Estimation of Streamflow Recharge

Estimated streamflow recharge is presented in table 12, which summarizes recharge for both continuously-gaged and ungaged streams. Values in table 12 have been adjusted, when appropriate, to reflect redistribution of estimated recharge to the Minnelusa outcrop that infiltrates into the Madison hydrogeologic unit. Because most of the loss occurs on the Madison outcrop, total streamflow recharge to the Madison hydrogeologic unit was only increased by about 1 percent due to redistribution, but streamflow recharge to the Minnelusa hydrogeologic unit decreased by about 8 percent.

Total estimated streamflow recharge rates for the Madison hydrogeologic unit for summer periods ranged from about 18 ft^3/s during dry years to almost 80 ft^3/s during wet years (table 12). Total streamflow recharge rates for the Madison hydrogeologic unit for winter periods ranged from about 12 ft^3/s during dry years to about 60 ft^3/s during wet years. Average streamflow recharge to the Minnelusa hydrogeologic unit (about 7 ft^3/s) was only about 14 percent of the combined streamflow recharge to the Madison and Minnelusa aquifers (45 ft^3/s). Increases in recharge rates during wet years largely were due to increases in the duration and quantity of stream base flow that was maintained over longer periods of time.

Continuously Gaged Streams

Calculations of streamflow recharge to the Madison and Minnelusa hydrogeologic units for continuously gaged streams are described in this section. Different loss zones required different approaches depending on loss-zone characteristics and gage location.

Battle Creek

Estimated streamflow recharge from Battle Creek to the Madison hydrogeologic unit averaged about 2.7 ft^3/s (table 12). Streamflow recharge to the Minnelusa hydrogeologic unit was assumed to be zero because the stream gains flow as a result of springflow along the Minnelusa outcrop (Hortness and Driscoll, 1998). Battle Creek exceeded its loss threshold to the Madison hydrogeologic unit 16 percent of the time during WY88-97 and did not flow at the gage upstream from the loss zone 6 percent of the time. Gage site 14 (pl. 3) is located about 2 mi upstream from the loss zone, and the drainage area for that location is about 88 percent of the total basin area contributing to the loss zone. Therefore, the gaged flow was increased proportionately to account for the ungaged flow. This synthetic record was used to compute streamflow recharge.

Spring Creek

Estimated streamflow recharge from Spring Creek to the Madison and Minnelusa hydrogeologic units averaged 9.9 and 0.8 ft^3/s, respectively (table 12). Although Spring Creek is impounded by a dam at Sheridan Lake, streamflow results primarily from uncontrolled overflow and fluctuates similarly to uncontrolled streams in the study area. Spring Creek has the second largest drainage area in the study area (table 11) and accounted for 24 percent of the total streamflow recharge to the Madison and Minnelusa hydrogeologic units during the 10-year period. Spring Creek exceeded its loss threshold of about 25 ft^3/s to the Madison and Minnelusa hydrogeologic units 21 percent of the time and did not flow at the gage above the loss zone 5 percent of time during the 10-year period. The continuous gage above the Spring Creek loss zone (pl. 3, gage site 24) accounts for all of the flow contributing to the loss zone and, therefore, required no adjustments to the measured flow.

Rapid Creek

Estimated streamflow recharge from Rapid Creek to the Madison and Minnelusa hydrogeologic units averaged 8.0 and 2.0 ft^3/s, respectively (table 12). Rapid Creek is regulated by releases from Pactola Reservoir, and releases greater than the loss threshold are generally maintained. Although Rapid Creek has the largest drainage area in the study area, the stream has a relatively small loss threshold of about 10 ft^3/s (Hortness and Driscoll, 1998) for the Madison and Minnelusa hydrogeologic units combined. Despite the small loss threshold, Rapid Creek accounted for about 22 percent of the total streamflow recharge to the Madison and Minnelusa hydrogeologic units because flow was seldom less than the threshold. Hortness and Driscoll (1998) did not estimate separate loss thresholds for the two hydrogeologic units; however, investigations by Hines (1991) indicate that about 80 percent of the total loss threshold can be attributed to the Madison hydrogeologic unit.

Flow from Tittle Springs, located on the Madison outcrop near Rapid Creek (pl. 1), probably originates from Rapid Creek (Hines, 1991). Therefore, this springflow was not included in streamflow-recharge or water-budget calculations.

Table 12. Streamflow recharge rates to the Madison and Minnelusa hydrogeologic units

[Recharge rates in cubic feet per second. Mdsn, Madison; Mnls, Minnelusa; W, winter; S, summer (W-88 = winter 1988)]

Stress period	Continuously gaged streams									
	Battle Creek[1]		Spring Creek		Rapid Creek		Boxelder Creek		Elk Creek[1]	
	Mdsn	Mnls	Mdsn	Mnls	Mdsn	Mnls	Mdsn	Mnls	Mdsn	Mnls
Dry Period										
W-88	0.3	0.0	1.1	0.0	8.0	2.0	4.2	0.0	1.2	0.0
S-88	**.5**	**.0**	**2.5**	**.0**	**8.0**	**2.0**	**5.7**	**.0**	**1.5**	**.0**
W-89	.2	.0	.2	.0	7.9	1.7	2.8	.0	.8	.0
S-89	**.7**	**.0**	**1.8**	**.0**	**8.0**	**2.0**	**5.3**	**.0**	**1.5**	**.0**
W-90	1.1	.0	1.3	.0	8.0	1.9	4.3	.0	1.2	.0
S-90	**4.1**	**.0**	**11.2**	**.9**	**8.0**	**2.0**	**7.7**	**.0**	**2.1**	**.0**
W-91	.8	.0	3.1	.0	8.0	1.8	2.4	.0	.7	.0
S-91	**4.4**	**.0**	**16.8**	**1.9**	**8.0**	**2.0**	**17.1**	**2.7**	**3.8**	**1.0**
W-92	1.5	.0	6.7	.0	8.0	2.0	7.8	.0	1.9	.0
S-92	**2.3**	**.0**	**8.2**	**.0**	**8.0**	**2.0**	**6.9**	**.0**	**2.9**	**.1**
W-93	1.1	.0	4.1	.1	8.0	1.9	5.0	.1	1.3	.1
Average dry	1.5	.0	5.2	.3	8.0	1.9	6.3	.3	1.7	.1
Wet Period										
S-93	**5.7**	**.0**	**19.9**	**2.6**	**8.0**	**2.0**	**25.3**	**5.5**	**4.8**	**2.3**
W-94	3.3	.0	11.1	.2	8.0	2.0	11.2	.5	3.0	.7
S-94	**2.1**	**.0**	**11.0**	**.9**	**8.0**	**2.0**	**19.2**	**3.8**	**4.1**	**1.6**
W-95	2.0	.0	7.1	.1	8.0	2.0	9.7	.1	3.5	.2
S-95	**5.0**	**.0**	**18.0**	**2.1**	**8.0**	**2.0**	**25.5**	**6.7**	**4.6**	**2.0**
W-96	3.1	.0	13.1	.1	8.0	2.0	14.1	.5	4.2	.5
S-96	**5.2**	**.0**	**20.3**	**2.5**	**8.0**	**2.0**	**28.8**	**7.6**	**3.4**	**3.4**
W-97	4.6	.0	18.5	1.5	8.0	2.0	21.5	2.1	3.1	1.9
S-97	**6.0**	**.0**	**21.0**	**3.4**	**8.0**	**2.0**	**32.3**	**12.6**	**3.0**	**3.9**
Average wet	4.1	.0	15.6	1.5	8.0	2.0	20.8	4.4	3.7	1.8
Overall average	2.7	.0	9.9	.8	8.0	2.0	12.8	2.1	2.6	.9

Table 12. Streamflow recharge rates to the Madison and Minnelusa hydrogeologic units—Continued

[Recharge rates in cubic feet per second. Mdsn, Madison; Mnls, Minnelusa; W, winter; S, summer (W-88 = winter 1988)]

Stress period	Ungaged streams										Total of all streams		Total Mdsn Mnls
	Deadman Gulch		Rockerville Gulch		Victoria Gulch		Unnamed tributary		Little Elk Creek				
	Mdsn	Mnls	Mdsn	Mnls	Mdsn	Mnls	Mdsn	Mnls	Mdsn	Mnls	Mdsn	Mnls	
Dry Period													
W-88	0.1	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.4	0.0	15.6	2.0	17.6
S-88	**.0**	**.0**	**.1**	**.0**	**.2**	**.0**	**.1**	**.0**	**.4**	**.2**	**19.0**	**2.2**	**21.2**
W-89	.0	.0	.1	.0	.0	.0	.0	.0	.3	.1	12.3	1.8	14.1
S-89	**.0**	**.0**	**.1**	**.0**	**.1**	**.0**	**.0**	**.0**	**.5**	**.1**	**18.0**	**2.1**	**20.1**
W-90	.0	.0	.1	.0	.1	.0	.0	.0	.4	.1	16.5	2.0	18.5
S-90	**.2**	**.0**	**.4**	**.0**	**.9**	**.0**	**.1**	**.0**	**.6**	**.3**	**35.3**	**3.2**	**38.5**
W-91	.1	.0	.1	.0	.2	.0	.0	.0	.3	.0	15.7	1.8	17.5
S-91	**.6**	**.1**	**1.2**	**.2**	**1.4**	**.0**	**.2**	**.0**	**.9**	**.9**	**54.4**	**8.8**	**63.2**
W-92	.1	.0	.3	.0	.4	.0	.1	.0	.7	.2	27.5	2.2	29.7
S-92	**.1**	**.0**	**.3**	**.0**	**.5**	**.0**	**.1**	**.0**	**.6**	**.1**	**29.9**	**2.2**	**32.1**
W-93	.1	.0	.2	.0	.3	.0	.0	.0	.5	.1	20.6	2.3	22.9
Average dry	.1	.0	.3	.0	.4	.0	.1	.0	.5	.2	24.1	2.8	26.9
Wet Period													
S-93	**.8**	**.0**	**1.7**	**.1**	**1.7**	**.0**	**.4**	**.0**	**1.1**	**1.6**	**69.4**	**14.1**	**83.5**
W-94	.4	.0	.9	.0	.8	.0	.1	.0	.8	.5	39.6	3.9	43.5
S-94	**.2**	**.0**	**.5**	**.0**	**.9**	**.0**	**.3**	**.0**	**.9**	**1.1**	**47.2**	**9.4**	**56.6**
W-95	.2	.0	.4	.0	.5	.0	.1	.0	.8	.3	32.3	2.7	35.0
S-95	**1.1**	**.1**	**2.1**	**.3**	**1.5**	**.0**	**.5**	**.1**	**1.1**	**1.6**	**67.4**	**14.9**	**82.3**
W-96	.5	.0	1.2	.0	.9	.0	.1	.0	.9	.7	46.1	3.8	49.9
S-96	**.8**	**.0**	**1.7**	**.1**	**1.7**	**.0**	**.5**	**.0**	**1.1**	**1.9**	**71.5**	**17.5**	**89.0**
W-97	.7	.0	1.6	.0	1.4	.0	.2	.0	1.0	1.4	60.6	8.9	69.5
S-97	**1.2**	**.1**	**2.5**	**.2**	**1.9**	**.0**	**.7**	**.1**	**1.2**	**2.1**	**77.8**	**24.4**	**102.2**
Average wet	.7	.0	1.4	.1	1.3	.0	.3	.0	1.0	1.2	56.9	11.1	68.0
Overall average	.4	.0	.8	.0	.8	.0	.2	.0	.7	.7	38.8	6.5	45.3

[1]Loss rate at model boundary. Table shows 50 percent of total loss assumed to enter the aquifer analysis area.

Boxelder Creek

Estimated streamflow recharge from Boxelder Creek to the Madison and Minnelusa hydrogeologic units averaged 12.8 and 2.1 ft^3/s, respectively (table 12). Loss threshold estimates for Boxelder Creek were complicated by hydrogeologic features in the outcrop areas. Three springs are located along Boxelder Creek within the Madison outcrop: Gravel Spring, Doty Spring, and Dome Spring (pl. 1). Rahn and Gries (1973) determined from dye testing that these springs are directly connected to upstream losses. Although complicated by variable springflow, estimated thresholds reflect approximate net losses (Hortness and Driscoll, 1998), and therefore, these springflows were not included in streamflow-recharge or water-budget calculations. Hortness and Driscoll (1998) estimated general loss thresholds of greater than 25 ft^3/s for the Madison outcrop, less than 20 ft^3/s for the Minnelusa outcrop, less than 5 ft^3/s for the Minnekahta outcrop, and a combined threshold for the three outcrops of approximately 50 ft^3/s. These estimates, however, did not consider the isolated Madison outcrop near the anticline along Boxelder Creek (pl. 1).

An important effect of the anticline is that it separates the Minnelusa recharge area to the west from Minnelusa aquifer to the east causing much of the recharge on the Minnelusa outcrop to enter the Madison aquifer. A hydrogeologic section through this area illustrates this point, showing that a large area of the Minnelusa hydrogeologic unit is mostly above the water table west of the anticline (fig. 22, section D-D′). Because the Minnelusa hydrogeologic unit in this area is largely in the unsaturated zone, there is little horizontal Darcian flow, and recharge to the Minnelusa outcrop can infiltrate vertically into the underlying Madison aquifer under the force of gravity. Considering these various hydrogeologic conditions, the estimated loss thresholds for the Madison and Minnelusa hydrogeologic units for this report are 30 and 16 ft^3/s, respectively, for a total of 46 ft^3/s (table 11).

Boxelder Creek has the third largest drainage area in the study area but accounted for the largest streamflow recharge to the Madison and Minnelusa hydrogeologic units, about 33 percent during the 10-year period. This relates to the fact that Boxelder Creek is located in the northern part of the study area where precipitation is greater and the loss threshold is the largest for streams in the study area (table 11). Boxelder Creek flowed continually during the 10-year period but exceeded its estimated loss threshold to the Madison and Minnelusa hydrogeologic units only 12 percent of the time. The continuous gage on Boxelder Creek above the loss zone (pl. 3, gage site 34) accounts for about 93 percent of the total basin area contributing to the loss zone. Therefore, the gaged flow was increased proportionately to account for the ungaged flow.

Elk Creek

Estimated streamflow recharge from Elk Creek to the Madison and Minnelusa hydrogeologic units averaged 2.6 and 0.9 ft^3/s, respectively (table 12). Measured flow in Elk Creek just upstream of the Madison outcrop (pl. 3, gage site 39) was used to calculate streamflow recharge. Because data for this site were not collected before September 1991, a synthetic flow record was generated for the missing period by regressing measured streamflow in Elk Creek against flow in Boxelder Creek at gage sites 39 and 34 (pl. 3). Because the Elk Creek loss zone is located at the northern boundary of the aquifer analysis area, only one-half of the streamflow recharge was assumed to flow into the aquifer analysis area.

Elk Creek flowed continually during the 10-year period and exceeded its loss threshold 11 percent of time. This basin generally receives greater precipitation than Boxelder Creek but is smaller in size and has a smaller loss threshold. Elk Creek accounted for about 8 percent of the total streamflow recharge to the Madison and Minnelusa hydrogeologic units.

Four tributaries downstream from gage site 39 contribute to flow in the Elk Creek loss zone (pl. 3). The drainage basins for these tributaries are partially on the Madison outcrop. Because direct precipitation on the outcrop is accounted for in areal recharge, only the areas of the basins outside the outcrop were used to estimate additional streamflow below gage site 39. These basin areas outside the outcrop have a total area of 13.6 mi^2, which is 63.3 percent of the basin above gage site 39; thus, the flow record at the gage (partially synthetic) was increased by 63.3 percent.

Results of streamflow measurements for several reaches of Elk Creek that were compiled by Hortness and Driscoll (1998) are presented in table 13 along with additional measurements made after August 20, 1996. Loss thresholds of 11 ft^3/s for the Madison outcrop and 8 ft^3/s for the Minnelusa outcrop (table 11) were estimated by Hortness and Driscoll (1998) based

Table 13. Elk Creek streamflow-loss rates for the Madison and Minnelusa outcrops

[Modified from Hortness and Driscoll (1998). All values given in cubic feet per second. Site locations are shown on plate 3 and listed in table 11. --, undetermined]

Date	Flow rate at gage site 39	Madison outcrop loss rate between gage sites 39 and 43	Madison outcrop loss rate between gage sites 43 and 44	Total Madison outcrop loss rate	Minnelusa outcrop loss rate (gage sites 44 to 45)
04-24-96	31.9	6.8	3.3	10.1	7.9
05-07-96	26.6	6.5	4.8	11.3	8.1
07-01-96	12.1	7.6	-7.5	.1	6.4
07-12-96	9.9	8.1	-5.4	2.7	5.3
07-22-96	7.4	8.2	-5.1	3.1	4.8
08-20-96	4.7	7.0	-5.2	1.8	4.5
10-03-96	3.8	5.4	-3.0	2.4	--
10-21-99	[1]5.2	--	-6.1	--	4.2

[1]Mean daily value.

on the first two measurement dates (April 24 and May 7, 1996). Subsequent measurements, which were made during particularly wet climatic conditions, indicated that the loss rate on the Minnelusa outcrop decreased only slightly, but the loss rate on the Madison outcrop decreased substantially because of streamflow gains in the reach between gage sites 43 and 44. Measured losses between gage sites 39 and 43 remained relatively stable.

Hortness and Driscoll (1998) attributed the streamflow gain that occurred between sites 43 and 44 to springflow from the Madison aquifer and indicated that local areal recharge during a climatically wet period contributed to springflow. A laccolith, which is exposed on the northern side of the springflow area (Strobel and others, 1999), could cause areal recharge water to be perched on low-permeability igneous intrusive bodies. Water stored in perched areas might seep downgradient and discharge as springflow after periods of greater precipitation. Conversely, part of the springflow could result from reemerging upstream losses because of the larger streamflows during that period. Because streamflow losses and gains both can occur in the same stream reach at the same time, it is not known what effect springflow has on streamflow losses. The complex nature of this transient springflow precludes the determination of the ratio of areal-recharge source water to streamflow-recharge source water. Therefore, it was arbitrarily assumed that one-half of the estimated springflow resulted from areal recharge and one-half resulted from streamflow recharge, and those estimates were adjusted accordingly (also see "Areal Recharge" section). In addition, estimated springflow was added to streamflow that could potentially be lost to the Minnelusa outcrop.

Based on streamflow gains (table 13) springflow was estimated as about 5 ft^3/s for the latter part of the summer-1996 period (S-96), 3 ft^3/s for the winter-1997 period (W-97), and 5 ft^3/s for the summer-1997 period (S-97). Because the earlier part of the 10-year period was climatically dryer, springflow was assumed not to have occurred prior to S-96.

Ungaged Streams

Ungaged streams include Deadman Gulch, Rockerville Gulch, Victoria Creek, the unnamed tributary, and Little Elk Creek (table 11 and pl. 3). These smaller basins accounted for about 8 percent (3.5 ft^3/s) of the total streamflow recharge to the Madison and Minnelusa hydrogeologic units (table 12).

Synthetic flow records were generated for smaller ungaged basins by correlating flow rates in nearby larger gaged basins. An assumption was made that flow rates are directly correlated to the size of the basin. Streamflow in Rapid Creek was not used to generate synthetic flow records because streamflow is regulated by Pactola Dam. Streamflow in Battle Creek was used to create a synthetic flow record for Deadman Gulch and Rockerville Gulch (pl. 3). Streamflow in Spring Creek was used to create a synthetic flow record for Victoria Creek. Streamflow in Boxelder Creek was used to create a synthetic flow record for the unnamed tributary and for Little Elk Creek. Streamflow in Little Elk Creek was estimated based on Boxelder Creek rather than Elk Creek because precipitation for Little Elk Creek is similar to that of Boxelder Creek (table 11 and pl. 3).

Loss thresholds for Victoria Creek and Little Elk Creek were determined by Hortness and Driscoll (1998) but were not determined for Deadman Gulch, Rockerville Gulch, and the unnamed tributary. Thresholds for these streams were assumed to be small compared to those of the larger streams and were estimated as 2 and 4 ft^3/s for the Madison and Minnelusa outcrops, respectively. The Minnelusa outcrop thresholds were assumed to be larger than thresholds for the Madison outcrop because stream reaches crossing the Minnelusa outcrop are longer than those of the Madison outcrop. Although these loss-threshold estimates are very uncertain, error in the estimate has a small effect on total calculated streamflow recharge because these basins account for less than 1 percent of the total area contributing to loss zones in the study area.

Areal Recharge

Areal recharge is recharge resulting from infiltration of precipitation on outcrops. Methods used in estimating areal recharge are discussed in the following section, after which estimates are presented.

Methods

The Madison and Minnelusa outcrop areas were each divided into five areal recharge zones, bounded by major streams that cross the outcrops. These zones include Battle Creek to Spring Creek (zone 1), Spring Creek to Rapid Creek (zone 2), Rapid Creek to Boxelder Creek (zone 3), Boxelder Creek to Little Elk Creek (zone 4), and Little Elk Creek to Elk Creek (zone 5) (table 14 and pl. 3). Average annual precipitation for each zone (table 14) shows that the northern outcrop areas receive a greater amount of precipitation than do the southern areas.

Evapotranspiration (ET) on the Precambrian core of the Black Hills could be estimated with greater confidence than in other areas of the Black Hills. This relates to an assumption that precipitation on the Precambrian core that does not evapotranspire infiltrates and reemerges as streamflow and can, therefore, be measured for a given basin. Therefore, streamflow yield on the Precambrian core was used as a surrogate to indirectly estimate recharge on the Madison and Minnelusa outcrops. Because of the high permeability of the Madison and Minnelusa outcrops, runoff from the outcrops is considered negligible (Carter, Driscoll, and Hamade, 2001) and therefore, recharge is assumed to be the difference between ET and precipitation. This method also assumes that ET on the Madison and Minnelusa outcrops is similar to that of the Precambrian core.

ET on the Precambrian core was estimated by correlating precipitation on drainage basins in the study area with basin yield. The estimated ET was then extrapolated to the Madison and Minnelusa outcrops areas. Because of the general decreased porosity with depth in these rocks (Rahn, 1985, p. 161), ground water probably does not infiltrate deeper than about 500 ft; however, a small amount of ground water probably moves from the Precambrian core into the Madison hydrogeologic unit via upward seepage through the Deadwood aquifer. Therefore, the ultimate destination of precipitation falling on drainage basins in the Precambrian core can be divided into three categories: (1) evapotranspiration, (2) flow into streams either as shallow ground-water interflow or direct runoff, or (3) ground-water outflow into overlying Paleozoic rocks near the periphery of the Precambrian core. Therefore, the fraction of precipitation that is evapotranspired can be estimated from equation 5.

$$\left(\frac{ET}{P}\right)_{PC} = 1 - \left(\frac{Y + GW_O}{P}\right)_{PC} \qquad (5)$$

where the subscript PC represents the Precambrian core and,

ET = evapotranspiration;

P = precipitation on basin;

Y = streamflow yield from basin in Precambrian core; and

GW_O = ground-water outflow from Precambrian core.

Table 14. Areal recharge zones and average annual precipitation on Madison and Minnelusa outcrops

[NA, not applicable]

Zone	Area covered	Area (square miles)		Average annual precipitation[1] (inches)	
		Madison	Minnelusa	Madison	Minnelusa
1	Battle Creek to Spring Creek	6.6	15.1	19.9	19.4
2	Spring Creek to Rapid Creek	4.6	7.1	19.1	18.6
3	Rapid Creek to Boxelder Creek	9.8	12.5	19.6	18.9
4	Boxelder Creek to Little Elk Creek	27.3	15.2	20.0	19.2
5	Little Elk Creek to Elk Creek	10.1	3.6	24.0	22.3
Total		58.4	53.5	NA	NA

[1]Calculated from precipitation data for WY61-98 (Driscoll, Hamade, and Kenner, 2000).

Because runoff is assumed to be zero on the Madison and Minnelusa outcrops, precipitation is equal to the sum of areal recharge and ET:

$$\left(\frac{R + ET}{P}\right)_{MM} = 1 \qquad (6)$$

where the subscript MM represents the Madison and Minnelusa outcrops and R = areal recharge.

Based on assumptions described previously:

$$\left(\frac{ET}{P}\right)_{MM} = \left(\frac{ET}{P}\right)_{PC}. \qquad (7)$$

Therefore, equations 5, 6 and 7 can be combined as:

$$\left(\frac{R}{P}\right)_{MM} = \left(\frac{Y + GW_O}{P}\right)_{PC} \qquad (8)$$

where the quantity, $Y + GW_O$, is the "total yield" from a drainage basin.

Four surface-water basins in the Precambrian core were analyzed to determine the terms on the right hand side of equation 8. These basins include Battle, Spring, Boxelder, and Elk Creeks measured above the Madison outcrop (table 11 and pl. 3). Although these basins mainly are composed of Precambrian rocks, small outcrop areas of Madison Limestone and Deadwood Formation exist near the western and eastern boundaries of some of the basins.

Monthly precipitation data (Driscoll, Hamade, and Kenner, 2000) were used to interpolate digital grids describing the distribution of precipitation for the drainage basins. These grids were used to compile average precipitation for each 6-month period for each of the drainage basins. Daily streamflow data for all four basins was separated into summer and winter seasons and averaged into 6-month time intervals (October 1 to March 31 and April 1 to September 30). Ground-water outflow from the Precambrian core (GW_O, eq. 5), which was estimated to be 6.3 ft^3/s (see "Seepage from Deadwood Aquifer" section), was proportioned according to basin area among all of the basins in the Precambrian core in the study area. The proportioned amount was then added to measured streamflow to compute total yield and divided by average precipitation for each of the four basins (eq. 6). Total yield versus precipitation was plotted, and separate curves were fitted through data for the winter and summer periods (fig. 29) using a least-squares method for nonlinear regression. The nonlinear regression produced a better fit (higher R^2 value) than linear regression, especially for the summer period. This relates to the fact that during intense precipitation events, ET consumes a smaller percentage of precipitation than for smaller precipitation events.

These fitted curves were used for estimating areal recharge to the Madison and Minnelusa outcrops for 6-month periods. Based on equation 8, areal recharge on the Madison and Minnelusa outcrops as a

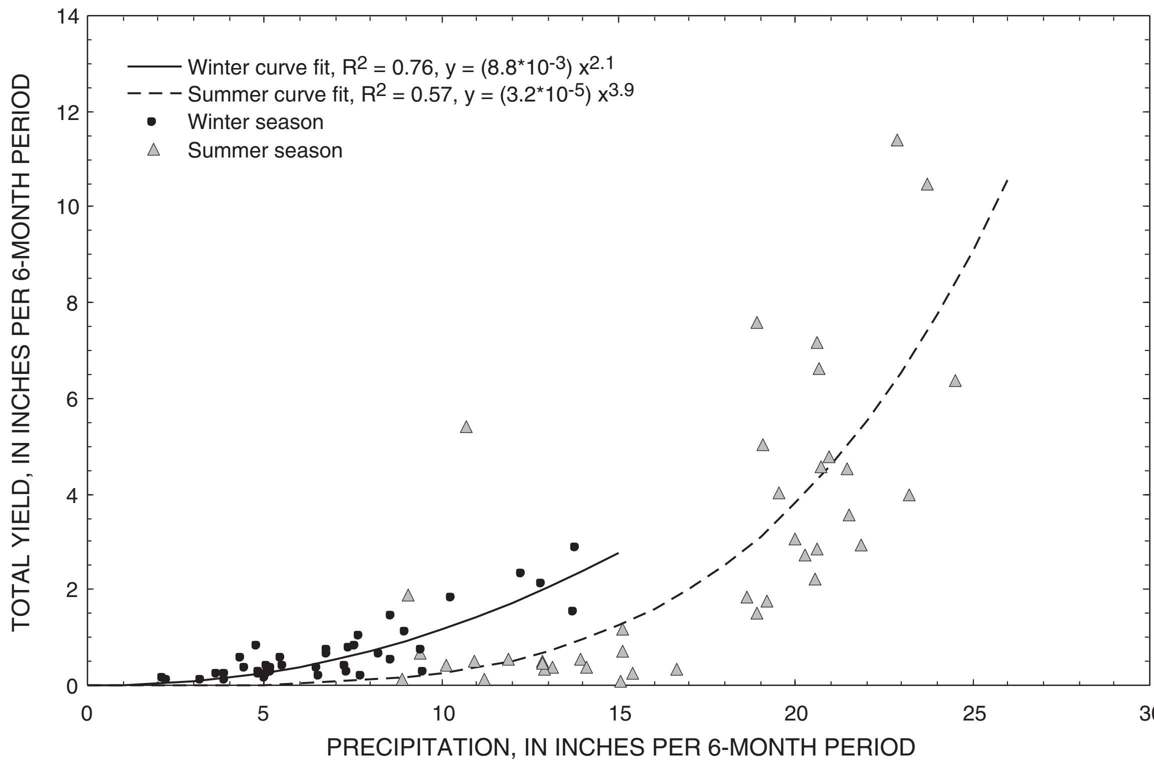

Figure 29. Correlation of total yield to precipitation on basins in Precambrian core.

function of precipitation was equated to total yield from basins in the Precambrian core. Precipitation for each areal recharge zone was calculated using the same method as for the Precambrian core and used to estimate areal recharge from the curves in figure 29. The winter curve shows that the colder months allow greater recharge for the same precipitation rate than the summer period. The summer curve shows substantially increasing total yield for precipitation exceeding 18 inches per 6-month period. The curves are not valid for precipitation exceeding the range of data shown in figure 29.

Areal recharge for the summer periods ranged from less than 1 inch to more than 5 inches per 6-month period with an average summer recharge of 2.3 inches (fig. 30). Areal recharge in the winter periods was less than 1 inch. The average areal recharge was 13 percent of precipitation. Areal recharge ranged from about 2 percent of precipitation in the summer of 1988 to about 26 percent in summer 1995 (fig. 31).

In the study area, the Minnelusa hydrogeologic unit contains “unsaturated areas,” as previously defined (see “Concepts of the Ground-Water Flow System” section), across about 73 percent of the outcrop (pl. 2). Some of the precipitation infiltrating the unsaturated area of the Minnelusa outcrop probably infiltrates the underlying Madison aquifer. The same assumptions for the redistribution of streamflow recharge also were applied to areal recharge (table 15).

Estimation of Areal Recharge

Estimated areal recharge rates for each of the five areal recharge zones for the Madison and Minnelusa hydrogeologic units are shown in table 16. About 64 percent of areal recharge occurred north of Boxelder Creek (zones 4 and 5) because of larger outcrop areas and greater precipitation amounts than the zones to the south. Average total areal recharge was about 49 percent of streamflow recharge (table 7) for the study area. Total areal recharge rates in the summer ranged from less than 3 ft^3/s during dry years to almost 100 ft^3/s during wet years. Areal recharge rates in the winter ranged from about 1 ft^3/s during dry years to about 12 ft^3/s during wet years. During the extremely wet summer-1995 period (S-95), areal recharge exceeded that of streamflow recharge (tables 12 and 16).

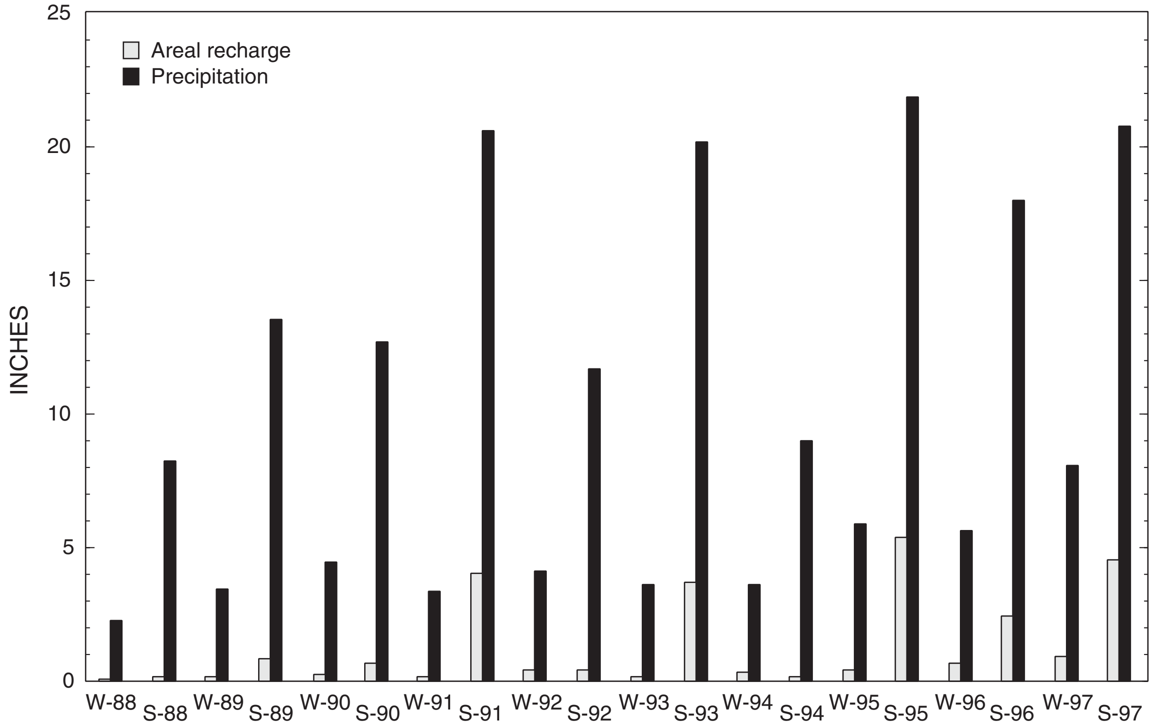

Figure 30. Spatially averaged precipitation and estimated areal recharge per 6-month period for the Madison and Minnelusa outcrops.

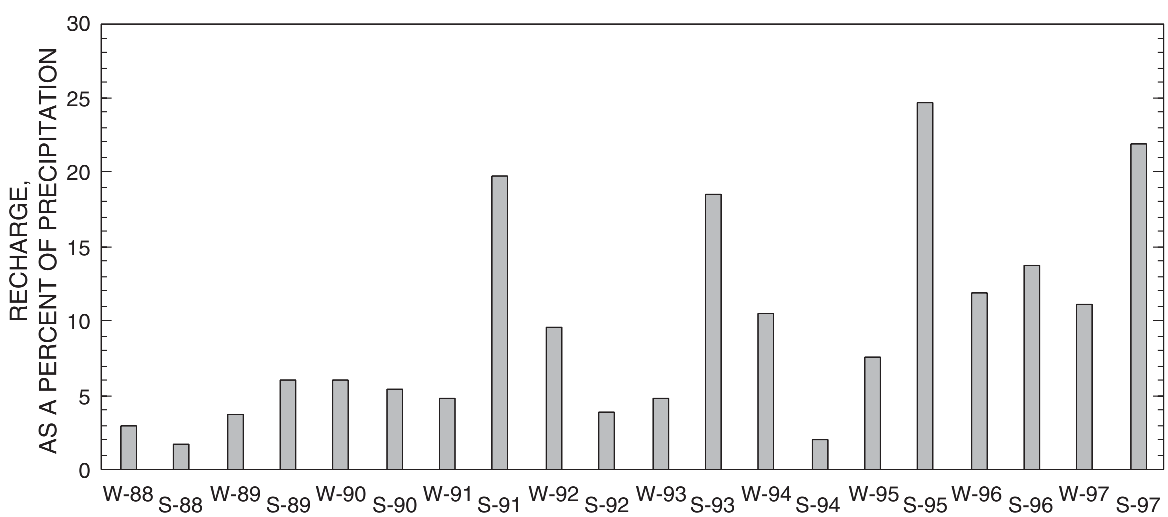

Figure 31. Spatially averaged areal recharge as a percentage of precipitation on the Madison and Minnelusa outcrops for winter (W) and summer (S).

Table 15. Redistribution of average areal recharge from the unsaturated area of the Minnelusa outcrop to the Madison aquifer in inches per 6-month period, WY88-97

Zone[1]	Recharge to Madison outcrop	Recharge to Minnelusa outcrop	Percentage of Minnelusa outcrop area unsaturated	Percentage of infiltration on Minnelusa outcrop redistributed	Adjusted Madison recharge	Adjusted Minnelusa recharge
	a	b	c	d	e	f
				d = c/2	e = a+b*d/100	f = b-b*d/100
1	1.2	0.9	59.4	29.7	1.5	0.7
2	1.0	.8	84.5	42.2	1.4	.5
3	1.4	1.1	70.0	35.0	1.8	.7
4	1.4	1.6	68.7	34.3	1.9	1.0
5	1.9	1.7	70.1	35.0	2.4	1.1

[1]Zones are described in table 14.

Table 16. Areal recharge rates to the Madison and Minnelusa hydrogeologic units by zones

[Recharge rates in cubic feet per second (ft^3/s); W, winter; S, summer (W-88 = winter 1988); Mdsn, Madison, Mnls, Minnelusa]

Stress period	Madison recharge by zone[1]					Minnelusa recharge by zone[1]					Total		Total Mdsn Mnls
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Mdsn	Mnls	
Dry Period													
W-88	0.0	0.0	0.1	0.3	0.5	0.0	0.0	0.0	0.1	0.1	0.9	0.2	1.1
S-88	**.2**	**.1**	**.1**	**.6**	**.9**	**.2**	**.0**	**.1**	**.1**	**.1**	**1.9**	**.5**	**2.4**
W-89	.1	.1	.3	.6	.5	.1	.0	.2	.2	.1	1.6	.6	2.2
S-89	**.9**	**1.6**	**2.0**	**3.1**	**2.4**	**1.0**	**.8**	**1.0**	**.9**	**.3**	**10.0**	**4.0**	**14.0**
W-90	.2	.1	.3	1.1	1.5	.2	.1	.2	.3	.2	3.2	1.0	4.2
S-90	**2.3**	**.8**	**1.2**	**2.2**	**.9**	**2.2**	**.5**	**.6**	**.7**	**.1**	**7.4**	**4.1**	**11.5**
W-91	.1	.1	.2	.6	.8	.1	.0	.1	.2	.1	1.8	.5	2.3
S-91	**4.5**	**5.5**	**11.0**	**24.0**	**7.5**	**4.3**	**2.6**	**4.9**	**6.4**	**1.3**	**52.5**	**19.5**	**72.0**
W-92	.3	.1	.3	.8	.9	.3	.1	.1	.2	.1	2.4	.8	3.2
S-92	**.5**	**.4**	**.9**	**3.1**	**1.0**	**.6**	**.2**	**.4**	**.9**	**.2**	**5.9**	**2.3**	**8.2**
W-93	.1	.1	.2	.7	1.1	.1	.0	.1	.2	.1	2.2	.5	2.7
Average dry	.8	.8	1.5	3.4	1.6	.8	.4	.7	.9	.2	8.2	3.1	11.3
Wet Period													
S-93	**6.2**	**4.0**	**6.2**	**19.6**	**10.0**	**7.1**	**2.3**	**3.5**	**5.3**	**1.7**	**46.0**	**19.9**	**65.9**
W-94	.1	.0	.2	.8	1.8	.0	.0	.1	.2	.2	2.9	.5	3.4
S-94	**.4**	**.1**	**.3**	**.8**	**.4**	**.4**	**.1**	**.1**	**.3**	**.1**	**2.0**	**1.0**	**3.0**
W-95	.3	.1	.6	2.4	3.1	.2	.0	.3	.6	.4	6.5	1.5	8.0
S-95	**5.5**	**2.1**	**10.9**	**35.8**	**18.4**	**5.5**	**1.1**	**4.6**	**11.6**	**2.9**	**72.7**	**25.7**	**98.4**
W-96	.2	.1	.5	2.2	2.8	.2	.1	.2	.5	.3	5.8	1.3	7.1
S-96	**3.0**	**1.5**	**4.3**	**17.8**	**4.5**	**3.0**	**.9**	**2.1**	**4.4**	**1.1**	**31.1**	**11.5**	**42.6**
W-97	.5	.4	1.3	4.8	2.6	.5	.2	.7	1.2	.6	9.6	3.2	12.8
S-97	**3.1**	**1.8**	**10.6**	**35.0**	**5.8**	**3.3**	**1.1**	**5.9**	**11.6**	**1.4**	**56.3**	**23.3**	**79.6**
Average wet	2.1	1.1	3.9	13.2	5.5	2.2	.6	1.9	4.0	1.0	25.9	9.8	35.7
Overall average	1.4	1.0	2.6	7.8	3.4	1.5	.5	1.3	2.3	.6	16.1	6.1	22.2

[1]See table 14 for description of zones.

Springflow

Springs in the aquifer analysis area that are included in water-budget calculations are Jackson-Cleghorn Springs, City Springs, Deadwood Avenue Springs, and springs along Boxelder and Elk Creeks (pl. 3). Geochemical analysis indicates that the largest spring complex in the aquifer analysis area, Jackson-Cleghorn, flows from the Madison aquifer (Back and others, 1983; Anderson and others, 1999). All of these springs are located in areas where hydraulic head in the Madison aquifer is generally higher than in the Minnelusa aquifer. Because of the upward hydraulic gradient, and for simplicity, it is assumed that the source of all springs considered is the Madison aquifer.

Flow from some springs can be relatively steady, whereas flow from others may fluctuate considerably. Topographic altitude, hydraulic head variation, and hydraulic properties of the overlying material may affect springflow rates. Flows from Tittle Springs, Gravel Spring, Doty Spring, and Dome Spring occur within the Madison streamflow-loss zones (pl. 1). Because estimated streamflow-loss thresholds represent approximate net loss (Hortness and Driscoll, 1998), flow from these springs was accounted for in streamflow loss estimates and, therefore, was omitted from water-budget calculations. A summary of springflow estimates and details on individual springs follow.

Estimation of Springflow

Springs included in the water budget area are listed in table 17. A total of about 31 ft^3/s is the estimated average flow from these springs for WY88-97. Total springflow averaged 25.3 ft^3/s for the dry period and 37.4 ft^3/s for the wet period.

Table 17. Summary of estimated springflow

[Discharge rates in cubic feet per second; W, winter; S, summer (W-88 = winter 1988)]

Stress period	Jackson-Cleghorn Springs	City Springs	Deadwood Avenue Springs	Boxelder Springs	Elk Springs	Total
			Dry Period			
W-88	21.6	1.9	2.8	0.0	0.3	26.6
S-88	21.6	**1.0**	2.8	.0	.3	**25.7**
W-89	21.6	1.0	2.8	.0	.0	25.4
S-89	21.6	**.7**	2.8	.0	.0	**25.1**
W-90	21.6	.8	2.8	.0	.0	25.2
S-90	21.6	**.8**	2.8	.0	.0	**25.2**
W-91	21.6	.3	2.8	.0	.1	24.8
S-91	21.6	**1.3**	2.8	.0	.1	**25.8**
W-92	21.6	.6	2.8	.0	.0	25.0
S-92	21.6	**.4**	2.8	.0	.0	**24.8**
W-93	21.6	.3	2.8	.2	.1	25.0
Average dry	21.6	.8	2.8	.0	.1	25.3
			Wet Period			
S-93	21.6	**2.1**	2.8	.2	.1	**26.8**
W-94	21.6	1.5	2.8	.0	.4	26.3
S-94	21.6	**1.4**	2.8	.0	.4	**26.2**
W-95	21.6	1.3	2.8	.5	8.6	34.8
S-95	21.6	**3.3**	2.8	.5	8.6	**36.8**
W-96	21.6	2.8	2.8	2.5	8.2	37.9
S-96	21.6	**4.0**	2.8	2.5	8.2	**39.1**
W-97	21.6	3.5	2.8	6.8	18.9	53.6
S-97	21.6	**4.9**	2.8	6.8	18.9	**55.0**
Average wet	21.6	2.8	2.8	2.2	8.0	37.4
Overall average	21.6	1.7	2.8	1.0	3.7	30.8

Jackson-Cleghorn Springs

Anderson and others (1999) estimated springflow from Jackson-Cleghorn Springs to be about 21.6 ft^3/s during WY88-89 using a control-volume analysis. This spring complex probably is a regional discharge point with a relatively stable flow (see "Hydraulic Response to Recharge" and "Flowpaths" sections). Therefore, in the absence of further data, the springflow was estimated to be constant at 21.6 ft^3/s for the 10-year period.

City Springs

Flow from City Springs and some unnamed springs about 0.3 mi to the east were estimated from the streamflow record at gage site 90 (table 11 and pl. 3), which is located about 2 mi downstream on a tributary of Rapid Creek. Base flow at this site was assumed to be equal to springflow and was estimated by using a hydrograph separation program called HYSEP (Sloto and Crouse, 1996). Estimated springflow for 6-month periods varied from 0.3 to 4.9 ft^3/s with an average of 1.7 ft^3/s.

Deadwood Avenue Springs

Flow from Deadwood Avenue Spring no. 1 was estimated from the streamflow record for gage site 91 (pl. 3 and table 11), which is located about 1 mi downstream on a tributary of Rapid Creek. Gage site 91 was measured continuously during WY88-90. Base flow at this site was assumed to be equal to flow from spring no. 1 and was estimated by using the hydrograph separation program HYSEP (Sloto and Crouse, 1996). The estimated base flow was relatively steady with a mean of 2.4 ft^3/s, a maximum and minimum daily rate of 1.8 and 3.3 ft^3/s, respectively, and standard deviation of 0.3. Because flow records were available only for a 3-year period, the mean value of 2.4 ft^3/s was used in water-budget calculations for the entire 10-year period for spring no. 1.

On October 18, 2000, Deadwood Avenue Springs nos. 1 and 2 were measured at 2.22 and 0.43 ft^3/s, respectively, at the locations where flow enters Rapid Creek. The fall of 2000 was very dry, and all flow in these streams was assumed to have originated from the springs. Because flow from spring no. 1 on this date was nearly equal to the estimated average, it was assumed that the measured flow from spring no. 2 was also equal to the average rate for that spring. Therefore, total flow for the two springs was estimated to be constant at 2.8 ft^3/s.

Boxelder Springs and Elk Springs

Springs along Boxelder Creek 2 mi west of I-90 and Elk Creek near I-90 (pl. 3) generally flow only when hydraulic head in the Madison aquifer is estimated to be above the land surface. Annual flow from these springs was estimated for WY87-97 by Carter, Driscoll, Hamade, and Jarrell (2001). These annual springflow estimates were included as 6-month time steps for this report by assuming flow remained constant during winter and summer for each year. Springflow was negligible during the early part of the analysis period until 1995 when flow increased rapidly due to rising water levels. The combined estimated flow from these springs during WY97 was about 26 ft^3/s.

Water Use

Locations of public supply, irrigation, and industrial wells are shown on plate 3. The city of Rapid City maintained water-use records that were used to compile data for water-budget calculations. Water use from public-supply wells outside of Rapid City was estimated by extrapolating per capita water use in Rapid City to populations served by other public water supplies. Irrigation and industrial water use was estimated based on water-permit information including pump capacities and acreage. A summary of water-use estimates follows, which is followed by separate descriptions of water use from Rapid City wells, other public-supply wells, irrigation, and industrial sources.

Estimation of Water Use

Rapid City withdrew an average of 3.8 ft^3/s (2,500,000 gal/d) from the Madison aquifer and 1.0 ft^3/s (680,000 gal/d) from the Minnelusa aquifer during WY88-97 (table 18), which was about 48 percent of all water use from the Madison and Minnelusa aquifers in the aquifer analysis area. In the 1980's, the city of Rapid City obtained much of its water from the Minnelusa aquifer. Madison aquifer production surpassed the Minnelusa aquifer production after 1991 as new city wells were completed. Other public-supply wells and domestic wells accounted for about 36 percent of all Madison and Minnelusa aquifer water use during WY88-97, while irrigation and industrial wells accounted for about 16 percent.

Water use from the Madison and Minnelusa aquifers accounts for about 14 percent of the total water budget for WY88-97 (table 7). Total withdrawal rates from the Madison aquifer averaged 6.7 ft^3/s and ranged from about 2 to 15 ft^3/s. Total withdrawal rates from the Minnelusa aquifer averaged 3.4 ft^3/s and ranged from about 2 to 5 ft^3/s (table 18).

Rapid City Wells

Rapid City's production wells (pl. 3) are completed primarily in the Madison aquifer (table 4). In response to drought conditions in the late 1980's, the city initiated a drilling program in the Madison aquifer to reduce dependence on surface water and infiltration galleries along Rapid Creek (Anderson and others,

Table 18. Water use from Madison and Minnelusa aquifers

[Rates in cubic feet per second; W, winter; S, summer (W-88 = winter 1988)]

Stress period	Madison aquifer				Minnelusa aquifer				Total Madison Minnelusa
	Rapid City	Other public and domestic water supplies	Industrial and irrigation	Total	Rapid City	Other public and domestic water supplies	Industrial and irrigation	Total	
Dry Period									
W-88	0.0	1.3	0.6	1.9	1.5	1.2	0.2	2.9	4.8
S-88	**.0**	**3.4**	**1.3**	**4.7**	**1.4**	**3.1**	**1.2**	**5.7**	**10.4**
W-89	.0	1.1	.6	1.7	.5	1.0	.2	1.7	3.4
S-89	**.1**	**2.0**	**1.3**	**3.4**	**.7**	**1.8**	**1.2**	**3.7**	**7.1**
W-90	.0	1.2	.6	1.8	1.6	1.1	.2	2.9	4.7
S-90	**.9**	**2.0**	**1.3**	**4.2**	**1.9**	**1.8**	**1.2**	**4.9**	**9.1**
W-91	1.0	1.4	.6	3.0	1.8	1.3	.2	3.3	6.3
S-91	**3.3**	**2.2**	**1.7**	**7.2**	**1.6**	**2.0**	**1.0**	**4.6**	**11.8**
W-92	3.6	1.2	.6	5.4	1.3	1.1	.2	2.6	8.0
S-92	**9.1**	**2.1**	**1.3**	**12.5**	**1.2**	**1.9**	**1.2**	**4.3**	**16.8**
W-93	1.7	1.4	.6	3.7	1.1	1.3	.2	2.6	6.3
Average dry	1.8	1.8	1.0	4.5	1.3	1.6	.6	3.6	8.1
Wet Period									
S-93	**10.6**	**1.9**	**1.1**	**13.6**	**1.1**	**1.8**	**1.1**	**4.0**	**17.6**
W-94	4.2	1.4	.6	6.2	.6	1.3	.2	2.1	8.3
S-94	**10.9**	**2.8**	**1.3**	**15.0**	**.3**	**2.6**	**1.2**	**4.1**	**19.1**
W-95	3.7	1.4	.7	5.8	.8	1.3	.2	2.3	8.1
S-95	**7.5**	**2.3**	**1.2**	**11.0**	**.6**	**2.1**	**1.0**	**3.7**	**14.7**
W-96	.9	1.6	.7	3.2	.5	1.4	.2	2.1	5.3
S-96	**7.6**	**2.6**	**1.2**	**11.4**	**.6**	**2.4**	**1.0**	**4.0**	**15.4**
W-97	3.2	1.6	.7	5.5	.8	1.5	.2	2.5	8.0
S-97	**8.4**	**2.3**	**1.2**	**11.9**	**.9**	**2.2**	**1.0**	**4.1**	**16.0**
Average wet	6.3	2.0	1.0	9.3	.7	1.8	.7	3.2	12.5
Overall average	3.8	1.9	1.0	6.7	1.0	1.7	.7	3.4	10.1

1999). Estimated water use for all Rapid City ground-water and surface-water sources is shown in table 19 and averaged about 20 ft^3/s during summer periods and 12 ft^3/s during winter periods. Average production from the Madison and Minnelusa aquifers is shown in table 20 and sometimes accounted for more than one-half of the total water use, with withdrawals from the Madison aquifer exceeding 10 ft^3/s during S-93 and S-94. The average withdrawal after 1991, when most of the Madison wells were completed, was about 7 ft^3/s. Table 19 shows total Rapid City water use as a fraction of the average for WY97 so that water use could be calculated for other public-supply wells based on Rapid City population equivalents in 1997.

Other Public-Supply Wells

The Madison and Minnelusa aquifers are used extensively as public water supplies outside of Rapid City. Most of these wells are located within a band about 2 to 3 mi wide, on or adjacent to the Minnelusa outcrop (pl. 3). These public water supplies predominately serve small suburban developments and commercial establishments (tables 21 and 22).

To estimate the water use from public water supplies outside of Rapid City, per capita water use was assumed to be similar to that of Rapid City. Average withdrawal from each public-supply well was estimated based on the population served by that well and the per capita water use within Rapid City. This assumption would, however, overestimate water use from public supplies outside of Rapid City because per capita commercial water use inside of Rapid City is greater than that outside. However, this overestimation of water use from public water supplies was assumed to be offset by water use from private domestic wells outside of Rapid City, which was neglected.

The estimated per capita water use for Rapid City during the winter-1997 period (W-97) was 123 gal/d and the summer-1997 period (S-97) was 177 gal/d. These were calculated by dividing water use for Rapid City in WY97 (table 19) by the population equivalent of 73,000 in 1997 (South Dakota Department of Environment and Natural Resources, written commun., 1999). Water use for each public water supply for WY97 was based on Rapid City population equivalents. Water use for each 6-month period was determined by multiplying by the water-use fraction of WY97 (table 19). Average water use for each public supply well for the 10-year period is shown in tables 21 and 22. The average withdrawal rate from the Madison aquifer totaled about 1.9 ft^3/s and ranged from 0.01 to 0.47 ft^3/s for individual water supplies. The average withdrawal rate from the Minnelusa aquifer totaled about 1.7 ft^3/s and ranged from 0.01 to 0.20 ft^3/s for individual water supplies.

Table 19. Total Rapid City water use as an average per stress period

[Includes all surface- and ground-water sources. Mgal/d, million gallons per day; ft^3/s, cubic feet per second; W, winter; S, summer (W-88 = winter 1988)]

Stress period	Total water use (Mgal/d)[1]	Total water use (ft^3/s)	Water use as fraction of average WY97 water use for each season
		Dry Period	
W-88	6.94	10.74	0.77
S-88	**18.79**	**29.07**	**1.46**
W-89	6.03	9.33	.67
S-89	**10.99**	**17.01**	**.85**
W-90	6.67	10.32	.74
S-90	**10.9**	**16.87**	**.85**
W-91	7.59	11.74	.84
S-91	**11.91**	**18.43**	**.92**
W-92	6.8	10.52	.76
S-92	**11.57**	**17.90**	**.90**
W-93	7.79	12.05	.87
		Wet Period	
S-93	**10.58**	**16.37**	**.82**
W-94	7.90	12.22	.88
S-94	**15.55**	**24.06**	**1.21**
W-95	7.81	12.08	.87
S-95	**12.81**	**19.82**	**.99**
W-96	8.46	13.09	.94
S-96	**14.19**	**21.96**	**1.10**
W-97	8.99	13.91	1.00
S-97	**12.89**	**19.95**	**1.00**

[1]Rapid City Water Department, written commun, 1999.

Table 20. Rapid City production well withdrawals

[Rate in cubic feet per second; Mdsn, Madison aquifer; Mnls, Minnelusa aquifer; W, winter; S, summer (W-88 = winter 1988). Source is Rapid City Water Department, written commun., 1999]

Stress period	Well name and the aquifer the well is completed in										Total	
	RC-1[1] Mdsn	RC-1[1] Mnls	RC-3[2] Mnls	RC-4 Mnls	RC-5 Mdsn	RC-6[3] Mdsn	RC-8 Mdsn	RC-9 Mdsn	RC-10 Mdsn	RC-11 Mdsn	Mdsn	Mnls
						Dry Period						
W-88	0.00	0.00	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.53
S-88	**.00**	**.00**	**.52**	**.90**	**.00**	**.00**	**.00**	**.00**	**.00**	**.00**	**.00**	**1.42**
W-89	.00	.00	.52	.01	.00	.00	.00	.00	.00	.00	.00	.53
S-89	**.07**	**.07**	**.48**	**.18**	**.00**	**.00**	**.00**	**.00**	**.00**	**.00**	**.07**	**.73**
W-90	.00	.00	.60	1.03	.00	.00	.00	.00	.00	.00	.00	1.63
S-90	**.21**	**.21**	**.69**	**.97**	**.71**	**.00**	**.00**	**.00**	**.00**	**.00**	**.92**	**1.87**
W-91	.10	.10	.74	.96	.34	.52	.00	.00	.00	.00	.96	1.80
S-91	**.32**	**.32**	**.30**	**.96**	**2.18**	**.48**	**.36**	**.00**	**.00**	**.00**	**3.34**	**1.58**
W-92	.31	.31	.00	1.00	3.12	.00	.14	.00	1.35	.00	4.92	1.31
S-92	**.31**	**.31**	**.00**	**.87**	**2.06**	**.64**	**.76**	**3.86**	**.26**	**.16**	**8.05**	**1.18**
W-93	.31	.31	.00	.80	.00	.06	.18	.85	1.99	.05	3.44	1.11
						Wet Period						
S-93	**.33**	**.33**	**.00**	**.79**	**.75**	**.81**	**1.21**	**5.22**	**1.62**	**.32**	**10.26**	**1.12**
W-94	.32	.32	.00	.32	.18	.65	.71	.48	2.53	.19	5.06	.64
S-94	**.31**	**.31**	**.00**	**.02**	**1.05**	**1.01**	**1.18**	**4.19**	**2.03**	**.65**	**10.42**	**.33**
W-95	.08	.08	.00	.73	.56	.16	.10	.53	2.14	.24	3.81	.81
S-95	**.00**	**.00**	**.00**	**.63**	**1.17**	**.59**	**1.11**	**2.07**	**.62**	**.39**	**5.95**	**.63**
W-96	.00	.00	.00	.48	.09	.00	.00	.19	1.86	.00	2.14	.48
S-96	**.00**	**.00**	**.00**	**.64**	**.94**	**.87**	**1.02**	**2.39**	**1.82**	**.51**	**7.55**	**.64**
W-97	.00	.00	.00	.83	.38	.16	.04	.72	2.07	.06	3.43	.83
S-97	**.00**	**.00**	**.00**	**.87**	**1.76**	**.47**	**.98**	**2.65**	**.00**	**.46**	**6.32**	**.87**
Average	**.13**	**.13**	**.22**	**.70**	**.77**	**.32**	**.39**	**1.16**	**.91**	**.15**	**3.83**	**1.05**

[1]Minnelusa and Madison aquifer withdrawals were each estimated as 0.4 times the total withdrawal because the well is open to the Minnelusa, Madison, and Deadwood aquifers.

[2]Also may produce from Madison aquifer.

[3]Also may produce from Minnelusa aquifer.

Table 21. Public water supply withdrawals from Madison aquifer excluding Rapid City wells

[gal/min, gallons per minute; ft^3/s, cubic feet per second; WY, water year; Well information (excluding withdrawals) is from South Dakota Department of Environment and Natural Resources, written commun., 1999]

Site number (pl. 3)	Public water-supply identification number	Name	Year of construction	Population equivalent[1]	Average estimated WY88-97 withdrawal (gal/min)	Average estimated WY88-97 withdrawal[2] (ft^3/s)
1	4602159	Stagebarn Subdivision	1993	165	18	0.04
2	4600893	Stagebarn Elementary School	1980	360	36	.08
3	4602000	Peaceful Pines	1976	102	9	.02
4	4600043a	Black Hawk Water Company	1986	900	90	.20
5	4600862	Weston Heights	1985	220	22	.05
6	4602106	Cavalry Trails Homeowner Association	1980	54	4	.01
7	4602150	Coca Cola Bottling Company	1991	70	9	.02
8	4600046	Box Elder	1982	2,137	211	.47
9	4600863a	Ponderosa Ridge	1974	45	4	.01
10	4600863	Ponderosa Ridge	1977	45	4	.01
11	4600253	Westberry Trails Water Users Association	1972	157	13	.03
12	4602084	Rimrock Ridge Water Association	1978	36	4	.01
13	4600264	Chapel Lane Water Company	1975	1,200	117	.26
14	4600265	Carriage Hills	1980	270	27	.06
15	4600274	Rapid Valley Sanitary District	1991	1,360	94	.21
16	4600405	Ponderosa Park	1950	54	4	.01
17	4602149	CPH - Countryside South	1972	35	4	.01
18	4600263a	CPH - Whispering Pines	1964	35	4	.01
19	4600263	CPH - Whispering Pines	1976	35	4	.01
20	4600050	Highland Hills	1986	40	4	.01
21	4600015	Spring Canyon Water Company	1968	42	4	.01
22	4600528	Bear Country	1975	304	31	.07
23	4600910a	Hart Ranch	1984	600	58	.13
24	4600910	Hart Ranch	1984	20	45	.10
25	4600948	Pine Grove	1983	270	27	.06
Total				8,556	847	1.90

[1]When the reported population for a public water supply included more than one well location, the population was prorated based on estimates from water managers or the well capacity.

[2]Average withdrawals less than 0.01 ft^3/s were rounded up to 0.01 ft^3/s for several smaller public water supplies.

Table 22. Public water supply withdrawals from Minnelusa aquifer excluding Rapid City wells

[gal/min, gallons per minute; ft^3/s, cubic feet per second; WY, water year. Well information (excluding withdrawals) is from South Dakota Department of Environment and Natural Resources, written commun., 1999]

Site number (pl. 3)	Public water-supply identification number	Name	Year of construction	Population equivalent[1]	Average WY88-97 withdrawal (gal/min)	Average WY88-97 withdrawal[2] (ft^3/s)
26	4600929	Elk Creek Steakhouse	1978	104	8	0.02
27	4600630	Elk Creek Resort	1994	60	5	.01
28	4602133	Covered Wagon Resort	--	390	40	.09
29	4602123	Dakotah Spirit Resort	--	100	8	.02
30	4600239	Elk Creek Water Company	1973	321	31	.07
31	4600421a	Wonderland Homes	1982	325	31	.07
32	4600639	Piedmont Medical Center	1976	75	8	.02
33	4600421	Wonderland Homes	1975	325	31	.07
34	4601000a	East Ridge Acres	1972	55	5	.01
35	4600402	The Niche	1974	50	5	.01
36	4600515	Midland Heights	1975	177	17	.04
37	4601000	East Ridge Acres	1978	55	5	.01
38	4600041a	Pine Hills Park	1984	150	13	.03
39	4600041	Pine Hills Park	1972	155	13	.03
40	4600516	Golden Meadows	1978	114	8	.02
41	4602165	Fort Welikit Family Campground	1994	27	4	.01
42	4600587	Heritage Park	1963	188	17	.04
43	4600042	Woodland Hills	1945	110	8	.02
44	4600043	Black Hawk Water Company	1982	885	85	.19
45	4600040	Valley View Mobile Home Park	1973	291	26	.06
46	4600257	Cimarron Park	1972	200	17	.04
47	4600514	Northdale Sanitary District	1978	489	49	.11
48	4600258	Leos Trailer Court	1990	25	4	.01
49	4602122	B & J Mobile Home Park	1994	156	5	.01
50	4600260	Ponderosa Mobile Home Ranch	1963	100	8	.02
51	4600269	Hidden Valley Water Association Inc.	1954	50	5	.01
52	4602039	Buck N Gator Bar	1960	100	8	.02
53	4602070	Dacotah Cement - North	1941	35	4	.01
54	4600643	Dacotah Cement - East/west	1923	75	8	.02
55	4600643a	Dacotah Cement - East/west	1934	75	8	.02
56	4600253a	Westberry Trails Water Users Association	1974	20	4	.01
57	4602182	Sioux San Hospital	1960	200	17	.04
58	4601062	Cedar Canyon Weslyan Camp	1956	93	8	.02
59	4600908	Lake Park Motel	1976	80	8	.02
60	4602134	Ponderosa Water Company	1985	38	4	.01
61	4602153	Pineview Water Association	1984	34	4	.01
62	4601115	Memorial Christian School	1976	177	17	.04
63	4600589	Travelodge	1992	175	8	.02

Table 22. Public water supply withdrawals from Minnelusa aquifer excluding Rapid City wells–Continued

[gal/min, gallons per minute; ft^3/s, cubic feet per second; WY, water year. Well information (excluding withdrawals) is from South Dakota Department of Environment and Natural Resources, written commun., 1999]

Site number (pl. 3)	Public water-supply identification number	Name	Year of construction	Population equivalent[1]	Average WY88-97 withdrawal (gal/min)	Average WY88-97 withdrawal[2] (ft^3/s)
64	4601037	Rushmore Waterslide	1984	500	49	0.11
65	4600890	Reptile Gardens Inc.	1965	900	89	.20
66	4601061	Flying T Chuckwagon Suppers	1993	204	17	.04
67	4602118	Dairy Barn - Hayloft B&b	1994	42	5	.01
68	4600669	Happy Holiday Inc.	1965	67	5	.01
Total				7,792	719	1.65

[1]When the reported population for a public water supply included more than one well location, the population was prorated based on estimates from water managers or the well capacity.

[2]Average withdrawals less than 0.01 ft^3/s were rounded up to 0.01 ft^3/s for several smaller public water supplies.

Irrigation and Industrial Water Use

Irrigation and industrial withdrawals from the Madison and Minnelusa aquifers were estimated from water-rights permit information (South Dakota Department of Environment and Natural Resources, written commun., 1999) including well capacity and acreage. Average withdrawal rates totaled about 0.95 ft^3/s from the Madison aquifer (table 23) and ranged from 0.03 to 0.55 ft^3/s for individual wells. Average withdrawal rates totaled 0.65 ft^3/s from the Minnelusa aquifer (table 24) and ranged from 0.04 to 0.2 ft^3/s for individual wells.

Table 23. Industrial and irrigation withdrawals from Madison aquifer

[gal/min, gallons per minute; ft^3/s, cubic feet per second; WY, water year]

Site number (pl. 3)	Water-rights permit number[1]	Year of construction	Average WY88-97 withdrawal[1] (gal/min)	Average WY88-97 withdrawal (ft^3/s)
69	2286-2	1993	31	0.07
70	2256-2	1992	76	.17
71	2313-2	1994	13	.03
72	454-2	1957	246	.55
73	1911-2	1984	58	.13
Total			424	.95

[1]Well information compiled from South Dakota Department of Environment and Natural Resources, written commun., 1999.

Table 24. Industrial and irrigation withdrawals from Minnelusa aquifer

[gal/min, gallons per minute; ft^3/s, cubic feet per second; WY, water year]

Site number (pl. 3)	Water-rights permit number[1]	Year of construction	Average WY88-97 withdrawal[1] (gal/min)	Average WY88-97 withdrawal (ft^3/s)
74	842-1	1968	35	0.08
75	1656-2	1954	89	.20
76	1798-2	1956	22	.05
77	815-2	1923	89	.20
78	2137-2	1990	35	.08
79	1901-2	1984	17	.04
Total			287	.65

[1]Well information compiled from South Dakota Department of Environment and Natural Resources, written commun., 1999.

Leakage to Overlying Aquifers

Water from the Minnelusa aquifer under artesian pressure probably moves into overlying units including the Minnekahta and Inyan Kara aquifers through fractures or breccia pipes. According to Davis and others (1961), the Inyan Kara aquifer probably receives some recharge from underlying aquifers because recharge on its outcrop is relatively small. Gott and others (1974) suggest that the upward leakage occurs through breccia pipes. Behal (1988) applied statistical analysis to water quality in the Inyan Kara aquifer, in which t-tests indicated water near lineaments was different from water away from lineaments for some constituents but not others. This statistical analysis also indicated that water near lineaments was geochemically similar to a mixture of Madison and Minnelusa aquifer water for some constituents but not others. Although these results were not conclusive, the analysis indicated a strong possibility that ground water leaks upward from the Madison and Minnelusa aquifers through fractures or breccia pipes.

Because very little data were available to estimate the upward leakage from the Minnelusa aquifer, the overall water-budget calculation was used to estimate this amount to be about 2 ft^3/s or about 3 percent of the total budget (table 7).

Regional Outflow

Regional outflow occurs from the Madison and Minnelusa aquifers across the eastern boundary of the aquifer analysis area and was calculated by Darcy's Law using the hydraulic gradient from plates 1 and 2 and estimated transmissivity (*T*). *T* along the eastern boundary was adjusted in balancing the water budgets. The eastern boundary was subdivided into 14 zones (pl. 3), and outflow from each zone was calculated separately (table 25). The values listed in table 25 are within the ranges of effective *T* shown in figures 9 and 10 and represent the *T* tensor perpendicular to the boundary. The northern and southern boundaries were assumed to be parallel to flow and, therefore, would have no flow across them. Outflow from the confining units was assumed to be negligible.

Hydraulic gradient along the eastern boundary was assumed to remain relatively constant; hence, estimated regional outflow also was constant throughout the 10-year period. Regional outflow was estimated to be about 11 ft^3/s for both the Madison and Minnelusa hydrogeologic units (table 25).

Table 25. Outflow from boundary zones

[Boundary zones shown on plate 3. ft, feet; ft^2/d, square feet per day; ft^3/s, cubic feet per second; T, transmissivity]

Boundary zone	Boundary width (ft)	Madison aquifer			Minnelusa aquifer		
		Hydraulic gradient	T (ft^2/d)	Outflow (ft^3/s)	Hydraulic gradient	T (ft^2/d)	Outflow (ft^3/s)
1	14,492	0.004	664	0.4	0.006	600	0.6
2	14,492	.006	664	.7	.007	600	.7
3	14,492	.005	664	.6	.009	600	.9
4	14,492	.003	664	.3	.012	600	1.2
5	14,492	.001	1,005	.2	.010	600	1.0
6	14,492	.000	3,096	.0	.012	600	1.2
7	14,217	.005	3,310	2.7	.008	600	.8
8	14,217	.004	1,009	.7	.009	600	.9
9	14,217	.007	664	.8	.008	600	.8
10	14,217	.011	664	1.2	.007	600	.7
11	14,217	.010	664	1.1	.007	600	.7
12	14,217	.007	664	.8	.007	600	.7
13	14,217	.007	664	.8	.007	600	.7
14	14,217	.006	664	.7	.003	600	.3
Total outflow across eastern boundary				11.0			11.2

SUMMARY

The Madison and Minnelusa aquifers are important sources of water for Rapid City and surrounding communities. To provide information for effective management of these important aquifers, a conceptual model of ground-water flow was developed. The western part of the study area includes drainage areas that contribute streamflow recharge to the Madison and Minnelusa aquifers. The eastern part of the study area is referred to as the aquifer analysis area and includes the part of the study area where the Madison and the Minnelusa aquifers exist.

In the study area, the Madison and Minnelusa hydrogeologic units outcrop on the eastern flank of the Black Hills and dip easterly. Recharge to the Madison and Minnelusa hydrogeologic units is from streamflow losses and areal recharge on outcrop areas. The Madison hydrogeologic unit includes the karstic Madison aquifer, which is the upper, more permeable 100 to 200 ft of the Madison Limestone, and the Madison confining unit, which consists of the lower, less permeable part of the Madison Limestone and the Englewood Formation. Reported well yields are as high as 2,500 gal/min. Overlying the Madison hydrogeologic unit is the Minnelusa hydrogeologic unit. This unit includes the Minnelusa aquifer, which is the upper, more permeable 200 to 300 ft of the Minnelusa Formation, and the Minnelusa confining unit, which consists of the lower, less permeable part. Reported well yields are as high as 700 gal/min.

Important concepts described in the conceptual model include streamflow recharge, areal recharge, ground-water flow, storage, unsaturated areas west of the unconfined areas, leakage between aquifers, springflow, and regional outflow.

Hydraulic properties described for the hydrogeologic units include transmissivity, vertical hydraulic conductivity, storage coefficient, and specific yield. Estimates of effective transmissivity for the Madison aquifer range from 500 to 20,000 ft^2/d with the highest values in the Jackson-Cleghorn Springs area and the lowest values in the northeastern and southeastern parts of the aquifer analysis area. Generalized estimated transmissivity distributions for the Minnelusa aquifer ranged from 500 to 10,000 ft^2/d with the highest values in the Jackson-Cleghorn Springs area and the lowest values in the eastern part of the aquifer analysis area. Anisotropic transmissivity in the Madison aquifer may be localized in orientation and has been documented to have tensor ratios as high as 45:1. Vertical hydraulic conductivities for the Minnelusa confining unit determined from aquifer tests in the Rapid City area range from 1.3×10^{-3} to 3.0×10^{-1} ft/d. Leakage between the Madison and Minnelusa aquifers is spatially variable, which is consistent with the large range of vertical hydraulic conductivity. The confined storage coefficient for the Madison and Minnelusa hydrogeologic units was estimated as 3×10^{-4}. Specific yield was estimated as 0.09 for the Madison and Minnelusa aquifers and 0.03 for the Madison and Minnelusa confining units.

Potentiometric surfaces for the Madison and Minnelusa aquifers interpreted from hydraulic head in wells show a general easterly gradient with many local variations and changes in slope. The hydraulic gradient was estimated to be about 70 ft/mi on average for both aquifers. Temporal hydraulic-head change during WY88-97 ranged from about 5 to 95 ft in continuous-record observation wells. Temporal hydraulic-head change is small in the Jackson-Cleghorn Springs area and increases with distance from the springs. Confined and unconfined areas are identified based on the structural tops of formations and the potentiometric surface. The location where the average potentiometric surfaces contact the top and bottom of the aquifers and the confining units determine the boundaries of unconfined zones. The areas of Madison and Minnelusa hydrogeologic units unconfined zones are about 53 and 36 mi^2, respectively. Although the unconfined area represents a small part of the entire aquifer analysis area (629 mi^2), change in storage in the unconfined area is orders of magnitude larger than that of the confined area.

Dye-tracer tests, stable isotopes, and hydrogeologic features were analyzed conjunctively to estimate generalized ground-water flowpaths in the Madison aquifer and to analyze their influence on the Minnelusa aquifer. Streamflow losses to the Madison hydrogeologic unit from Boxelder Creek generally flow southward from the loss zone along structural features before flowing eastward. Rapid Creek streamflow loss generally flows north from its loss zone before moving towards Jackson-Cleghorn Springs or toward the east. Most of the streamflow loss from Spring Creek moves north towards Jackson-Cleghorn Springs. The western Rapid City area between Boxelder Creek and Spring Creek is described as a high-flow area and is characterized as having undergone extensive tectonic activity, greater brecciation in the Minnelusa Formation, high transmissivities, generally upward hydraulic gradients

from the Madison to Minnelusa aquifer, many karst springs, and converging flowpaths.

Water-budget analysis of the Madison and Minnelusa hydrogeologic units for WY88-97 was divided into 6-month stress periods representing winter and summer seasons. WY88-97 included periods of both low and high recharge rates and were representative of the range of hydrologic conditions during the last 30 years. Three budgets were developed for the water-budget analysis: (1) a dry-period budget for declining water levels, October 1987 through March 1993; (2) a wet-period budget for rising water levels, April 1993 through September 1997; and (3) a full 10-year period budget. By simultaneously balancing these three water budgets, initial estimates of recharge, discharge, change in storage, and related properties were refined. Compiled water-budget flow components include streamflow recharge, areal recharge, seepage from Deadwood aquifer, water use, outflow to overlying units, regional outflow, springflow, and change in ground-water storage.

Total streamflow recharge increased from about 27 ft^3/s during the dry period to 68 ft^3/s during the wet period and accounted for 45 ft^3/s or 61 percent of the total budget for the10-year period. Streamflow recharge to the Minnelusa hydrogeologic unit was only 14 percent of the total streamflow recharge. Total areal recharge for the dry and wet periods was 11 and 36 ft^3/s, respectively, and 22 ft^3/s or 30 percent of the 10-year budget.

Average springflow for the dry and wet periods was 25 and 37 ft^3/s, respectively, and accounted for 31 ft^3/s or 42 percent of the 10-year budget. Water use increased from about 8 ft^3/s during the dry period to 13 ft^3/s during the wet period with a slight decrease in Minnelusa aquifer withdrawals and an increase in Madison aquifer withdrawals resulting from newly completed wells. Water use accounted for 10 ft^3/s or 14 percent of the 10-year budget. Regional ground-water outflow was 22 ft^3/s or 30 percent of the 10-year budget. Leakage to hydrogeologic units overlying the Minnelusa aquifer was about 2 ft^3/s for the 10-year budget. Average net leakage from the Madison hydrogeologic unit to the Minnelusa hydrogeologic unit was 8 ft^3/s.

Ground-water storage was initially estimated from changes in hydraulic head in confined and unconfined areas, specific yields, and storage coefficients. These properties were refined based on water-budget balances. Total storage decreased by about 8 ft^3/s for the dry period and increased 21 ft^3/s for the wet period with a net increase in storage for the 10-year period of 5.0 ft^3/s.

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APPENDICES

APPENDIX A: AQUIFER TEST AT RC-9

An aquifer test of the Madison aquifer was conducted in October 1995 by pumping well RC-9 and measuring drawdown in wells CHLN-2, RC-11, CL-2, and SP-2 (fig. 9). Industrial and municipal withdrawals from the Madison aquifer were discontinued in the area 9 days before the aquifer test began, during the pumping period, and for 6 days after pumping. The pumping rate from RC-9 was about 2,550 gal/min. A schematic diagram of RC-9 is shown in figure 32, and conceptual illustration of the aquifer test is shown in figure 33. Hydraulic-head trends were measured for 5 days prior to the test. Based on this trend and the level of recovery after a period equivalent to that of pumping (6 days), a hydraulic-head trend was estimated for the pumping and recovery period (fig. 34). The estimated trend line reflects the fact that full recovery does not take place after a period equivalent to that of pumping (Driscoll, 1986, p. 252-253). Drawdown was calculated as the difference between this trend line and the measured hydraulic head (fig. 35). The trend line was checked by extrapolating the drawdown curve that would occur if pumping had continued through the recovery period. The extrapolated drawdown curve was calculated by requiring that $L_1 = L_2$ for every Δt value (fig. 35) (Ferris and others, 1962, p. 100-102). If the extrapolated drawdown curve appeared reasonable, the trend line was assumed to be a good estimate.

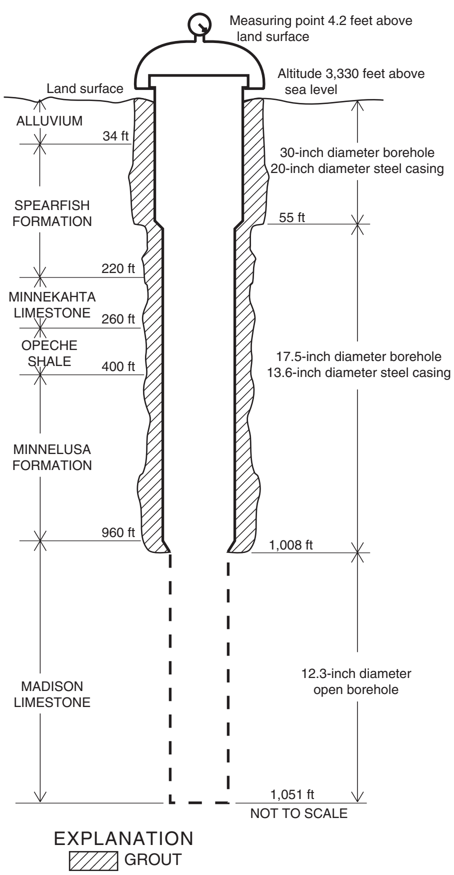

Figure 32. Schematic showing construction details of Rapid City well no. 9 (RC-9, site 49, table 28, plate 1) completed in the Madison aquifer.

Before any analysis of data, all measurements were corrected for fluctuations induced by changes in barometric pressure (Ferris and others, 1962; Kruseman and de Ridder, 1991). Prior to the aquifer test, the relationship between barometric pressure and hydraulic head in each observation well was established. This relationship was used to correct the data so that it represents drawdown under conditions of constant barometric pressure. Measured drawdown corrected for trend and barometric effects is listed in table 27 at the end of this section.

The drawdown portion of the curves was analyzed using the method of Hantush (1960) for estimating aquifer properties in a leaky confined aquifer. The method assumes there is storage in the intervening confining unit(s). The analysis computes *T, S,* and β, which is given by the following equation:

$$\beta = \frac{r}{4}\left[\sqrt{\frac{K_v'\,S'}{b'\,TS}} + \sqrt{\frac{K_v''\,S''}{b''\,TS}}\right] \qquad (9)$$

where

β = a dimensionless "lumped" parameter;
r = distance from the pumped well to the observation well [L];
T = transmissivity of the pumped aquifer [L^2/T];
K_v' = vertical hydraulic conductivity of the overlying confining unit [L/T];
K_v'' = vertical hydraulic conductivity of the underlying confining unit [L/T];
S = storage coefficient of the pumped aquifer [dimensionless];
S′ = storage coefficient of the overlying confining unit [dimensionless];
S″ = storage coefficient of the underlying confining unit [dimensionless];
b′ = thickness of the overlying confining unit [L]; and
b″ = thickness of the underlying confining unit [L].

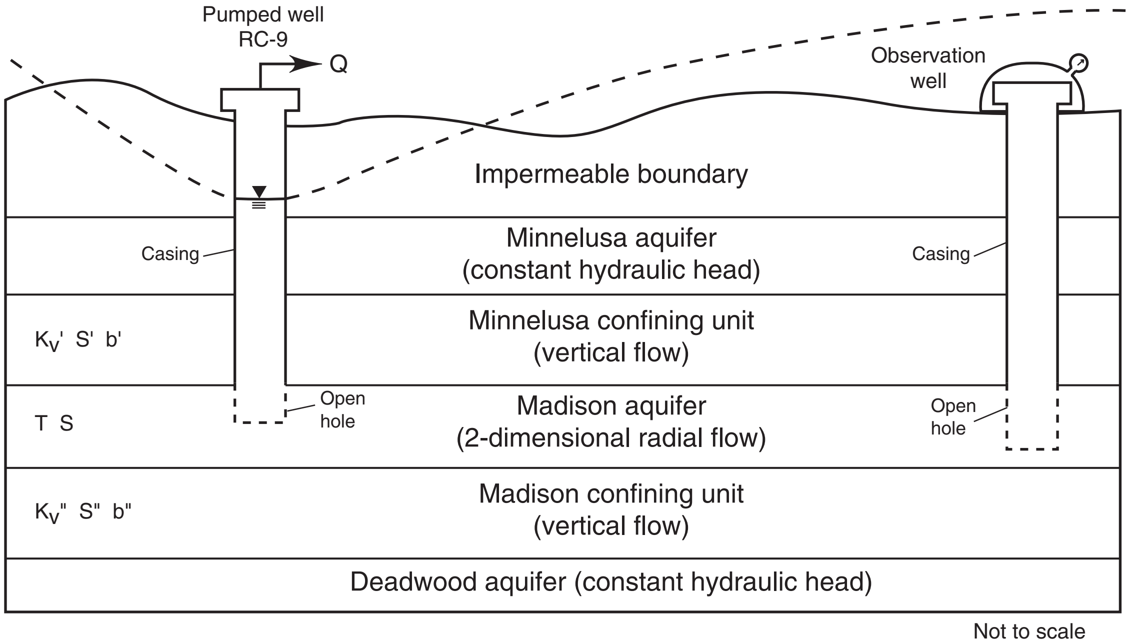

Figure 33. Diagram showing aquifer test conceptual model for multiple aquifer system.

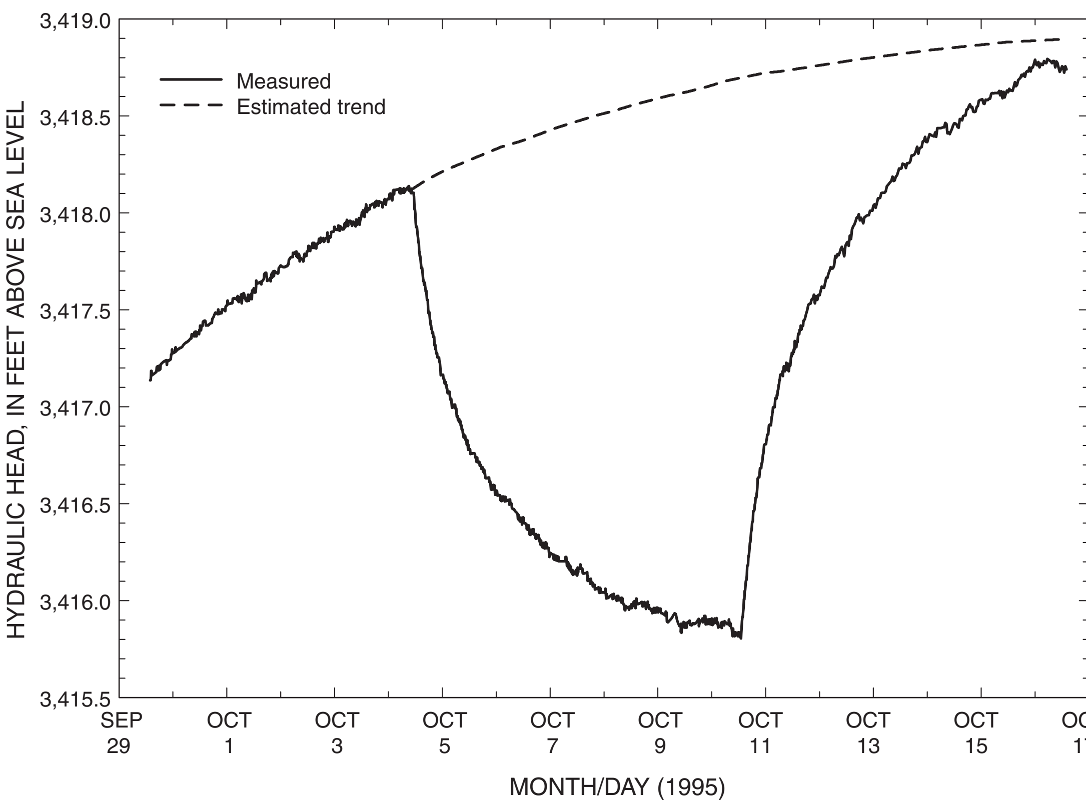

Figure 34. Aquifer test well hydrograph for CL-2 (site 50, table 28, plate 1). The trend line is the estimated water level that would have occurred without pumping.

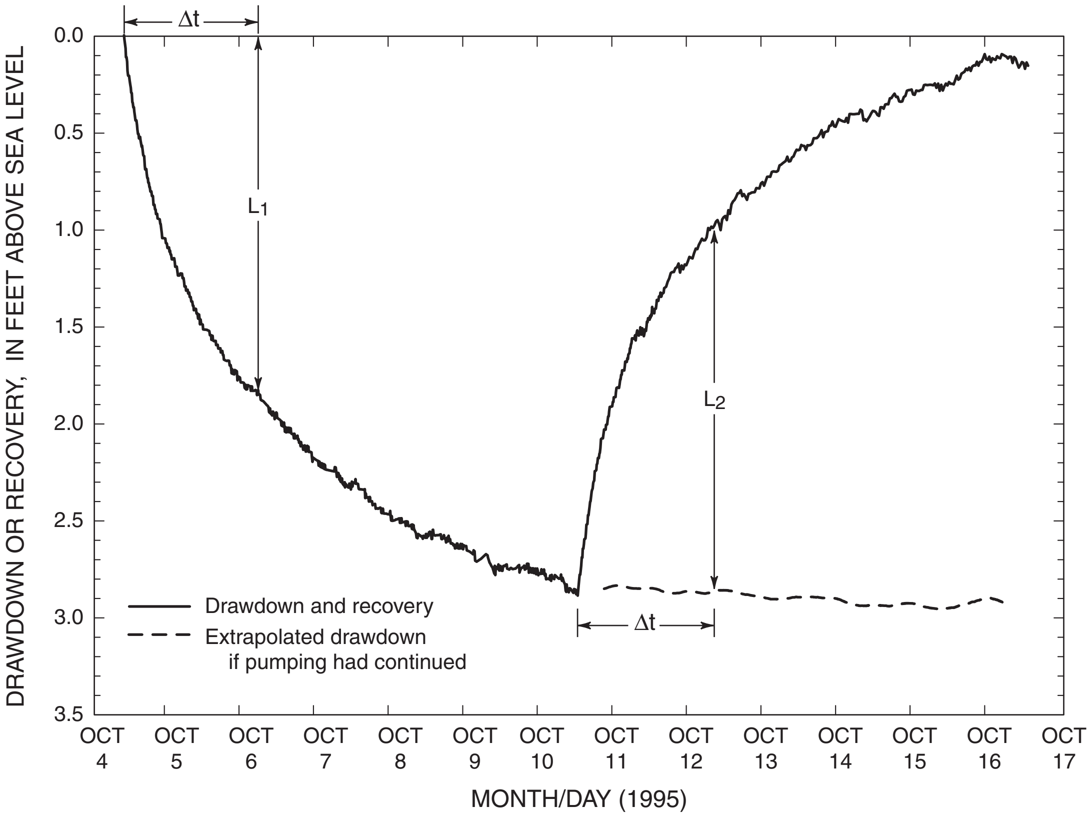

Figure 35. Drawdown and recovery curves for CL-2 (site 50, table 28 and plate 1). Curve shows drawdown if pumping had continued. For the extrapolated drawdown, $L_2 = L_1$ for every Δt.

Aquifer properties were estimated using a nonlinear least squares parameter estimation technique to achieve a best fit of the drawdown data (fig. 36). Although this curve fitting method allows upper and lower limits to be placed on parameter values to be estimated, estimates were all within reasonable ranges without any constraints imposed. Table 26 shows the properties estimated by the Hantush (1960) method. K_v for the Minnelusa confining unit was computed using equation 9 by assuming that S' for the Minnelusa confining unit is 10^{-4} and b' is 300 ft. It was also assumed that K_v for the Minnelusa confining unit was at least one order of magnitude greater than that of the Madison confining unit, which makes the second term in equation 9 negligible. Because of this, no values of K_v or S for the Madison confining unit are reported.

Except for RC-11, the pumped well and observation wells do not fully penetrate the aquifer. The flow pattern to partially penetrating wells is different from fully penetrating wells. However, these effects are negligible when the distance from pumped well to observation well is larger than twice the saturated aquifer thickness (Todd, 1980, p. 149-150). This was confirmed because the aquifer test analysis produced the same results with and without applying corrections for partial penetration.

Interference in the aquifer test occurred in well SP-2 when well BHPL (fig. 9) began pumping about 2 days into the test. The increased drawdown in SP-2 was estimated and corrected for by applying the method of Hantush and Jacob (1955) to the variable pumping rate of BHPL. This method was used because it was applied in a previous investigation whereby well RC-5 was pumped and drawdown measured in SP-2 (Greene, 1993). That aquifer test was interpreted as indicating the presence of anisotropic transmissivity. Because these three wells are nearly in a line, it was assumed that the directional T and other aquifer properties between RC-5 and SP-2 were similar to that between BHPL and SP-2. Therefore, by applying the same analytical model as in Greene (1993) and using the same properties, the drawdown at SP-2 resulting only from pumping at BHPL could be estimated because of the principle of superposition (Reilly and others, 1987). This drawdown was then subtracted from the total drawdown to obtain the drawdown resulting from withdrawal at RC-9.

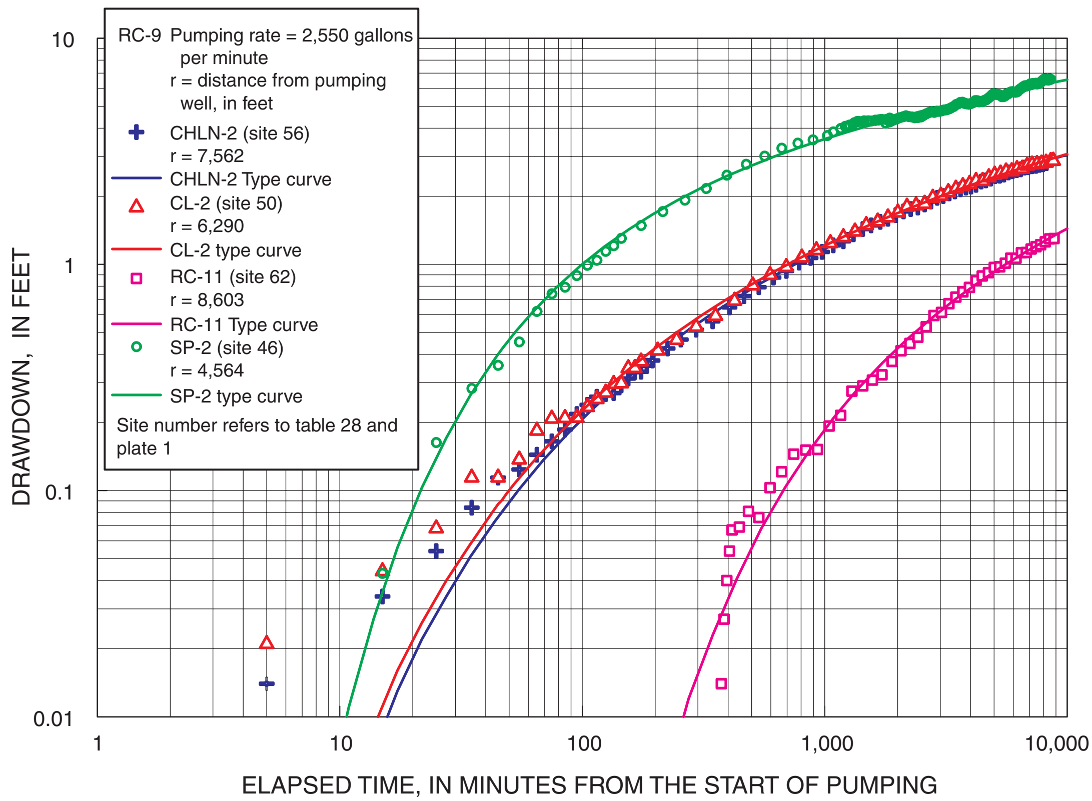

Figure 36. Drawdown curves and curve fit for the Hantush (1960) method for RC-9 aquifer test, October 1995.

Table 26. Aquifer properties for the Madison aquifer estimated by the Hantush (1960) method

[ft, feet; ft^2/d, feet squared per day; ft/d, feet per day; *r*, distance from pumped well; *T*, transmissivity; *S*, storage coefficient; β, lumped parameter; K_v, vertical hydraulic conductivity]

Observation well and site number (pl. 1)	*r* (ft)	*T* (ft^2/d)	*S* (dimensionless)	β (dimensionless)	K_v of Minnelusa confining unit (ft/d)
CL-2 (50)	6,290	14,700	2.1×10^{-5}	2.1	1.7
RC-11 (62)	8,603	11,500	2.7×10^{-4}	1.2	2.7
CHLN-2 (56)	7,562	14,100	1.4×10^{-5}	2.3	.9
SP-2 (46)	4,564	13,900	6.8×10^{-5}	.36	.3

Table 27. Drawdown data for the RC-9 aquifer test

Observation well CHLN-2 (site 56)		Observation well CL-2 (site 50)		Observation well RC-11 (site 62)		Observation well SP-2 (site 46)	
Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)
5	0.01	5	0.02	375	0.01	15	0.04
15	.03	15	.04	385	.03	25	.16
25	.05	25	.07	395	.04	35	.28
35	.08	35	.11	405	.05	45	.36
45	.11	45	.11	415	.07	55	.45
55	.12	55	.14	445	.07	65	.62
65	.14	65	.18	485	.08	75	.74
75	.17	75	.21	535	.08	85	.79
85	.19	85	.21	595	.10	95	.89
95	.22	95	.21	665	.12	105	.99
105	.24	105	.23	745	.14	115	1.04
115	.26	115	.25	835	.15	125	1.14
125	.27	125	.27	935	.15	135	1.21
135	.27	135	.30	1,045	.19	145	1.30
145	.29	145	.30	1,165	.22	175	1.48
155	.31	155	.35	1,295	.28	215	1.71
165	.33	165	.35	1,435	.29	265	1.92
175	.34	175	.37	1,575	.31	325	2.16
185	.36	205	.42	1,725	.33	395	2.48
195	.38	245	.46	1,895	.37	475	2.77
225	.43	295	.53	2,065	.42	565	3.01
255	.46	355	.59	2,245	.45	665	3.26
295	.51	425	.69	2,425	.48	775	3.44
345	.56	505	.81	2,625	.53	895	3.55
405	.65	595	.90	2,825	.59	1,025	3.71
465	.72	695	.97	3,035	.61	1,165	3.99
535	.79	805	1.07	3,255	.67	1,305	4.17
615	.87	925	1.16	3,475	.72	1,455	4.31
695	.94	1,055	1.24	3,715	.76	1,625	4.33
785	1.02	1,195	1.32	3,955	.79	1,795	4.37
875	1.07	1,335	1.40	4,215	.85	1,085	3.85
975	1.14	1,485	1.49	4,465	.89	1,225	4.08
1,085	1.21	1,655	1.55	4,735	.92	1,365	4.28

Table 27. Drawdown data for the RC-9 aquifer test–Continued

Observation well CHLN-2 (site 56)		Observation well CL-2 (site 50)		Observation well RC-11 (site 62)		Observation well SP-2 (site 46)	
Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)
1,195	1.27	1,825	1.61	5,005	0.97	1,515	4.31
1,315	1.36	2,005	1.70	5,275	.98	1,685	4.37
1,435	1.43	2,185	1.80	5,565	1.01	1,855	4.43
1,555	1.49	2,385	1.82	5,855	1.07	1,165	3.99
1,695	1.54	2,585	1.85	6,155	1.06	1,215	4.07
1,825	1.59	2,795	1.97	6,475	1.13	1,265	4.13
1,965	1.65	3,015	2.01	6,785	1.13	1,325	4.22
2,115	1.71	3,235	2.08	7,105	1.17	1,385	4.28
2,265	1.75	3,475	2.16	7,445	1.20	1,435	4.28
2,425	1.78	3,715	2.22	7,775	1.22	1,495	4.30
2,585	1.84	3,965	2.27	8,125	1.26	1,555	4.30
2,745	1.90	4,215	2.34	8,465	1.30	1,615	4.33
2,915	1.97	4,485	2.34	8,825	1.30	1,665	4.34
3,085	2.01	4,755	2.43			1,725	4.37
3,265	2.06	5,025	2.49			1,785	4.21
3,445	2.10	5,315	2.52			1,855	4.26
3,635	2.15	5,605	2.57			1,915	4.34
3,825	2.19	5,905	2.58			1,975	4.39
4,015	2.21	6,215	2.64			2,035	4.45
4,215	2.25	6,525	2.65			2,105	4.49
4,425	2.32	6,845	2.73			2,165	4.54
4,625	2.35	7,175	2.77			2,225	4.50
4,845	2.39	7,505	2.78			2,295	4.48
5,055	2.46	7,855	2.79			2,355	4.45
5,275	2.46	8,195	2.81			2,425	4.46
5,495	2.50	8,555	2.86			2,495	4.48
5,725	2.55	8,765	2.87			2,555	4.56
5,955	2.58					2,625	4.63
6,195	2.61					2,695	4.69
6,435	2.63					2,765	4.74
6,675	2.68					2,835	4.70
6,915	2.69					2,905	4.76
7,175	2.72					2,975	4.75

Table 27. Drawdown data for the RC-9 aquifer test–Continued

Observation well CHLN-2 (site 56)		Observation well CL-2 (site 50)		Observation well RC-11 (site 62)		Observation well SP-2 (site 46)	
Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)
7,435	2.73					3,045	4.77
7,695	2.75					3,115	4.81
7,955	2.77					3,185	4.82
8,215	2.80					3,265	4.87
						3,335	4.93
						3,405	4.99
						3,485	5.08
						3,555	5.12
						3,625	5.20
						3,705	5.21
						3,775	5.15
						3,855	5.13
						3,935	5.11
						4,005	5.14
						4,095	5.19
						4,175	5.29
						4,255	5.30
						4,335	5.23
						4,405	5.25
						4,485	5.24
						4,565	5.31
						4,645	5.34
						4,725	5.43
						4,815	5.52
						4,895	5.61
						4,975	5.69
						5,055	5.65
						5,135	5.64
						5,225	5.63
						5,305	5.58
						5,385	5.51
						5,475	5.52
						5,555	5.56

Table 27. Drawdown data for the RC-9 aquifer test–Continued

Observation well CHLN-2 (site 56)		Observation well CL-2 (site 50)		Observation well RC-11 (site 62)		Observation well SP-2 (site 46)	
Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)	Elapsed time since start of pumping (minutes)	Drawdown (feet)
						5,645	5.68
						5,725	5.69
						5,815	5.76
						5,895	5.79
						5,985	5.80
						6,075	5.77
						6,155	5.77
						6,245	5.81
						6,335	5.90
						6,425	5.97
						6,515	6.04
						6,605	6.10
						6,695	6.16
						6,775	6.13
						6,865	6.17
						6,955	6.19
						7,055	6.28
						7,165	6.24
						7,255	6.30
						7,345	6.29
						7,435	6.32
						7,525	6.27
						7,625	6.31
						7,715	6.32
						7,805	6.41
						7,905	6.48
						7,995	6.56
						8,085	6.61
						8,185	6.59
						8,275	6.54
						8,375	6.52
						8,465	6.60
						8,565	6.57

APPENDIX B: ADDITIONAL TABLES AND HYDROGRAPHS

Table 28. Water wells completed in the Madison aquifer

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 1)	Station identification number	Local number	Name	Adjusted hydraulic head (feet above sea level)	Land surface altitude (feet above sea level)	Use code	Depth (feet)
1	441759103261202	4N6E19AABA2	MD-90A Tilford No. 2 (TF-2)	3,621	3,637	1	840
2	441500103253501	3N6E 5CACC		3,655	3,690	4	238
3	441337103225002	3N6E15ABB2	MD-94A Piedmont No. 2 (PDMT-2)	3,603	3,475	1	880
4	441220103213601	3N6E23ACD		3,341	3,540	2	918
5	441157103234301	3N6E21DDCD		3,854	3,900	4	71
6	440958103253401	2N6E 5BAC		4,340	4,640	4	400
7	440934103252001	2N6E 5CAD		4,280	4,465	4	245
8	440933103250701	2N6E 5DBD		4,280	4,500	4	282
9	441636103183801	2N7E 8BBC	Blackhawk Water Company No. 4	3,511	3,530	2	1,160
10	440851103044801	2N9E 7CDCC	Ellsworth AFB	2,687	3,230	4	4,640
11	440828103222601	2N6E10DD		3,895	4,120	4	380
12	440826103174701	2N7E 8DDCC2		3,450	3,600	4	790
13	440823103162701	2N7E16AAB		3,448	3,400	3	1,530
14	440820103232601	2N6E15BBBD		3,981	4,290	4	372
15	440811103222201	2N6E15ADAA	PE-95C Doty Madison	3,808	4,059	1	425
16	440807103225801	2N6E15BDA		3,973	4,260	4	340
17	440804103230501	2N6E15BDB		3,976	4,260	4	370
18	440804103223001	2N6E15AD		3,874	4,160	4	420
19	440804103222701	2N6E15ADDB		3,774	4,140	4	400
20	440753103110801	2N8E13BDCD	Ellsworth AFB No. 3	--	3,190	4	4,440
21	440758103225601	2N6E15CBDD		3,913	4,260	4	540
22	440753103232401	2N6E15CBBD		3,980	4,260	4	410
23	440749103221501	2N6E14CBC		3,772	4,120	4	560
24	440744103223401	2N6E15DDB		3,876	4,210	4	407
25	440658103213001	2N6E23DBAB		3,660	3,860	4	420
26	440655103140501	2N7E23DACD	Rapid City No. 8 (RC-8)	3,423	3,527	2	2,680
27	440650103193201	2N7E19CDAD		3,528	3,990	4	745
28	440631103211201	2N6E26AAD		3,645	3,940	4	357
29	440630103192501	2N7E30BADC		3,536	4,000	4	745
30	440629103040901	2N9E29BBCC	City of Box Elder	2,575	3,043	2	4,450
31	440622103152701	2N7E27ACAB	Coke Plant	3,481	3,400	3	1460
32	440612103152001	2N7E27DABB	Rapid City No. 10 (RC-10)	3,444	3,363	2	1,790

Table 28. Water wells completed in the Madison aquifer–Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 1)	Station identification number	Local number	Name	Adjusted hydraulic head (feet above sea level)	Land surface altitude (feet above sea level)	Use code	Depth (feet)
33	440544103180002	2N7E32ABBC2	PE-89C City Quarry No. 2 (CQ-2)	3,451	3,492	1	826
34	440540103211301	2N6E35AADA2		3,646	4,120	2	740
35	440526103173001	2N7E32ADDD	Rapid City No. 6 (RC-6)	3,447	3,440	2	1,300
36	440523103155701	2N7E34BDCC	Black Hills Power & Light (BHPL)	3,424	3,300	3	--
37	440518103193001	2N7E31CAB		3,477	3,670	4	420
38	440512103215701	2N6E35CAC		3,734	4,130	4	436
39	440508103220701	2N6E35CCAB		3,764	4,140	4	450
40	440500103193601	2N7E31CCCA	Westberry Trails No. 2 (WT-2)	3,520	3,974	2	680
41	440453103184001	1N7E 5BBBC		3,405	3,785	4	560
42	440446103193201	1N7E 6BACB		3,430	4,020	4	770
43	440446103161701	1N7E 3BBCC	Lime Creek (LC)	3,417	3,314	1	1,390
44	440441103193301	1N7E 6BDCD		3,428	4,080	4	930
45	440432103191401	1N7E 6ACCC		3,405	3,940	4	770
46	440430103160202	1N7E 3CBAA2	PE-65A Sioux Park No. 2 (SP-2)	3,423	3,297	1	1,170
47	440427103131701	1N7E 1DBBB	Rapid City No. 7 (RC-7, Star Village)	3,146	3,396	1	3,280
48	440337103191801	1N7E 7ACBD		3,418	3,640	4	380
49	440342103160701	1N7E10BCDB	Rapid City No. 9 (RC-9)	3,415	3,330	2	1,051
50	440338103173302	1N7E 8ADDD2	PE-89A Canyon Lake (CL-2)	3,418	3,371	1	700
51	440334103095601	1N8E 9CAB2	Rapid Valley No. 4	2,655	3,108	4	3,800
52	440326103180702	1N7E 8DBCC	Jackson Springs Well 1A (JS-1A)	3,418	3,380	4	640
53	440310103173802	1N7E 8DDCD2	Chapel Lane No. 3 (CHLN-3)	3,418	3,410	2	940
54	440308103184601	1N7E18AAAD	PE-96A Cleghorn (CLEG)	3,417	3,414	1	200
55	440308103180701	1N7E17ABCC		3,419	3,430	4	460
56	440300103173501	1N7E17AAAC	Chapel Lane No. 2 (CHLN-2)	3,419	3,433	2	820
57	440247103192401	1N7E18AACB		3,415	3,720	4	400
58	440302103194601	1N7E18BDBA		3,438	3,640	4	450
59	440247103191701	1N7E18ACCC		3,434	3,540	4	150
60	440238103185201	1N7E18DADB		3,416	3,620	4	321
61	440223103173201	1N7E17DDDA	Carriage Hills No. 1	3,426	3,871	2	725
62	440220103164001	1N7E16DCDC	Rapid City No. 11 (RC-11)	3,423	3,487	2	1,280
63	440205103172001	1N7E21BCAB		3,445	3,900	4	--
64	440054103173801	1N7E29DAAC		3,475	3,900	4	1,000
65	440523103194201	1N7E31BCAD		3,806	4,260	4	598
66	440004103174001	1N7E32DABA	Highland Hills	3,531	3,999	2	780

Table 28. Water wells completed in the Madison aquifer–Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 1)	Station identification number	Local number	Name	Adjusted hydraulic head (feet above sea level)	Land surface altitude (feet above sea level)	Use code	Depth (feet)
67	435937103184101	1S7E 5BAA		3,626	3,920	2	--
68	435916103161801	1S7E 3CDBD	PE-86A Reptile Gardens (RG)	3,497	3,520	1	1,220
69	435903103181301	1S7E 8ABAA		3,594	4,100	4	754
70	435851103184201	1S7E 8BDBA		3,580	4,180	4	640
71	435851103143501	1S7E11ACAB	Hart Ranch No. 2	3,498	3,466	2	1,740
72	435746103160601	1S7E15CBBB		3,488	3,985	4	820
73	435718103130301	1S8E19BBBB	Hart Ranch No. 1	3,498	3,555	2	2,600
74	435635103181401	1S7E20DCAD	Pine Grove	3,515	4,120	2	903
75	435619103161901	1S7E27BACA		3,509	4,140	4	1,190
76	435518103173001	1S7E33BDBD		3,530	4,090	4	680
77	435227103185301	2S7E17CCAA	PE-95A Hayward (HWRD)	3,542	3,932	1	540
			Wells Not Shown on Plate 1 (unreliable hydraulic heads)				
78	442217103272201	5N5E26ABDA		3,129	3,625	4	1,460
79	440443103161301	1N7E 3BBCD	Rapid City No. 5 (RC-5)	--	3,310	2	1,292
80	442058103273001	5N5E36DBCB		3,204	3,720	2	1,050
81	441845103352001	4N4E13B		4,890	5,050	4	227
82	441838103344301	4N4E13A		4,720	4,880	4	227
83	441830103312701	4N5E16BDD		4,540	4,620	4	115
84	441817103311901	4N5E16DBC		4,455	4,620	4	360
85	440933103253301	2N6E 5CAC		4,300	4,500	4	245
86	440908103193401	2N7E 7BAC		3,439	3,679	4	--
87	440805103223001	2N6E15AD		3,786	4,160	4	430
88	440810103234401	2N6E15BC		4,022	4,300	4	505
89	440755103231801	2N6E15CBA		4,015	4,320	4	480
90	440758103214301	2N6E14CAC		3,804	4,150	4	540
91	440737103222501	2N6E15DDD		3,781	4,160	4	415
92	440636103214701	2N6E26BAAC		3,694	3,950	4	340
93	440602103194201	2N7E31BCB		3,393	3,770	4	525
94	440244103191901	1N7E18BAC		3,417	3,620	4	380
95	440254103191801	1N7E18ACB		3,420	3,630	4	320
96	440248103195001	1N7E18BCC		3,585	3,600	4	32
97	440245103192501	1N7E18CAAB		3,410	3,500	4	280
98	440242103192301	1N7E18CAA		3,342	3,440	4	280
99	440241103194001	1N7E18CBA		3,650	3,700	4	185
100	435143103184401	2S7E20BDC		3,490	3,890	4	624

Table 29. Water wells completed in the Minnelusa aquifer

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head (feet above sea level)	Land surface altitude (feet above sea level)	Use code	Depth (feet)
102	441812103230501	4N6E16DCB		3,454	3,460	4	1,460
103	441826103263301	4N6E17CCDA		3,564	3,578	4	590
104	441759103261201	4N6E19AABA	MD-84B Tilford No. 1 (TF-1)	3,608	3,636	1	302
105	441701103251101	4N6E29ABC	Piedmont East (PDMT-East)	3,515	3,542	1	180
106	441656103261601	4N6E30A		3,592	3,860	4	340
107	441649103262401	4N6E30ADCC		3,593	3,930	4	540
108	441620103255301	4N6E29CCC		3,529	3,630	4	240
109	441612103252801	4N6E32BAA		3,532	3,590	4	265
110	441606103252501	4N6E32BAD		3,557	3,620	4	225
111	441556103253201	4N6E32BBDD		3,514	3,680	4	280
112	441504103230301	3N6E 3BCBC		3,428	3,460	4	755
113	441500103240601	3N6E 4		3,422	3,520	4	300
114	441453103243801	3N6E 4CB		3,486	3,570	4	328
115	442221103245501	3N6E 5DA		3,527	3,590	4	250
116	441314103233301	3N6E10ABAA		3,412	3,400	4	425
117	441424103243601	3N6E 9BBCD		3,506	3,780	4	320
118	441421103242302	3N6E 9BCBB2		3,510	3,740	4	365
119	441400103231501	3N6E10BDDB		3,478	3,435	4	625
120	441358103241801	3N6E 9CABB		3,526	3,760	4	260
121	441643103232801	3N6E10CCC		3,490	3,530	4	275
122	441339103232701	3N6E16AAAB		3,530	3,570	4	237
123	441338103233201	3N6E16AABA		3,528	3,590	4	190
124	441337103225001	3N6E15ABBB	MD-84A Piedmont No. 1 (PDMT-1)	3,481	3,475	1	440
125	441335103223202	3N6E15AAB		3,414	3,490	4	110
126	441335103223201	3N6E15AB		3,414	3,490	4	100
127	441333103222801	3N6E15AAAC		3,457	3,470	4	640
128	441331103230701	3N6E15BA3		3,454	3,530	4	160
129	441322103234202	3N6E16AD2		3,547	3,660	4	260
130	441322103234201	3N6E16AD		3,581	3,660	4	340
131	441315103224001	3N6E15DABBB		3,489	3,530	4	365
132	441257103222501	3N6E15DAA		3,458	3,590	4	263
133	441241103183401	3N7E20BB2		3,268	3,460	4	340

Table 29. Water wells completed in the Minnelusa aquifer–Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head (feet above sea level)	Land surface altitude (feet above sea level)	Use code	Depth (feet)
134	441219103204801	3N6E24CABB		3,414	3,570	2	1,005
135	441242103215701	3N6E23CAB		3,495	3,730	4	288
136	441216103215801	3N6E23CABD		3,477	3,700	4	460
137	441210103215101	3N6E23CADA		3,483	3,570	4	328
138	441212103201501	3N6E24DBDA		3,366	3,840	2	1,542
139	441211103213701	3N6E23DBCA		3,458	3,560	4	375
140	441202103211301	3N6E23DDAC		3,476	3,558	4	860
141	441318103221301	3N6E24CADD		3,449	3,600	4	824
142	442137103213801	3N6E23DCB 4		3,444	3,600	4	300
143	441202103213301	3N6E23DC		3,474	3,580	4	360
144	441200103213001	3N6E23DCCB		3,471	3,605	4	305
145	441157103213701	3N6E23DDDC		3,445	3,580	4	440
146	441220103214001	3N6E23DCDC		3,451	3,608	4	360
147	441151103213002	3N6E26AABB		3,459	3,600	4	395
148	441147103270001	3N7E30BCAD		3,413	3,870	2	1,600
149	441136103221301	3N6E26ACAD		3,415	3,680	4	360
150	441134103211601	3N6E26ADBB		3,460	3,645	4	300
151	441131103200101	3N6E25ADDA		3,418	3,615	4	783
152	441130103205601	3N6E25BCDC		3,466	3,630	4	400
153	441119103210301	3N6E25CBCB		3,453	3,680	4	303
154	441105103192001	3N7E30CDD		3,454	3,650	4	1,120
155	441125103203001	3N6E25DCCD		3,413	3,690	4	500
156	441038103203001	3N6E36BADB		3,403	3,735	4	420
157	441049103203701	3N6E36BADD		3,423	3,725	4	400
158	441047103203301	3N6E36BDAA		3,423	3,720	4	400
159	441323103232301	3N6E36BDCA		3,496	3,780	4	520
160	441040103203201	3N6E36BDDA		3,438	3,740	4	--
161	441038103203002	3N6E36B		3,492	3,820	4	400
162	441037103203502	3N6E36BDD2		3,472	3,760	4	360
163	441037103203501	3N6E36BDD		3,450	3,760	4	360
164	441033103193001	3N7E31CAA		3,463	3,630	4	520
165	441031103195201	3N7E31CBBC		3,443	3,690	4	462

Table 29. Water wells completed in the Minnelusa aquifer–Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head (feet above sea level)	Land surface altitude (feet above sea level)	Use code	Depth (feet)
166	441024103201301	3N6E36DBD		3,487	3,720	4	440
167	441023103204001	3N6E36CADD		3,474	3,780	4	565
168	441023103203101	3N6E36DBCC		3,440	3,810	4	540
169	441023103203001	3N6E36DBBD		3,423	3,740	4	312
170	441007103201101	2N6E 1AABB		3,432	3,725	4	340
171	440930103175201	2N7E 5DBDD		3,489	3,460	4	--
172	440936103191801	2N7E 6CDAC	Blackhawk Water Co. No. 3	3,447	3,545	2	340
173	440919103170501	2N7E 4CDCD		3,416	3,405	4	920
174	440929103163501	2N7E 4DDC		3,379	3,435	4	1,025
175	440916103163301	2N7E 9AABB		3,392	3,420	4	1,260
176	440907103183501	2N7E 8BBCD	Blackhawk Water Co. No. 2	3,386	3,510	2	750
177	440908103193101	2N7E 7BACA		3,462	3,720	4	480
178	440901103184801	2N7E 7ADAB	Blackhawk Water Co. No. 1	3,403	3,580	2	600
179	440829103183801	2N7E 8CCC		3,414	3,560	4	590
180	440826103174601	2N7E 8DDCC		3,410	3,600	4	815
181	440818103180801	2N7E17BAAD	PE-84B Blackhawk No. 1 (BLHK-1)	3,422	3,500	1	560
182	440818103174701	2N7E17BACA		3,449	3,500	4	650
183	440800103163001	2N7E16		3,313	3,360	4	320
184	440738103173901	2N7E17DDBD		3,409	3,450	4	371
185	440736103173701	2N7E17DDAA		3,412	3,450	2	400
186	440719103174801	2N7E20ABAD		3,434	3,480	4	263
187	440636103152001	2N7E27AABA		3,400	3,435	4	992
188	440635103161801	2N7E27BBCB		3,420	3,450	3	--
189	440607103155901	2N7E27CAAB		3,383	3,360	3	615
190	440606103174701	2N7E29DACB		3,419	3,600	4	349
191	440605103174701	2N7E29DAC1		3,419	3,600	4	349
192	440552103173401	2N7E29DAC5		3,421	3,570	4	220
193	440603103174501	2N7E29DAC3		3,427	3,600	4	190
194	440552103162301	2N7E28DACD		3,336	3,360	3	300
195	440557103174401	2N7E29DDB		3,414	3,600	4	308
196	440556103174801	2N7E29DDBD2		3,449	3,620	4	320
197	440542103172501	2N7E28CC		3,410	3,500	4	320

Table 29. Water wells completed in the Minnelusa aquifer–Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head (feet above sea level)	Land surface altitude (feet above sea level)	Use code	Depth (feet)
198	440639103173701	2N7E29DDCA		3,443	3,620	4	340
199	440545103173501	2N7E32AAAC		3,438	3,610	4	300
200	440544103180001	2N7E32ABBD	PE-89D City Quarry No. 1 (CQ-1)	3,450	3,492	1	--
201	440544103174301	2N7E32AABD		3,444	3,640	4	302
202	440544103173601	2N7E32AAA		3,468	3,640	4	340
203	440540103194601	2N7E31BBCD		3,553	3,810	4	270
204	440539103205401	2N6E36BBD		3,769	4,080	4	390
205	440538103161001	2N7E34B		3,328	3,340	4	220
206	440534103174801	2N7E32AACD		3,467	3,640	4	195
207	440534103171401	2N7E33BCAA		3,450	3,460	4	200
208	440533103193801	2N7E31BCAA		3,416	3,720	4	440
209	440528103161001	2N7E34BCCA	PE-64A Cement Plant (CP)	3,412	3,331	1	400
210	440528103155201	2N7E34BDAD		3,406	3,350	4	585
211	440521103184401	2N7E32BCCC		3,471	3,602	4	--
212	440532103182001	2N7E32CADA		3,462	3,510	4	310
213	440514103161401	2N7E34CBCD		3,403	3,340	3	371
214	450512103182101	2N7E32CAC		3,434	3,520	4	230
215	440516103194001	2N7E31CDCB	Westberry Trails No. 1 (WT-1)	3,406	3,860	2	565
216	440501103181501	2N7E32CDAD		3,475	3,520	4	200
217	440459103181001	2N7E32CDDD		3,450	3,480	4	180
218	440458103181101	2N7E32CDDDB		3,450	3,480	4	180
219	440452103155301	1N7E 3BABD	South Dakota ARNG	3,396	3,340	4	600
220	440449103181501	1N7E 5ABCA		3,435	3,490	4	207
221	440446103181801	1N7E 5BAC		3,415	3,700	4	430
222	440445103181601	1N7E 5BACA		3,470	3,700	4	360
223	440430103160201	1N7E 3CBAA	PE 64B Sioux Park No. 1 (SP-1)	3,392	3,300	1	570
224	440423103180501	1N7E 5DBCA	West Camp Rapid No. 3 (WCR-3)	3,400	3,580	1	224
225	440403103183701	1N7E 5CDD		3,382	3,580	4	330
226	440347103190501	1N7E 7ACA		3,435	3,497	4	--
227	440344103190801	1N7E 7AC		3,456	3,506	4	152
228	440344103173701	1N7E 8AC		3,360	3,460	4	140
229	440338103173301	1N7E 8ADDD	PE-89B Canyon Lake No. 1 (CL-1)	3,360	3,371	1	--

Table 29. Water wells completed in the Minnelusa aquifer–Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head (feet above sea level)	Land surface altitude (feet above sea level)	Use code	Depth (feet)
230	440331103155101	1N7E10CADD		3,396	3,410	4	700
231	440326103180703	1N7E 8DBCC2	Jackson Springs Well 1B (JS-1B)	3,395	3,380	1	--
232	440321103181001	1N7E 8CDAA		3,365	3,460	4	135
233	440310103173801	1N7E 8DDCD	Chapel Lane No. 1 (CHLN-1)	3,383	3,410	1	360
234	440309103170101	1N7E16BAAB		3,360	3,430	4	183
235	440308103183001	1N7E17BBA		3,435	3,480	4	--
236	440308103172501	1N7E16BBB		3,378	3,580	4	312
237	440308103144301	1N7E14BABD		3,353	3,833	4	1,817
238	440336103165301	1N7E16BBBB		3,353	3,575	4	250
239	440307103181501	1N7E17BABD		3,399	3,724	4	--
240	440305103164501	1N7E16BADA2		3,364	3,440	4	250
241	440211103165601	1N7E16BADA		3,370	3,440	4	207
242	440301103165701	1N7E16BAD		3,350	3,440	4	300
243	440300103170901	1N7E16BAC		3,380	3,500	4	220
244	440257103171101	1N7E16BACC		3,355	3,520	4	240
245	440252103172201	1N7E16BC		3,336	3,540	4	280
246	440249103182101	1N7E17BDC		3,450	3,480	4	115
247	440247103165401	1N7E16BDBB		3,342	3,500	4	235
248	440242103170801	1N7E16CAB		3,386	3,500	4	260
249	440244103154102	1N7E15CBBD2		3,374	3,475	4	460
250	440236103145801	1N7E14CBCA		3,351	3,880	4	1,650
251	440233103170501	1N7E16CACD		3,387	3,580	4	258
252	440223103161701	1N7E15CCBC		3,381	3,440	2	360
253	440224103172601	1N7E16CCCA	Carriage Hills No. 2	3,372	3,840	2	612
254	440214103153501	1N7E15DCCA		3,388	3,600	2	780
255	440211103165201	1N7E21BADA		3,401	3,650	4	422
256	440211103164301	1N7E21ABDB		3,409	3,570	4	200
257	440204103150001	1N7E23BCB		3,392	3,858	4	1,680
258	440203103143601	1N7E23BDAB		3,390	3,840	4	1,870
259	440158103160401	1N7E22BDCC	Spring Brook South No. 3	3,429	3,565	2	445
260	440149103164901	1N7E21DBBD	Wildwood North	3,412	3,675	1	--
261	440130103163401	1N7E21DDCD	Wildwood South	3,429	3,720	1	400

Table 29. Water wells completed in the Minnelusa aquifer–Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head (feet above sea level)	Land surface altitude (feet above sea level)	Use code	Depth (feet)
262	440103103144801	1N7E26BCDA		3,376	3,720	4	1545
263	440059103154101	1N7E27DADB		3,456	3,815	4	1,430
264	440048103145001	1N7E26CCAA		3,455	3,820	4	1,460
265	440038103172601	1N7E28CCC		3,475	3,840	4	600
266	440031103162701	1N7E33AAA		3,459	3,830	4	560
267	440028103160801	1N7E34BAC		3,412	3,815	4	660
268	440027103161001	1N7E34BBCA		3,499	3,840	4	516
269	440022103163401	1N7E33AABC		3,494	3,850	4	623
270	440007103165301	1N7E33ADBB		3,455	3,840	4	540
271	440010103154201	1N7E34		3,404	3,820	4	700
272	435916103161802	1S7E 3CDBD2	PE-94A Reptile Gardens No. 2 (RG-2)	3,493	3,519	1	660
273	435858103155701	1S7E10ABBD		3,476	3,518	4	515
274	435803103160301	1S7E15ABC		3,539	3,680	4	245
275	445809103162201	1S7E15CABA		3,548	3,765	4	430
276	435720103141601	1S7E13CBCA	Hart Ranch No. 3	3,547	3,780	2	1,525
277	435352103170801	2S7E 4ACDB		3,558	3,800	4	358
278	435325103171701	2S7E 9CBDA		3,527	3,960	4	580
279	435225103172801	2S7E16CACA		3,551	3,700	4	240
280	435119103175001	2S7E21CCC		3,536	3,865	4	500
281	435115103170501	2S7E21DDC		3,511	3,750	4	350
			Wells Not Shown on Plate 2 (unreliable hydraulic heads)				
282	442213103283101	5N5E26ABD		3,124	3,620	4	1,375
283	442158103284701	5N5E26		3,248	3,800	4	1,140
284	442146103272001	5N5E25CADB		3,113	3,710	2	1,000
285	442108103270301	5N5E36ADD		3,164	3,690	2	1,120
286	441903103261601	4N6E7DDBB		3,464	3,710	4	700
287	441641103252001	4N6E29BCAD		3,627	3,700	4	176
288	441648103264001	4N6E30BDA		3,743	4,000	4	540
289	441640103245901	4N6E29DAB		3,612	3,620	4	220
290	441549103252002	4N6E32(2)		3,480	3,618	4	220
291	441544103253001	4N6E32CA		3,628	3,640	4	260
292	441538103255601	4N6E32CCB		3,770	3,800	4	300

Table 29. Water wells completed in the Minnelusa aquifer–Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head (feet above sea level)	Land surface altitude (feet above sea level)	Use code	Depth (feet)
Wells Not Shown on Plate 2 (unreliable hydraulic heads)—Continued							
293	441522103252501	3N6E 5BAB		3,430	3,700	4	558
294	441443103223701	3N6E 3DD		3,305	3,420	4	1260
295	441441103252301	3N6E 5CD		3,620	3,650	4	140
296	441228103185301	3N7E19ADCA		3,429	3,540	4	1,200
297	441108103205701	3N6E25CC		3,383	3,670	4	--
298	441118103210001	3N6E25CCDD		3,400	3,720	4	370
299	441051103205901	3N6E36BBCA		3,363	3,760	4	570
300	441029103202201	3N6E36DB		3,547	3,722	4	338
301	440930103190501	2N7E 6DCD		3,426	3,520	4	--
302	440927103173501	2N7E 5DDA		3,380	3,440	4	885
303	440913103194001	2N7E 7BB		--	3,520	4	380
304	440820103164701	2N7E16ABBD		3,267	3,400	4	445
305	440747103174901	2N7E17D		3,399	3,460	4	440
306	440702103181401	2N7E20CAAC		3,300	3,580	4	380
307	440605103182801	2N7E29DBD		3,505	3,685	4	330
308	440525103171701	2N7E33BCD		3,340	3,430	4	240
309	440522103185301	2N7E31ADCD		3,534	3,680	4	247
310	440518103163604	2N7E33DAB4		3,388	3,400	4	220
311	440517103194801	2N7E31CBBD		3,672	3,800	4	260
312	440508103221001	2N6E35CCBA		3,827	4,180	4	582
313	440458103180101	2N7E32CCDC		3,400	3,640	4	--
314	440447103183101	1N7E 5BBDB		3,394	3,770	4	500
315	440414103164601	1N7E 4DCB	Rapid City No. 4 (RC-4)	--	3,350	2	1,080
316	441351103171301	1N7E 9BBCA	Rapid City No. 3 (RC-3)	--	3,376	2	902
317	440338103171601	1N7E 9BCDC	Rapid City No. 1 (RC-1)	--	3,360	2	1,460
318	440331103200301	1N6E12DAAC		3,560	3,860	4	415
319	440328103191001	1N7E7DBC		3,640	3,700	4	155
320	440302103172601	1N7E16BAD2		3,415	3,440	4	222
321	440255103172601	1N7E16BCB		3,432	3,560	4	200
322	440249103172701	1N7E16BCC		3,404	3,580	4	317
323	440246103180801	1N7E17		3,683	3,700	4	78

Table 29. Water wells completed in the Minnelusa aquifer–Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head (feet above sea level)	Land surface altitude (feet above sea level)	Use code	Depth (feet)
Wells Not Shown on Plate 2 (unreliable hydraulic heads)—Continued							
324	440331103142701	1N7E11DBAD		3,164	3,560	4	1,755
325	440234103171201	1N7E16CACC		3,415	3,600	4	300
326	440202103165801	1N7E21BDA		3,384	3,760	4	565
327	440158103165601	1N7E21(2)		3,622	3,740	4	240
328	440155103165001	1N7E21ACC		3,574	3,660	4	--
329	440149103144301	1N7E23CAB		3,425	3,810	4	1,563
330	440148103164101	1N7E21DBA		3,388	3,620	4	602
331	440130103153901	1N7E22DCC		3,365	3,780	4	875
332	440129103161301	1N7E22CCC		3,591	3,650	4	315
333	440022103171301	1N7E33(3)		3,693	3,860	4	430
334	435845103163401	1S7E10BCAC		3,476	3,700	4	300
335	435340103161001	2S7E10BAD		3,366	3,660	4	675
336	435053103170001	2S7E28ADCB		3,492	3,760	4	300
337	435052103182801	2S7E29		3,661	3,800	4	--
338	435052103172901	2S7E28BDCA		3,459	3,825	4	425
339	435050103170501	2S7E28ACDC		3,608	3,700	4	167
340	435050103165301	2S7E28ADD		3,571	3,740	4	320
341	435042103180301	2S7E29DACA		3,527	3,590	4	75
342	435048103171301	2S7E28CABA		3,439	3,545	4	320
343	435031103173401	2S7E28CDBC		3,488	3,560	4	77
344	435028103240601	2S7E28DDCB		3,477	3,760	4	309
345	435018103155801	2S7E34ABBA	CU-83A West Hermosa (WH)	3,554	3,478	1	510
346	435019103173101	2S7E33BABA		3,533	3,820	4	468
347	435010103173001	2S7E33BAC		3,500	3,760	4	292
348	435008103162501	2S7E34BDBC		3,477	3,500	4	225
349	435006103163801	2S7E34BCB		3,590	3,560	4	240

Some wells were monitored discontinuously or were monitored continuously for brief periods (figs. 37-39). Although very few hydraulic-head measurements have been made at the Hart Ranch wells, the measurements indicate that a continuous hydrograph at these locations probably would be very similar to that of well RG (fig. 37).

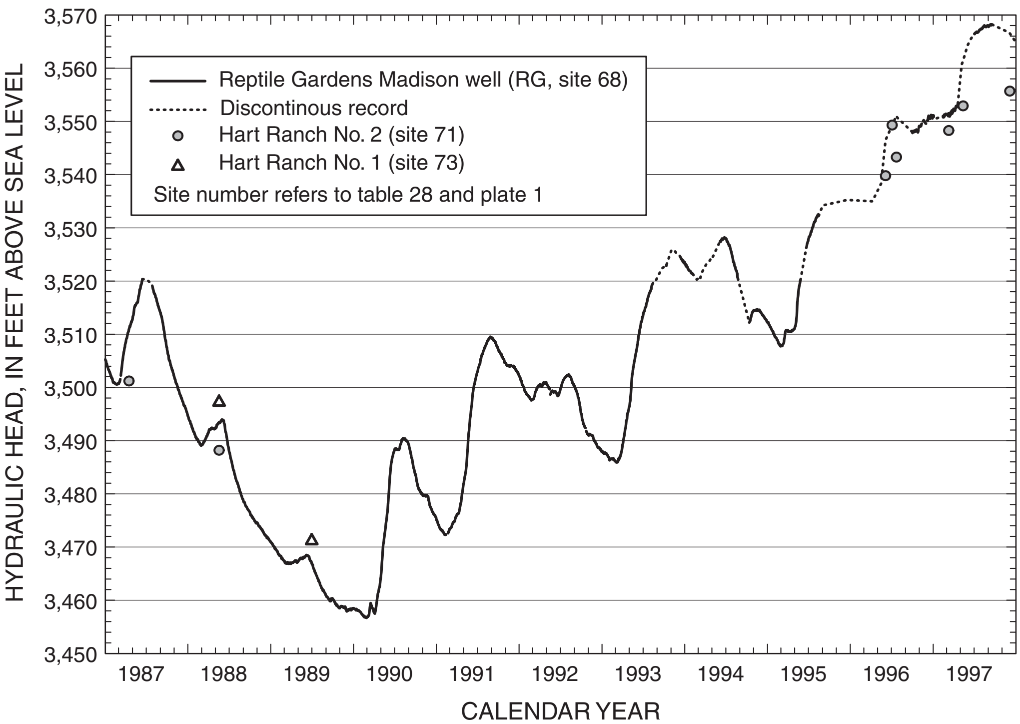

Figure 37. Hydraulic head in Hart Ranch No. 1 and 2 wells plotted with the Reptile Gardens (RG) Madison well. The three wells were completed in the Madison aquifer. The plot shows the similarity of hydraulic head in the Hart Ranch wells to that of the Reptile Gardens well.

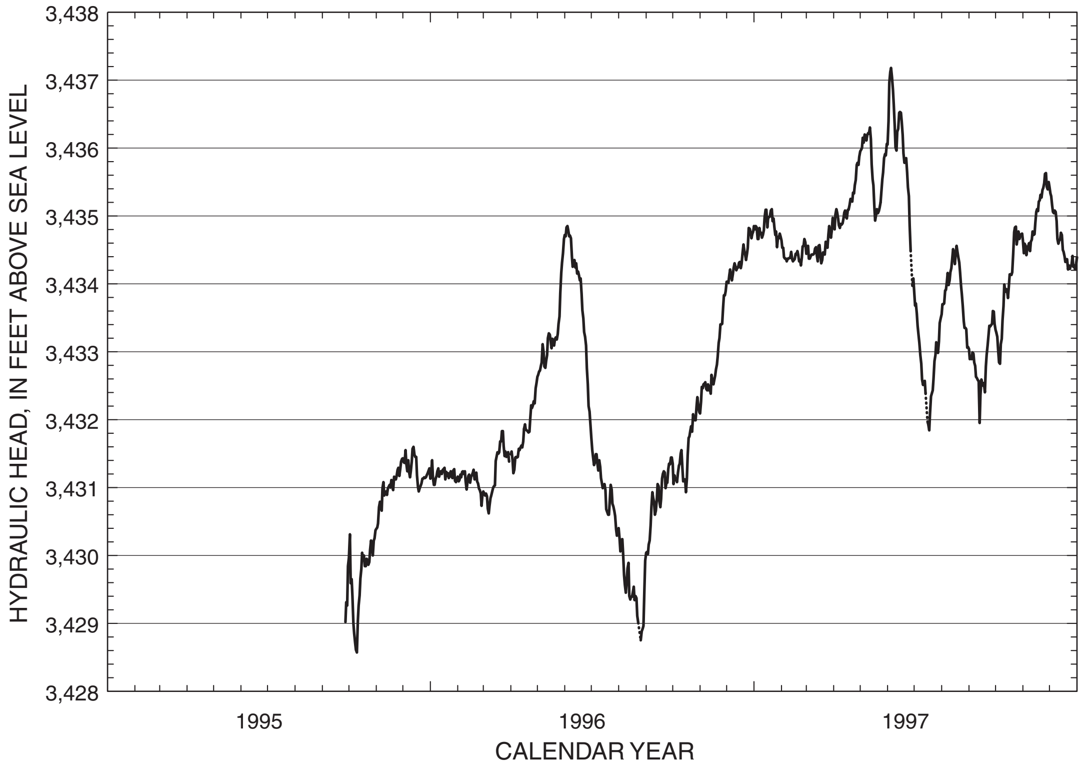

Figure 38. Hydraulic head in well RC-11 (site 62, table 28 and plate 1) completed in the Madison aquifer. The well is influenced by pumping during the summer months.

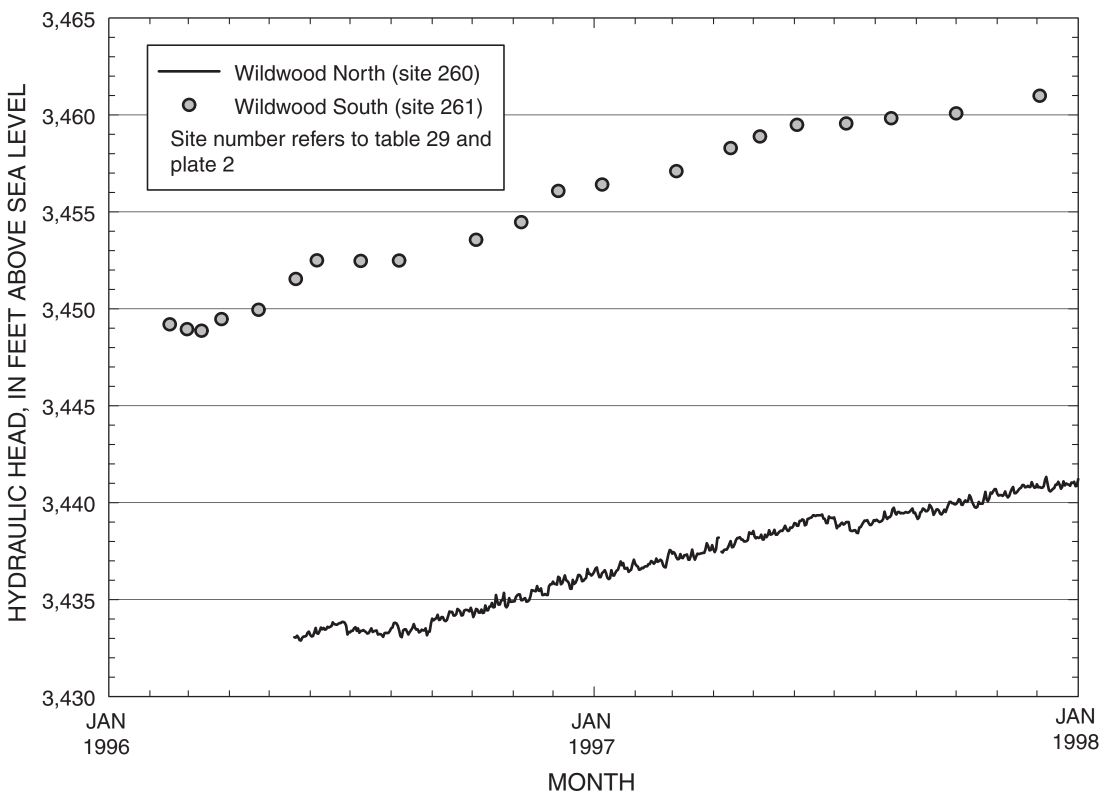

Figure 39. Hydraulic head in the Wildwood North and South wells completed in the Minnelusa aquifer.