## Recharge from Gaged Streams

Gaged streams include basins with either continuous- or miscellaneous-record measurement sites. A summary of loss thresholds and drainage areas for gaged streams is provided in table 2. Loss threshold values for the gaged streams are from Hortness and Driscoll (1998), with the exception of six streams for which loss thresholds were adjusted (table 2), as previously described. Additional details regarding adjustment of loss thresholds are provided in subsequent discussions for individual streams. Loss threshold values denoted in table 2 with less than (<) or greater than (>) are not clearly defined, but are used in subsequent calculations without adjustment. Drainage areas are adjusted where applicable by subtracting any "connected" outcrop areas of the Madison Limestone and Minnelusa Formation, as previously described.

### Continuous-Record Gaging Stations

Annual streamflow recharge is determined for 11 of the 13 basins with continuous streamflow records (fig. 10). Basins 16 and 16A are considered together for recharge calculations. Losses are not calculated for Whitewood Creek (basin 36) because the loss threshold is considered negligible (Hortness and Driscoll, 1998). Recharge calculations for five of the continuous-record basins (Battle, Boxelder, Elk, Spearfish, and Bear Butte Creeks) involve consideration of four miscellaneous-record basins (numbers 21, 30, 38, and 39) and two ungaged basins (numbers 8A and 18A). Thus, these six basins will not be included in subsequent sections addressing miscellaneous-record sites and ungaged streams.

#### Calculated Streamflow Recharge

Daily recharge to the Madison and Minnelusa aquifers is calculated using available records of daily flow for 11 continuous-record gages along with measured loss thresholds for these streams, using the general methods previously described. The daily recharge rates are aggregated to yield annual rates for each year of record. Details of recharge calculations follow, with results for all 11 streams summarized later in this section.

Beaver Creek (basin 1) and French Creek (basin 7) require no adjustments to drainage areas or loss thresholds (table 2). Individual losses to the Madison and Minnelusa are calculated for French Creek because individual loss thresholds have been determined. For Beaver Creek, an estimated average flow of 0.2 $ft^3/s$ is used for the entire month of October 1992 because a complete record was not available.

The loss threshold for Battle Creek (basin 8) is adjusted (table 2) to include runoff generated in an ungaged tributary (basin 8A) using a drainage-area ratio of 1.1. This ratio is used to adjust measured flows reported by Hortness and Driscoll (1998) for site 8, which is used to adjust the loss threshold. The ratio also is used to generate a synthetic record of daily mean flows for site 8 that accounts for the increased drainage area.

No adjustments are needed for Grace Coolidge Creek (basin 10). Individual recharge rates are calculated for the Madison and Minnelusa aquifers for this basin.

The gaging station for Bear Gulch (basin 11) is located downstream of the loss zone and any flow measured at this gaging station must be flow that exceeded the loss threshold value of 0.4 $ft^3/s$. For days of zero flow, it is not known how much flow, if any, is recharge to the Madison aquifer. Thus, for calculation purposes, recharge is assumed equal to one-half the loss threshold, or 0.2 $ft^3/s$. For days with measured flow (greater than 0), the calculated recharge to the Madison aquifer is 0.4 $ft^3/s$.

Hortness and Driscoll (1998) concluded that sealing efforts along Spring Creek (basin 14) probably succeeded in reducing losses, based on reports by Powell (1940). Information regarding possible changes in loss rates is extremely sparse; thus, individual loss rates reported by Hortness and Driscoll (1998) for the Madison and Minnelusa aquifers are used for all calculations. This may result in overestimation of actual recharge for some years.

The Rapid Creek drainage is divided into two basins (fig. 10). Basin 16A is located downstream from site 16 (fig. 9), which measures releases from Pactola Dam. Releases generally are larger than the loss threshold of 10 $ft^3/s$; therefore, tributary inflows generally are inconsequential. From 1947 through 1998, the flow below Pactola Dam was less than the loss threshold only about 7 percent of the time (1,278 days out of 18,993 days). During periods of low flow, minimal tributary inflows would be expected; thus, inflows from basin 16A are neglected in calculating recharge from Rapid Creek.

**Table 2.** Summary of loss thresholds and associated drainage areas of selected streams

[Associated station type: C, continuous-record; M, miscellaneous-record; UG, ungaged. ft$^3$/s, cubic feet per second; mi$^2$, square miles; >, greater than; <, less than; e, estimated; --, none used; ND, not determined; NA, not applicable]

| Basin number | Stream name | Associated station type | Drainage area (mi$^2$) | Adjusted drainage area[1] (mi$^2$) | Loss threshold[2] (ft$^3$/s) | Adjusted loss threshold (ft$^3$/s) | Aquifers potentially receiving recharge |
|---|---|---|---|---|---|---|---|
| 1 | Beaver Creek | C | 45.8 | -- | 5 | -- | Madison, Minnelusa, Minnekahta |
| 2 | Reaves Gulch | M | 6.86 | -- | >0.2 | -- | Madison |
| 3 | Highland Creek | M | 8.69 | -- | e10 | -- | Madison, Minnelusa, Minnekahta |
| 4 | South Fork Lame Johnny Creek | M | 4.34 | -- | 1.4 | -- | Madison, Minnelusa |
| 5 | Flynn Creek | M | 10.3 | -- | ([3]) | | |
| 6 | North Fork Lame Johnny Creek | M | 2.80 | -- | 2.3 | -- | Deadwood, Madison |
| 7 | French Creek | C | 105 | -- | 11<br>4 | -- | Madison<br>Minnelusa |
| 8 | Battle Creek | C | 58 | -- | 12 | 14 | Madison |
| 8A | Battle Creek tributary | UG | 6.59 | 5.33 | ([3]) | | |
| 10 | Grace Coolidge Creek | C | 25.2 | -- | 18<br>3 | -- | Madison<br>Minnelusa |
| 11 | Bear Gulch | C | 4.23 | -- | .4 | -- | Deadwood, Madison, White River Group |
| 12 | Spokane Creek | M | 4.92 | -- | 2.2 | 3.7 | Deadwood, Madison, Minnelusa, Minnekahta |
| 13 | Spokane Creek | M | 3.76 | 2.52 | ([3]) | | |
| 14 | Spring Creek | C | 163 | -- | 21<br>3.5 | -- | Madison<br>Minnelusa |
| 16 | Rapid Creek | C | 320 | -- | 10 | -- | Deadwood, Madison, Minnelusa |
| 16A | Rapid Creek | C | 33.33 | -- | ([3]) | | |
| 17 | Victoria Creek | M | 6.82 | -- | 1 | 2.1 | Deadwood, Madison |
| 17A | Victoria Creek | UG | 5.33 | 4.27 | ([3]) | | |
| 18 | Boxelder Creek | C | 96 | 90 | >25<br><20 | -- | Madison<br>Minnelusa |
| 18A | Boxelder Creek tributary | UG | 13.3 | -- | ([3]) | | |
| 20 | Elk Creek | C | 21.5 | -- | 11<br>8 | -- | Madison<br>Minnelusa |
| 21 | Elk Creek | M | 23.8 | 12.1 | ([3]) | | |
| 23 | Little Elk Creek | M | 12.56 | -- | 0.7<br>2.6 | -- | Madison<br>Minnelusa |
| 24 | Bear Gulch | M | 6.17 | -- | 4 | -- | Deadwood, Madison, Minnelusa |
| 25 | Beaver Creek | M | 6.86 | -- | 9 | 13 | Deadwood, Madison, Minnelusa, Minnekahta |
| 25A | Beaver Creek | UG | 2.90 | 2.15 | ND | | |
| 26 | Iron Creek | M | 8.16 | -- | 0 | -- | NA |

**Table 2.** Summary of loss thresholds and associated drainage areas of selected streams–Continued

[Associated station type: C, continuous-record; M, miscellaneous-record; UG, ungaged. $ft^3/s$, cubic feet per second; $mi^2$, square miles; >, greater than; <, less than; e, estimated; --, none used; ND, not determined; NA, not applicable]

| Basin number | Stream name | Associated station type | Drainage area ($mi^2$) | Adjusted drainage area[1] ($mi^2$) | Loss threshold[2] ($ft^3/s$) | Adjusted loss threshold ($ft^3/s$) | Aquifers potentially receiving recharge |
|---|---|---|---|---|---|---|---|
| 29 | Spearfish Creek | C | 139 | -- | [4]2 | -- | Madison, Minnelusa |
| 30 | Spearfish Creek | M | 8.44 | -- | [5]21 | -- | Madison, Minnelusa |
| 32 | Higgins Gulch | M | 12.55 | -- | 0 | -- | NA |
| 33 | False Bottom Creek | M | 5.55 | -- | 1.4<br>7.3 | 2.9<br>15.1 | Madison<br>Minnelusa |
| 34 | False Bottom Creek | M | 8.91 | 4.92 | ND | | |
| 36 | Whitewood Creek | C | 40.6 | -- | 0 | -- | NA |
| 36A | Whitewood Creek | UG | 5.15 | -- | | | |
| 37 | Bear Butte Creek | C | 16.6 | -- | 3.8<br>4.1 | -- | Madison<br>Minnelusa |
| 38 | Bear Butte Creek | M | 32.23 | 19.2 | | | |
| 39 | Bear Butte Creek | M | 5.59 | 3.33 | 4.2 | | Minnelusa |

[1]Outcrop areas of the Madison Limestone and Minnelusa Formation that are considered to contribute to the regional basin were subtracted.
[2]From Hortness and Driscoll, 1998.
[3]Basin has common loss zone with preceding basin; same loss thresholds and aquifers apply.
[4]Loss within diversion aqueduct.
[5]Threshold loss when flow in Spearfish Creek exceeds the estimated capacity of the diversion aqueduct (115 to 135 $ft^3/s$).

Recharge calculations from Boxelder Creek (basin 18) are complicated by tributary inflows from basin 18A, springflow that occurs within the loss zone, and an isolated outcrop of the Madison Limestone that occurs within the reach largely underlain by the Minnelusa Formation. Hortness and Driscoll (1998) estimated the loss threshold to be greater than 25 $ft^3/s$ for the Madison aquifer and probably less than 20 $ft^3/s$ for the Minnelusa aquifer because recharge that may occur to the isolated outcrop of the Madison Limestone cannot be quantified. Calculations of the combined recharge to the Madison and Minnelusa aquifers probably are more accurate than the individual recharge estimates.

Daily mean flows for site 18 (Boxelder Creek near Nemo) are used to generate a synthetic record of daily mean flows that accounts for runoff generated in the ungaged area that is tributary to Boxelder Creek (basin 18A), using a drainage-area ratio of 1.1. This synthetic record is used to estimate individual and combined recharge to the Madison and Minnelusa aquifers.

Inflows to Elk Creek from tributaries in basin 21, which are located downstream from site 20, are not included in the measured flow at site 20; however, these tributaries were considered by Hortness and Driscoll (1998) in determining the loss threshold. The contribution of the tributaries is estimated using a drainage-area ratio of 1.56, which is the sum of the adjusted drainage areas for sites 20 and 21, divided by the drainage area for site 20. Individual losses to the Madison and Minnelusa aquifers are calculated.

Calculation of recharge from Spearfish Creek is complicated by a hydroelectric diversion installed by Homestake Mining Company in 1910 (Blackstone, 1914). An aqueduct diverts flow from a diversion dam located just downstream from site 29 (fig. 9). Flow is returned to Spearfish Creek at a hydroelectric plant located just upstream from site 31. The aqueduct bypasses the loss zone along Spearfish Creek, which is located between sites 30 and 31. The maximum capacity of the aqueduct diversion was estimated by Hortness and Driscoll (1998) to be between 115 to 135 $ft^3/s$. Above this threshold, excess flows are carried to the loss zone along the natural channel of Spearfish Creek, which has a loss threshold of 21 $ft^3/s$ (table 2). A transmission loss of approximately 2 $ft^3/s$, which is assumed to recharge the Madison and Minnelusa aquifers, occurs in the aqueduct (Hortness and Driscoll, 1998).

In calculating recharge from Spearfish Creek, a constant transmission loss of 2 $ft^3/s$ in the aqueduct is assumed. Routine losses also occur in the natural channel from tributary inflows and springflow in the reach between sites 29 and 30 (basin 30). Numerous miscellaneous flow measurements are available for site 30, which are used to develop a synthetic daily record, based on correlations with daily flow records for site 29. A linear regression analysis using measured values for site 30 for 1988-97 yielded a poor $R^2$ (coefficient of determination) value ($R^2$=0.35), but performed well for predicting low to moderate flows. A second regression was performed using only the period 1988-93, which was dominated by low to moderate flows. The second regression equation was similar to the first, but the resulting $R^2$ value was much higher ($R^2$=0.84). Because the flows at site 30 only are important during low to moderate flows, the second equation [Flow (site 30) = 0.0916*Flow(site 29) - 0.79] is used to generate a synthetic record from 1950-98 using daily mean flows at site 29.

Additional recharge occurs in the natural channel when the flow of Spearfish Creek exceeds the estimated maximum diversion of 115 to 135 $ft^3/s$. Daily flow values for site 31 are adjusted for the transmission loss (2 $ft^3/s$) and natural-channel loss (21 $ft^3/s$), as necessary, for computing daily losses. When the flow at site 31 is less than 113 $ft^3/s$, it is assumed that the flow upstream of the aqueduct diversion is less than 115 $ft^3/s$, with no flow bypassing the diversion. When flow exceeds 133 $ft^3/s$, it is assumed that flow upstream of the aqueduct diversion is greater than 156 $ft^3/s$ and has exceeded the capacity of the aqueduct and the loss threshold of the natural channel; thus, calculated recharge is 21 $ft^3/s$ in the natural channel. When the flow is between 113 and 133 $ft^3/s$, it is assumed that the flow upstream has exceeded the capacity of the aqueduct but has not exceeded the loss threshold. For these cases, it is estimated that one-half the loss threshold, or 10.5 $ft^3/s$, is recharged in the natural channel.

Inflows to Bear Butte Creek from major tributaries in basins 38 and 39, which are located downstream from site 37, are not included in the measured flow at site 37. Tributaries were considered, however, by Hortness and Driscoll (1998) in determining loss thresholds to the Madison and Minnelusa aquifers. Thus, no adjustments are made to the loss thresholds (table 2); however, contributions of tributaries within basins 38 and 39 are accounted for in estimating streamflow recharge within the Bear Butte Creek Basin. Basin 38 consists of outcrops of the Madison Limestone and Minnelusa Formation, intermixed with various other outcrops. Thus, it is assumed that 90 percent of flow generated within this basin would be streamflow recharge, which is assumed to be equally divided between the Madison and Minnelusa aquifers. The contribution for basin 39 is attributed entirely to the Minnelusa aquifer. The contributions of the tributaries within basins 38 and 39 are estimated using drainage-area ratios. Adjusted drainage areas for both basins are divided by the drainage area of basin 37, which yields 1.16 for basin 38 and 0.20 for basin 39. These values then are multiplied by the daily mean flow for site 37 to generate a synthetic record of daily mean flows for the entire period of record for both basin 38 and basin 39.

Annual recharge rates for the 11 streams with continuous-record gaging stations are summarized in table 3, which is ordered by length of available streamflow record for subsequent analyses. The shaded cells in table 3 indicate years for which recharge can be calculated directly from daily flow records, which includes at least 1992-98 for all 11 streams. Estimates for periods without daily records also are presented in table 3 (unshaded cells); methods used for deriving the estimates are described in a subsequent section (Extrapolation of Streamflow Recharge Estimates). Table 3 also provides a subtotal of annual recharge from 9 of the streams that have minimal effects from regulation, along with the total for all 11 streams.

Annual recharge for the streams with continuous-record gaging stations is highly variable. For example, calculated recharge in 1997 is over three times greater than in 1992 (table 3). The proportions of annual streamflow recharge contributed by each of the nine individual streams with minimal regulation, relative to the subtotal for these nine streams, is fairly uniform, however, as shown in table 4. Rapid Creek and Spearfish Creek, which are subject to substantial regulation, are excluded from that analysis. Annual recharge rates for Rapid Creek and Spearfish Creek are quite consistent relative to other basins (table 3), which would indicate large variability in percentage contribution for these two streams.

**Table 3.** Annual recharge for basins with continuous-record stations, water years 1950-98

[Shaded cells show calculated values for period of daily flow record. Unshaded cells show values derived from extrapolation of streamflow recharge estimates. --, not determined]

| Water year | Annual recharge (cubic feet per second) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rapid Creek (basins 16 and 16A) | Spearfish Creek (basins 29 and 30) | Battle Creek (basins 8 and 8A) | Boxelder Creek (basins 18 and 18A) | Grace Coolidge Creek (basin 10) | French Creek (basin 7) | Spring Creek (basin 14) | Bear Butte Creek (basins 37, 38, 39) | Bear Gulch (basin 11) | Beaver Creek (basin 1) | Elk Creek (basins 20 and 21) | Subtotal[1] | Total[2] |
| 1950 | 10.00 | 5.14 | 3.50 | 9.89 | 2.22 | 4.22 | 6.33 | 8.62 | 0.36 | 1.74 | 7.62 | 44.50 | 59.64 |
| 1951 | 9.96 | 4.65 | 3.36 | 8.14 | 2.34 | 3.87 | 5.91 | 7.72 | .35 | 1.22 | 7.06 | 39.96 | 54.57 |
| 1952 | 9.98 | 5.58 | 5.01 | 12.70 | 3.97 | 5.05 | 18.95 | 9.61 | .33 | .81 | 7.26 | 63.67 | 79.23 |
| 1953 | 10.00 | 5.83 | 3.84 | 11.46 | 2.27 | 4.33 | 11.93 | 8.79 | .36 | 1.81 | 7.72 | 52.51 | 68.34 |
| 1954 | 10.00 | 4.84 | 3.01 | 7.19 | 1.80 | 3.31 | 2.22 | 7.47 | .35 | 1.17 | 6.79 | 33.32 | 48.16 |
| 1955 | 10.00 | 5.48 | 2.87 | 7.28 | 1.71 | 3.53 | 0.00 | 7.80 | .36 | 1.51 | 7.15 | 32.21 | 47.69 |
| 1956 | 9.97 | 4.71 | 3.06 | 6.60 | 1.98 | 3.21 | 3.74 | 7.00 | .34 | .86 | 6.51 | 33.29 | 47.97 |
| 1957 | 9.02 | 4.95 | 5.50 | 12.90 | 4.98 | 5.64 | 19.99 | 10.15 | .31 | .39 | 7.19 | 67.05 | 81.02 |
| 1958 | 8.65 | 4.81 | 3.44 | 7.60 | 2.48 | 3.63 | 6.41 | 7.48 | .33 | .81 | 6.65 | 38.83 | 52.29 |
| 1959 | 9.45 | 4.38 | 3.01 | 5.39 | 1.93 | 2.64 | 4.74 | 6.21 | .32 | .29 | 5.82 | 30.35 | 44.18 |
| 1960 | 8.71 | 4.08 | 2.97 | 5.55 | 1.82 | 2.63 | 4.58 | 6.25 | .33 | .40 | 5.90 | 30.41 | 43.20 |
| 1961 | 9.67 | 3.70 | 2.87 | 4.39 | 1.72 | 2.14 | 4.70 | 5.56 | .31 | .00 | 5.34 | 27.04 | 40.41 |
| 1962 | 7.82 | 4.78 | 4.43 | 16.39 | 4.54 | 6.36 | 16.78 | 12.49 | .35 | 1.64 | 8.47 | 71.45 | 84.05 |
| 1963 | 7.78 | 6.45 | 6.61 | 13.56 | 4.10 | 6.07 | 4.94 | 12.21 | .35 | 1.80 | 8.47 | 58.12 | 72.35 |
| 1964 | 10.00 | 6.64 | 5.61 | 11.78 | 2.59 | 5.17 | 4.68 | 10.11 | .38 | 2.39 | 8.53 | 51.24 | 67.88 |
| 1965 | 10.00 | 8.19 | 5.79 | 21.06 | 5.53 | 8.58 | 7.59 | 17.16 | .38 | 3.07 | 10.53 | 79.70 | 97.89 |
| 1966 | 10.00 | 6.56 | 3.94 | 12.22 | 2.31 | 4.85 | 9.11 | 9.59 | .38 | 2.34 | 8.35 | 53.08 | 69.64 |
| 1967 | 10.00 | 6.44 | 5.18 | 18.13 | 4.33 | 7.05 | 11.54 | 11.91 | .35 | 1.72 | 7.75 | 67.97 | 84.41 |
| 1968 | 10.00 | 5.84 | 3.84 | 9.57 | 2.97 | 4.22 | 7.28 | 9.04 | .32 | .27 | 6.05 | 43.57 | 59.41 |
| 1969 | 9.99 | 6.15 | 3.11 | 9.18 | 2.33 | 3.81 | 6.21 | 7.47 | .32 | .20 | 5.12 | 37.76 | 53.90 |
| 1970 | 10.00 | 8.26 | 3.89 | 16.76 | 3.18 | 6.14 | 9.45 | 9.14 | .35 | 1.49 | 6.11 | 56.50 | 74.76 |
| 1971 | 10.00 | 8.02 | 5.01 | 19.21 | 4.21 | 7.27 | 11.64 | 11.55 | .35 | 1.90 | 7.54 | 68.68 | 86.70 |
| 1972 | 9.86 | 8.01 | 5.59 | 18.18 | 4.68 | 7.24 | 12.08 | 12.78 | .35 | 1.73 | 8.26 | 70.89 | 88.76 |
| 1973 | 10.00 | 8.72 | 5.56 | 16.79 | 4.63 | 6.86 | 11.64 | 12.73 | .35 | 1.49 | 8.23 | 68.29 | 87.01 |
| 1974 | 10.00 | 6.63 | 1.81 | 6.58 | 1.15 | 2.57 | 3.76 | 4.69 | .31 | .00 | 3.48 | 24.35 | 40.98 |

**Table 3.** Annual recharge for basins with continuous-record stations, water years 1950-98–Continued

[Shaded cells show calculated values for period of daily flow record. Unshaded cells show values derived from extrapolation of streamflow recharge estimates. --, not determined]

| Water year | Annual recharge (cubic feet per second) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rapid Creek (basins 16 and 16A) | Spearfish Creek (basins 29 and 30) | Battle Creek (basins 8 and 8A) | Boxelder Creek (basins 18 and 18A) | Grace Coolidge Creek (basin 10) | French Creek (basin 7) | Spring Creek (basin 14) | Bear Butte Creek (basins 37, 38, 39) | Bear Gulch (basin 11) | Beaver Creek (basin 1) | Elk Creek (basins 20 and 21) | Subtotal[1] | Total[2] |
| 1975 | 9.99 | 6.55 | 3.67 | 14.89 | 2.95 | 5.55 | 8.62 | 8.67 | 0.34 | 1.17 | 5.83 | 51.69 | 68.23 |
| 1976 | 10.00 | 6.59 | 5.16 | 15.18 | 4.25 | 6.27 | 10.65 | 11.87 | .34 | 1.22 | 7.73 | 62.67 | 79.26 |
| 1977 | 10.00 | 6.72 | 2.93 | 14.73 | 1.27 | 5.20 | 7.60 | 7.08 | .34 | 1.14 | 4.89 | 45.18 | 61.90 |
| 1978 | 9.99 | 7.67 | 4.46 | 15.84 | 3.90 | 6.14 | 9.93 | 10.37 | .34 | 1.33 | 6.83 | 59.14 | 76.80 |
| 1979 | 10.00 | 6.28 | 4.13 | 8.79 | 3.66 | 4.14 | 7.42 | 9.65 | .32 | .13 | 6.41 | 44.64 | 60.92 |
| 1980 | 10.00 | 5.59 | 2.72 | 5.94 | 1.17 | 2.79 | 4.76 | 6.65 | .31 | .00 | 4.63 | 28.98 | 44.57 |
| 1981 | 10.00 | 5.03 | 3.01 | 4.55 | 2.45 | 2.54 | 4.71 | 7.25 | .31 | .00 | 4.99 | 29.80 | 44.83 |
| 1982 | 9.90 | 6.30 | 4.14 | 10.14 | 3.89 | 4.50 | 7.84 | 9.69 | .32 | .36 | 6.43 | 47.32 | 63.52 |
| 1983 | 10.00 | 7.82 | 3.81 | 21.64 | 2.48 | 7.05 | 10.78 | 8.97 | .36 | 2.31 | 6.01 | 63.42 | 81.24 |
| 1984 | 10.00 | 8.03 | 4.89 | 19.63 | 3.97 | 6.86 | 11.60 | 11.28 | .36 | 1.97 | 7.37 | 67.92 | 85.95 |
| 1985 | 10.00 | 5.48 | 1.22 | 7.17 | .82 | 3.53 | 3.16 | 3.42 | .31 | .00 | 2.73 | 22.36 | 37.84 |
| 1986 | 10.00 | 5.65 | 4.32 | 13.10 | 2.03 | 3.63 | 8.94 | 10.07 | .33 | .87 | 6.66 | 49.97 | 65.62 |
| 1987 | 10.00 | 4.83 | 6.22 | 10.92 | 3.49 | 5.50 | 10.64 | 14.15 | .33 | .50 | 9.07 | 60.82 | 75.65 |
| 1988 | 10.00 | 4.92 | .76 | 5.07 | .61 | 2.11 | 1.80 | 2.44 | .31 | .00 | 2.15 | 15.25 | 30.17 |
| 1989 | 10.00 | 5.03 | .89 | 4.19 | 1.20 | 1.02 | .98 | 5.56 | .30 | .00 | 2.31 | 16.46 | 31.49 |
| 1990 | 10.00 | 5.04 | 5.09 | 6.18 | 3.40 | 3.65 | 6.76 | 6.76 | .33 | .00 | 7.63 | 39.80 | 54.84 |
| 1991 | 9.99 | 4.94 | 5.15 | 11.21 | 4.92 | 5.63 | 10.92 | 11.25 | .29 | .23 | 7.71 | 57.32 | 72.25 |
| 1992 | 10.00 | 4.78 | 3.72 | 7.57 | 2.98 | 4.48 | 7.46 | 5.03 | .32 | .33 | 4.67 | 36.55 | 51.33 |
| 1993 | 10.00 | 5.26 | 6.66 | 18.05 | 7.12 | 7.26 | 13.35 | 12.76 | .34 | .76 | 8.36 | 74.66 | 89.92 |
| 1994 | 10.00 | 6.78 | 5.21 | 17.53 | 3.27 | 6.02 | 11.63 | 14.24 | .35 | 1.35 | 9.15 | 68.75 | 85.53 |
| 1995 | 10.00 | 8.56 | 6.17 | 21.09 | 7.20 | 8.91 | 13.64 | 21.52 | .36 | 2.77 | 10.04 | 91.70 | 110.26 |
| 1996 | 10.00 | 9.20 | 8.10 | 25.55 | 6.45 | 10.92 | 18.02 | 18.12 | .39 | 3.98 | 11.52 | 103.07 | 122.27 |
| 1997 | 10.00 | 10.92 | 10.50 | 34.08 | 9.31 | 13.07 | 22.15 | 25.60 | .39 | 3.89 | 13.91 | 132.89 | 153.81 |
| 1998 | 10.00 | 9.59 | 8.26 | 28.30 | 7.57 | 12.12 | 18.89 | 15.27 | .39 | 3.56 | 12.25 | 106.61 | 126.20 |

[1]Subtotal for nine basins with minimal regulation (excludes Rapid and Spearfish Creeks). Individual values may not sum to subtotal due to independent rounding.
[2]Total for all basins. Individual values may not sum to total due to independent rounding.

**Table 4**. Calculated percentages of annual streamflow recharge for nine streams with minimal regulation, water years 1992-98

[$ft^3/s$, cubic feet per second; --, not determined]

| Water year | Percent of subtotal of annual recharge[1] | | | | | | | | | Subtotal of annual recharge[2] ($ft^3/s$) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Battle Creek (basins 8 and 8A) | Boxelder Creek (basins 18 and 18A) | Grace Coolidge Creek (basin 10) | French Creek (basin 7) | Spring Creek (basin 14) | Bear Butte Creek (basins 37, 38, 39) | Bear Gulch (basin 11) | Beaver Creek (basin 1) | Elk Creek (basins 20 and 21) | |
| 1992 | 10.17 | 20.71 | 8.15 | 12.27 | 20.40 | 13.77 | 0.88 | 0.89 | 12.77 | 36.55 |
| 1993 | 8.92 | 24.17 | 9.54 | 9.73 | 17.87 | 17.10 | .46 | 1.02 | 11.19 | 74.66 |
| 1994 | 7.58 | 25.51 | 4.75 | 8.75 | 16.92 | 20.72 | .51 | 1.96 | 13.31 | 68.75 |
| 1995 | 6.73 | 23.00 | 7.86 | 9.72 | 14.88 | 23.47 | .39 | 3.02 | 10.94 | 91.70 |
| 1996 | 7.86 | 24.79 | 6.26 | 10.60 | 17.49 | 17.58 | .38 | 3.86 | 11.18 | 103.07 |
| 1997 | 7.90 | 25.64 | 7.01 | 9.83 | 16.66 | 19.26 | .29 | 2.93 | 10.47 | 132.89 |
| 1998 | 7.75 | 26.54 | 7.10 | 11.37 | 17.72 | 14.32 | .37 | 3.34 | 11.49 | 106.61 |
| Average | 8.13 | 24.34 | 7.24 | 10.32 | 17.42 | 18.03 | 0.47 | 2.43 | 11.62 | -- |

[1]Individual values may not sum to 100 percent because of independent rounding.
[2]Subtotals taken from table 3.

Individual threshold values available for the Madison and Minnelusa aquifers were available for six streams (French, Grace Coolidge, Spring, Boxelder, Elk, and Bear Butte Creeks). Annual recharge rates, by aquifer, are summarized for these streams in table 5.

### Extrapolation of Streamflow Recharge Estimates

Calculated streamflow recharge for 1992-98 is not representative of the long-term average because of above-average precipitation during this period (Driscoll, Hamade, and Kenner, 2000). To determine an unbiased average, estimates of recharge over an extended period that includes both above- and below-average precipitation conditions are needed. A record extending back to the 1950's would include these conditions. However, only the records from Rapid Creek and Spearfish Creek extend back to 1950, and the majority of the records do not extend prior to the late 1980's (table 1). This section describes methods used to extrapolate recharge estimates back to 1950 for streams with continuous-record gaging stations.

Of the unregulated streams with continuous-record gages (excluding Rapid Creek and Spearfish Creek), Battle Creek and Boxelder Creek have the longest periods of record. Single and multiple linear regression analyses were performed, using annual recharge from Battle Creek and Boxelder Creek as possible explanatory variables for annual recharge from the other seven streams (data presented in table 3). The best regression equation with either one or both explanatory variables was selected based on the $R^2$ values and statistical significance of the explanatory variables. Results of the multiple/single regression analyses are summarized in table 6, with resulting $R^2$ values ranging from 0.69 to 0.99. The equations determined by the multiple/single regression (table 6) were used to extrapolate recharge for the streams with continuous-record gages for years without streamflow records for 1967-91.

The preceding regressions provided satisfactory estimates for missing values during 1967-91. Another method was needed, however, to estimate recharge for 1950-66. Several gaging stations in the Black Hills area that are located downstream of loss zones have continuous records of flow dating back to at least 1950 (Miller and Driscoll, 1998). Four gaging stations (table 1) were selected as possible representative indicators of flow for the nine gages with no records for 1950-67. Locations of Battle Creek at Hermosa (site 9), Spring Creek near Hermosa (site 15), and Redwater River above Belle Fourche (site 35) are shown in figure 9. The location of Elk Creek near Elm Springs (site 22; 06425500) is shown in figure 1.

**Table 5.** Annual recharge, by aquifer, for streams with continuous-record stations, water years 1967-98

[--, not determined]

| Water year | Annual recharge[1] (cubic feet per second) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | French Creek (basin 7) | | Grace Coolidge Creek (basin 10) | | Spring Creek (basin 14) | | Boxelder Creek[2] (basins 18 and 18A) | | Elk Creek (basins 20 and 21) | | Bear Butte Creek (basins 37, 38, and 39) | |
| | Madison | Minnelusa | Madison | Minnelusa | Madison | Minnelusa | Madison | Minnelusa | Madison | Minnelusa | Madison | Minnelusa |
| 1967 | -- | -- | -- | -- | -- | -- | 13.96 | 4.17 | -- | -- | -- | -- |
| 1968 | -- | -- | -- | -- | -- | -- | 9.50 | .07 | -- | -- | -- | -- |
| 1969 | -- | -- | -- | -- | -- | -- | 8.60 | .59 | -- | -- | -- | -- |
| 1970 | -- | -- | -- | -- | -- | -- | 12.40 | 4.36 | -- | -- | -- | -- |
| 1971 | -- | -- | -- | -- | -- | -- | 14.21 | 4.99 | -- | -- | -- | -- |
| 1972 | -- | -- | -- | -- | -- | -- | 14.48 | 3.70 | -- | -- | -- | -- |
| 1973 | -- | -- | -- | -- | -- | -- | 13.82 | 2.97 | -- | -- | -- | -- |
| 1974 | -- | -- | -- | -- | -- | -- | 6.58 | .00 | -- | -- | -- | -- |
| 1975 | -- | -- | -- | -- | -- | -- | 11.05 | 3.84 | -- | -- | -- | -- |
| 1976 | -- | -- | -- | -- | -- | -- | 12.95 | 2.23 | -- | -- | -- | -- |
| 1977 | -- | -- | 1.27 | 0.00 | -- | -- | 12.09 | 2.65 | -- | -- | -- | -- |
| 1978 | -- | -- | 3.66 | .24 | -- | -- | 12.89 | 2.95 | -- | -- | -- | -- |
| 1979 | -- | -- | 3.52 | .14 | -- | -- | 8.74 | .05 | -- | -- | -- | -- |
| 1980 | -- | -- | 1.17 | .00 | -- | -- | 5.93 | .01 | -- | -- | -- | -- |
| 1981 | -- | -- | 2.36 | .08 | -- | -- | 4.55 | .00 | -- | -- | -- | -- |
| 1982 | -- | -- | 3.76 | .13 | -- | -- | 8.66 | 1.48 | -- | -- | -- | -- |
| 1983 | 6.47 | 0.59 | 2.49 | .00 | -- | -- | 17.18 | 4.45 | -- | -- | -- | -- |
| 1984 | 5.82 | 1.05 | 3.85 | .11 | -- | -- | 14.94 | 4.69 | -- | -- | -- | -- |
| 1985 | 3.50 | .03 | .82 | .00 | -- | -- | 6.97 | .20 | -- | -- | -- | -- |
| 1986 | 3.44 | .19 | 2.03 | .00 | -- | -- | 11.38 | 1.72 | -- | -- | -- | -- |
| 1987 | 5.01 | .50 | 3.49 | .00 | 9.94 | 0.71 | 10.10 | .82 | -- | -- | -- | -- |
| 1988 | 1.95 | .16 | .60 | .01 | 1.80 | .00 | 5.05 | .02 | -- | -- | -- | -- |
| 1989 | 1.02 | .00 | 1.18 | .02 | .98 | .01 | 4.18 | .00 | -- | -- | 3.19 | 2.37 |
| 1990 | 3.21 | .44 | 3.31 | .09 | 6.28 | .48 | 6.18 | .00 | -- | -- | 3.64 | 3.12 |
| 1991 | 4.85 | .79 | 4.60 | .32 | 9.97 | .96 | 9.05 | 2.17 | -- | -- | 5.65 | 5.60 |
| 1992 | 4.34 | .14 | 2.98 | .00 | 7.45 | .01 | 7.57 | .00 | 4.61 | .06 | 3.07 | 1.96 |
| 1993 | 6.02 | 1.24 | 6.82 | .30 | 11.99 | 1.36 | 13.41 | 4.64 | 5.97 | 2.38 | 6.22 | 6.54 |
| 1994 | 5.36 | .65 | 3.27 | .00 | 11.07 | .56 | 13.75 | 3.78 | 6.95 | 2.20 | 7.23 | 7.01 |
| 1995 | 7.28 | 1.63 | 6.76 | .44 | 12.56 | 1.08 | 15.72 | 5.37 | 7.91 | 2.13 | 10.87 | 10.65 |
| 1996 | 9.25 | 1.67 | 6.27 | .19 | 16.72 | 1.31 | 19.00 | 6.55 | 8.87 | 2.65 | 9.09 | 9.03 |
| 1997 | 10.39 | 2.68 | 8.99 | .32 | 19.72 | 2.43 | 22.60 | 11.48 | 9.96 | 3.95 | 12.60 | 13.01 |
| 1998 | 9.98 | 2.14 | 7.42 | .15 | 16.67 | 2.22 | 21.07 | 7.23 | 8.97 | 3.28 | 7.66 | 7.61 |

[1]Individual recharge estimates may not sum exactly to combined estimates in table 3 due to independent rounding.
[2]Individual recharge estimates probably are not as accurate as combined recharge estimates.

**Table 6.** Regression equations used to estimate average annual streamflow recharge for nine streams with continuous-record stations

[--, not used; all regressions performed using units of cubic feet per second]

| Stream | Recharge regression[1] (1967-91) | | | | Streamflow regression[2] (1950-66) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Intercept | Battle Creek coefficient | Boxelder Creek coefficient | $R^2$ for equation | Intercept | Battle Creek at Hermosa coefficient | Spring Creek near Hermosa coefficient | Elk Creek near Elm Springs coefficient | Redwater River above Belle Fourche coefficient | $R^2$ for equation |
| Battle Creek | -- | -- | -- | -- | 2.4377 | 0.1027 | -- | 0.0149 | -- | 0.6376 |
| Boxelder Creek | -- | -- | -- | -- | .6269 | .1744 | -- | .0661 | 0.0629 | .7812 |
| Grace Coolidge Creek | -0.5681 | 0.8617 | 0.0239 | 0.8600 | 1.5650 | .1498 | -- | -- | -- | .8300 |
| French Creek | .0618 | .4255 | .2640 | .9504 | .2904 | .0952 | -- | -- | .0307 | .8050 |
| Spring Creek | -.5360 | 1.3025 | .2938 | .9859 | 9.8398 | 1.2121 | -1.2064 | .2807 | -.1120 | .8931 |
| Bear Butte Creek | .8113 | 2.1422 | -- | .6932 | 3.4155 | -- | .2080 | -- | .0487 | .9121 |
| Bear Gulch | .2911 | -- | .0033 | .7581 | .2635 | -.0020 | -- | -- | .0009 | .8484 |
| Beaver Creek | -1.3553 | -- | .1696 | .8457 | -1.9310 | -.0531 | -- | -- | .0341 | .9053 |
| Elk Creek | 1.1810 | 1.2676 | -- | .8768 | 2.4484 | -- | -- | -- | .0396 | .7175 |

[1]Regression performed using calculated annual recharge for selected streams (dependent variable) with average annual recharge for Battle Creek and/or Boxelder Creek (explanatory variable).
[2]Stepwise regression performed using calculated annual recharge for selected streams (dependent variable) with annual flow at selected streams (explanatory variable).

A stepwise regression analysis was performed using the average annual mean flow of these four representative streams as possible explanatory variables for annual streamflow recharge for selected streams. The explanatory variables were considered significant only if the p-values (attained level of significance) were less than 0.15. Results of stepwise regression analyses are provided in table 6. The best regression for some of the streams included only one of the four representative gaging stations, whereas the best regression for Spring Creek included all four representative gaging stations. The results of the stepwise regression generally were good with $R^2$ values ranging from 0.64 to 0.91. The equations determined by the stepwise regression (table 6) were used to estimate recharge for selected streams beginning with 1950.

The recharge estimates based on both the recharge regressions (1967-91) and the stepwise regressions (1950-98) are presented in table 17 in the Supplemental Information section. The calculated recharge rates also are included in table 17 for comparison purposes, along with a summary of mean values for calculated values and estimates for the periods 1950-98, 1967-98, and 1992-98. Comparisons of calculated values and means to estimated values and means for 1992-98 are particularly informative. Differences between calculated and estimated values generally are small and exhibit no apparent bias (consistently lower or higher). It is recognized that large uncertainties exist for estimates for any site for any year. However, these favorable comparisons provide confidence that the methods used provide credible, unbiased estimates. The recharge estimates used in the final streamflow recharge total are presented in table 3.

### Miscellaneous-Record Measurement Sites

This section presents estimates of streamflow recharge for 11 basins with miscellaneous-record measurement sites. Daily flow records are not available for these basins; however, loss thresholds (table 2) were determined by Hortness and Driscoll (1998). Four basins with miscellaneous-record measurement sites (basins 21, 30, 38, and 39) were considered earlier with continuous-record gaging stations. Hortness and Driscoll (1998) determined that Iron Creek (basin 26) and Higgins Gulch (basin 32) are gaining streams across the outcrops of the Madison Limestone and Minnelusa Formation; therefore, no recharge is calculated for these two sites.

Loss thresholds are adjusted for Spokane Creek, Victoria Creek, Beaver Creek, and False Bottom Creek (table 2) using the methods previously described. The loss thresholds for Victoria Creek and Beaver Creek include losses from ungaged areas (basins 17A and 25A). Therefore, these ungaged areas are included with the following analyses and will not be included in a subsequent section addressing ungaged streams.

Annual recharge was calculated by applying previously determined loss thresholds against synthetic records of daily flow. A representative continuous-record gaging station was selected for each miscellaneous-record basin based on proximity, streamflow characteristics, and elevation. Daily flow records were synthesized by applying drainage-area ratios to daily flows for the representative continuous-record gages. Representative gaging stations and drainage-area ratios, which are based on adjusted drainage areas, are listed in table 7. In several cases, two basins associated with the same stream are combined for calculation of recharge. Individual recharge to the Madison and Minnelusa aquifers is determined for two basins.

Annual recharge from the miscellaneous-record basins is summarized in table 8 for 1992-98. The miscellaneous-record basins in the northern Black Hills (Little Elk, Bear Gulch, Beaver, and False Bottom) generally provide more recharge than those in the central or southern Black Hills. Estimates of recharge from these basins for 1950-91 are presented in a subsequent section (Summary of Streamflow Recharge, 1950-98).

**Table 7.** Summary of selected information used to estimate recharge from streams with miscellaneous-record measurement sites

| Stream name and basin number | Representative continuous-record gaging station | Drainage-area ratio |
|---|---|---|
| Reaves Gulch (2) | French Creek (site 7) | 0.065 |
| Highland Creek (3) | French Creek (site 7) | .083 |
| South Fork Lame Johnny Creek and Flynn Creek (4 and 5) | French Creek (site 7) | .139 |
| North Fork Lame Johnny Creek (6) | French Creek (site 7) | .027 |
| Spokane Creek (12 and 13) | Battle Creek (site 8) | .128 |
| Victoria Creek (17 and 17A) | Battle Creek (site 8) | .191 |
| Little Elk Creek (23) | Boxelder Creek (site 18) | .131 |
| Bear Gulch (24) | Annie Creek (site 27) | 1.74 |
| Beaver Creek (25 and 25A) | Squaw Creek (site 28) | 1.30 |
| False Bottom Creek (33 and 34) | Squaw Creek (site 28) | 1.50 |

**Table 8.** Annual recharge for streams with miscellaneous-record measurement sites, water years 1992-98

| Water year | Annual recharge (cubic feet per second) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Reaves Gulch (basin 2) | Highland Creek (basin 3) | South Fork Lame Johnny Creek and Flynn Creek (basins 4 and 5) | North Fork Lame Johnny Creek (basin 6) | Spokane Creek (basins 12 and 13) | Victoria Creek (basins 17 and 17A) | Little Elk Creek (basin 23) | Bear Gulch (basin 24) | Beaver Creek (basins 25 and 25A) | False Bottom Creek (basins 33 and 34) | Total[1] |
| 1992 | 0.17 | 0.37 | 0.60 | 0.12 | 0.45 | 0.64 | 0.90 | 0.56 | 1.23 | 1.46 | 6.50 |
| 1993 | .15 | .96 | .79 | .30 | 1.14 | 1.06 | 1.69 | 1.36 | 3.16 | 3.88 | 14.49 |
| 1994 | .17 | .59 | .72 | .19 | .65 | .88 | 1.72 | 1.50 | 2.97 | 3.66 | 13.05 |
| 1995 | .19 | 2.27 | .95 | .63 | 1.24 | 1.13 | 1.96 | 2.27 | 5.07 | 6.27 | 21.98 |
| 1996 | .20 | 1.45 | 1.22 | .46 | 1.17 | 1.33 | 2.39 | 1.79 | 5.08 | 6.36 | 21.45 |
| 1997 | .20 | 2.01 | 1.34 | .64 | 1.79 | 1.67 | 2.89 | 2.13 | 4.75 | 5.92 | 23.36 |
| 1998 | .20 | 1.59 | 1.30 | .51 | 1.25 | 1.33 | 2.67 | 2.25 | 3.33 | 4.01 | 18.45 |

[1]Individual estimates may not sum to total due to independent rounding.

Annual recharge rates, by aquifer, are presented in table 9 for the two miscellaneous-record measurement sites for which individual loss thresholds had been determined by Hortness and Driscoll (1998). For both Little Elk Creek and False Bottom Creek, annual recharge estimates for the Madison aquifer were relatively consistent for 1992-98; whereas, recharge for the Minnelusa aquifer in 1992 was much smaller than in the other years. This is because most of the flow in 1992 was lost to the Madison aquifer before reaching the outcrop of the Minnelusa Formation.

## Recharge from Ungaged Streams

Ungaged basins generally consist of small drainage areas with undetermined loss thresholds that are situated between larger basins for which loss thresholds have been determined (fig. 10). Recharge for five ungaged basins were considered earlier with either continuous-record gaging stations (basins 8A, 18A, and 36A) or miscellaneous-record measurement sites (basins 17A and 25A). Flow seldom occurs downstream from the loss zones in these small basins; thus, a simplifying assumption is made that 90 percent of streamflow generated within these basins becomes recharge to the Madison and Minnelusa aquifers. Annual streamflow for selected representative continuous-record gages is used to estimate annual streamflow in the ungaged streams based on the ratio of drainage areas.

**Table 9**. Annual recharge, by aquifer, for streams with miscellaneous-record measurement sites, water years 1992-98

| Water year | Annual recharge[1] (cubic feet per second) | | | |
|---|---|---|---|---|
| | Little Elk Creek (basin 23) | | False Bottom Creek (basins 33 and 34) | |
| | Madison | Minnelusa | Madison | Minnelusa |
| 1992 | 0.66 | 0.24 | 1.17 | 0.29 |
| 1993 | .59 | 1.11 | 1.63 | 2.25 |
| 1994 | .70 | 1.03 | 1.69 | 1.98 |
| 1995 | .70 | 1.27 | 2.43 | 3.84 |
| 1996 | .70 | 1.70 | 2.49 | 3.87 |
| 1997 | .70 | 2.19 | 2.59 | 3.33 |
| 1998 | .70 | 1.99 | 1.97 | 2.04 |

[1]Individual recharge estimates may not sum exactly to combined estimates in table 8 due to independent rounding.

Four continuous-record gages were selected to represent streamflow in 18 ungaged basins (fig. 11), with each ungaged basin assigned to one of the representative gages. The drainage areas for all ungaged basins associated with each gage were summed, and common drainage-area ratios were computed. Annual streamflow for 1992-98 for each of the representative gages was then multiplied by the applicable ratio to yield annual streamflow for each group of ungaged basins. Annual recharge for the ungaged basins (computed as 90 percent of streamflow) is summarized by group in table 10. Estimates of recharge from ungaged basins for 1950-91 are addressed in the following section.

**Table 10**. Annual streamflow recharge from ungaged basins, water years 1992-98

[--, not determined]

| Water year | Annual recharge (cubic feet per second) | | | | | |
|---|---|---|---|---|---|---|
| | Ungaged basins and representative continuous-record stations | | | | | Total[1] |
| | Basins 40-50 (French Creek) | Basins 51-55 (Battle Creek) | Basin 56 (Bear Butte Creek) | Basin 57 (Squaw Creek) | Wyoming basins | |
| 1992 | 2.02 | 0.67 | 1.31 | 0.89 | 3.58 | 8.47 |
| 1993 | 5.29 | 2.91 | 4.36 | 2.83 | 9.04 | 24.42 |
| 1994 | 3.11 | .97 | 5.03 | 3.52 | 8.94 | 21.58 |
| 1995 | 15.30 | 5.33 | 8.41 | 7.60 | 14.68 | 51.33 |
| 1996 | 7.76 | 2.77 | 6.53 | 4.96 | 13.74 | 35.76 |
| 1997 | 10.89 | 4.56 | 9.79 | 5.38 | 13.76 | 44.38 |
| 1998 | 8.60 | 2.48 | 4.86 | 3.02 | 11.16 | 30.12 |
| Combined area (square miles) | 51.47 | 12.41 | 10.55 | 6.96 | -- | -- |

[1]Individual recharge estimates may not sum to total due to independent rounding.

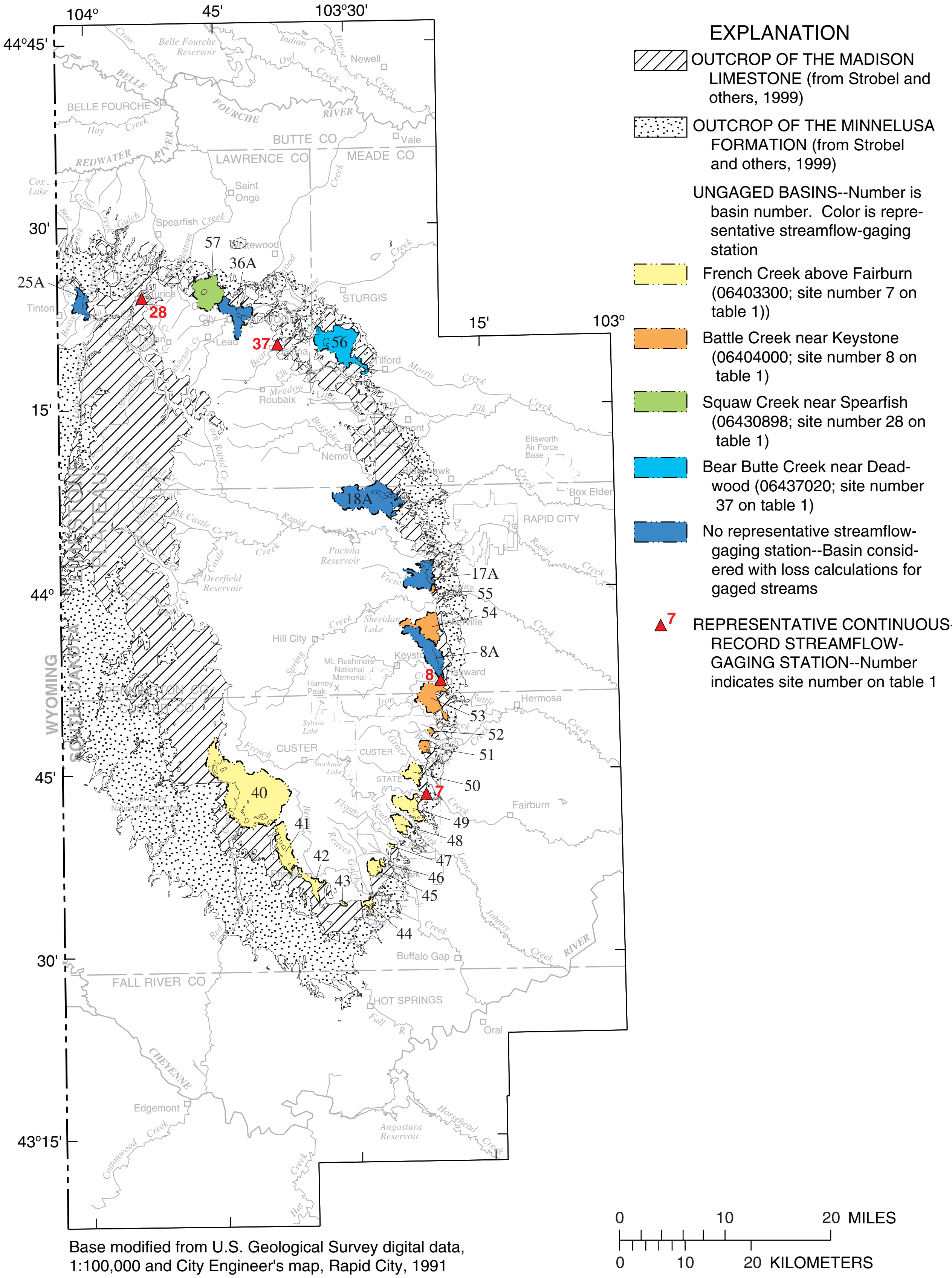



**Figure 11**. Assignment of representative streamflow-gaging stations for ungaged streams.

In addition to the 18 ungaged basins in South Dakota, there are several small areas in Wyoming where the Madison and Minnelusa aquifers probably receive recharge from streams originating on outcrops of Tertiary intrusives. No information regarding the streamflow characteristics, loss thresholds, or basin delineation for recharge purposes is available regarding these areas. The small outcrop areas are approximately twice as large as combined drainage areas for the miscellaneous-record measurement sites of Bear Gulch (basin 24) and Beaver Creek (basins 25 and 25A), with similar elevations. Thus, it is assumed that streamflow recharge in Wyoming is equal to twice the sum of estimated recharge in Bear Gulch and Beaver Creek (table 8) basins. The recharge estimated for the Wyoming basins also is presented in table 10.

## Summary of Streamflow Recharge, 1950-98

Estimates of annual streamflow recharge from streams with continuous-record gaging stations are complete from 1950-98. Estimates for basins with miscellaneous-record measurement sites and ungaged streams are complete only for 1992-98; thus, recharge estimates need to be extrapolated to calculate combined streamflow recharge from all sources for 1950-98.

Combined streamflow recharge for all sources (excluding Rapid and Spearfish Creeks) for 1992-98 is provided in table 11, along with the annual percentages of combined recharge for each of the three types of basins. The annual percentages for each basin type are relatively uniform in comparison to combined recharge, which varies considerably. Streams with continuous-record gages (excluding Rapid and Spearfish Creeks) account for about 65 percent of combined recharge, the miscellaneous-record streams account for about 13 percent, and ungaged streams account for about 22 percent (table 11). These average percentages are used in estimating recharge for the period 1950-91 for the miscellaneous-record and ungaged streams. First, the subtotal of annual recharge for the nine continuous-record streams with minimal regulation (table 3) was divided by 0.65 (representing 65 percent) to estimate combined streamflow recharge from all sources (excluding Rapid and Spearfish Creeks). This figure was multiplied by 13 percent to estimate annual recharge for the miscellaneous-record streams, and by 22 percent for the ungaged streams to complete estimates for 1950-91.

Estimates of total streamflow recharge for 1950-98, including recharge attributed to Rapid Creek and Spearfish Creek, are presented in table 12. Streamflow recharge for 1950-98 averages about 98 $ft^3/s$ and

**Table 11**. Estimated streamflow recharge for selected continuous-record, miscellaneous-record, and ungaged basins, water years 1992-98

[$ft^3/s$, cubic feet per second]

| Water year | Continuous record[1] | | Miscellaneous record | | Ungaged | | Combined recharge ($ft^3/s$) |
|---|---|---|---|---|---|---|---|
| | Annual recharge ($ft^3/s$) | Percent of combined recharge[2] | Annual recharge ($ft^3/s$) | Percent of combined recharge[2] | Annual recharge ($ft^3/s$) | Percent of combined recharge[2] | |
| 1992 | 36.55 | 70.95 | 6.50 | 12.62 | 8.47 | 16.44 | 51.52 |
| 1993 | 74.66 | 65.74 | 14.49 | 12.76 | 24.42 | 21.50 | 113.57 |
| 1994 | 68.75 | 66.50 | 13.05 | 12.62 | 21.58 | 20.88 | 103.38 |
| 1995 | 91.70 | 55.57 | 21.98 | 13.32 | 51.33 | 31.11 | 165.01 |
| 1996 | 103.07 | 64.31 | 21.45 | 13.38 | 35.76 | 22.31 | 160.28 |
| 1997 | 132.89 | 66.24 | 23.36 | 11.64 | 44.38 | 22.12 | 200.63 |
| 1998 | 106.61 | 68.70 | 18.45 | 11.89 | 30.12 | 19.41 | 155.18 |
| Average | 87.75 | 65.43 | 17.04 | 12.60 | 30.87 | 21.97 | 135.66 |

[1]Excluding recharge from Rapid Creek and Spearfish Creek.
[2]Individual values may not sum to 100 percent due to independent rounding.

has ranged from about 38 $ft^3/s$ in 1988 to about 222 $ft^3/s$ in 1997. Of these amounts, the combined contributions from Rapid and Spearfish Creeks average about 16 percent and have ranged from 9 to 39 percent. The highest annual recharge rates generally occurred during the late 1990's; thus, the earlier presumption (based on above-average precipitation) that using recharge estimates for 1992-98 would overestimate long-term streamflow recharge is substantiated.

Moving averages for 3-, 5-, and 10-year periods also are shown in table 12. These moving averages are useful for identifying multi-year trends in streamflow recharge. Some of the lowest recharge rates occurred during the early 1960's, early 1980's, and late 1980's based on the 3-year averages (table 12).

## PRECIPITATION RECHARGE

Infiltration of precipitation on outcrops of the Madison Limestone and Minnelusa Formation provides recharge to the Madison and Minnelusa aquifers. Precipitation in the study area increases from south to north and with increasing elevation as shown in the isohyetal map for water years 1950-98 (fig. 12). This map was derived from 1,000-by-1,000-meter grids based on precipitation data presented by Driscoll, Hamade, and Kenner (2000), who used a geographic information system (GIS) to generate spatial precipitation distributions from point precipitation data for 94 gages in the Black Hills area.

An overview of processes involved and assumptions made in estimating precipitation recharge was presented in a previous section discussing methods for quantifying precipitation recharge. In general, yield efficiencies (the ratio of basin yield to precipitation) are computed for selected drainage basins and are used to generate a map of generalized average yield efficiency for the Black Hills area. A simplifying assumption is made that yield efficiency is a reasonable surrogate for the efficiency of precipitation recharge to the Madison and Minnelusa aquifers. Relations between annual yield efficiency and annual precipitation are used to develop an algorithm for computing annual yield, as a surrogate for recharge, based on annual precipitation for 1,000-by-1,000-meter grids. The method is used to estimate annual precipitation recharge for 1931-98.

### Yield Efficiency

Annual yields, which are calculated by dividing annual streamflow by drainage area and converting to inches, have been determined for 20 selected gaging stations (fig. 13) for the periods of record shown in table 13. Effects from various forms of regulation such as withdrawals or diversions generally are relatively minor for these stations; thus, streamflow records are reasonably representative of basin yield. Annual yields generally increase from south to north, with the largest yields occurring in streams draining the higher elevations of the northern Black Hills. These variations in annual yield are consistent with climatic patterns for the Black Hills area, including: (1) increasing precipitation from south to north; (2) increasing precipitation with increasing elevation; and (3) decreasing evapotranspiration rates with increasing elevation (Miller and Driscoll, 1998).

The annual yields listed in table 13 and shown in figure 13 cannot be directly compared because of large differences in periods of record. Measured yields for many of the stations with short periods of record are representative of extremely wet climatic conditions that have prevailed since about 1990. In addition, basin yields are calculated from surface drainage areas, which are not necessarily congruent with contributing ground-water areas. Drainage basins where streamflow is known to be dominated by ground-water discharge (fig. 6) include Rhoads Fork, Castle Creek, Spearfish Creek, and Little Spearfish Creek (sites 9, 10, 13, and 15 in table 13). Jarrell (2000) documented incongruences in contributing surface- and ground-water areas for these basins based on structure contours of the top of the Deadwood Formation. The most notable differences in annual yield (fig. 13) are for Rhoads Fork and Castle Creek, which are located in close proximity (fig. 13) and have similar precipitation patterns (fig. 12).

Yields in the Spearfish Creek basins generally resemble yields of other nearby basins. The yield of Annie Creek (site 14) is somewhat lower than adjacent basins, which could result from extensive mining activities within the basin, which utilize substantial quantities of water through evaporation for heap-leach processes.

**Table 12**. Estimated total streamflow recharge, in cubic feet per second, from all sources, water years 1950-98

[--, not computed]

| Water year | Annual recharge | | | | | | Moving averages for total streamflow recharge | | |
|---|---|---|---|---|---|---|---|---|---|
| | Continuous-record streams | | | Miscel-laneous-record streams | Ungaged streams | Total[2] | 3-year average | 5-year average | 10-year average |
| | Rapid Creek | Spearfish Creek | Others[1] | | | | | | |
| 1950 | 10.00 | 5.14 | 44.50 | 9.59 | 10.27 | 79.50 | -- | -- | -- |
| 1951 | 9.96 | 4.65 | 39.96 | 7.99 | 13.53 | 76.09 | -- | -- | -- |
| 1952 | 9.98 | 5.58 | 63.67 | 12.73 | 21.55 | 113.52 | 89.70 | -- | -- |
| 1953 | 10.00 | 5.83 | 52.51 | 10.50 | 17.77 | 96.62 | 95.41 | -- | -- |
| 1954 | 10.00 | 4.84 | 33.32 | 6.66 | 11.28 | 66.10 | 92.08 | 86.37 | -- |
| 1955 | 10.00 | 5.48 | 32.21 | 6.44 | 10.90 | 65.04 | 75.92 | 83.47 | -- |
| 1956 | 9.97 | 4.71 | 33.29 | 6.66 | 11.27 | 65.90 | 65.68 | 81.43 | -- |
| 1957 | 9.02 | 4.95 | 67.05 | 13.41 | 22.69 | 117.12 | 82.68 | 82.15 | -- |
| 1958 | 8.65 | 4.81 | 38.83 | 7.77 | 13.14 | 73.20 | 85.41 | 77.47 | -- |
| 1959 | 9.45 | 4.38 | 30.35 | 6.07 | 10.27 | 60.53 | 83.61 | 76.36 | 81.36 |
| 1960 | 8.71 | 4.08 | 30.41 | 6.08 | 10.29 | 59.57 | 64.43 | 75.26 | 79.37 |
| 1961 | 9.67 | 3.70 | 27.04 | 5.41 | 9.15 | 54.97 | 58.36 | 73.08 | 77.26 |
| 1962 | 7.82 | 4.78 | 71.45 | 14.29 | 24.18 | 122.52 | 79.02 | 74.16 | 78.16 |
| 1963 | 7.78 | 6.45 | 58.12 | 11.62 | 19.67 | 103.64 | 93.71 | 80.25 | 78.86 |
| 1964 | 10.00 | 6.64 | 51.24 | 10.25 | 17.34 | 95.48 | 107.21 | 87.24 | 81.80 |
| 1965 | 10.00 | 8.19 | 79.70 | 15.94 | 26.97 | 140.80 | 113.31 | 103.48 | 89.37 |
| 1966 | 10.00 | 6.56 | 53.08 | 10.62 | 17.97 | 98.23 | 111.50 | 112.13 | 92.61 |
| 1967 | 10.00 | 6.44 | 67.97 | 13.59 | 23.00 | 121.00 | 120.01 | 111.83 | 92.99 |
| 1968 | 10.00 | 5.84 | 43.57 | 8.71 | 14.75 | 82.87 | 100.70 | 107.68 | 93.96 |
| 1969 | 9.99 | 6.15 | 37.76 | 7.55 | 12.78 | 74.24 | 92.70 | 103.43 | 95.33 |
| 1970 | 10.00 | 8.26 | 56.50 | 11.30 | 19.12 | 105.19 | 87.43 | 96.31 | 99.89 |
| 1971 | 10.00 | 8.02 | 68.68 | 13.74 | 23.24 | 123.68 | 101.03 | 101.40 | 106.76 |
| 1972 | 9.86 | 8.01 | 70.89 | 14.18 | 23.99 | 126.93 | 118.60 | 102.58 | 107.20 |
| 1973 | 10.00 | 8.72 | 68.29 | 13.66 | 23.11 | 123.78 | 124.79 | 110.76 | 109.22 |
| 1974 | 10.00 | 6.63 | 24.35 | 4.87 | 8.24 | 54.09 | 101.60 | 106.73 | 105.08 |
| 1975 | 9.99 | 6.55 | 51.69 | 10.34 | 17.50 | 96.06 | 91.31 | 104.91 | 100.61 |
| 1976 | 10.00 | 6.59 | 62.67 | 12.53 | 21.21 | 113.01 | 87.72 | 102.77 | 102.08 |
| 1977 | 10.00 | 6.72 | 45.18 | 9.04 | 15.29 | 86.23 | 98.43 | 94.63 | 98.61 |
| 1978 | 9.99 | 7.67 | 59.14 | 11.83 | 20.02 | 108.65 | 102.63 | 91.61 | 101.19 |

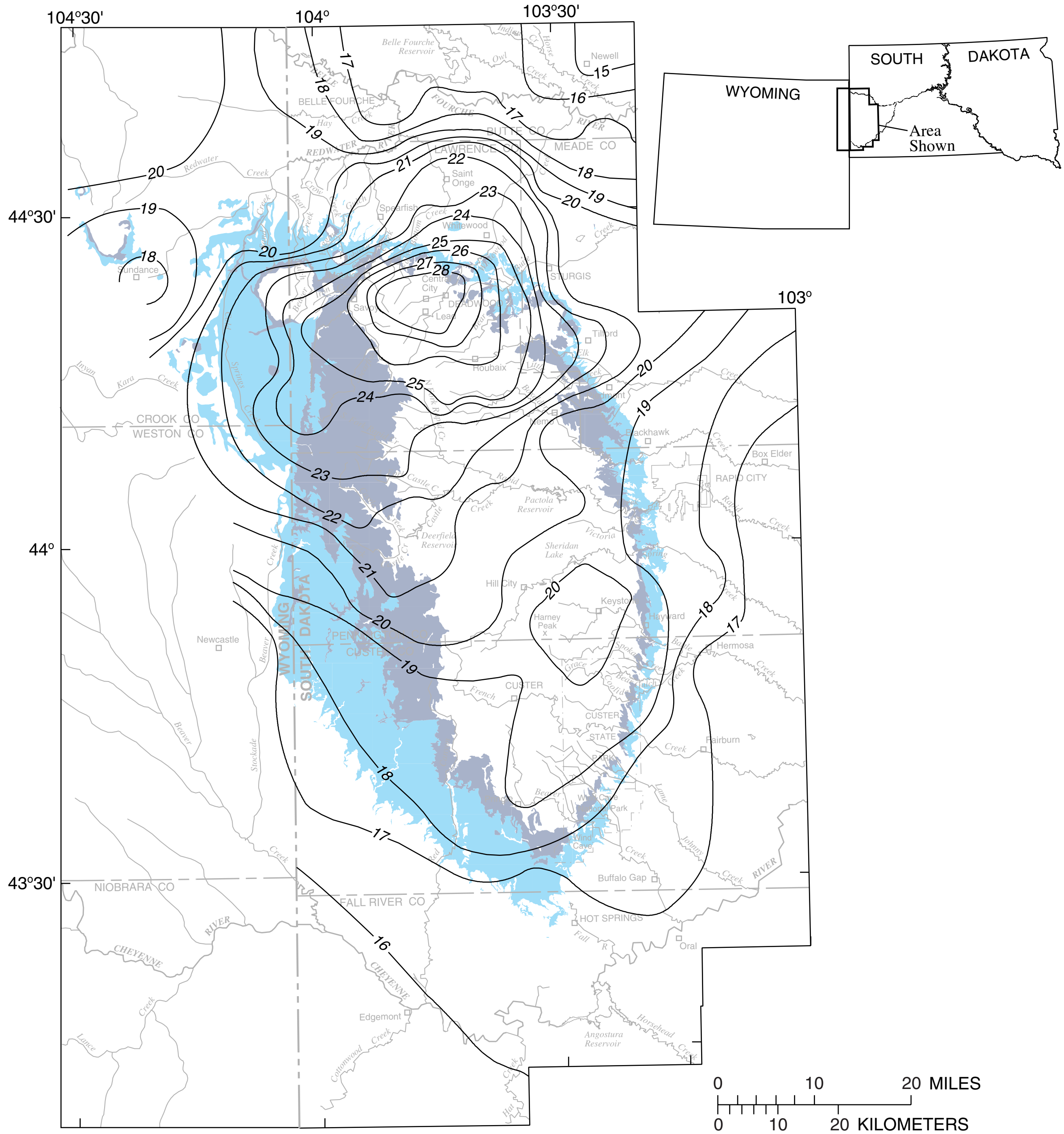
**Table 12**. Estimated total streamflow recharge, in cubic feet per second, from all sources, water years 1950-98–Continued

[--, not computed]

| Water year | Annual recharge | | | | | | Moving averages for total streamflow recharge | | |
|---|---|---|---|---|---|---|---|---|---|
| | Continuous-record streams | | | Miscel-laneous-record streams | Ungaged streams | Total[2] | 3-year average | 5-year average | 10-year average |
| | Rapid Creek | Spearfish Creek | Others[1] | | | | | | |
| 1979 | 10.00 | 6.28 | 44.64 | 8.93 | 15.11 | 84.96 | 93.28 | 97.78 | 102.26 |
| 1980 | 10.00 | 5.59 | 28.98 | 5.80 | 9.81 | 60.17 | 84.59 | 90.60 | 97.76 |
| 1981 | 10.00 | 5.03 | 29.80 | 5.96 | 10.09 | 60.88 | 68.67 | 80.18 | 91.48 |
| 1982 | 9.90 | 6.30 | 47.32 | 9.46 | 16.02 | 89.00 | 70.02 | 80.73 | 87.68 |
| 1983 | 10.00 | 7.82 | 63.42 | 12.68 | 21.46 | 115.39 | 88.42 | 82.08 | 86.84 |
| 1984 | 10.00 | 8.03 | 67.92 | 13.58 | 22.99 | 122.53 | 108.97 | 89.59 | 93.69 |
| 1985 | 10.00 | 5.48 | 22.36 | 4.47 | 7.57 | 49.88 | 95.93 | 87.54 | 89.07 |
| 1986 | 10.00 | 5.65 | 49.97 | 9.99 | 16.91 | 92.52 | 88.31 | 93.86 | 87.02 |
| 1987 | 10.00 | 4.83 | 60.82 | 12.16 | 20.59 | 108.41 | 83.60 | 97.74 | 89.24 |
| 1988 | 10.00 | 4.92 | 15.25 | 3.05 | 5.16 | 38.38 | 79.77 | 82.34 | 82.21 |
| 1989 | 10.00 | 5.03 | 16.46 | 3.29 | 5.57 | 40.36 | 62.38 | 65.91 | 77.75 |
| 1990 | 10.00 | 5.04 | 39.80 | 7.96 | 13.47 | 76.27 | 51.67 | 71.19 | 79.36 |
| 1991 | 9.99 | 4.94 | 57.32 | 11.46 | 19.40 | 103.11 | 73.25 | 73.30 | 83.58 |
| 1992 | 10.00 | 4.78 | 36.55 | 6.50 | 8.47 | 66.30 | 81.89 | 64.88 | 81.31 |
| 1993 | 10.00 | 5.26 | 74.66 | 14.49 | 24.42 | 128.83 | 99.42 | 82.97 | 82.66 |
| 1994 | 10.00 | 6.78 | 68.75 | 13.05 | 21.58 | 120.16 | 105.10 | 98.93 | 82.42 |
| 1995 | 10.00 | 8.56 | 91.70 | 21.98 | 51.33 | 183.57 | 144.18 | 120.39 | 95.79 |
| 1996 | 10.00 | 9.20 | 103.07 | 21.45 | 35.76 | 179.48 | 161.07 | 135.67 | 104.49 |
| 1997 | 10.00 | 10.92 | 132.89 | 23.36 | 44.38 | 221.55 | 194.87 | 166.72 | 115.80 |
| 1998 | 10.00 | 9.59 | 106.61 | 18.45 | 30.12 | 174.77 | 191.93 | 175.90 | 129.44 |
| Average | 9.81 | 6.25 | 53.50 | 10.64 | 18.18 | 98.39 | -- | -- | -- |

[1]Other streams with minimal regulation, including Battle Creek, Boxelder Creek, Grace Coolidge Creek, French Creek, Spring Creek, Bear Butte Creek, Bear Gulch, Beaver Creek, and Elk Creek.

[2]Values may not exactly sum to total due to independent rounding.




Base modified from U.S. Geological Survey digital data, 1:100,000 and City Engineer's map, Rapid City, 1991

EXPLANATION

CONNECTED OUTCROP OF THE MADISON LIMESTONE (from Strobel and others, 1999; DeWitt and others, 1989)

CONNECTED OUTCROP OF THE MINNELUSA FORMATION (from Strobel and others, 1999; DeWitt and others, 1989)

—20— LINE OF EQUAL AVERAGE ANNUAL PRECIPITATION--Interval 1 inch

**Figure 12.** Isohyetal map showing distribution of average annual precipitation for Black Hills area, water years 1950-98.

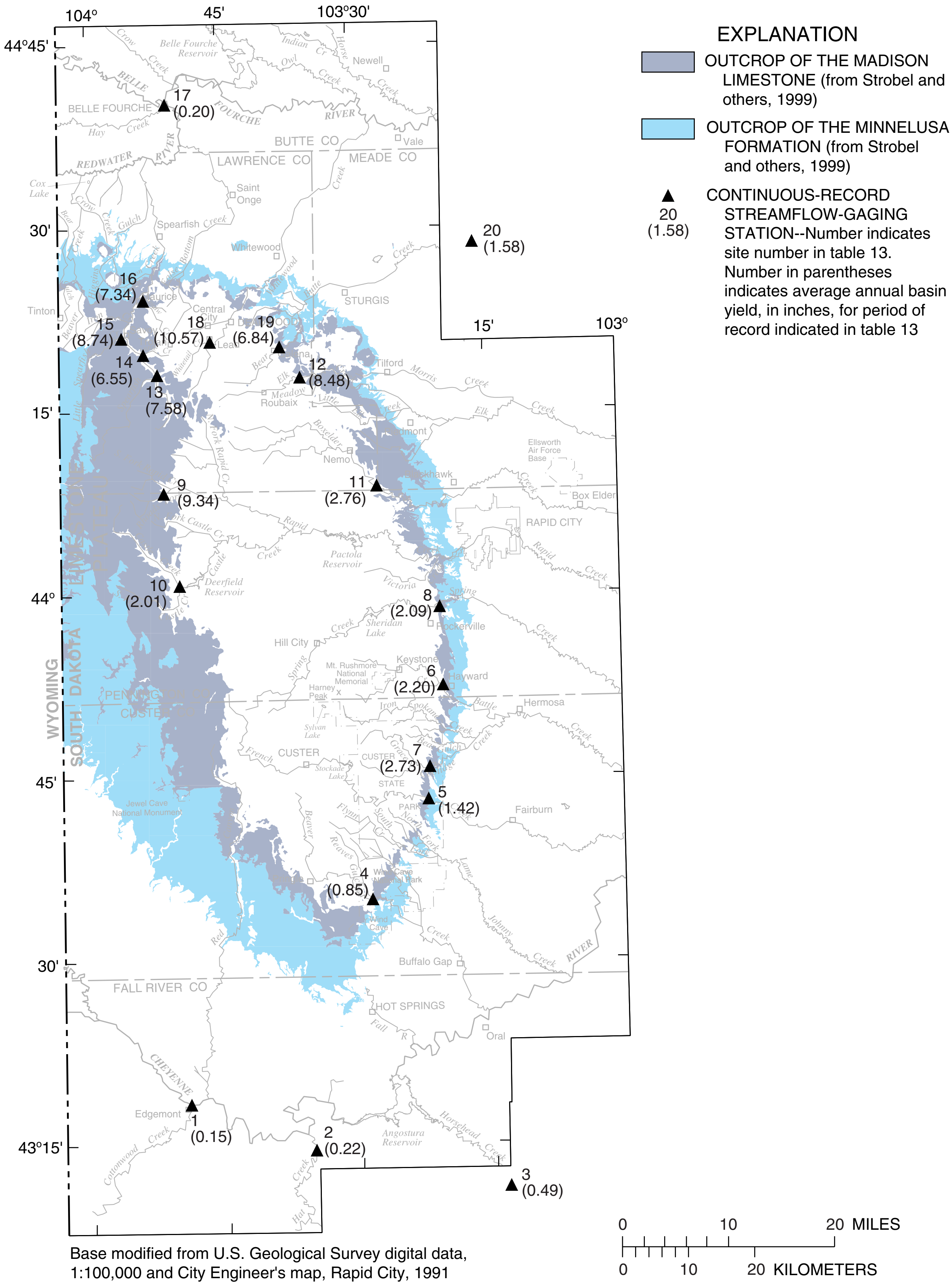



**Figure 13**. Measured average annual basin yields, based on surface drainage areas, for selected streamflow-gaging stations (periods of record for measured yield are not consistent).

**Table 13.** Summary of selected site information for streamflow-gaging stations used in determining annual yield

| Site number | Station number | Station name | Latitude (degrees, minutes, seconds) | Longitude (degrees, minutes, seconds) | Elevation of gage | Drainage area (square miles) | Period of record used (water years) | Measured annual yield for period of record (inches) | Used in determining best-fit runoff efficiency |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 06395000 | Cheyenne River at Edgemont | 43 18 20 | 103 49 14 | 3,415 | 7,143 | 1947-98 | 0.15 | No |
| 2 | 06400000 | Hat Creek near Edgemont | 43 14 24 | 103 35 16 | 3,296 | 1,044 | 1951-98 | .22 | No |
| 3 | 06400875 | Horsehead Creek at Oelrichs | 43 11 17 | 103 13 34 | 3,320 | 187 | 1984-98 | .49 | No |
| 4 | 06402430 | Beaver Creek near Pringle | 43 34 53 | 103 28 34 | 4,180 | 45.8 | 1991-98 | .85 | Yes |
| 5 | 06403300 | French Creek above Fairburn | 43 43 02 | 103 22 03 | 3,850 | 105 | 1983-98 | 1.42 | Yes |
| 6 | 06404000 | Battle Creek near Keystone | 43 52 21 | 103 20 10 | 3,800 | 58.0 | 1962-98 | 2.20 | Yes |
| 7 | 06404998 | Grace Coolidge Creek near Game Lodge, near Custer | 43 45 40 | 103 21 49 | 4,100 | 25.2 | 1977-98 | 2.73 | Yes |
| 8 | 06407500 | Spring Creek near Keystone | 43 58 45 | 103 20 25 | 3,885 | 163 | 1987-98 | 2.09 | Yes |
| 9 | 06408700 | Rhoads Fork near Rochford | 44 08 12 | 103 51 29 | 5,965 | [1]7.95 | 1983-98 | 9.34 | No |
| 10 | 06409000 | Castle Creek above Deerfield Reservoir, near Hill City | 44 00 49 | 103 49 48 | 5,920 | [1]79.2 | 1948-98 | 2.01 | No |
| 11 | 06422500 | Boxelder Creek near Nemo | 44 08 38 | 103 27 16 | 4,320 | 96.0 | 1967-98 | 2.76 | Yes |
| 12 | 06424000 | Elk Creek near Roubaix | 44 17 41 | 103 35 47 | 4,881 | 21.5 | 1992-98 | 8.48 | Yes |
| 13 | 06430770 | Spearfish Creek near Lead | 44 17 56 | 103 52 02 | 5,310 | [1]63.5 | 1989-98 | [2]7.58 | No |
| 14 | 06430800 | Annie Creek near Lead | 44 19 37 | 103 53 38 | 5,125 | 3.55 | 1989-98 | 6.55 | Yes |
| 15 | 06430850 | Little Spearfish Creek near Lead | 44 20 58 | 103 56 08 | 5,020 | [1]25.8 | 1989-98 | 8.74 | No |
| 16 | 06430898 | Squaw Creek near Spearfish | 44 24 04 | 103 53 35 | 4,480 | 6.95 | 1989-98 | 7.34 | Yes |
| 17 | 06433500 | Hay Creek at Belle Fourche | 44 40 01 | 103 50 46 | 3,005 | 121 | 1954-96 | .20 | No |
| 18 | 06436156 | Whitetail Creek at Lead | 44 20 36 | 103 45 57 | 5,080 | 6.15 | 1989-98 | 10.57 | Yes |
| 19 | 06437020 | Bear Butte Creek near Deadwood | 44 20 08 | 103 38 06 | 4,750 | 16.6 | 1989-98 | 6.84 | Yes |
| 20 | 06437500 | Bear Butte Creek near Sturgis | 44 28 35 | 103 15 50 | 2,780 | [3]120 | 1946-72 | 1.58 | No |

[1]Contributing areas for surface water and ground water are not necessarily congruent.
[2]A flow of 10 cubic feet per second was added to the measured streamflow to account for diverted flow.
[3]Approximate drainage area below loss zone. Actual drainage area is 192 square miles.

Because of differences in apparent yield characteristics resulting from various factors, a method was developed to estimate long-term basin yield in relation to annual precipitation. A digital grid (with cell sizes of 1,000-by-1,000 meters) showing average annual precipitation distribution for 1950-98 ($P_{average}$ grid), which corresponds with figure 12, was generated using data from Driscoll, Hamade, and Kenner (2000). Similar grids of annual precipitation for each year during 1931-98 also were generated to extend recharge estimates back as far as possible. Annual and average precipitation were determined for 1950-98 for drainage areas for stations listed in table 13, using the digital precipitation grids. The average precipitation for the period of record and for 1950-98 for each station are presented in table 14.

Although precipitation records are available for 1950-98, few streamflow records available are for that entire period. The majority of the gaging stations have streamflow records that begin in the late 1980's to early 1990's. Thus, a method was developed for estimating long-term annual yields for the gaging stations with incomplete record, based on precipitation. The first step was to examine relations between precipitation and yield efficiency, which is computed as:

$$YE_{annual} = \frac{Q_{annual}}{P_{annual}} \times 100 \qquad (1)$$

where

$YE_{annual}$ = annual yield efficiency, in percent;
$Q_{annual}$ = annual yield, in inches; and
$P_{annual}$ = annual precipitation, in inches.

Regression analyses of yield efficiency as a function of annual precipitation were performed for all gaging stations, with resulting equations and $R^2$ values shown in table 14. The equations were then used with annual precipitation data to predict average yield efficiency for 1950-98. Equations for three gages are not realistic and are not included in table 14 (Rhoads Fork, Castle Creek, and Little Spearfish Creek). For these gages, average yield efficiencies for the available period of record are used to represent efficiencies for 1950-98. The linear relations between yield efficiency and precipitation for 15 of the gages with the best relations ($R^2$ values) are shown in figure 14, along with exponential curves for selected gages that are described in subsequent discussions.

Average yield efficiency values for 1950-98 (from table 14), which are based on surface areas, are shown in figure 15. A map of generalized average annual yield efficiency (the percentage of precipitation that is available either for runoff or recharge) for the study area is presented in figure 16. Contouring was done to reflect conditions upstream from representative gages, including influences of contributing ground-water areas in the Limestone Plateau area (Jarrell, 2000). Additional yield efficiency values estimated for gages located outside the study area (including Wyoming) also were used. Topography and precipitation also were considered when contouring in areas with sparse yield efficiency data. A digital grid (1,000-by-1,000 meters) of the yield efficiency distribution shown in figure 16 was generated for subsequent analyses.

A systematic approach was developed for predicting annual yield efficiency, by adjusting average efficiency on the basis of relations between annual and average precipitation. The following exponential equation provided good results:

$$YE_{annual} = \left[\frac{P_{annual}}{P_{average}}\right]^n \times YE_{average} \qquad (2)$$

where

$YE_{annual}$ = annual yield efficiency, in percent;
$P_{annual}$ = annual precipitation, in inches;
$P_{average}$ = average precipitation for 1950-98, in inches;
$YE_{average}$ = average yield efficiency for 1950-98, in percent; and
$n$ = exponent.

Best-fit exponential curves and curves for an exponent of 1.6 (ultimately selected for the systematic approach) are shown in figure 14. Gages dominated by ground-water discharge (sites 9, 10, 13, 15) and those not located on or near the Precambrian core (sites 1, 2, 3, and 17) were not used for curve fitting. In addition, site 20 was not used because of its non-recent period of record. The best-fit exponents range from 1.1 to 2.5 (table 14), and $R^2$ values generally are similar or better than for the linear regression equations. For most gages, both of the exponential curves closely resemble results from the linear regressions through most of the range of measured precipitation.

**Table 14.** Summary of selected precipitation information, equations, and runoff estimates for streamflow-gaging stations used in estimating precipitation recharge

[--, not computed]

| Site number | Station name | Average precipitation over drainage basin (inches): Period of record (streamflow) | Average precipitation over drainage basin (inches): 1950-98 | Yield efficiency, Linear regression equation: Intercept | Yield efficiency, Linear regression equation: Precipitation coefficient | Yield efficiency, Linear regression equation: $R^2$ | Yield efficiency, Linear regression equation: Average yield efficiency[1] 1950-98 (percent) | Yield efficiency, Exponential regression equation: Best-fit exponent | Yield efficiency, Exponential regression equation: $R^2$ | Annual yield, Period of record: Measured (inches) | Annual yield, Period of record: Computer algorithm[1] (inches) | Annual yield, Linear regression equation: Intercept | Annual yield, Linear regression equation: Precipitation coefficient | Annual yield, Linear regression equation: $R^2$ | Annual yield, Linear regression equation: Estimated average annual yield 1950-98 (inches) | Annual yield: Computer algorithm[2] annual yield 1950-98 (inches) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Cheyenne River | 17.21 | 17.22 | -0.0019 | 0.0006 | 0.0941 | [3]0.9 | -- | -- | 0.15 | -- | -- | -- | -- | -- | -- |
| 2 | Hat Creek | 16.00 | 15.95 | -.0076 | .0013 | .1049 | 1.3 | -- | -- | .22 | -- | -- | -- | -- | -- | -- |
| 3 | Horsehead Creek | 17.31 | 16.59 | -.0604 | .0049 | .4220 | 2.1 | -- | -- | .49 | -- | -- | -- | -- | -- | -- |
| 4 | Beaver Creek | 24.16 | 18.88 | -.0310 | .0026 | .3208 | 1.8 | 2.2 | 0.3813 | .85 | 1.34 | -1.6328 | 0.1027 | 0.5223 | 0.36 | 0.74 |
| 5 | French Creek | 20.95 | 19.45 | -.0476 | .0052 | .4902 | 5.4 | 1.9 | .5654 | 1.42 | 1.67 | -2.4960 | .1867 | .6480 | 1.15 | 1.36 |
| 6 | Battle Creek | 21.56 | 20.27 | -.0628 | .0072 | .6067 | 8.3 | 1.6 | .5920 | 2.20 | 2.32 | -3.3050 | .2552 | .7636 | 1.89 | 2.01 |
| 7 | Grace Coolidge Creek | 21.37 | 19.95 | -.1087 | .0104 | .6433 | 9.9 | 1.9 | .6809 | 2.73 | 1.94 | -5.2603 | .3740 | .7344 | 2.29 | 1.62 |
| 8 | Spring Creek | 21.77 | 19.90 | -.1222 | .0095 | .6967 | 6.7 | 2.5 | .7463 | 2.09 | 2.15 | -4.4738 | .3013 | .8045 | 1.58 | 1.69 |
| 9 | Rhoads Fork | 22.63 | 23.23 | -- | -- | -- | [4]41.8 | -- | -- | 9.34 | 5.87 | 7.2214 | .0772 | .0399 | 9.01 | 5.72 |
| 10 | Castle Creek | 21.65 | 21.76 | -- | -- | -- | [3]9.3 | -- | -- | 2.01 | 3.58 | 0.0985 | -.0002 | .3146 | 2.02 | 3.63 |
| 11 | Boxelder Creek | 22.98 | 22.79 | -.0995 | .0091 | .4463 | 10.8 | 2.1 | .5210 | 2.76 | 2.77 | -5.0893 | .3417 | .5981 | 2.71 | 2.68 |
| 12 | Elk Creek | 31.06 | 26.05 | -.0352 | .0096 | .3424 | 21.5 | 1.1 | .3421 | 8.48 | 9.36 | -8.7673 | .5552 | .7026 | 5.70 | 6.08 |
| 13 | Spearfish Creek | 27.63 | 24.67 | .1009 | .0061 | .2975 | 25.1 | -- | -- | [5]7.58 | 10.49 | -4.8582 | .4501 | .7192 | 6.24 | 7.86 |
| 14 | Annie Creek | 29.46 | 26.57 | -.2342 | .0150 | .6753 | 16.4 | 2.1 | .6858 | 6.55 | 9.85 | -13.8630 | .6929 | .8187 | 4.66 | 7.61 |
| 15 | Little Spearfish Creek | 27.44 | 25.26 | -- | -- | -- | [4]31.8 | -- | -- | 8.74 | 9.95 | -.4435 | .3346 | .5229 | 8.01 | 7.97 |
| 16 | Squaw Creek | 29.02 | 26.89 | -.0751 | .0108 | .5195 | 21.5 | 1.3 | .5224 | 7.34 | 7.30 | -10.0420 | .5990 | .7963 | 6.07 | 5.81 |
| 17 | Hay Creek | 18.28 | 18.16 | -.0137 | .0013 | .4052 | 1.0 | -- | -- | .20 | -- | -- | -- | -- | -- | -- |
| 18 | Whitetail Creek | 31.19 | 28.08 | -.1464 | .0149 | .6216 | 27.2 | 1.4 | .5968 | 10.57 | 10.59 | -14.421 | .8013 | .8152 | 8.10 | 8.13 |
| 19 | Bear Butte Creek (Deadwood) | 29.62 | 26.86 | -.0975 | .0106 | .5032 | 18.7 | 1.4 | .4860 | 6.84 | 8.02 | -9.5062 | .5519 | .7850 | 5.34 | 6.25 |
| 20 | Bear Butte Creek (Sturgis) | 23.68 | 23.85 | -.1144 | .0075 | .5614 | 6.0 | -- | -- | 1.58 | -- | -- | -- | -- | -- | -- |

[1]Unless noted otherwise, estimated using regression equation for runoff efficiency versus precipitation.
[2]Estimated using exponent of 1.6.
[3]Period of record sufficient for computation of yield efficiency.
[4]Estimated using average runoff efficiency for the available period of record.
[5]A flow of 10 cubic feet per second was added to the measured streamflow to account for diverted flow.

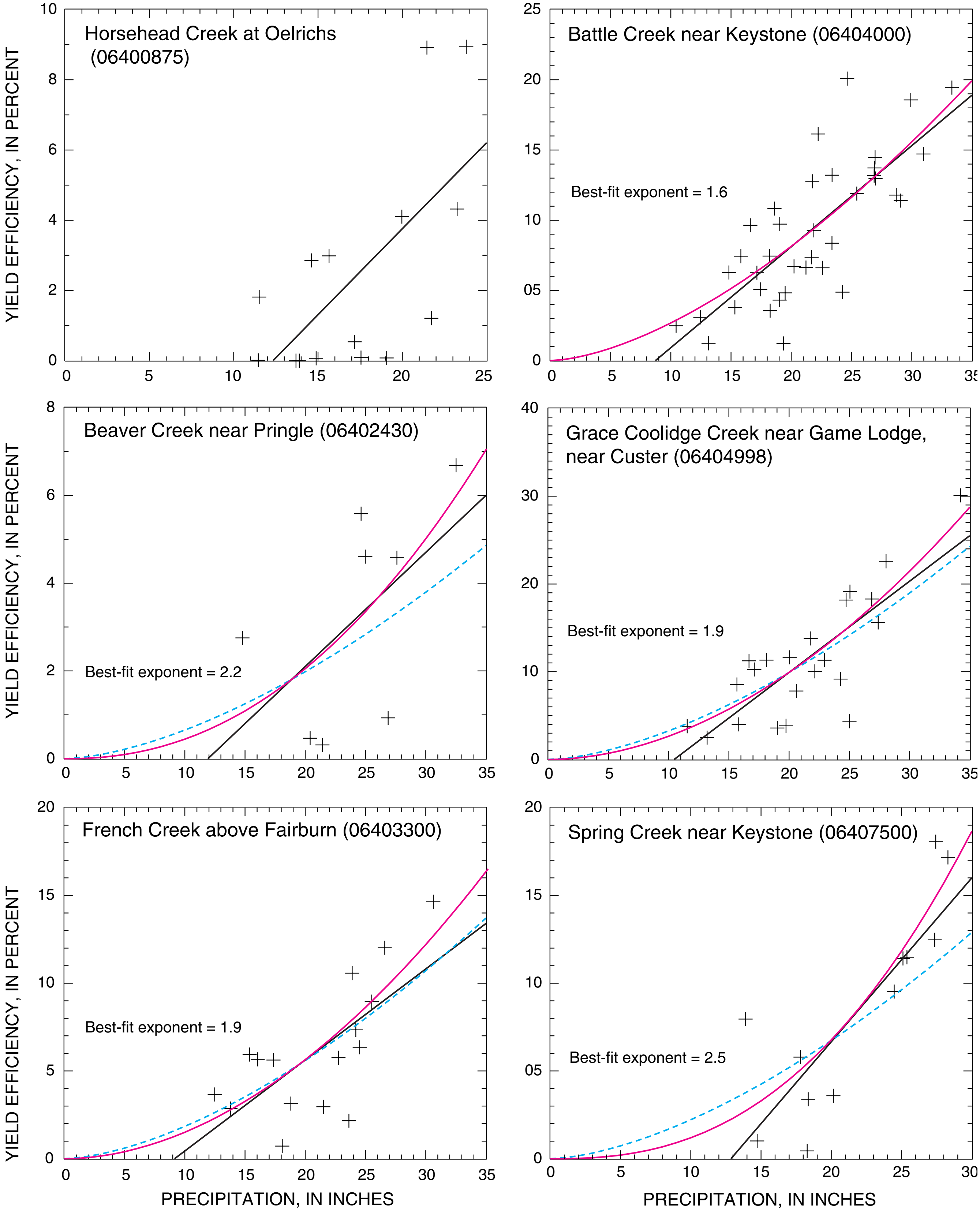



**Figure 14.** Regression plots of yield efficiency with precipitation for selected streamflow-gaging stations.

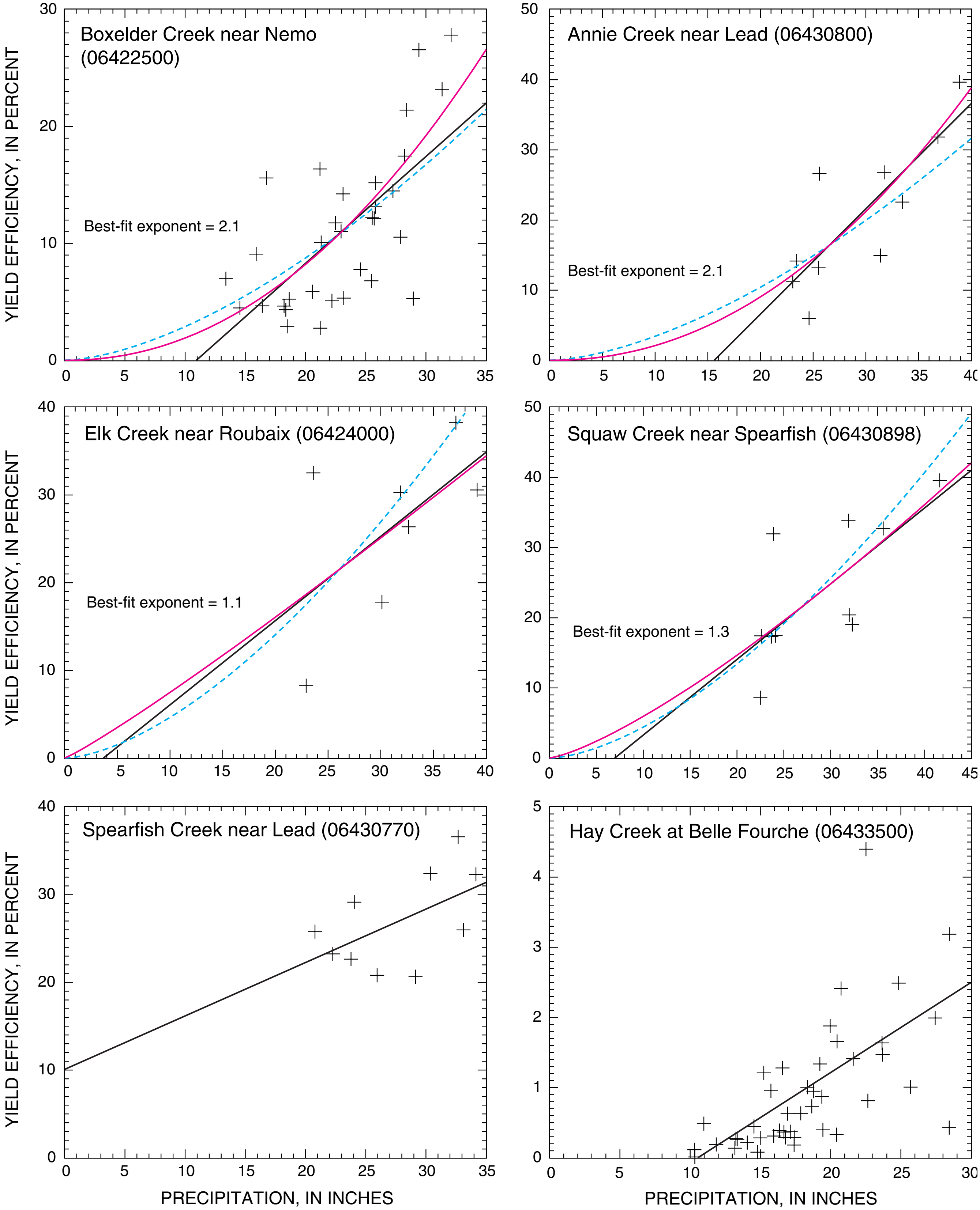



**Figure 14.** Regression plots of yield efficiency with precipitation for selected streamflow-gaging stations.--Continued

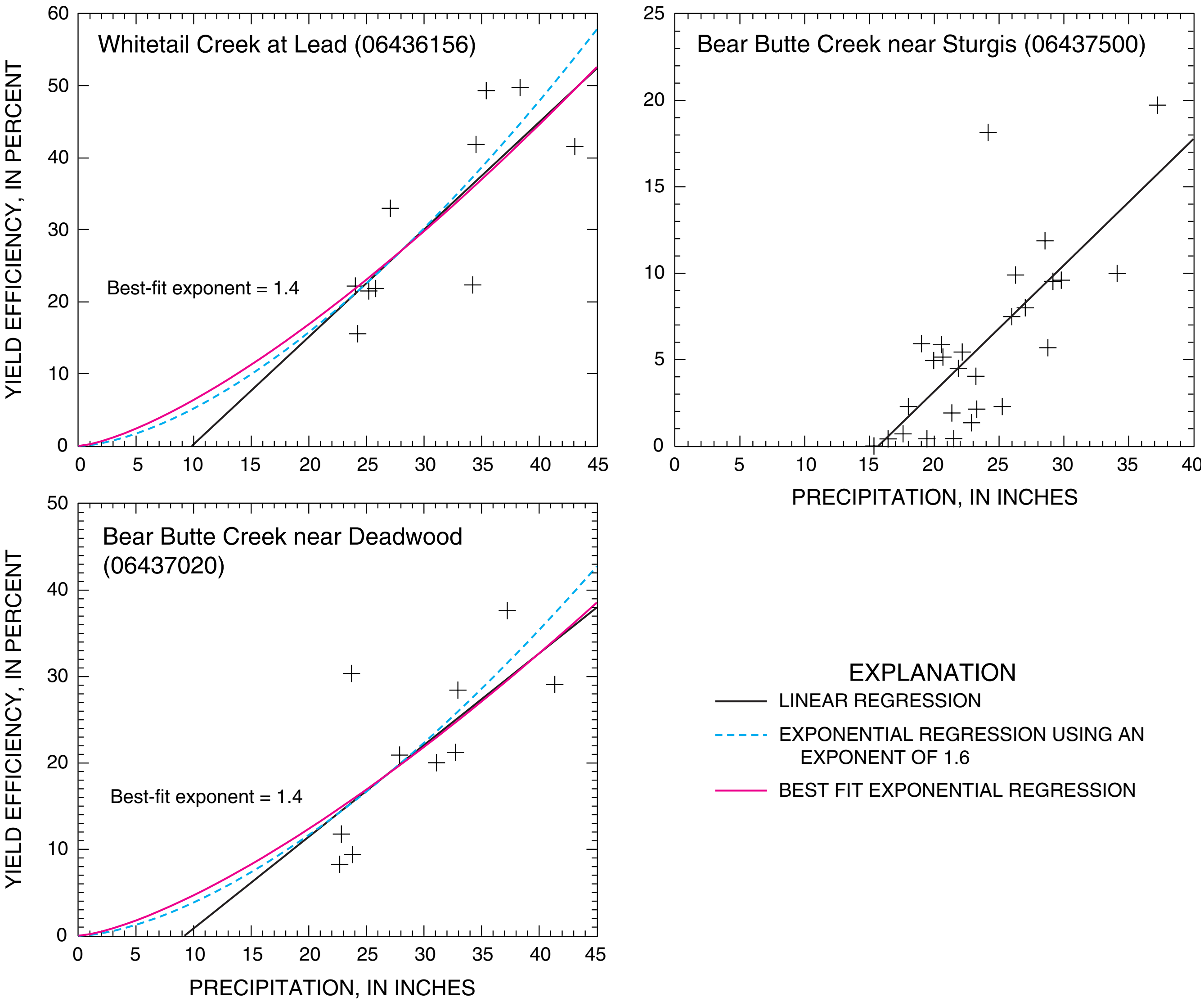



**Figure 14.** Regression plots of yield efficiency with precipitation for selected streamflow-gaging stations.--Continued

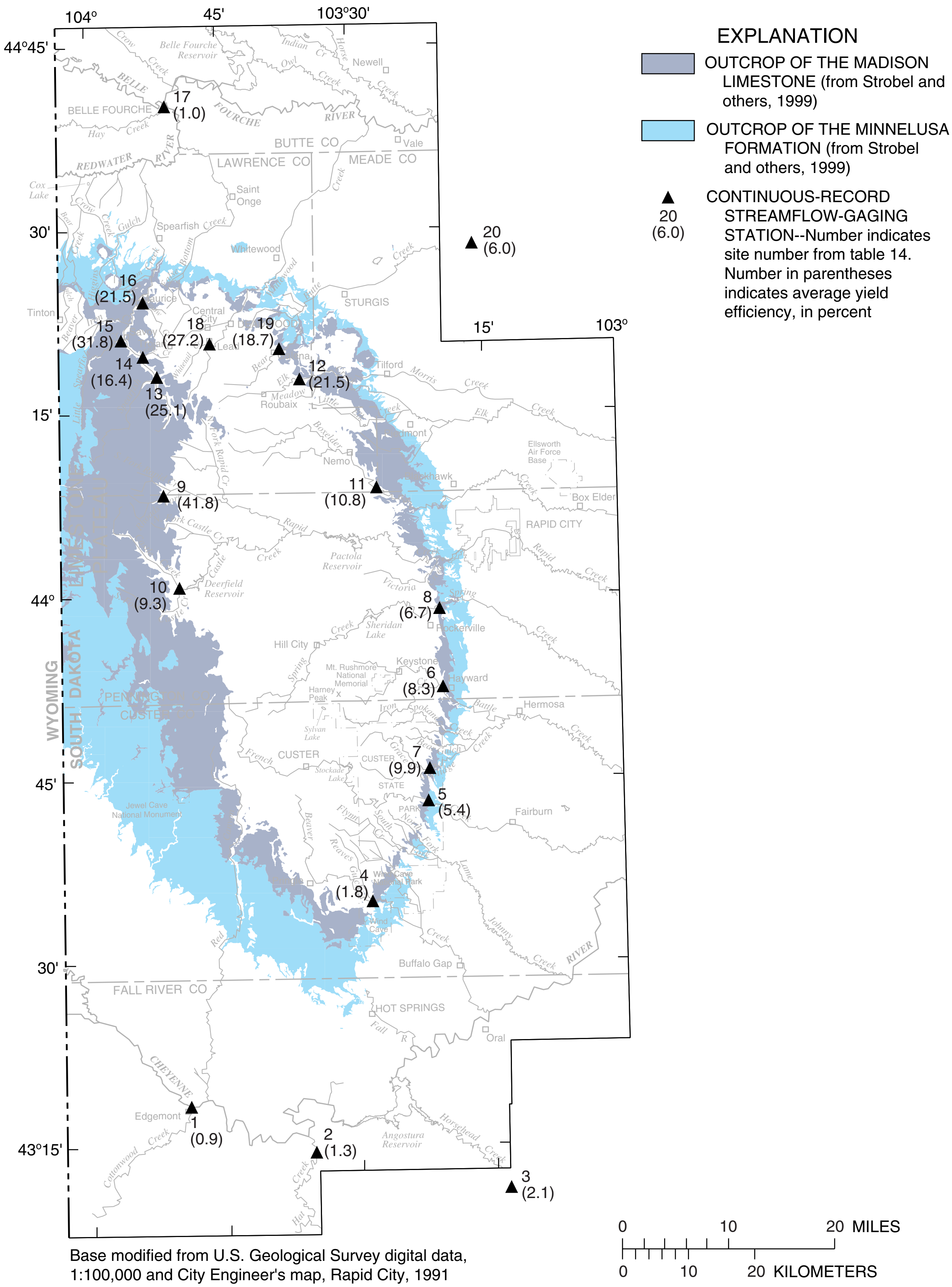
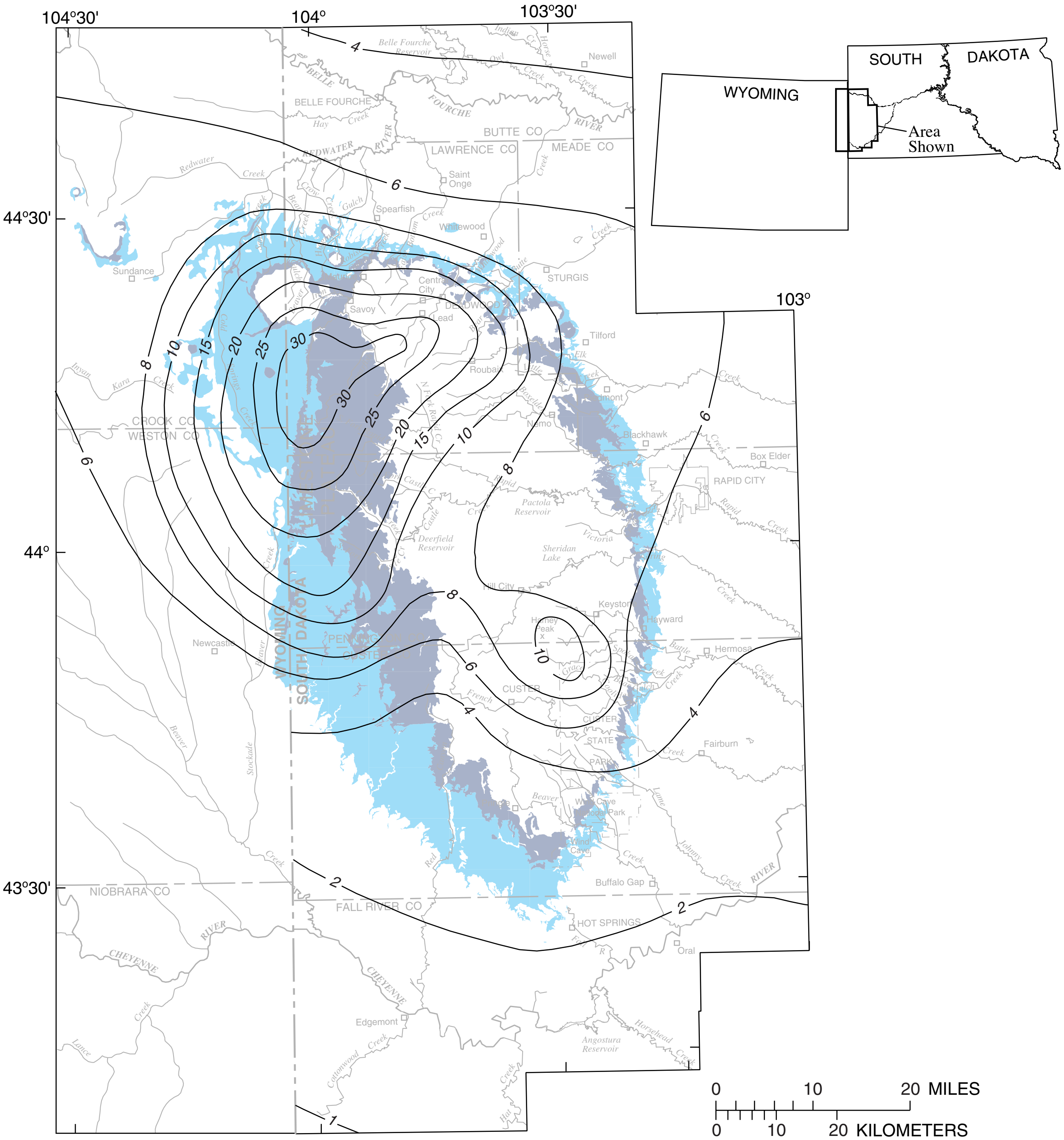



**Figure 15**. Estimated yield efficiencies for water years 1950-98, based on surface drainage areas, for selected gaging stations.




Base modified from U.S. Geological Survey digital data, 1:100,000 and City Engineer's map, Rapid City, 1991

EXPLANATION

CONNECTED OUTCROP OF THE MADISON LIMESTONE FOR WHICH PRECIPITATION RECHARGE IS PRESCRIBED (from Strobel and others, 1999; DeWitt and others, 1989)

CONNECTED OUTCROP OF THE MINNELUSA FORMATION FOR WHICH PRECIPITATION RECHARGE IS PRESCRIBED (from Strobel and others, 1999; DeWitt and others, 1989)

—15— LINE OF EQUAL AVERAGE ANNUAL YIELD EFFICIENCY-- Interval 1, 2, or 5 percent

**Figure 16**. Generalized average annual yield efficiency (in percent of annual precipitation), water years 1950-98.

Annual yield for a given year can be calculated using a selected value for $n$, by rearranging equation 1 to solve for $Q_{annual}$ and by substituting equation 2 in place of $YE_{annual}$ to produce the following equation:

$$Q_{annual} = \left[\frac{P_{annual}}{P_{average}}\right]^n \times \frac{YE_{average}}{100} \times P_{annual} \quad (3)$$

A computer algorithm, which utilizes the set of three digital grids ($P_{average}$, $P_{annual}$, and $YE_{average}$) with equation 3, was developed to generate digital grids of annual yield ($Q_{annual}$) for each year during 1950-98 using exponents of 1.4, 1.6, and 2.0. A value of 1.6 was selected and is used for calculation of precipitation recharge based on comparisons for selected gaging stations between measured annual yield and the computer algorithm annual yield (results using an exponent of 1.6 are presented in table 14).

Because the period of record is relatively short for many of the gaging stations, a method for comparing long-term annual yields to the computer algorithm was desired. For this, linear regression analyses were performed between annual yield and precipitation for the selected gaging stations for the period of record, with resulting equations (table 14) used to estimate the average annual yields for 1950-98 for each of the 15 gaging stations located on or near the Precambrian core. Estimates also were generated using the computer algorithm (table 14), which generally compare quite favorably with the regression estimates, with no apparent tendency of consistent overestimation or underestimation. An exception is Annie Creek, for which annual yields are notably lower than in adjacent basins (fig. 13). Estimates derived using the computer algorithm for Rhoads Fork and Castle Creek also are notably different than the regression estimates, but probably are much more representative of ground-water recharge that occurs within the surface drainage areas for these basins.

## Recharge Estimates

As previously stated, the major assumptions in determining recharge to the Madison and Minnelusa aquifers from precipitation are that (1) all precipitation on outcrops of the Madison Limestone and Minnelusa Formation that is not evapotranspirated becomes recharge, and (2) yield efficiency is a reasonable surrogate for the efficiency of precipitation recharge. Therefore, *recharge* is assumed equal to *annual yield*. The computer algorithm using equation 3 was used to estimate annual recharge from infiltration of precipitation on outcrops of the Madison Limestone and Minnelusa Formation (table 15). A digital grid for the distribution of annual yield over the study area was generated for each year during 1931-98. Annual yield was then applied to the outcrop areas, from which annual recharge volumes were computed. Estimates of annual recharge, in inches, were obtained by dividing by the connected outcrop areas (fig. 7) of the Madison Limestone and Minnelusa Formation, which are about 301,160 acres and 427,160 acres, respectively.

The long-term (1931-98) average for precipitation recharge to both the Madison and Minnelusa aquifers is about 182,000 acre-ft per year, or an average of about 251 $ft^3/s$ (table 15). The average for 1950-98 is about 10 percent higher, because the dry conditions of the 1930's are excluded. The minimum recharge rate (about 31 $ft^3/s$) occurred in 1936. This extreme value is important because it provides an indication of just how low the recharge rate could be during a severe drought. Also, the 10-year average for 1931-40 (about 130 $ft^3/s$) is much smaller than all other 10-year averages. The maximum 3-year average of about 577 $ft^3/s$ for 1995-97 includes the annual maximum of about 664 $ft^3/s$ for 1995.

The average (1931-98) recharge depth to the Madison aquifer (3.59 inches) is about 1 inch larger than for the Minnelusa aquifer because of the orographic effects. Average recharge volumes are nearly identical, however, because the outcrop area for the Minnelusa Formation is almost 50 percent larger than for the Madison Limestone. For 1950-98, precipitation recharge averages about 135 $ft^3/s$ to each aquifer, compared with combined streamflow recharge of about 98 $ft^3/s$ for both aquifers (table 12). Although streamflow recharge is presumed larger for the Madison aquifer, substantial streamflow recharge to the Minnelusa aquifer is apparent for many streams (tables 5 and 9). If the Madison aquifer is assumed to receive either 65 or 75 percent of combined streamflow recharge to both aquifers, the resulting proportion of total recharge (about 370 $ft^3/s$) is about 54 or 57 percent, respectively. Considering the margin of error associated with recharge estimates, it reasonably can be concluded that on average, the Madison aquifer receives about 55 percent of total recharge to both aquifers, relative to about 45 percent for the Minnelusa aquifer.

**Table 15.** Estimated precipitation recharge, water years 1931-98

[--, not applicable]

| Water year | Average annual recharge | | | | | | | | Moving averages for total precipitation recharge (cubic feet per second) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Madison aquifer | | | Minnelusa aquifer | | | Total[1] | | | | |
| | Acre-feet | Inches | Cubic feet per second | Acre-feet | Inches | Cubic feet per second | Acre-feet | Cubic feet per second | 3-year average | 5-year average | 10-year average |
| 1931 | 18,893 | 0.75 | 26.03 | 22,689 | 0.64 | 31.34 | 41,582 | 57.37 | -- | -- | -- |
| 1932 | 104,910 | 4.18 | 144.51 | 108,389 | 3.04 | 149.31 | 213,299 | 293.82 | -- | -- | -- |
| 1933 | 93,592 | 3.73 | 128.92 | 96,909 | 2.72 | 133.86 | 190,501 | 262.78 | 204.66 | -- | -- |
| 1934 | 19,633 | .78 | 27.05 | 20,020 | .56 | 27.65 | 396,53 | 54.70 | 203.77 | -- | -- |
| 1935 | 49,792 | 1.98 | 68.59 | 49,917 | 1.40 | 68.95 | 99,710 | 137.54 | 151.67 | 161.24 | -- |
| 1936 | 10,330 | .41 | 14.23 | 12,235 | .34 | 16.85 | 22,565 | 31.08 | 74.44 | 155.98 | -- |
| 1937 | 36,772 | 1.47 | 50.65 | 42,780 | 1.20 | 59.09 | 79,552 | 109.75 | 92.79 | 119.17 | -- |
| 1938 | 43,661 | 1.74 | 60.14 | 47,180 | 1.33 | 65.17 | 90,841 | 125.31 | 88.71 | 91.68 | -- |
| 1939 | 45,769 | 1.82 | 63.05 | 46,685 | 1.31 | 64.49 | 92,455 | 127.53 | 120.86 | 106.24 | -- |
| 1940 | 31,424 | 1.25 | 43.29 | 38,398 | 1.08 | 52.89 | 69,822 | 96.18 | 116.34 | 97.97 | 129.61 |
| 1941 | 123,352 | 4.92 | 169.92 | 141,690 | 3.98 | 195.71 | 265,041 | 365.63 | 196.45 | 164.88 | 160.43 |
| 1942 | 90,236 | 3.60 | 124.30 | 105,367 | 2.96 | 145.54 | 195,603 | 269.84 | 243.88 | 196.90 | 158.03 |
| 1943 | 73,755 | 2.94 | 101.60 | 70,489 | 1.98 | 97.36 | 144,244 | 198.96 | 278.14 | 211.63 | 151.65 |
| 1944 | 57,153 | 2.28 | 78.73 | 66,466 | 1.87 | 91.56 | 123,620 | 170.29 | 213.03 | 220.18 | 163.21 |
| 1945 | 126,361 | 5.03 | 174.06 | 131,968 | 3.71 | 182.28 | 258,329 | 356.35 | 241.87 | 272.21 | 185.09 |
| 1946 | 201,948 | 8.05 | 278.18 | 213,204 | 5.99 | 294.49 | 415,152 | 572.68 | 366.44 | 313.62 | 239.25 |
| 1947 | 83,367 | 3.32 | 114.84 | 85,390 | 2.40 | 117.95 | 168,757 | 232.79 | 387.27 | 306.21 | 251.56 |
| 1948 | 73,557 | 2.93 | 101.32 | 69,360 | 1.95 | 95.54 | 142,917 | 196.87 | 334.11 | 305.79 | 258.71 |
| 1949 | 42,660 | 1.70 | 58.76 | 44,713 | 1.26 | 61.76 | 87,373 | 120.53 | 183.39 | 295.84 | 258.01 |
| 1950 | 65,960 | 2.63 | 90.86 | 63,715 | 1.79 | 88.01 | 129,675 | 178.87 | 165.42 | 260.35 | 266.28 |
| 1951 | 54,942 | 2.19 | 75.68 | 61,586 | 1.73 | 85.07 | 116,528 | 160.75 | 153.38 | 177.96 | 245.79 |
| 1952 | 68,076 | 2.71 | 93.77 | 62,618 | 1.76 | 86.26 | 130,694 | 180.03 | 173.22 | 167.41 | 236.81 |
| 1953 | 69,612 | 2.77 | 95.89 | 64,021 | 1.80 | 88.43 | 133,632 | 184.32 | 175.03 | 164.90 | 235.35 |
| 1954 | 35,972 | 1.43 | 49.55 | 33,344 | .94 | 46.06 | 69,315 | 95.61 | 153.32 | 159.92 | 227.88 |
| 1955 | 98,14 | 3.93 | 135.84 | 95,720 | 2.69 | 132.22 | 194,334 | 268.06 | 182.66 | 177.75 | 219.05 |
| 1956 | 48,578 | 1.94 | 66.92 | 48,743 | 1.37 | 67.14 | 97,320 | 134.06 | 165.91 | 172.42 | 175.19 |
| 1957 | 101,919 | 4.06 | 140.39 | 99,660 | 2.80 | 137.66 | 201,579 | 278.05 | 226.72 | 192.02 | 179.71 |
| 1958 | 67,458 | 2.69 | 92.92 | 66,854 | 1.88 | 92.34 | 134,313 | 185.27 | 199.13 | 192.21 | 178.55 |
| 1959 | 53,660 | 2.14 | 73.92 | 48,106 | 1.35 | 66.45 | 101,765 | 140.36 | 201.23 | 201.16 | 180.54 |
| 1960 | 45,077 | 1.80 | 62.09 | 40,288 | 1.13 | 55.50 | 85,365 | 117.59 | 147.74 | 171.07 | 174.41 |
| 1961 | 25,240 | 1.01 | 34.77 | 24,697 | .69 | 34.11 | 49,937 | 68.88 | 108.95 | 158.03 | 165.22 |
| 1962 | 181,288 | 7.22 | 249.73 | 190,767 | 5.36 | 263.50 | 372,055 | 513.23 | 233.23 | 205.07 | 198.54 |
| 1963 | 160,252 | 6.39 | 220.75 | 148,987 | 4.19 | 205.79 | 309,239 | 426.54 | 336.22 | 253.32 | 222.76 |
| 1964 | 177,805 | 7.08 | 244.93 | 165,465 | 4.65 | 227.93 | 343,269 | 472.86 | 470.87 | 319.82 | 260.49 |
| 1965 | 189,703 | 7.56 | 261.32 | 191,479 | 5.38 | 264.49 | 381,182 | 525.80 | 475.07 | 401.46 | 286.26 |
| 1966 | 47,142 | 1.88 | 64.94 | 51,523 | 1.45 | 71.17 | 98,665 | 136.11 | 378.25 | 414.91 | 286.47 |
| 1967 | 112,610 | 4.49 | 155.12 | 118,968 | 3.34 | 164.33 | 231,578 | 319.45 | 327.12 | 376.15 | 290.61 |

**Table 15**. Estimated precipitation recharge, water years 1931-98–Continued

[--, not applicable]

| Water year | Average annual recharge | | | | | | | | Moving averages for total precipitation recharge (cubic feet per second) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Madison aquifer | | | Minnelusa aquifer | | | Total[1] | | | | |
| | Acre-feet | Inches | Cubic feet per second | Acre-feet | Inches | Cubic feet per second | Acre-feet | Cubic feet per second | 3-year average | 5-year average | 10-year average |
| 1968 | 89,044 | 3.55 | 122.66 | 90,202 | 2.53 | 124.25 | 179,247 | 246.91 | 234.16 | 340.23 | 296.77 |
| 1969 | 81,287 | 3.24 | 111.97 | 75,237 | 2.11 | 103.92 | 156,524 | 215.90 | 260.75 | 288.83 | 304.33 |
| 1970 | 103,859 | 4.14 | 143.07 | 108,969 | 3.06 | 150.52 | 212,828 | 293.58 | 252.13 | 242.39 | 321.93 |
| 1971 | 131,686 | 5.25 | 181.40 | 133,218 | 3.74 | 184.01 | 264,904 | 365.41 | 291.63 | 288.25 | 351.58 |
| 1972 | 144,955 | 5.78 | 199.68 | 158,830 | 4.46 | 218.79 | 303,785 | 418.46 | 359.15 | 308.05 | 342.10 |
| 1973 | 101,269 | 4.04 | 139.50 | 104,185 | 2.93 | 143.91 | 205,454 | 283.41 | 355.76 | 315.35 | 327.79 |
| 1974 | 45,817 | 1.83 | 63.11 | 46,849 | 1.32 | 64.71 | 92,666 | 127.82 | 276.57 | 297.74 | 293.29 |
| 1975 | 64,831 | 2.58 | 89.30 | 64,523 | 1.81 | 89.12 | 129,353 | 178.43 | 196.55 | 274.71 | 258.55 |
| 1976 | 129,177 | 5.15 | 177.94 | 136,841 | 3.84 | 188.50 | 266,018 | 366.44 | 224.23 | 274.91 | 281.58 |
| 1977 | 101,136 | 4.03 | 139.32 | 94,250 | 2.65 | 130.19 | 195,386 | 269.50 | 271.46 | 245.12 | 276.59 |
| 1978 | 120,579 | 4.80 | 166.10 | 121,332 | 3.41 | 167.59 | 241,910 | 333.69 | 323.21 | 255.18 | 285.26 |
| 1979 | 87,646 | 3.49 | 120.73 | 81,463 | 2.29 | 112.52 | 169,110 | 233.26 | 278.82 | 276.26 | 287.00 |
| 1980 | 41,282 | 1.64 | 56.87 | 40,068 | 1.13 | 55.19 | 81,350 | 112.06 | 226.34 | 262.99 | 268.85 |
| 1981 | 60,203 | 2.40 | 82.93 | 63,398 | 1.78 | 87.57 | 123,601 | 170.50 | 171.94 | 223.80 | 249.36 |
| 1982 | 185,043 | 7.37 | 254.90 | 187,727 | 5.27 | 259.30 | 372,770 | 514.20 | 265.59 | 272.74 | 258.93 |
| 1983 | 62,625 | 2.50 | 86.27 | 58,874 | 1.65 | 81.32 | 121,498 | 167.59 | 284.10 | 239.52 | 247.35 |
| 1984 | 90,023 | 3.59 | 124.01 | 100,315 | 2.82 | 138.18 | 190,338 | 262.19 | 314.66 | 245.31 | 260.79 |
| 1985 | 25,120 | 1.00 | 34.60 | 24,839 | .70 | 34.31 | 49,959 | 68.91 | 166.23 | 236.68 | 249.83 |
| 1986 | 117,823 | 4.69 | 162.30 | 140,696 | 3.95 | 194.34 | 258,519 | 356.64 | 229.25 | 273.91 | 248.85 |
| 1987 | 41,588 | 1.66 | 57.29 | 49,982 | 1.40 | 69.04 | 91,570 | 126.33 | 183.96 | 196.33 | 234.54 |
| 1988 | 35,186 | 1.40 | 48.47 | 39,128 | 1.10 | 53.90 | 74,314 | 102.37 | 195.11 | 183.29 | 211.40 |
| 1989 | 51,750 | 2.06 | 71.29 | 54,566 | 1.53 | 75.37 | 106,316 | 146.66 | 125.12 | 160.18 | 202.74 |
| 1990 | 66,118 | 2.63 | 91.08 | 72,304 | 2.03 | 99.87 | 138,422 | 190.95 | 146.66 | 184.59 | 210.63 |
| 1991 | 106,135 | 4.23 | 146.20 | 116,167 | 3.26 | 160.46 | 222,302 | 306.66 | 214.76 | 174.59 | 224.25 |
| 1992 | 73,065 | 2.91 | 100.65 | 71,624 | 2.01 | 98.66 | 144,689 | 199.31 | 232.31 | 189.19 | 192.76 |
| 1993 | 153,727 | 6.13 | 211.76 | 168,387 | 4.73 | 232.59 | 322,114 | 444.35 | 316.77 | 257.59 | 220.44 |
| 1994 | 71,800 | 2.86 | 98.90 | 75,722 | 2.13 | 104.59 | 147,522 | 203.50 | 282.39 | 268.95 | 214.57 |
| 1995 | 225,419 | 8.98 | 310.52 | 255,774 | 7.19 | 353.30 | 481,193 | 663.81 | 437.22 | 363.53 | 274.06 |
| 1996 | 185,600 | 7.40 | 255.66 | 193,579 | 5.44 | 266.66 | 379,179 | 522.32 | 463.21 | 406.66 | 290.62 |
| 1997 | 216,306 | 8.62 | 297.96 | 179,447 | 5.04 | 247.87 | 395,753 | 545.83 | 577.32 | 475.96 | 332.58 |
| 1998 | 178,568 | 7.12 | 245.98 | 153,771 | 4.32 | 212.40 | 332,339 | 458.38 | 508.84 | 478.77 | 368.18 |
| Average 1950-98 | 97,808 | 3.90 | 134.73 | 98,751 | 2.77 | 136.31 | 196,559 | 271.04 | -- | -- | -- |
| Average 1931-98 | 89,996 | 3.59 | 123.97 | 91,951 | 2.58 | 126.93 | 181,947 | 250.90 | -- | -- | -- |

[1]Individual recharge estimates may not sum to total due to independent rounding.

To illustrate recharge patterns throughout the study area, annual digital grids were averaged over 49 years to yield a distribution of average annual recharge for 1950-98 (fig. 17). The average annual recharge from precipitation ranges from 0.4 inch in the southern Black Hills to 8.7 inches in the northwestern Black Hills. This corresponds with average yield efficiencies in the outcrop areas that range from just over 2 percent in the south to almost 35 percent in the north (fig. 16) and annual precipitation ranging from about 17 to 26 inches (fig. 12).

## COMBINED RECHARGE, 1931-98

Annual streamflow recharge (table 12) and precipitation recharge (table 15) were summed (table 16) to yield total combined recharge rates to the Madison and Minnelusa aquifers. Table 16 includes estimates of streamflow recharge for 1931-49 that were not included in table 12. Methods for deriving these estimates are described in the following discussion. Because precipitation recharge was very low during the 1930's, it was important to have estimates of combined recharge for this period. However, for all recharge estimates presented in this report, the earlier estimates have larger uncertainties due to sparser data.

Various regression methods were examined for estimating streamflow recharge for the period 1931-49, based on precipitation recharge rates and precipitation over the study area. The best regression ($R^2$= 0.8119) was based on recharge for the period 1989 through 1998, which is a period with abundant streamflow records and a wide range of recharge rates. This regression yielded the following equation to estimate streamflow recharge based on precipitation recharge: Streamflow Recharge = (0.294 x Precipitation Recharge) + 21.319.

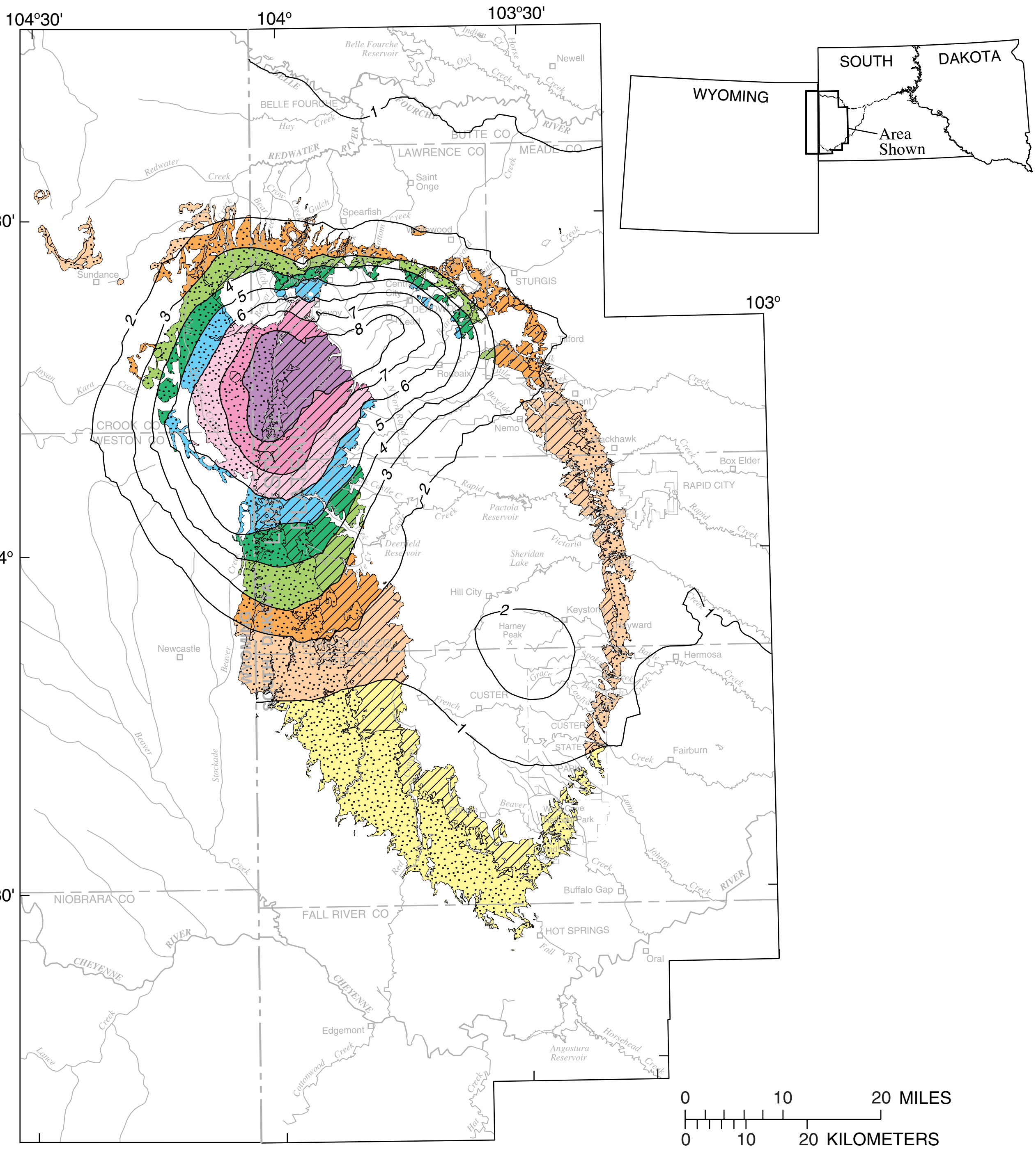
Annual ranks for streamflow recharge, precipitation recharge, and combined recharge are provided in table 16. Of recent years, the driest year for combined recharge is 1985, with a rank of 65. In comparison, 3 years during the 1930's (1931, 1934, and 1936) are much drier, with combined recharge rates that are considerably smaller. The 10-year moving average for 1931-40 is much smaller than any of the subsequent 10-year averages. This period also includes many minimal values for the 3- and 5-year averages, which again are much smaller than subsequent averages. This clearly illustrates the importance of estimating streamflow recharge for 1931-49.

Ranks for the different recharge categories generally are quite similar (table 16); however, because combined recharge generally is dominated by precipitation recharge, these categories have the most similarity. Trends in streamflow recharge occasionally lag precipitation recharge because of effects of antecedent conditions. A good example is 1997, which is the maximum year for streamflow recharge (table 16).

Combined streamflow and precipitation recharge averaged about 344 $ft^3/s$ for 1931-98 and ranged from about 62 $ft^3/s$ in 1936 to about 847 $ft^3/s$ in 1995 (table 16). Streamflow recharge averaged about 93 $ft^3/s$, or 27 percent of combined recharge, and precipitation recharge averaged about 251 $ft^3/s$, or 73 percent of combined recharge.

Plots of annual streamflow recharge, precipitation recharge, and combined recharge are provided in figure 18. It is apparent that combined recharge for the period 1962-98 is much larger than for 1931-61, which was identified by Driscoll, Hamade, and Kenner (2000) as a period of generally deficit precipitation departures, relative to the 1931-98 average. Combined recharge during 1962-98 exceeds the 1931-98 average for 21 of 37 years; however, the 1931-98 average is exceeded for only 7 of 31 years during 1931-61 (table 16). The most prolonged low-recharge period is 1947-61, with only one year above average for combined recharge; however, recharge amounts generally were lower during the 1930's. The 1990's are distinct as the period of highest recharge.

The relative proportion of recharge contributed by streamflow losses and infiltration of precipitation is highly variable (fig. 18). The minimum value for combined recharge (about 62 $ft^3/s$ for 1936) consists of 49.5 and 50.5 percent, respectively, from streamflow and precipitation recharge (table 16). This compares with 21.7 and 78.3 percent, respectively, for the maximum recharge value of about 847 $ft^3/s$ in 1995. Thus, it is apparent that the relative proportion contributed by streamflow recharge increases as combined recharge decreases.




Base modified from U.S. Geological Survey digital data,
1:100,000 and City Engineer's map, Rapid City, 1991

## EXPLANATION

OUTCROP OF THE MADISON LIMESTONE FOR WHICH PRECIPITATION RECHARGE IS PRESCRIBED

OUTCROP OF THE MINNELUSA FORMATION FOR WHICH PRECIPITATION RECHARGE IS PRESCRIBED

— 2 — LINE OF EQUAL YIELD POTENTIAL--Number indicates average annual yield potential. Interval 1 inch

AVERAGE ANNUAL RECHARGE, IN INCHES

- Less than 1
- Between 1 and 2
- Between 2 and 3
- Between 3 and 4
- Between 4 and 5
- Between 5 and 6
- Between 6 and 7
- Between 7 and 8
- Between 8 and 9

**Figure 17**. Estimated annual yield potential and average annual recharge from precipitation on outcrops of the Madison Limestone and Minnelusa Formation, water years 1950-98.

**Table 16.** Summary of streamflow, precipitation, and combined recharge, water years 1931-98

[--, not applicable]

| Water year | Streamflow recharge | | Precipitation recharge | | Combined recharge | | | Moving averages for combined recharge (cubic feet per second) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Total (cubic feet per second) | Rank | Total (cubic feet per second) | Rank | Total (acre-feet) | Total[1] (cubic feet per second) | Rank | 3-year average | 5-year average | 10-year average |
| 1931 | 38.17 | 66 | 57.37 | 66 | 69,161 | 95.53 | 66 | -- | -- | -- |
| 1932 | 107.61 | 23 | 293.82 | 21 | 291,426 | 401.44 | 22 | -- | -- | -- |
| 1933 | 98.50 | 28 | 262.78 | 28 | 261,555 | 361.28 | 27 | 286.08 | -- | -- |
| 1934 | 37.38 | 67 | 54.70 | 67 | 66,663 | 92.08 | 67 | 284.93 | -- | -- |
| 1935 | 61.71 | 51 | 137.54 | 50 | 144,250 | 199.25 | 52 | 217.54 | 229.92 | -- |
| 1936 | 30.45 | 68 | 31.08 | 68 | 44,668 | 61.53 | 68 | 117.62 | 223.12 | -- |
| 1937 | 53.55 | 61 | 109.75 | 60 | 118,224 | 163.30 | 60 | 141.36 | 175.49 | -- |
| 1938 | 58.12 | 57 | 125.31 | 56 | 132,804 | 183.44 | 55 | 136.09 | 139.92 | -- |
| 1939 | 58.78 | 56 | 127.53 | 54 | 134,882 | 186.31 | 54 | 177.68 | 158.77 | -- |
| 1940 | 49.57 | 63 | 96.18 | 62 | 105,807 | 145.75 | 62 | 171.83 | 148.07 | 188.99 |
| 1941 | 128.70 | 8 | 365.63 | 14 | 357,886 | 494.34 | 13 | 275.47 | 234.63 | 228.87 |
| 1942 | 100.57 | 27 | 269.84 | 25 | 268,165 | 370.41 | 26 | 336.83 | 276.05 | 225.77 |
| 1943 | 79.75 | 39 | 198.96 | 36 | 201,784 | 278.72 | 38 | 381.16 | 295.11 | 217.51 |
| 1944 | 71.33 | 46 | 170.29 | 45 | 175,404 | 241.62 | 45 | 296.92 | 306.17 | 232.47 |
| 1945 | 125.98 | 10 | 356.35 | 17 | 349,191 | 482.33 | 15 | 334.22 | 373.48 | 260.78 |
| 1946 | 189.51 | 2 | 572.68 | 2 | 551,800 | 762.19 | 3 | 495.38 | 427.05 | 330.84 |
| 1947 | 89.69 | 34 | 232.79 | 32 | 233,458 | 322.47 | 32 | 522.33 | 417.47 | 346.76 |
| 1948 | 79.14 | 41 | 196.87 | 37 | 200,370 | 276.01 | 39 | 453.56 | 416.92 | 356.02 |
| 1949 | 56.72 | 58 | 120.53 | 57 | 128,316 | 177.24 | 57 | 258.57 | 404.05 | 355.11 |
| 1950 | 79.50 | 40 | 178.87 | 42 | 187,044 | 258.36 | 44 | 237.20 | 359.25 | 366.37 |
| 1951 | 76.09 | 43 | 160.75 | 47 | 171,464 | 236.84 | 46 | 224.15 | 254.18 | 340.62 |
| 1952 | 113.52 | 19 | 180.03 | 41 | 213,103 | 293.55 | 34 | 262.92 | 248.40 | 332.93 |
| 1953 | 96.62 | 30 | 184.32 | 40 | 203,391 | 280.94 | 37 | 270.44 | 249.39 | 333.16 |
| 1954 | 66.10 | 48 | 95.61 | 63 | 117,073 | 161.71 | 61 | 245.40 | 246.28 | 325.16 |
| 1955 | 65.04 | 50 | 268.06 | 27 | 241,146 | 333.09 | 29 | 258.58 | 261.23 | 310.24 |
| 1956 | 65.90 | 49 | 134.06 | 52 | 145,161 | 199.96 | 51 | 231.59 | 253.85 | 254.02 |
| 1957 | 117.12 | 17 | 278.05 | 24 | 286,090 | 395.17 | 24 | 309.41 | 274.17 | 261.29 |
| 1958 | 73.20 | 45 | 185.27 | 39 | 187,124 | 258.47 | 43 | 284.53 | 269.68 | 259.53 |
| 1959 | 60.53 | 53 | 140.36 | 49 | 145,438 | 200.89 | 50 | 284.84 | 277.52 | 261.90 |
| 1960 | 59.57 | 55 | 117.59 | 58 | 128,609 | 177.16 | 58 | 212.17 | 246.33 | 253.78 |
| 1961 | 54.97 | 59 | 68.88 | 65 | 89,663 | 123.85 | 64 | 167.30 | 231.11 | 242.48 |
| 1962 | 122.52 | 14 | 513.23 | 7 | 460,262 | 635.75 | 6 | 312.25 | 279.22 | 276.70 |
| 1963 | 103.64 | 25 | 426.54 | 11 | 383,833 | 530.18 | 12 | 429.93 | 333.57 | 301.62 |
| 1964 | 95.48 | 32 | 472.86 | 8 | 412,579 | 568.33 | 10 | 578.09 | 407.05 | 342.29 |
| 1965 | 140.80 | 6 | 525.80 | 4 | 482,596 | 666.60 | 5 | 588.37 | 504.94 | 375.64 |
| 1966 | 98.23 | 29 | 136.11 | 51 | 169,647 | 234.33 | 48 | 489.75 | 527.04 | 379.07 |
| 1967 | 121.00 | 15 | 319.45 | 19 | 318,871 | 440.45 | 19 | 447.13 | 487.98 | 383.60 |

**Table 16**. Summary of streamflow, precipitation, and combined recharge, water years 1931-98–Continued

[--, not applicable]

| Water year | Streamflow recharge | | Precipitation recharge | | Combined recharge | | | Moving averages for combined recharge (cubic feet per second) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Total (cubic feet per second) | Rank | Total (cubic feet per second) | Rank | Total (acre-feet) | Total[1] (cubic feet per second) | Rank | 3-year average | 5-year average | 10-year average |
| 1968 | 82.87 | 38 | 246.91 | 30 | 239,404 | 329.78 | 30 | 334.85 | 447.90 | 390.73 |
| 1969 | 74.24 | 44 | 215.90 | 33 | 210,052 | 290.14 | 35 | 353.46 | 392.26 | 399.66 |
| 1970 | 105.19 | 24 | 293.58 | 22 | 288,696 | 398.77 | 23 | 339.56 | 338.69 | 421.82 |
| 1971 | 123.68 | 12 | 365.41 | 15 | 354,085 | 489.09 | 14 | 392.67 | 389.65 | 458.34 |
| 1972 | 126.93 | 9 | 418.46 | 12 | 395,933 | 545.40 | 11 | 477.75 | 410.64 | 449.31 |
| 1973 | 123.78 | 11 | 283.41 | 23 | 294,785 | 407.18 | 21 | 480.56 | 426.12 | 437.01 |
| 1974 | 54.09 | 60 | 127.82 | 53 | 131,704 | 181.92 | 56 | 378.17 | 404.47 | 398.37 |
| 1975 | 96.06 | 31 | 178.43 | 43 | 198,722 | 274.49 | 40 | 287.86 | 379.62 | 359.16 |
| 1976 | 113.01 | 20 | 366.44 | 13 | 348,057 | 479.45 | 16 | 311.95 | 377.69 | 383.67 |
| 1977 | 86.23 | 36 | 269.50 | 26 | 257,537 | 355.73 | 28 | 369.89 | 339.75 | 375.20 |
| 1978 | 108.65 | 21 | 333.69 | 18 | 320,240 | 442.34 | 18 | 425.84 | 346.79 | 386.45 |
| 1979 | 84.96 | 37 | 233.26 | 31 | 230,381 | 318.22 | 33 | 372.10 | 374.05 | 389.26 |
| 1980 | 60.17 | 54 | 112.06 | 59 | 125,030 | 172.23 | 59 | 310.93 | 353.59 | 366.61 |
| 1981 | 60.88 | 52 | 170.50 | 44 | 167,511 | 231.38 | 49 | 240.61 | 303.98 | 340.83 |
| 1982 | 89.00 | 35 | 514.20 | 6 | 436,697 | 603.20 | 8 | 335.60 | 353.47 | 346.61 |
| 1983 | 115.39 | 18 | 167.59 | 46 | 204,861 | 282.97 | 36 | 372.52 | 321.60 | 334.19 |
| 1984 | 122.53 | 13 | 262.19 | 29 | 279,288 | 384.72 | 25 | 423.63 | 334.90 | 354.47 |
| 1985 | 49.88 | 62 | 68.91 | 64 | 86,000 | 118.79 | 65 | 262.16 | 324.21 | 338.90 |
| 1986 | 92.52 | 33 | 356.64 | 16 | 325,184 | 449.17 | 17 | 317.56 | 367.77 | 335.88 |
| 1987 | 108.41 | 22 | 126.33 | 55 | 169,937 | 234.73 | 47 | 267.56 | 294.08 | 323.78 |
| 1988 | 38.38 | 65 | 102.37 | 61 | 102,170 | 140.74 | 63 | 274.88 | 265.63 | 293.62 |
| 1989 | 40.36 | 64 | 146.66 | 48 | 135,389 | 187.01 | 53 | 187.49 | 226.09 | 280.49 |
| 1990 | 76.27 | 42 | 190.95 | 38 | 193,458 | 267.22 | 41 | 198.32 | 255.77 | 289.99 |
| 1991 | 103.11 | 26 | 306.66 | 20 | 296,660 | 409.77 | 20 | 288.00 | 247.89 | 307.83 |
| 1992 | 66.30 | 47 | 199.31 | 35 | 192,820 | 265.61 | 42 | 314.20 | 254.07 | 274.07 |
| 1993 | 128.83 | 7 | 444.35 | 10 | 414,963 | 573.18 | 9 | 416.19 | 340.56 | 303.09 |
| 1994 | 120.16 | 16 | 203.50 | 34 | 234,312 | 323.65 | 31 | 387.48 | 367.89 | 296.99 |
| 1995 | 183.57 | 3 | 663.81 | 1 | 613,475 | 847.38 | 1 | 581.40 | 483.92 | 369.85 |
| 1996 | 179.48 | 4 | 522.32 | 5 | 509,472 | 701.80 | 4 | 624.28 | 542.32 | 395.11 |
| 1997 | 221.55 | 1 | 545.83 | 3 | 555,558 | 767.38 | 2 | 772.19 | 642.68 | 448.37 |
| 1998 | 174.77 | 5 | 458.38 | 9 | 458,380 | 633.15 | 7 | 700.78 | 654.67 | 497.62 |
| Number | | 68 | | 68 | | | 68 | | | |
| Minimum | 30.45 | | 31.08 | | 44,668 | 61.53 | | -- | -- | -- |
| Maximum | 221.55 | | 663.81 | | 613,475 | 847.38 | | -- | -- | -- |
| Average | 93.18 | | 250.90 | | 249,260 | 344.08 | | -- | -- | -- |

[1]Individual recharge estimates may not sum to total due to independent rounding.

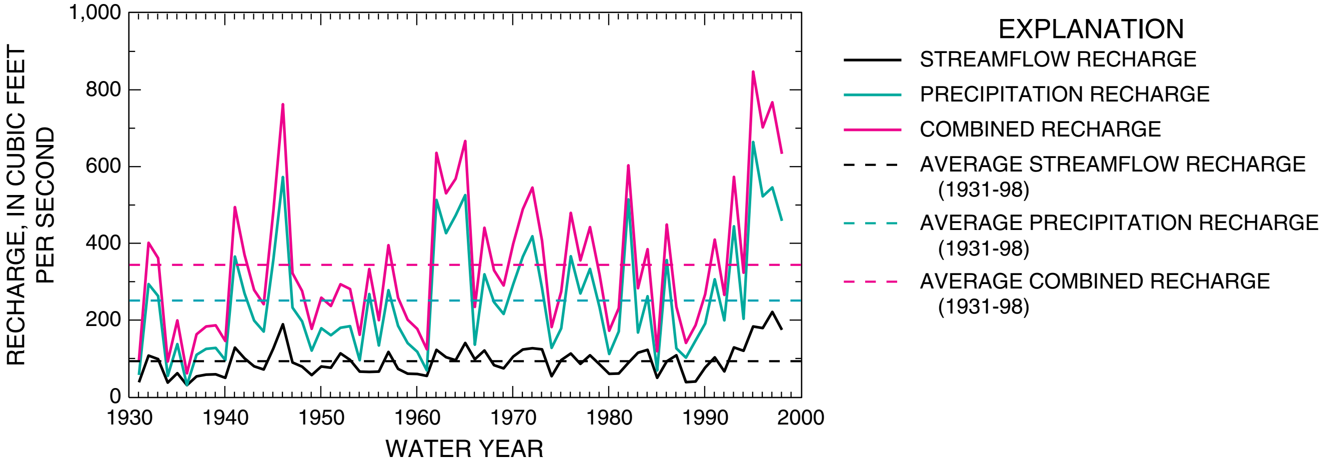



**Figure 18.** Average annual streamflow, precipitation, and combined recharge.

Recharge along the southeastern flank of the Black Hills probably is dominated by streamflow recharge. Distinctions between streamflow and precipitation recharge have not been computed for specific areas; however, the southeastern flank has small outcrops of Madison Limestone and Minnelusa Formation located in an area with minimal yield efficiency (fig. 16). A number of relatively large streams from Rapid Creek south to Beaver Creek provide a relatively consistent source of streamflow recharge. The western flank of the Black Hills is almost entirely dominated by precipitation recharge because of the large outcrop areas of Madison Limestone and Minnelusa Formation and absence of perennial streams that provide recharge.

The relative contribution from streamflow and precipitation recharge is highly variable along the northern and northeastern flanks of the Black Hills. Yield efficiencies generally are higher than along the southeastern flank; however, the width of outcrops varies considerably. Furthermore, many of the contributing areas for streamflow are small, relative to outcrop areas. In addition, streamflow recharge for Spearfish and Whitewood Creeks has been limited by anthropogenic effects.

Additional insights regarding the relative uncertainties of recharge estimates also are available from examination of table 16. It can be concluded that uncertainties regarding estimates of streamflow recharge for miscellaneous-record and ungaged basins are relatively small compared to overall uncertainty. These areas contribute only about 29 percent of average streamflow recharge (table 12), which constitutes only about 26 percent of total combined recharge (table 16). Thus, these areas generally contribute less than 10 percent of overall recharge. It is further apparent that the largest uncertainty regarding estimated recharge is associated with precipitation recharge, which dominates combined recharge for average conditions. Although the possibility of bias exists for estimates of precipitation recharge, the method used provides a consistent, systematic approach that could be adjusted in various ways, if a consistent bias is later identified and quantified. Results of initial water-budget analyses by Hamade (2000) showed no indication of large biases in estimates of precipitation recharge.

Minimum and maximum average annual precipitation amounts for the Black Hills area between 1931 and 1998 were estimated by Driscoll, Hamade, and Kenner (2000) as 10.22 inches for 1936 and 27.39 inches for 1995. These also are the years for which minimum and maximum recharge are estimated (table 16). Although the absolute level of accuracy for recharge estimates is unknown, there is confidence that on a relative scale the estimates presented herein are consistently realistic.

## SUMMARY

The Madison and Minnelusa aquifers are two of the most important aquifers in the Black Hills area. Long-term estimates of recharge to the Madison and Minnelusa aquifers are important for managing the water resources in the Black Hills area of South Dakota and Wyoming. Recharge occurs primarily from streamflow losses and infiltration of precipitation on outcrop areas. Annual recharge from these combined sources is estimated for water years 1931-98. All estimates are for recharge that contributes to regional ground-water flow patterns and that occurs in outcrop areas connected to the regional flow system. Estimates exclude recharge to outcrops areas that are isolated from the regional flow system (erosional remnants), which generally results in ground-water discharge to area streams.

Streamflow losses provide a consistent source of recharge to the Madison and Minnelusa aquifers. Most streams generally lose their entire flow in crossing these outcrops (loss zones), up to "threshold" rates that are unique for each stream. Streamflow recharge is calculated directly for 11 streams by applying estimated loss thresholds (from previous investigations) to available records of daily streamflow obtained from continuous-record gaging stations located upstream from loss zones. Availability of daily records ranges from 1992-98 for one station to 1950-98 for two stations. Daily streamflow records are extrapolated, when necessary, using correlations with long-term gages, to develop annual estimates of streamflow recharge for 1950-98.

Streamflow recharge is estimated for a number of smaller basins, using previously determined loss thresholds for miscellaneous-record sites. Synthetic records of daily streamflow for 1992-98 are developed for these basins, using drainage-area ratios applied to records for nearby continuous-record gaging stations, with recharge calculated directly by applying the loss thresholds. Recharge estimates are further extrapolated for 1950-91, based on the average percentage of streamflow recharge contributed by these basins during 1992-98, relative to overall streamflow recharge.

Streamflow recharge also is estimated for drainage areas with undetermined loss thresholds (ungaged basins) that are situated between larger basins with known thresholds. Recharge estimates for 1992-98 are based on estimates of annual streamflow derived using drainage-area ratios, relative to representative gaged streams. Recharge is assumed equal to 90 percent of annual streamflow, and estimates are again extrapolated for 1950-91, based on the average percentage of streamflow recharge contributed by these basins.

Precipitation recharge is estimated using relations between precipitation and basin yield for the Black Hills area. Streamflow records are available for numerous basins dominated by crystalline outcrops, where regional ground-water flow is considered negligible and basin yield represents the residual between precipitation and evapotranspiration. Streamflow records also are available for several streams, which are dominated by ground-water discharge from the Madison and/or Minnelusa aquifers. Basin yields for some of these streams are quite similar to yields in crystalline basins; however, presumed incongruences in contributing surface- and ground-water areas result in dissimilar yields for several streams.

Because of apparent differences in yield characteristics, positive correlations between annual yield efficiency (ratio of basin yield to precipitation) and precipitation are used in developing a systematic approach for estimating recharge efficiency. These relations are used to compute yield efficiencies for missing years of record between 1950 and 1998. Average yield efficiencies for this period are used to generate a map of generalized average yield efficiency for the Black Hills area. A simplifying assumption is made that yield efficiency can be used as a surrogate for recharge efficiency to the Madison and Minnelusa aquifers. An exponential equation for adjusting average yield efficiency, based on the ratio of annual to average precipitation, is used to predict annual yield (or recharge) efficiency. A geographic information system (GIS) algorithm is used to compute annual recharge, based on comparison of 1,000-by-1,000-meter grids for average precipitation, annual precipitation, and average yield efficiency. This method is used to estimate annual precipitation recharge for 1931-98, based on precipitation records for this period. Estimates of precipitation recharge for 1931-49 are used to estimate streamflow recharge for the same period, based on correlations between the two variables for 1989-98.

Yield efficiency, which is used as a surrogate for the efficiency of precipitation recharge, is highly variable in the Black Hills area and ranges from an average of just over 2 percent in the south to in excess of 30 percent in the north. Accordingly, average precipitation recharge ranges from about 0.4 inch in the southern Black Hills to 8.7 inches in the northwestern Black Hills.

Combined streamflow and precipitation recharge averaged about 344 $ft^3/s$ for 1931-98. Streamflow recharge averaged about 93 $ft^3/s$, or 27 percent of combined recharge, and precipitation recharge averaged about 251 $ft^3/s$, or 73 percent of combined recharge. Combined recharge ranged from about 62 $ft^3/s$ in 1936 to 847 $ft^3/s$ in 1995. The lowest recharge amounts generally occurred during the 1930's; however, a more prolonged period of low recharge occurred during 1947-61. Recharge during 1931-61 is below average for most years, and recharge during 1962-98 is above average for many years. Recharge during the 1990's is higher than for any other period.

Precipitation recharge is consistently larger than streamflow recharge; however, the relative proportion of streamflow recharge increases as combined recharge decreases. The minimum value for combined recharge (about 62 $ft^3/s$ for 1936) consists of 49.5 and 50.5 percent, respectively, from streamflow and precipitation recharge. This compares with 21.7 and 78.3 percent, respectively, for the maximum recharge value of about 847 $ft^3/s$ in 1995.

For 1931-98, average precipitation recharge to the Madison aquifer is about 3.6 inches, compared with 2.6 inches for the Minnelusa aquifer. Because the outcrop area of the Minnelusa Formation is larger, however, recharge volumes are nearly identical. Streamflow recharge to the Madison aquifer is presumed slightly larger than for the Minnelusa aquifer, primarily because of preferential recharge resulting from an upgradient location. Considering both precipitation and streamflow recharge, the Madison aquifer receives about 55 percent of combined recharge, relative to about 45 percent for the Minnelusa aquifer. Relative recharge proportions, however, have considerable temporal variability and very large spatial variability, depending on outcrop patterns.

The western flank of the Black Hills is almost entirely dominated by precipitation recharge, because of the large outcrop areas of Madison Limestone and Minnelusa Formation and absence of perennial streams. Recharge along the southeastern flank of the Black Hills generally is dominated by streamflow recharge. The relative contribution from streamflow and precipitation recharge is highly variable along the northern and northeastern flanks of the Black Hills.

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