ESTIMATING RECHARGE USING RELATIONS BETWEEN PRECIPITATION AND YIELD IN A MOUNTAINOUS AREA WITH LARGE VARIABILITY IN PRECIPITATION

1.0 Introduction

Long-term estimates of recharge to bedrock aquifers are useful for many purposes such as water-resource management and modeling; however, accounting for variability in recharge that results from spatial and temporal variability in precipitation can be difficult. For the Black Hills area of western South Dakota and eastern Wyoming, streamflow yield is highly influenced by annual precipitation, with yield efficiency (annual yield divided by annual precipitation) increasing with increasing annual precipitation (Driscoll and Carter, 2001). Spatial variability in annual yield characteristics for Black Hills streams is shown to be predictably influenced by precipitation patterns. Relations between annual yield efficiency and precipitation for streams with minimal ground-water influence were used as a means of estimating recharge efficiency (annual recharge divided by annual precipitation) for areas dominated by ground-water influence, as described in this paper.

Large spatial and temporal variability in precipitation has large influence on recharge to bedrock aquifers in the Black Hills area. Precipitation patterns (fig. 1) are highly influenced by orography, where land-surface altitudes range from 2,207 m above the National Geodetic Vertical Datum of 1929 (NGVD 29) at Harney Peak to about 900 m above NGVD 29 in the adjacent plains. Average annual precipitation generally increases with increasing altitude, and ranges from about 38 to 71 cm in the area. Conversely, temperatures and associated evapotranspiration generally decrease with increasing altitude, which, in combination with increased precipitation, results in increased potential for ground-water recharge and streamflow at higher altitudes. Average pan evaporation for April through October is about 127 cm at Oral (in the southeastern part of the study area) and about 76 cm at Pactola Reservoir (in the central Black Hills area) (U.S. Department of Commerce, 1999). Large temporal variability in annual precipitation in the area (fig. 2) also has large influence on annual recharge rates.

Two of the most important bedrock aquifers in the Black Hills area are the Minnelusa and Madison aquifers, both of which receive recharge from infiltration of precipitation on their outcrops and from streamflow losses that occur in zones of high secondary porosity along stream channels. The Minnelusa aquifer occurs within layers of sandstone and gypsum in the upper portion of the Pennsylvanian- and Permian-age Minnelusa Formation and within layers of sandstone, dolomite, and anhydrite in the lower portion. The Minnelusa aquifer has primary porosity in the sandstone units and secondary porosity from fracturing and collapse breccia associated with dissolution of interbedded evaporites. The Madison aquifer generally occurs within the karstic upper part of the Mississippian-age Madison Limestone; however, the entire Madison Limestone and the Devonian- and Mississippian-age Englewood Formation are included in the delineation of the aquifer by Strobel et al. (1999). Numerous fractures and solution openings in the Madison Limestone provide extensive secondary porosity in the aquifer.

Various estimates of recharge to the Madison and Minnelusa aquifers from infiltration of precipitation have been made for the Black Hills area (Cox, 1962; Rahn and Gries, 1973; Peter, 1985; Downey, 1986; Ghannam, 1993; Dayananda, 1993; Greene, 1997). All of these were gross estimates that generally were based on water-budget approaches or on estimated percentages of average annual precipitation over widespread areas. Previous estimates have ranged from 1.5 cm/yr in the southern Black Hills to about 17 cm/yr in the northern Black Hills.

For the Black Hills area, Carter et al. (2001a) showed that the efficiency of streamflow yield in drainages with minimal ground-water influence was similar to the efficiency of precipitation recharge to the Madison and Minnelusa aquifers. Relations between precipitation and yield efficiency were used to develop a series of geographic information system (GIS) algorithms for systematically estimating annual recharge from infiltration of precipitation to aquifers in the Black Hills area. This paper describes the GIS method used to estimate annual recharge rates for water years 1931-1998 in the Black Hills area of western South Dakota and eastern Wyoming and an average recharge rate for water years 1950-1998. The method provides a consistent, reproducible means of obtaining reasonable estimates of recharge from precipitation needed for extensive hydrologic budgets developed as part of a large, regional hydrologic assessment described by Driscoll (1992).

2.0 Recharge processes and conceptualization

As described below, direct runoff is extremely uncommon, and can be considered negligible within outcrops of the Madison and Minnelusa aquifers; thus, recharge from infiltration of precipitation is essentially the residual between precipitation and evapotranspiration. Distances to the water table are highly variable, but typically are many tens of meters or more. Evapotranspiration rates decrease gradually with increasing altitude and also change with aspect primarily because of differences in energy input (Wrage, 1994). However, large variability in actual evapotranspiration can occur within short distances because of large potential differences in various factors within the root zone such as vegetative characteristics, soil characteristics (e.g., thickness, infiltration rates, storage capacity), and characteristics of the underlying bedrock. Measured evapotranspiration rates of the Black Hills pine forest do not exist, and estimation of evapotranspiration generally involves extensive modeling efforts that require input of hourly climatic data (Fluke, 1996).

Similarly, use of pan evaporation data would have very limited utility for estimation of annual recharge. Except for very wet years, annual evaporation typically exceeds annual precipitation for most of the Black Hills area. Thus, evapotranspiration generally is limited by precipitation amounts and availability of soil moisture.

Extremely large secondary porosity within the Minnelusa and Madison aquifers is evident in the dramatic streamflow losses to these aquifers, which can be as much as 1.4 m^3/s for Boxelder Creek northwest of Rapid City (Hortness and Driscoll, 1998). Both aquifers commonly have fractures and solution features in outcrop sections. However, the fact that both aquifers have large secondary porosity in some locations does not necessarily imply that infiltration rates will be uniformly large in all outcrop sections. Both aquifers are prone to large heterogeneity in aquifer characteristics (Cox, 1962; Greene, 1993; Greene and Rahn, 1995; Long and Putnam, 2002).

A perspective on the infiltration capacity of the Minnelusa and Madison aquifers on a watershed scale can be obtained by examination of streamflow information for selected streamflow-gaging stations. Duration hydrographs are presented in figure 3 for four gages (graphs A through D) located in or near the Limestone Plateau area on the western flank of the Black Hills, which is dominated by large outcrop areas of the Madison Limestone and Minnelusa Formation; locations of stations are shown in figure 1. Flow at these gages is dominated by base flow originating from ground-water discharge from the Minnelusa and Madison aquifers; correlations between annual streamflow and precipitation are weak for these streams (Driscoll and Carter, 2001). Surface drainage areas for these gages are not necessarily congruent with contributing ground-water areas, which were estimated on the basis of structural information by Jarrell (2000) for the four gages. For comparison, a duration hydrograph is presented for a gaging station on Battle Creek (graph E, fig. 3), the drainage area of which is dominated by Precambrian igneous and metamorphic rocks, which comprise the ‘‘crystalline core area’’ of the Black Hills uplift (fig. 1). In contrast to flows at stations in the Limestone Plateau area, the flow of Battle Creek is highly variable and responsive to short-term or seasonal climatic conditions, indicating dominance from surface-water flow components relative to ground-water flow components.

An important observation from examination of the duration hydrographs is that direct surface runoff from outcrops of the Madison Limestone and Minnelusa Formation is very uncommon. Surface runoff is virtually nonexistent for Rhoads Fork (graph A, fig. 3), for which the surface drainage area is comprised almost entirely of the Madison Limestone. Increasingly larger components of surface runoff are apparent for graphs D, C, and B, respectively, which can be attributed to increasingly larger percentages of rocks other than the Madison Limestone and Minnelusa Formation within these drainage basins. Additional supporting documentation of the infrequence occurrence of direct runoff from these outcrops is provided by Miller and Driscoll (1998), who summarize streamflow characteristics in the Black Hills area. These observations are the basis of a simplifying assumption that direct surface runoff from the Madison Limestone and Minnelusa Formation is almost nonexistent and can be neglected for many purposes associated with calculation of recharge to these aquifers. By neglecting surface runoff, it can be assumed that the portion of precipitation on these formations that is not evapotranspired becomes recharge, as schematically illustrated in figure 4.

The difference between precipitation and basin yield within the crystalline core area is used as an indirect measure of evapotranspiration. Although recharge does occur to numerous localized aquifers in the fractured crystalline rocks, these aquifers are not regional as indicated by the fact that wells constructed in Precambrian rocks in western South Dakota outside of the Black Hills have not encountered measurable amounts of ground water (Rahn, 1985). Additionally, well yields and fracture porosity decrease with increasing depth in the Precambrian rocks (Rahn, 1985). Therefore, a second assumption was made that regional ground-water flow in the crystalline rocks can be considered negligible (fig. 4). Further documentation of this assumption was presented by Driscoll and Carter (2001).

Streamflow records are available for numerous drainage basins within the crystalline core area, which are appropriate for use in estimating basin yield. In the absence of a regional ground-water flow component in this area, basin yield can be considered as the residual between precipitation and evapotranspiration, for periods sufficiently long to neglect change in storage. These assumptions were the basis for a concept that streamflow yield in the crystalline core setting could be used as a surrogate for the efficiency of precipitation recharge to the Madison and Minnelusa aquifers by assuming that evapotranspiration on the Madison and Minnelusa outcrops is similar to that within nearby parts of the crystalline core area. Annual yields for streams situated in Precambrian rocks compared favorably with yields (adjusted for estimated ground-water contributing areas) for streams originating as springs that constitute ground-water discharge from the Limestone Plateau area (Jarrell, 2000).

3.0 Precipitation and yield efficiency

Driscoll et al. (2000) developed a GIS grid, with a spacing of 1,000 m, of monthly and annual precipitation distributions based on measurements from 94 precipitation gages in the Black Hills area for water years 1931-1998; a water year (WY) is the 12-month period from October 1 to September 30, and is designated by the calendar year in which it ends. This GIS grid was subsequently used for calculation of annual precipitation for selected drainage areas and outcrop areas, and also was incorporated in the GIS algorithm used for calculating recharge (Carter et al., 2001a). Data from Driscoll et al. (2000) were used to generate a digital grid (1000-by-1000 m) for annual precipitation distributions for each year from WY 1931 to WY 1998 (P_i grid) and a digital grid for the average annual precipitation distribution for WY 1950-1998 ($P_{average}$ grid); the $P_{average}$ grid corresponds with the contours shown in figure 1.

Annual yield efficiencies (YE_i), which represent the percentage of precipitation that is available either for runoff or recharge, were calculated by dividing annual yield (Q_i) [L], which is the amount of water that runs off a drainage basin in a year and expressed here as a depth of water on the drainage basin, for 11 gaging stations in the crystalline core area by annual precipitation (P_i) [L] on contributing drainage areas as represented in the following equation:

$$YE_i = \frac{Q_i}{P_i} \times 100 \qquad (1)$$

where i = 1, 2, …., N and represents the year of interest

Relations between precipitation and annual yield efficiency are shown in figure 5 for these 11 gaging stations (fig. 6) representative of the crystalline core setting. A simple linear regression line is shown for each gage; R^2 values ranged from 0.32 for Beaver Creek to 0.68 for Annie Creek (see Carter et al., 2001a, table 14, for more details). These relations were used to derive the estimates of average yield efficiency for WY 1950-1998 from generally shorter periods of record for a variety of different timeframes. A map of generalized average annual yield efficiency for the study area is shown in figure 6, which includes estimated yield efficiencies for gages outside of the crystalline core setting. Contouring was done to reflect conditions upstream from representative gages, including influences of contributing ground-water areas in the Limestone Plateau area. As previously stated, contributing surface drainages for the four gages located in the Limestone Plateau area in South Dakota (fig. 1) are not necessarily congruent with ground-water contributing areas, which results in anomalously low or high yield efficiencies. Yield efficiencies for these four gages (fig. 6) were adjusted using contributing ground-water areas determined by Jarrell (2000). Contributing ground-water areas were not determined for the two gages located in Wyoming on the Limestone Plateau (fig. 6), but probably are smaller than the corresponding surface drainages, which would result in anomalously low yield efficiencies. Thus, contouring reflects presumably higher yield efficiencies for these two gages. A digital grid (1,000-by-1,000 m) of the yield efficiency distribution shown in fig. 6 was generated for subsequent analyses ($YE_{average}$ grid).

Two exponential curves also are depicted in figure 5 for each gaging station. Both exponential equations are of the form:

$$YE = \left(\frac{P}{P_{ave}} \right)^n \times YE_{ave} \qquad (2)$$

where

YE = annual yield efficiency, in percent;

P = annual precipitation for the basin, in cm;

P_{ave} = average annual precipitation for the basin, in cm;

YE_{ave} = average annual yield efficiency, in percent;

n = exponent

One of the exponential curves (fig. 5) represents a "best-fit" exponent, for the fit of the short-term (period of record) data points using the long-term (WY 1950-1998) values for average precipitation (P_{ave}) and yield efficiency (YE_{ave}) within the equation. The best-fit exponents range from 1.1 to 2.5; R^2 values for the relations ranged from 0.34 for Elk Creek to 0.75 for Spring Creek and generally were higher than R^2 values yielded from the linear regressions. A second curve also is shown that depicts the fit for a common exponent of 1.6 for each gage, which was selected as best representing the range of best-fit exponents (Carter et al., 2001a). As shown, predictions of yield efficiency for the common exponent of 1.6 are comparable to those for the linear regression and best-fit exponent, especially through the mid-range of precipitation values.

Equations (1) and (2) can be combined in (3) to compute annual yield for a basin:

$$Q_i = \left(\frac{P_i}{P_{ave}}\right)^n \times \left(\frac{YE_{ave}}{100}\right) \times P_i \quad (3)$$

where Q_i is the annual yield, in cm, from a basin for year i, and P_i is the annual precipitation, in cm, over the basin.

4.0 Application of the yield-efficiency algorithm

The selection of a single common exponent for use with a single common equation facilitated development of a systematic GIS algorithm, referred to as the yield-efficiency algorithm, for estimation of annual recharge from infiltration of precipitation, based on annual precipitation on outcrop areas. A computer algorithm, which utilized the set of three digital grids (P_{ave}, P_i, and YE_{ave}) with equation (3), was developed to generate digital grids of annual yield (Q_i) for each year during WY 1950-1998 using an exponent of 1.6.

The application of the method is illustrated with the following example, which assumes that precipitation for given year (P_i) at a given grid cell is 40 cm, relative to a long-term average (P_{ave}) of 50 cm per year, and that average yield efficiency (YE_{ave}) for that cell is 10 percent.

Estimated yield efficiency for that year using equation 2 would be 7.0 percent. Thus, estimated annual yield (or recharge, for the assumption of the Madison and Minnelusa aquifers) using equation 3 would be 2.8 cm. For the same cell with P_i exactly equal to the average (50 cm), yield efficiency also would be average (10 percent) and estimated yield would be 5.0 cm. For the same cell with P_i of 60 cm, estimated efficiency would be 13.4 percent, resulting in estimated yield of 8.0 cm. The error bar about the recharge estimates is of course unknown; however, the estimates can be systematically replicated.

4.1 Recharge estimates for the Madison and Minnelusa aquifers

The digital grids of Q_i that were generated were applied to the outcrop areas of the Madison Limestone and Minnelusa Formation to determine annual recharge volumes in m^3/s. Based on the previously mentioned assumption that all precipitation on outcrop areas of the Madison Limestone and Minnelusa Formation that is not evapotranspired becomes recharge, *annual yield* was assumed to equal *recharge* on these formations. Estimates of annual recharge, in cm, were obtained by dividing the recharge volume by the outcrop areas of the Madison Limestone and Minnelusa Formation, which are about 1219 km^2 and 1729 km^2, respectively. The spatial distribution of average annual recharge to the Madison and Minnelusa aquifers (WY 1950-1998), along with lines of equal average annual yield potential for all of the Black Hills area, is shown in figure 7. The annual yield potential is the amount of water that is potentially yielded either as streamflow or recharge. Generally, this yield occurs as streamflow for outcrop areas that are considered confining units and as recharge in aquifer outcrops. The average annual recharge from precipitation was estimated to range from 1 cm in the southern Black Hills to 22 cm in the northwestern Black Hills.

Estimates of annual recharge rates to the Madison and Minnelusa aquifers from infiltration of precipitation during WY 1931-1998 are presented in figure 8. The minimum recharge rate of about 0.9 m^3/s occurred in 1936, and provides an indication of recharge conditions during a severe drought. The maximum recharge rate of about 18.8 m^3/s was estimated for 1995, during extremely wet climatic conditions in the Black Hills area. Estimates also are provided in figure 8 for streamflow recharge that occurs in streamflow-loss zones where streams cross the aquifer outcrops, primarily along the northern and eastern flanks of the Black Hills. Additional details regarding estimation of streamflow recharge rates were described by Carter et al. (2001a). Detailed water budgets developed by Carter et al. (2001b) for the Madison and Minnelusa aquifers indicated that the recharge estimates were consistent with other water budget components

4.2 Other applications

Recharge from infiltration of precipitation was estimated for several other aquifers in the Black Hills area by application of coefficients (between 0.0 and 1.0) to estimates of total annual yield (Driscoll and Carter, 2001). The coefficient simply apportioned total estimated yield between aquifer recharge and streamflow yield based on formation properties. For example, Driscoll and Carter (2001) applied a small coefficient (0.05) to calculate recharge for units comprised mostly of shale because infiltration (aquifer recharge) for these units is small whereas streamflow yield is large. The yield-efficiency algorithm also was utilized extensively by Driscoll and Carter (2001) for estimating streamflow yield from ungaged drainage areas for use in surface-water budgets developed for the Black Hills area. These efforts involved estimation of annual yield for areas beyond the Madison and Minnelusa outcrops, for which the method was originally developed. This work included an evaluation of yield estimates, which indicated that estimates for areas beyond the Madison and Minnelusa outcrops were reasonable. These evaluations also provided confidence that the yield-efficiency algorithm systematically produced reasonable and reproducible estimates of total yield from the spatial distribution of annual precipitation.

5.0 Conclusions

Relations between precipitation and yield efficiency were used to develop a series of geographical information system (GIS) algorithms to estimate annual recharge rates in the Black Hills of western South Dakota and eastern Wyoming. The spatial distribution of yield efficiency followed a predictable pattern throughout the Black Hills area. Because yield efficiency increases with increasing annual precipitation, the algorithm allowed for variable recharge rates based on annual precipitation rather than assuming a flat percentage of annual precipitation. Although this GIS method was developed initially for estimating precipitation recharge for the Madison and Minnelusa aquifers, applications for estimating streamflow yield and recharge for other aquifers also are appropriate. This application could be applied to other aquifer systems in areas where recharge is influenced by large spatial and temporal variability in precipitation. Uncertainties associated with the method cannot be evaluated precisely. However, additional water-budget analyses for both ground water and surface water in the Black Hills area provided confidence that the estimates yielded by this method are realistic and provide a consistent, systematic approach to estimating recharge

Acknowledgments

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Figures

1. Isohyetal map showing distribution of average annual precipitation for the Black Hills area, water years 1950-1998 (modified from Carter et al., 2001a). Outcrops of the Madison Limestone, Minnelusa Formation, and the crystalline core setting also are shown.

2. Long-term trends in precipitation for the Black Hills area, water years 1931-1998 (modified from Driscoll et al., 2000)

3. Daily-duration hydrographs for selected streamflow-gaging stations. Locations of stations are shown in figure 1.

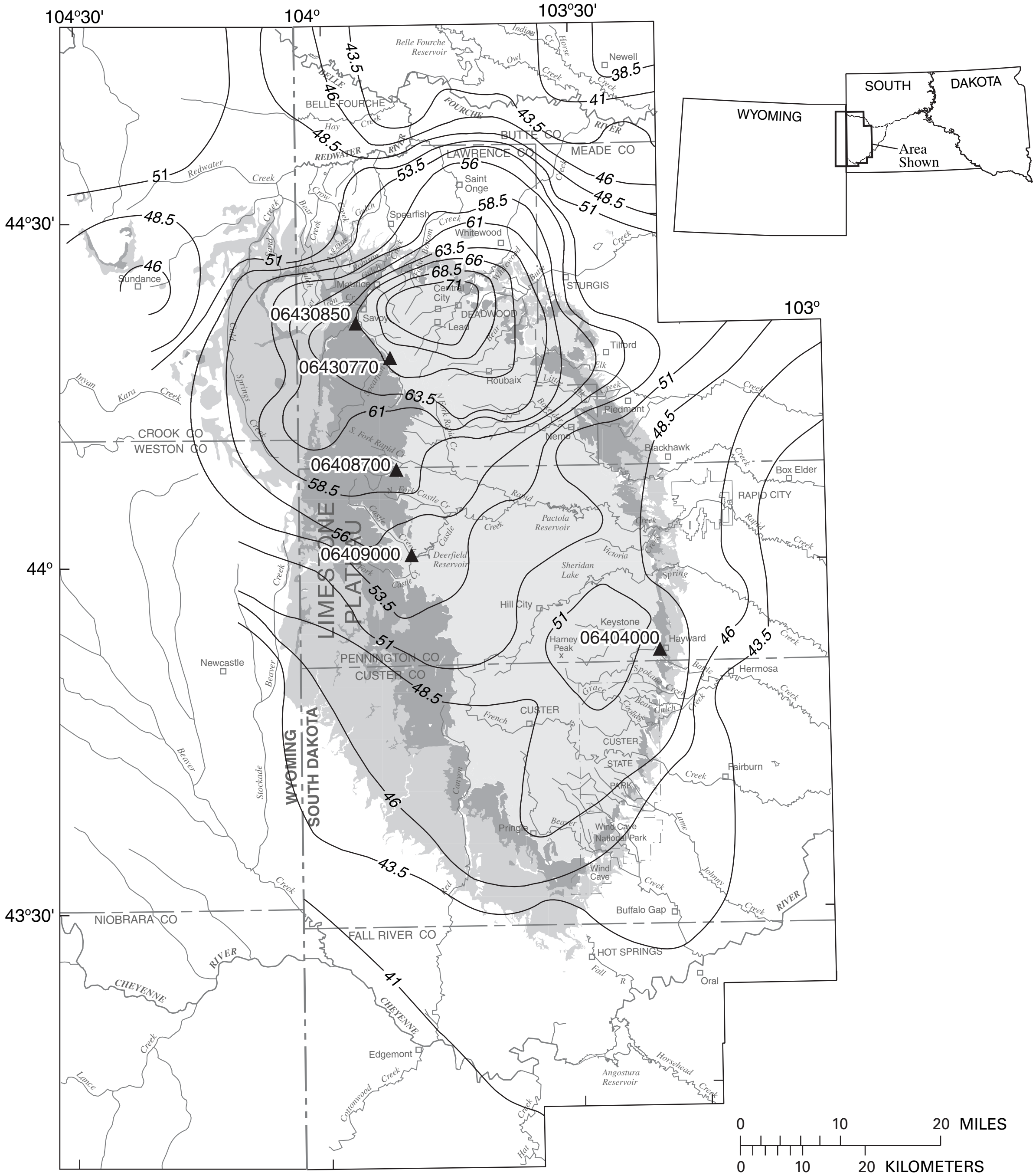
4. Schematic diagram illustrating recharge and streamflow characteristics for selected outcrop types (from Carter et al., 2001a)

5. Regression plots of yield efficiency with precipitation for selected streamflow gaging stations

6. Generalized average annual yield efficiency (in percent of annual precipitation), water years 1950-1998 (from Carter et al., 2001a)

7. Estimated annual yield potential and average annual recharge from precipitation on outcrops of the Madison Limestone and Minnelusa Formation, water years 1950-1998 (modified from Carter et al., 2001a)

8. Average annual streamflow, precipitation, and combined recharge rates for the Minnelusa and Madison aquifers in the Black Hills area, water years 1931-1998 (modified from Carter et al., 2001a)



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 (from Strobel et al., 1999; DeWitt et al., 1989)

Outcrop of the Minnelusa Formation (from Strobel et al., 1999; DeWitt et al., 1989)

Predominantly igneous and metamorphic rocks; classified as "crystalline core" setting (from Driscoll and Carter, 2001)

—20— **Line of equal average annual precipitation**—Interval 2.5 centimeters

▲ 06404000 **Streamflow-gaging station shown in figure 3—**Number indicates station identification number

Figure 1. Isohyetal map showing distribution of average annual precipitation for Black Hills area, water years 1950-98 (modified from Carter et al., 2001a). Outcrops of the Madison Limestone, Minnelusa Formation, and the crystalline core setting also are shown.

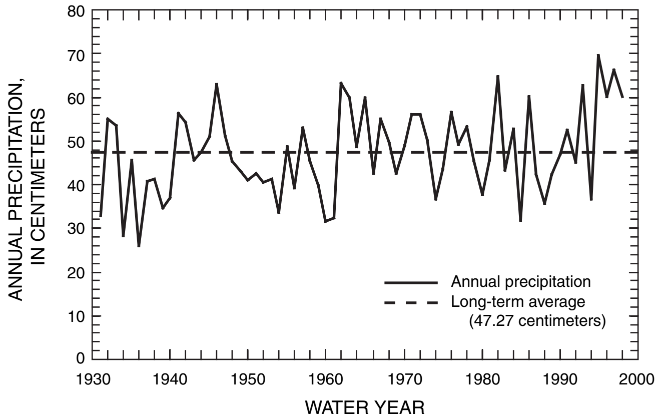


Figure 2. Long-term trends in precipitation for the Black Hills area, water years 1931-98 (modified from Driscoll et al. 2000).

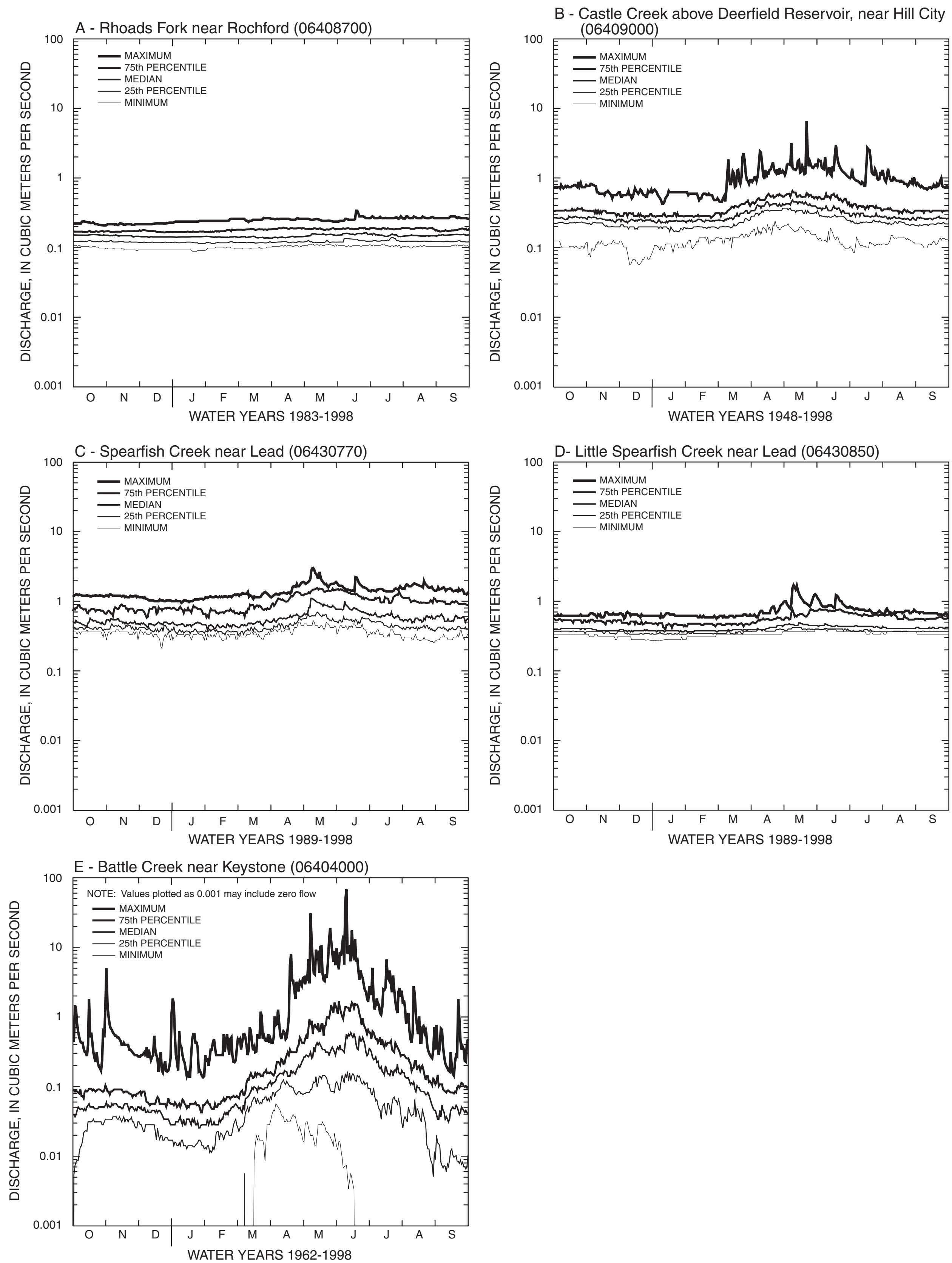


Figure 3. Daily-duration hydrographs for selected streamflow-gaging stations. Locations of stations are shown in figure 1.

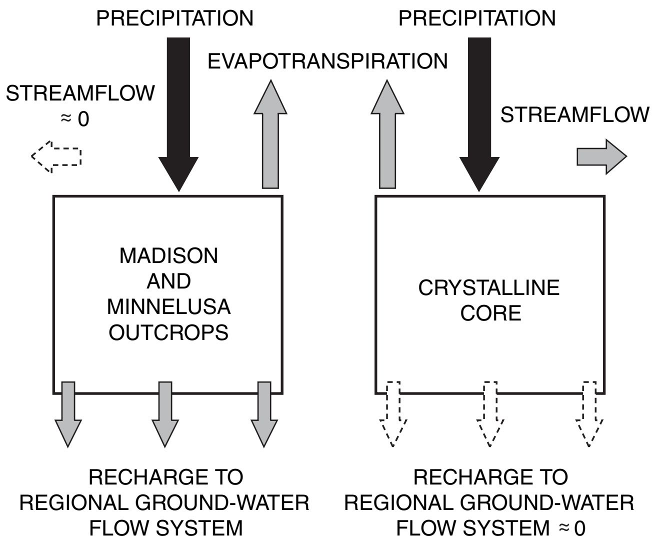


Figure 4. Schematic diagram illustrating recharge and streamflow characteristics for selected outcrop types (from Carter et al., 2001a).

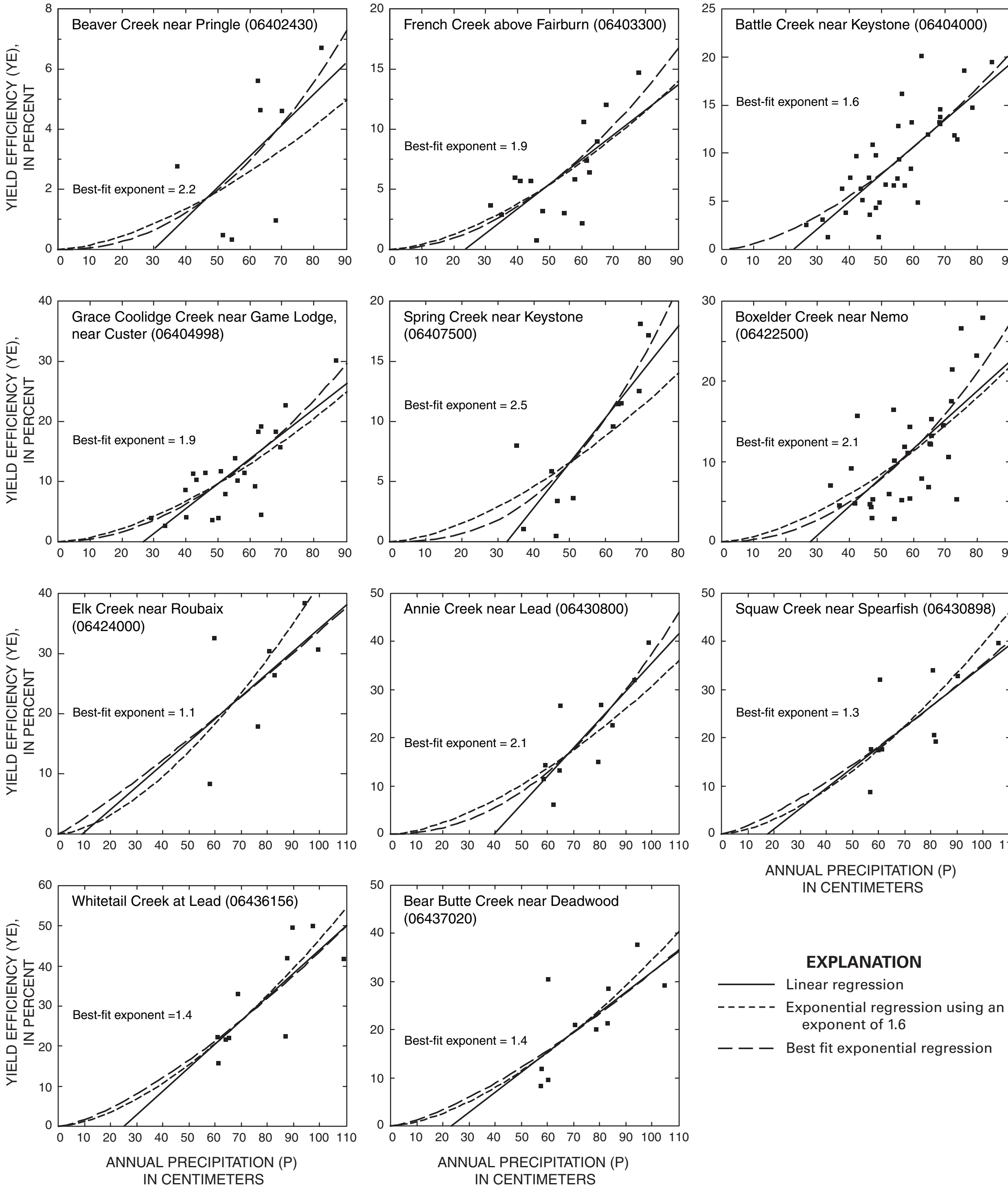
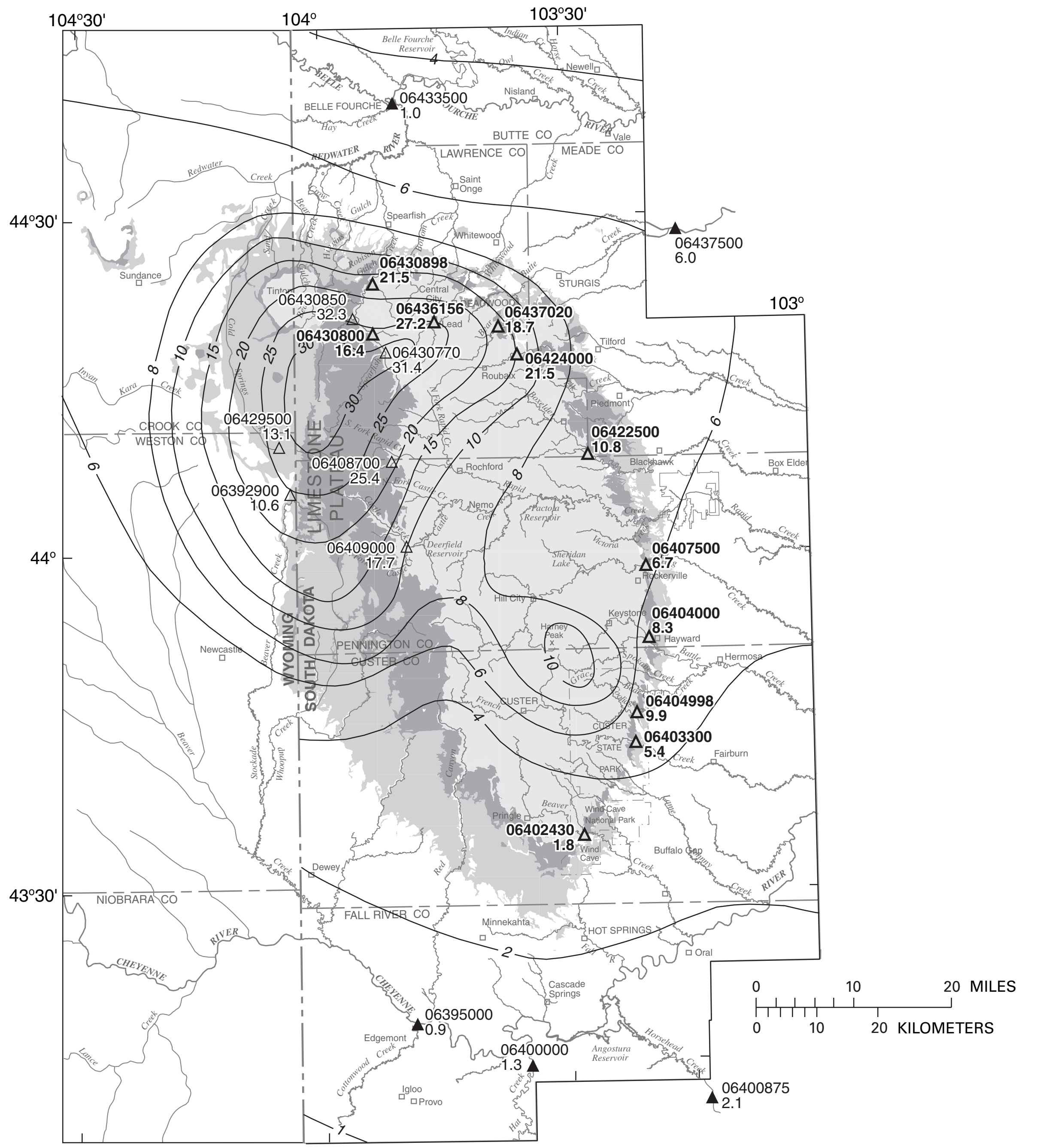


Figure 5. Regression plots of yield efficiency with precipitation for selected streamflow-gaging stations.



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

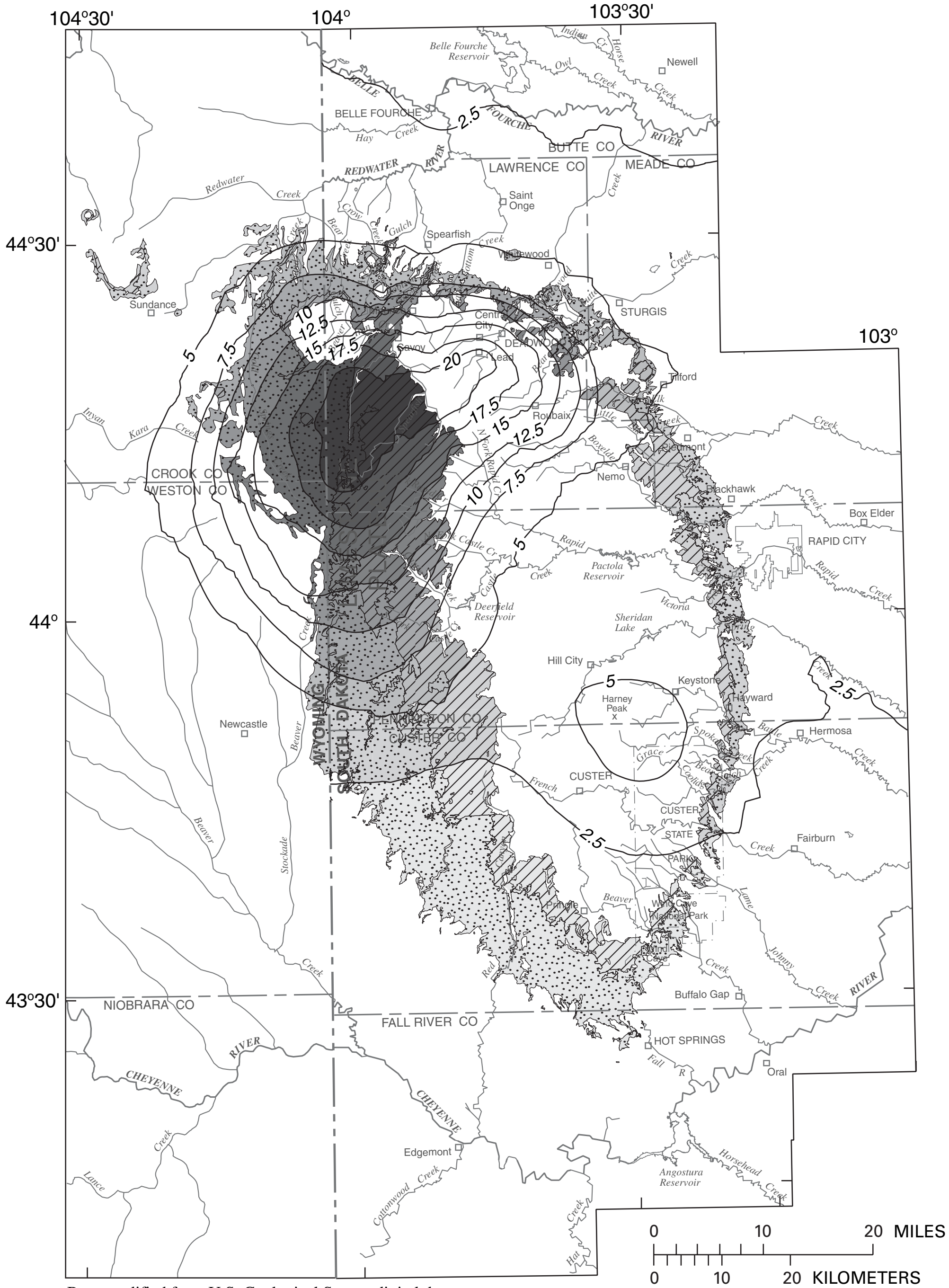
EXPLANATION

- **Outcrop of the Madison Limestone**
- **Outcrop of the Minnelusa Formation**
- **Predominantly igneous and metamorphic rocks; classified as "crystalline core" setting** (from Driscoll and Carter, 2001)
- —15— **Line of equal average annual yield efficiency—**Interval 1, 2, or 5 percent

Streamflow-gaging station—Numbers indicate site number and estimated yield efficiency, in percent, for water years 1950-1998

- △ 06430850 32.3 — Substantial influence from ground-water discharge in Limestone Plateau area
- **△ 06402250 10.8** — Representative of "crystalline core" setting
- ▲ 06433500 1.0 — Outside "crystalline core" setting

Figure 6. Generalized average annual yield efficiency (in percent of annual precipitation), water years 1950-1998 (from Carter et al., 2001a).



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

— 5 — **Line of equal yield potential—**Number indicates average annual yield potential. Interval 2.5 centimeters

Average annual recharge, in centimeters

- Less than 2.5
- Between 2.5 and 5
- Between 5 and 7.5
- Between 7.5 and 10
- Between 10 and 12.5
- Between 12.5 and 15
- Between 15 and 17.5
- Between 17.5 and 20
- Greater than 20

Figure 7. Estimated annual yield potential and average annual recharge from precipitation on outcrops of the Madison Limestone and Minnelusa Formation, water years 1950-1998 (modified from Carter et al., 2001a).

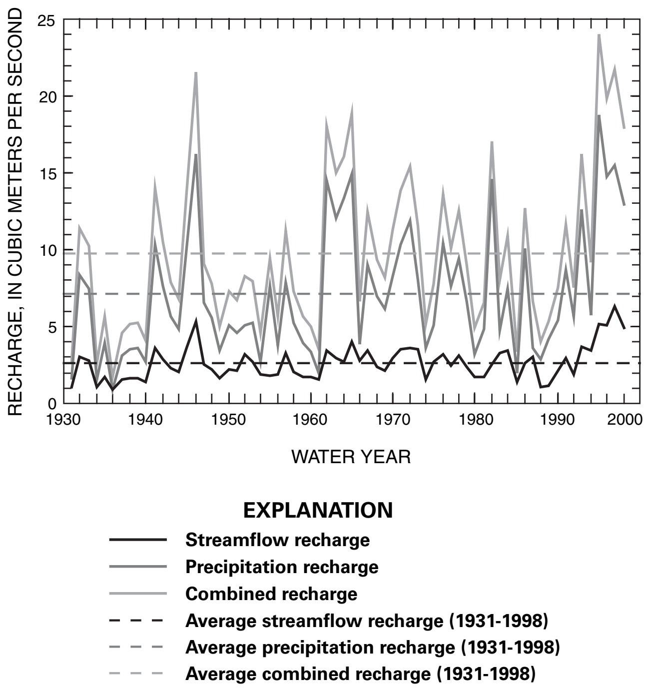


Figure 8. Average annual streamflow, precipitation, and combined recharge rates for the Minnelusa and Madison aquifers in the Black Hills area, water years 1931-1998 (modified from Carter et al., 2001a).