish artesian springflow, impacting surface-water resources, before large-scale declines in ground-water levels would occur. Thus, increased development probably has the potential to influence the balance of this dynamic "plumbing system."

Ground-water discharge at artesian springs was referred to as "rejected recharge" by Huntoon (1985), who hypothesized that recharge is rejected as the aquifer's ability to transmit water decreases in a downgradient direction. This is an important concept in understanding the hydraulic behavior of the Madison and Minnelusa aquifer system, and has important water-management implications. In essence, artesian springs act as a "relief valve" for the Madison and Minnelusa aquifers. These aquifers have a "maximum-sustainable equilibrium" water level, which is controlled by the rejected recharge of artesian springs. Large-scale well withdrawals from these aquifers near artesian springs could diminish springflow before large-scale declines in ground-water levels would occur. However, the large recharge potential of the Madison and Minnelusa aquifers probably has the potential to replenish springflow and water levels relatively quickly during episodic periods of prolonged wet (high-recharge) conditions.

The previous concept could provide a tool for future management of ground-water resources, but would require recognition of the potential impact on surface-water resources. Many large springs currently have relatively stable flow, while others, including both small and large springs, have large variability in flow characteristics. Large-scale development of the Madison and Minnelusa aquifers probably has the potential to influence the balance of this dynamic "plumbing system." Potential effects would be most pronounced during prolonged drought periods, which would result in decreased recharge and increased demand.

Additional insights regarding potential effects of large-scale development of the Madison and Minnelusa aquifers can be obtained by reviewing the water budget for these aquifers for the entire Black Hills area (including both South Dakota and Wyoming) that was presented in table 11. For this budget, the dominant outflow component is artesian springflow of 169 cubic feet per second, which is larger than combined well withdrawals (28 cubic feet per second) and net ground-water outflow from the study area (100 cubic feet per second). Although springflow of many artesian springs responds slowly to changes in recharge conditions (both decreases and increases), springflow at other springs responds more quickly. Similar responses to large-scale increases in well withdrawals probably would occur.

Extremely large increases in well withdrawals probably would be required to substantially decrease study area ground-water outflows, which generally are directly proportional to the hydraulic gradient away from the uplift. Large changes in hydraulic head near the uplift would be necessary to substantially change the hydraulic gradient. Thus, large-scale development of the Madison and Minnelusa aquifers probably would result primarily in decreased artesian springflow, with relatively minor decreases in ground-water outflow from the uplift area.

Photograph by Joyce E. Williamson

The Black Hills Hydrology Study has provided an abundance of information regarding the water resources of the Black Hills area. Major findings of the study are summarized in the first section of this report. Although abundant information has been obtained, various questions remain unanswered. Potential needs for additional study are listed in the following section.