Estimated Recharge to the Madison and Minnelusa Aquifers in the Black Hills Area, South Dakota and Wyoming, Water Years 1931-98

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ABSTRACT

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. Thus, annual recharge from streamflow losses and infiltration of precipitation on outcrop areas 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 outcrop areas that are isolated from the regional flow system, which generally results in ground-water discharge to area streams.

Streamflow recharge is calculated directly for 11 streams in the Black Hills area that have continuous-record gaging stations located upstream from loss zones, using available records of daily streamflow, against which estimated loss thresholds (from previous investigations) are applied. 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 loss thresholds for miscellaneous-record sites. Annual recharge estimates are derived from synthetic records of daily streamflow for 1992-98, which are based on drainage-area ratios applied to continuous-record gaging stations. 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 small drainage areas with undetermined loss thresholds that are situated between larger basins with known thresholds. Estimates for 1992-98 are based on estimates of annual streamflow derived using drainage-area ratios, with assumed losses equal to 90 percent of annual streamflow. Recharge estimates also are extrapolated for 1950-91, based on the average percentage of streamflow recharge contributed by these basins.

Precipitation recharge for 1931-98 is estimated using relations between precipitation and streamflow (or basin yield) for representative gaging stations. Basin yields are first normalized, relative to drainage area, by expressing in inches per unit of drainage area. Yields are further converted to yield efficiencies, by dividing by precipitation on contributing drainage areas. Relations between yield efficiency and precipitation are identified, which are developed for use in generically estimating annual yield for given areas, based on average yield efficiency and annual precipitation. The resulting annual yield is used as a surrogate for estimating annual recharge from infiltration of precipitation on outcrop areas of the Madison and Minnelusa aquifers. Annual yield (or recharge) efficiencies are estimated to

range from about 2 percent to in excess of 30 percent, with corresponding average annual recharge estimates ranging from 0.4 inch in the southern Black Hills to about 8.7 inches in the northwestern Black Hills.

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. Combined streamflow and precipitation recharge to both aquifers 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 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.

For 1931-98, average precipitation recharge to the Madison aquifer is about 3.6 inches, compared with 2.6 inches for the Minnelusa aquifer. However, recharge volumes to these aquifers are nearly identical because the outcrop area of the Minnelusa Formation is larger than the outcrop area of the Madison Limestone. 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.

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.

INTRODUCTION

The Black Hills area is an important resource center that provides an economic base for western South Dakota through tourism, agriculture, the timber industry, and mineral resources. In addition, water originating from the area is used for municipal, industrial, agricultural, and recreational purposes throughout much of western South Dakota. The Black Hills area also is an important recharge area for aquifers in the northern Great Plains.

Population growth, resource development, and periodic droughts have the potential to affect the quantity, quality, and availability of water within the Black Hills area. Because of this concern, the Black Hills Hydrology Study was initiated in 1990 to assess the quantity, quality, and distribution of surface water and ground water in the Black Hills area of South Dakota (Driscoll, 1992). This long-term study is a cooperative effort between the U.S. Geological Survey (USGS), the South Dakota Department of Environment and Natural Resources, and the West Dakota Water Development District, which represents various local and county cooperators.

The Madison and Minnelusa aquifers are two of the most important aquifers in the Black Hills area and are a major emphasis of the Black Hills Hydrology Study. These aquifers are utilized for domestic, municipal, agricultural, and industrial uses. Recharge to these aquifers occurs primarily from infiltration of streamflow losses and infiltration of precipitation on outcrop areas. Long-term estimates of recharge to the Madison and Minnelusa aquifers are important for managing the water resources in the Black Hills area.

Purpose and Scope

The purpose of this report is to describe methods for quantifying recharge to the Madison and Minnelusa aquifers in the Black Hills area of South Dakota and Wyoming and to estimate combined recharge to these aquifers. Annual estimates for water years 1931-98 are presented for recharge from (1) infiltration of streamflow losses (streamflow recharge), and (2) infiltration of precipitation (precipitation recharge). Recharge estimates for the two aquifers are combined because streamflow recharge cannot be quantified separately for most streams. Individual estimates of precipitation recharge are provided because calculations can be based on individual outcrop areas. Recharge estimates

are for "regional recharge," which consists of recharge to outcrops of the Madison Limestone and Minnelusa Formation that are connected to the regional flow system, as discussed in a subsequent section. This excludes recharge to outcrops that are isolated from the regional flow system (erosional remnants).

Based on water-level data for paired wells (Driscoll, Bradford, and Moran, 2000), there is the potential for leakage to the Madison aquifer from the underlying Deadwood aquifer in some areas and from the Madison aquifer to the Deadwood aquifer in other areas. There also is potential for upward leakage from the Madison and Minnelusa aquifers to overlying aquifers such as the Inyan Kara aquifer. No attempt is made to quantify leakage to or from the Madison and Minnelusa aquifers because of insufficient information; the scope of this report is limited to streamflow recharge and precipitation recharge.

Description of Study Area

The study area for the Black Hills Hydrology Study consists of the topographically defined Black Hills and adjacent areas located in western South Dakota (fig. 1). Outcrops of the Madison Limestone and Minnelusa Formation, as well as the generalized outer extent of the Inyan Kara Group, which approximates the outer extent of the Black Hills area, also are shown in figure 1. Outcrop areas of the Madison Limestone and Minnelusa Formation in the Black Hills of Wyoming (just west of the study area) also are considered in this report as described in a following section. The study area for the Black Hills Hydrology Study includes most of the larger communities in western South Dakota and contains about one-third of the State's population.

Physiography, Land Use, and Climate

The Black Hills uplift formed as an elongated dome about 60 to 65 million years ago during the Laramide orogeny (DeWitt and others, 1986). The dome trends north-northwest and is about 120 mi long and 60 mi wide. Elevations range from 7,242 ft above sea level at Harney Peak to about 3,000 ft in the adjacent plains. Most of the higher elevations are heavily forested with ponderosa pine, which is the primary product of an active timber industry. White spruce, quaking aspen, paper birch, and other native trees and shrubs are found in cooler, wetter areas (Orr, 1959). The lower elevations surrounding the Black Hills primarily are urban, suburban, and agricultural. Numerous deciduous species such as cottonwood, ash, elm, oak, and willow are common along stream bottoms in the lower elevations. Rangeland, hayland, and winter wheat farming are the principal agricultural uses for dryland areas. Alfalfa, corn, and vegetables are produced in bottom lands and in irrigated areas. Various other crops, primarily for cattle fodder, are produced in both dryland areas and in bottom lands.

Beginning in the 1870's, the Black Hills have been explored and mined for many mineral resources including gold, silver, tin, tungsten, mica, feldspar, bentonite, beryl, lead, zinc, uranium, lithium, sand, gravel, and oil (U.S. Department of Interior, 1967). Mining methods have included placer mining, small surface pits, large open pits, and underground mines.

The overall climate of the study area is continental, with generally low precipitation amounts, hot summers, cold winters, and extreme variations in both precipitation and temperatures (Johnson, 1933). Climatic conditions are affected by regional patterns, with the northern Black Hills influenced primarily by moist air currents out of the northwest, and the southern Black Hills influenced more by dry, continental air currents out of the south-southeast. Local climatic conditions are affected by topography, with generally lower temperatures and higher precipitation at the higher elevations.

The average annual precipitation for the study area (1931-98) is 18.61 inches and has ranged from 10.22 inches for water year 1936 to 27.39 inches for water year 1995 (Driscoll, Hamade, and Kenner, 2000). The largest precipitation amounts typically occur in the northern Black Hills near Lead, where average annual precipitation exceeds 29 inches. Annual averages (1931-98) for counties within the study area range from 16.35 inches for Fall River County to 23.11 inches for Lawrence County (Driscoll, Hamade, and Kenner, 2000). The average annual temperature is 43.9°F (U.S. Department of Commerce, 1999) and ranges from 48.7°F at Hot Springs to approximately 37°F near Deerfield Reservoir. Average annual evaporation generally exceeds average annual precipitation throughout the study area. Average pan evaporation for April through October is about 30 inches at Pactola Reservoir and about 50 inches at Oral.

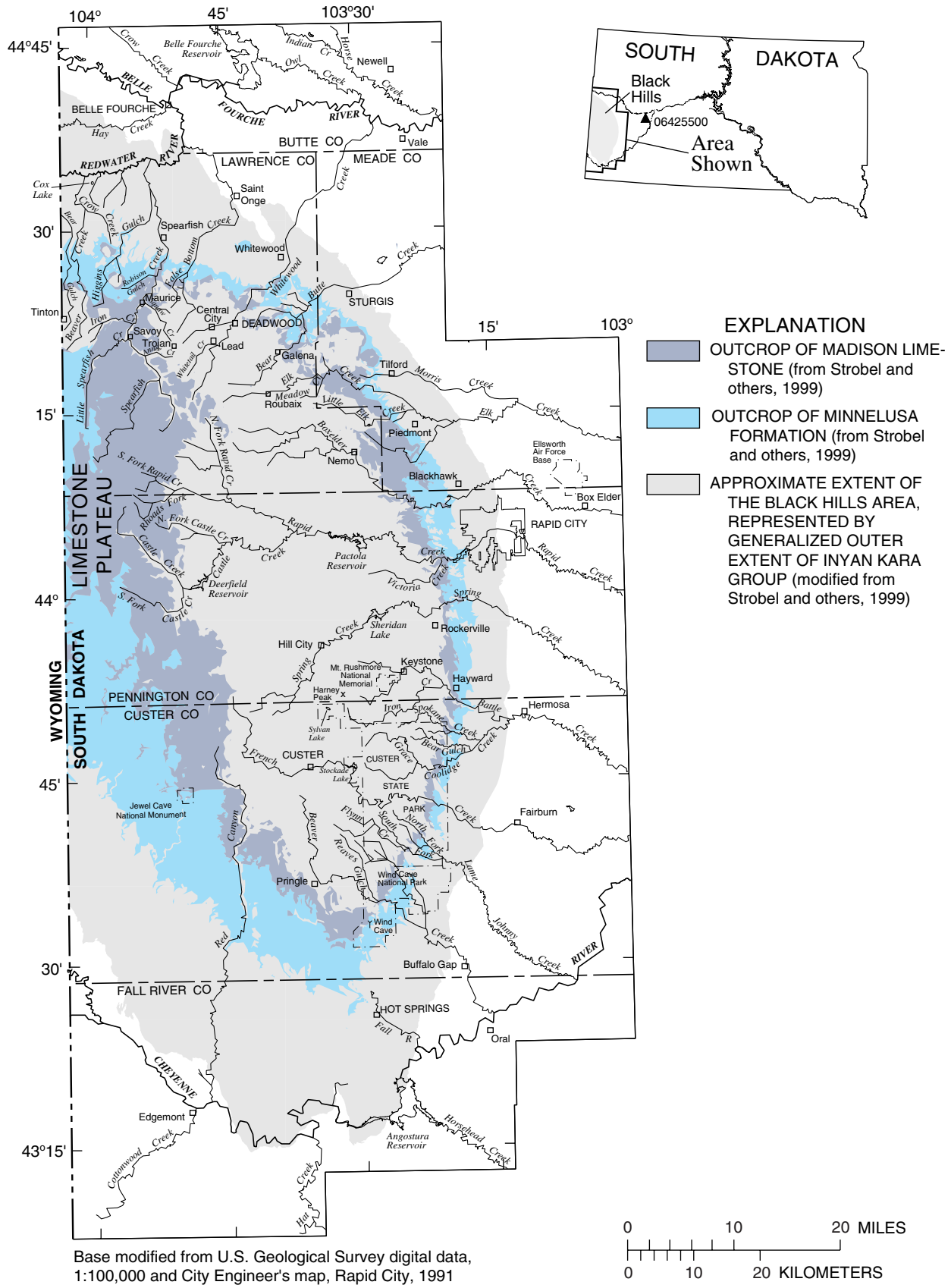

Figure 1. Area of investigation for the Black Hills Hydrology Study. Streamflow-gaging station located outside of study area that was used in developing recharge estimates is shown on index map.