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FINAL REPORT

Reconnaissance Elements of the Western Dakota Region of South Dakota -- Part 2

Prepared for:
Planning Division
Corps of Engineers
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Task I - Define the Base Condition

A. Ground Water Inventory

("Ground Water Resources of Western South Dakota")

B. Weather Modification

C. Terrain Analysis for Gravity Distribution

Task II - Input/Output Model for White and Grand River Basins

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GROUND WATER RESOURCES
OF
WESTERN SOUTH DAKOTA

by

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August 23, 1979

Sponsored by:

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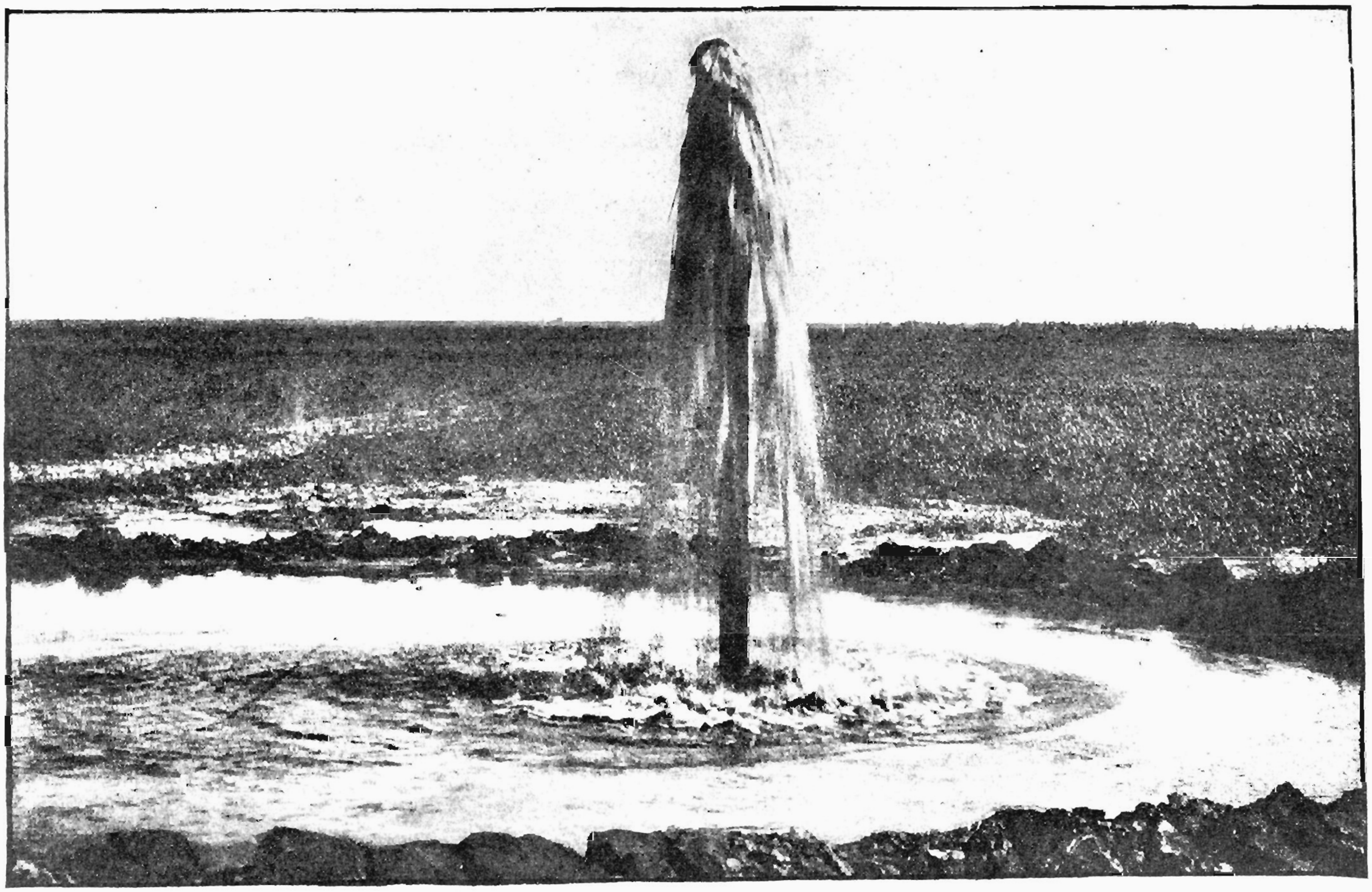

ARTESIAN WELL ON FRAZIER RANCH, 10 MILES NORTHWEST OF MITCHELL, S. DAK.
295 feet deep.

Flowing artesian well near Mitchell, S. D.
Photograph by N. H. Darton, 1909. From
U. S. Geological Survey Water-Supply Paper 227.

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CHAPTER I

INTRODUCTION

1.1 Background

This report is part of a water resources study of western South Dakota, sponsored by the U. S. Army Corps of Engineers. The study was divided between the Water Resources Research Institute at South Dakota State University in Brookings, S. D., and the Department of Geology and Geological Engineering at South Dakota School of Mines and Technology in Rapid City, S. D. The effort by the School of Mines is largely to determine the ground water resources; the effort by the State University is largely to determine surface water resources.

1.2 Acknowledgements

This project was funded by the Planning Division of the Corps of Engineers, Omaha Office. Acknowledgement is given to the Project Monitor, William F. Swegle, for his help and encouragement during this study. Special thanks is due to Arden D. Davis for his assistance in the writing of this report. Ed Glassgow, Black Hills Conservancy Subdistrict, and Keith Kuchenbecker, West River Conservancy Subdistrict, offered helpful suggestions in the course of preparation of this report. J. Paul Gries, Fred V.Steece,South Dakota Geological Survey, and Lee Case, U. S. Geological Survey, kindly reviewed this report.

1.3 Purpose

The Western Dakota Region of South Dakota Study was authorized by Congress to develop alternative comprehensive water supply plans for municipal, industrial, rural domestic, agricultural, and environmental uses. The study area includes all of South Dakota west of the Missouri River.

This report stems from work performed from May to August, 1979, and is a "Stage 1" study, i.e., a reconnaissance effort to determine whether potential solutions to the area's water supply problems are feasible, and whether additional study is warranted. The purpose of the reconnaissance effort is (1) to define water supply problems in order to permit more detailed analysis, and (2) to identify potential measures for the solution of these problems.

The specific tasks assigned to the School of Mines area are as follows:

Task I - Active Base Condition
  (A) Ground Water Inventory
  (B) Weather Modification Potential
  (C) Terrain Analysis for Aqueducts

Task II - Operationalize the Input/Output Model (Water Budget) for the White and Grand River Basin

Task III - Propose Water Resources Problems and Planning Objectives

The subject of this report is Task IA, the ground water inventory.

1.4 Description of Study Area

1.4.1 *Geography and Physiography*

Western South Dakota is in the unglaciated portion of the northern Great Plains physiographic province of the United States (Thornbury, 1965). The topography typically consists of broad, gently rolling grassland with local badlands or "breaks". The forested Black Hills area is a dissected domal uplift with an exposed core of Precambrian rocks encircled by hogbacks of sedimentary rocks. The plains surrounding the Black Hills have altitudes of about 2,000 to 3,000 ft, while the altitude of Harney Peak, the highest mountain in the Black Hills, is 7,242 ft.

The Missouri River divides South Dakota into an eastern and western region. The major streams in western South Dakota flow easterly into the Missouri River, and include, from north to south, the Grand, Moreau, Cheyenne, Bad, and White Rivers. In this study the drainage basins (Figure 2) allow for a subdivision of western South Dakota for purposes of water resources discussion.

1.4.2 *Climate and Soils*

Western South Dakota has a semi-arid climate. The mean annual precipitation ranges from less than 13 inches in the northwestern part of the State to over 24 inches in the Black Hills. In most years 75% of the precipitation falls during the April to September growing season. The temperature is typical of mid-continental areas, and is marked by extreme cold in the winter and exteme heat in the summer. The average annual temperature of Rapid City is 49°F.

The soils in western South Dakota are typically very thin alkaline soils. Clayey ("gumbo") soils develop on the Pierre Shale throughout much of the prairie where Cretaceous and early Tertiary rocks are present. Sandy and silty soils occur in the Sand Hills and Loessal areas. Soils are virtually absent in the Badlands. The Black Hills contain thick residual soils of colluvial and alluvial origin in lowland areas.

1.4.3 *Geology and Mineral Deposits*

The geology of western South Dakota consists of rocks ranging in age from Precambrian to Holocene. The Black Hills uplift is elliptical in outline, and is approximately 125 miles long and 65 miles wide. The central core consists of Precambrian granite and metamorphic rocks. These rocks are surrounded by a belt of sandstones and limestones of Cambrian to Permian age (see Figure 1). The "Red Valley", underlain by the Triassic Spearfish Formation, nearly encircles the Black Hills. A hogback (the "Dakota Sandstone") is strikingly developed just outside the Red Valley. The plains area is underlain by marine Cretaceous shales including the Pierre Shale. Scattered erosional remnants of Tertiary deposits occur in the prairie area; these deposits have been eroded by streams into buttes and mesas, exhibiting Badlands topography.

Numerous mineral deposits of all kinds occur in western South Dakota. They include the famous Homestake gold mine at Lead, and the large cement quarries at Rapid City. The value of mineral production in 1977 was about $100 million. The reader may refer to publications by the U. S. Geological Survey (1975), Gries (1974), and U. S. Bur. Mines (1978) for further information about mineral resources.

CHAPTER II

GROUND WATER INVENTORY

Ground water constitutes a large and reliable source of water for domestic, stock, industrial, and municipal use in western South Dakota. According to the U. S. Geological Survey (1975, p. 179), "The major undeveloped source of water in South Dakota is underground in water-bearing beds of rock or sediment called aquifers".

This report assesses the ground-water resources of western South Dakota by examining the hydrogeologic properties of all the rocks present. A discussion of the quantity and quality of water in storage in each of 19 hydrogeologic units is presented. Data are subdivided into 14 stream basins (Figure 2) to facilitate Input/Output computer modeling.

There are published reports on the general occurrence of ground water in South Dakota. This includes a classic study of the artesian basin by Darton (1909), and more recent comprehensive reports by the U. S. Geological Survey (1964, 1975; Taylor, 1978; McGuiness, 1962, 1963) and the S. D. Geological Survey (Agnew et al., 1962). Numerous reports are also available discussing selected aquifers. To date, no quantitative assessment of all the ground water in western South Dakota has been made.

Table 1 shows the stratigraphic section for the Black Hills area. These rocks and their equivalents are present under western South Dakota. Nineteen hydrogeologic units were chosen based on the author's familiarity with the geology of western South Dakota and because of their common hydrogeologic properties. Some units, such as the Madison Limestone (Unit #4), are quite permeable and are excellent aquifers. Other units, such as the Spearfish Formation (Unit #8), have low permeability, and are largely aquitards.

The following discussion treats the water quality, quantity, well yields, and recharge rates of each unit. The units are discussed from the oldest to youngest rocks.

2.1 Unit #1 - Crystalline Rocks

2.1.1 *Total Ground Water in Storage*

Hydrogeologic Unit #1 includes: (1) Precambrian igneous and metamorphic rocks, and (2) Tertiary igneous rocks. Precambrian rocks crop out in the core of the Black Hills (see Figure 3), and occur beneath the sedimentary rocks elsewhere in western South Dakota. Tertiary igneous rocks are found as local intrusive masses in the northern Black Hills.

For the purpose of this report both the Precambrian and Tertiary crystalline rocks are identified as a single hydrogeologic unit because they have similar hydrogeologic properties, quite distinct from the sedimentary rocks (hydrogeologic Units #2 to #18). Crystalline rocks are distinguished by low porosity, and transmit water to wells along joints, faults, and fractures.

The volume of ground water stored in Unit #1 is difficult to assess. Only ground water in the exposed crystalline rock areas in the Black Hills is considered in this investigation, because wells bottoming in Precambrian rocks elsewhere in western South Dakota have not encountered measurable amounts of ground water. The area of exposed crystalline rocks (Figure 4) is 25 x 10^9 ft^2 (Table 2). For the purpose of this investigation, only 500 ft thickness of Unit #1 is considered to have ground water. Below these depths lithostatic pressure keeps most water-transmitting voids closed (Davis and DeWiest, 1965). For instance, the Homestake Mine, about 8,000 ft deep in Precambrian rocks, is noted for its absence of water. The total volume of Unit #1 under consideration is 288 million acre-ft (see Table 2).

Voids in Unit #1 exist either as small intergranular openings (primary porosity) or small fractures (secondary porosity). The total porosity (Appendix B) is assumed to be 3%. Therefore, the total amount of ground water in Unit #1 is 8.6 million acre-ft (Table 2).

The effective porosity, containing the recoverable ground water primarily in cracks and joints, is assumed to be 1% (Appendix B). Therefore, the amount of recoverable ground water in Unit #1 is 2.9 million acre-ft.

2.1.2 *Water Quality*

Appendix C shows water quality for all 19 hydrogeologic units. Water from Unit #1 has good quality. All known wells in crystalline rocks have less than 500 ppm TDS (Table 2). The reason for the low dissolved minerals is the absence of soluble minerals characteristic of sedimentary rocks. According to the S. D. DEP (1976), the best quality water in South Dakota (70 ppm TDS) is found at Mt. Rushmore National Monument, which comes from wells in granite and schist (Powell et al., 1973).

All available Sodium Adsorption Ratio (SAR) data for Unit #1 are less than 6 (see Appendix C).

2.1.3 *Well Yields and Present Uses*

Appendix D shows known pumping test data for Unit #1. The average specific capacity for Unit #1, 0.78 gpm/ft, is probably not representative for all wells drilled, because available data includes only the best producing wells. Poor producing wells or "dry holes" are abandoned and not reported. The best known producing well, Mt. Rushmore well #3, has a specific capacity of 1.74 gpm/ft.

Presently the crystalline rocks serve as sources of water primarily for domestic and stock wells, and for some municipal water. The towns of Custer and Rockerville have wells in Precambrian rocks. Lead obtains its water from water draining the Cutting Mine in Precambrian rocks. The total ground water withdrawn from Unit #1 is not known, but is estimated at less than 10^3 acre-ft/yr.

2.1.4 *Sustained Yield and Recharge Sites*

The crystalline rocks, because of their limited porosity and permeability, cannot in general be considered as a significant aquifer in western South Dakota. In a study of the hydrogeology of the Black Hills, Rahn and Gries (1973) referred to the crystalline rocks as a relatively impermeable unit (aquitard).

The amount of ground water recharge to these rocks is not known. It undoubtedly is very low, because little precipitation sinks below the root zone in the crystalline rocks. It is unlikely that Unit #1 could produce much more water than is presently being extracted without "mining" the water (producing a widespread permanent decline in the water table).

2.1.5 *Additional Studies*

No additional studies of the hydrogeology of the crystalline are recommended.

2.2 Unit #2 - Deadwood Formation

2.2.1 *Total Ground Water in Storage*

The Deadwood Formation crops out in the Black Hills, and dips down under the surrounding prairie (Figure 5). Exposed in the Black Hills, the Deadwood has a maximum thickness of about 450 ft near Deadwood, and consists of about equal thicknesses of sandstone, limestone and shale. The stratigraphy of the Deadwood has been described in detail by Darton and Paige (1925), Gries (1952), and Steece (1978).

The Deadwood is over 600 ft thick in northwestern South Dakota, but pinches out in southern South Dakota (Figure 4). The total volume of Unit #2 is 5,620 million acre-ft (see Appendix A and Table 3).

From Appendix B it is determined that the total porosity of Unit #2 averages 10%. It is assumed that the unit is completely saturated. Therefore the total volume of water present is 562 million acre-ft (Table 3). Since the effective porosity is 50% of the total porosity, there is 281 million acre-ft of recoverable ground water in the Deadwood in western South Dakota.

2.2.2 *Water Quality*

The water quality in Unit #2 is difficult to assess due to lack of data. There are few water wells in the Deadwood because it is not very permeable and is overlain by productive aquifers, which are extensively utilized.

No contours of TDS or SAR are shown on Figure 5. It is believed, however, based on available data (Appendix C) that the water quality deteriorates rapidly within a few miles downdip of the outcrop areas. Steece (1978), for instance, reports that saline water occurs in oil test holes in northwestern South Dakota. Therefore, at the scale of this study and as shown on Table 3, all of the water in the Deadwood is believed to be greater than 3,000 ppm TDS and 6 SAR.

2.2.3 *Well Yields and Present Uses*

Appendix D lists available pumping test data. Limited aquifer tests are known for Unit #2.

The unit has moderately low permeability as a whole, and has been described as the "relatively impermeable Deadwood...aquitard" by Rahn and Gries (1973, p. 6). However, some small springs do occur below sandy units in Black Hills outcrops. Steece (1978, p. 69) has identified some sand units in oil well test cuttings that have "...porous and permeable sand sequences...".

Presently the only known ground water withdrawn from the Deadwood are a few stock and domestic wells in or close to the outcrop area near Deadwood and Rapid City, South Dakota.

Based on the limited permeability, it is doubtful that the Deadwood could sustain any large ground water withdrawals.

2.2.4 *Sustained Yield and Recharge Sites*

There are not enough data available to predict the sustained rate of ground water withdrawal from Unit #2. Due to limited permeability, however, it is unlikely that the unit could sustain withdrawals greater than domestic or stock needs.

2.2.5 *Additional Studies*

Water quality and pumping test data are needed in order to assess the availability of ground water from Unit #2.

2.3 Unit #3 - Ordovician to Devonian Systems

2.3.1 *Total Ground Water in Storage*

Unit #3 includes all strata of Ordovician, Silurian, and Devonian age. These rocks occur between the Deadwood Formation and Madison Limestone. The major formations in Unit #3 are the Winnepeg, Whitewood (Red River), and Englewood Formations, which crop out in the Black Hills area, and their equivalents in the Williston Basin in northwestern South Dakota.

The Ordovician Winnipeg Formation is typically a green shale and siltstone, ranging from 0 to about 150 ft thick, disconformably overlying the Cambrian Deadwood Formation. The Ordovician Whitewood Formation is a porous dolomitic limestone, ranging from 0 to about 550 ft thick, conformably overlying the Winnipeg. Strata of Devonian, and in some places Silurian, age overlie the Ordovician strata. The Englewood Formation of Devonian (?) and Mississippian age crops out in the Black Hills; this Formation is predominately limestone and dolomite, but includes evaporites in the Williston Basin. (The Englewood is hydraulically connected to the overlying Pahasapa Limestone, and could logically be considered part of Unit #4). The Devonian system ranges from 0 to about 500 ft thick.

Although Unit #3 includes some aquitards as well as aquifers, the

Ordovician through Devonian systems are combined in this report because they are largely carbonates having similar geographic distribution and thickness, and are rarely used as a source of ground water because they contain saline water.

Figure 6 shows the thickness of Unit #3. This isopach map is approximate due to limited data. The total thickness reaches a maximum of about 1400 ft in northwestern South Dakota. The Winnipeg, Whitewood, and Englewood and equivalents all become proportionally thicker to the northwest, and make up about 10%, 50%, and 40% of the section thickness shown on Figure 6.

Porosity in Unit #3 is great. The Whitewood (or Red River, equivalent to the Bighorn Dolomite in Wyoming), for example, has been studied in detail, and is known to contain intercrystalline, solution, and fracture porosity (Carroll, 1979). The total porosity of Unit #3 is estimated at 20% (see Appendix A). It is assumed that the entire unit is saturated. The total volume of Unit #3 is 12,421 million acre-ft and the total volume of water in Unit #3 is 2,484 million acre-ft. Only an estimated 50% of the water in Unit #3 is available to wells. Thus the total volume of recoverable ground water is 1,246 million acre-ft (see Table 4).

2.3.2 *Water Quality*

Except near the Black Hills, the water in Unit #3 has very poor quality. Salt water occurs in the Whitewood Formation in Perkins and Harding Counties (Tullis et al., 1954). Water from Devonian strata is reported from oil exploration tests to contain as much as 100,000 ppm TDS (U. S. Geological Survey, 1975).

Figure 6 shows contours of TDS. These contours are based on limited data (see Appendix B), and hence are very tenuous. Table 4 shows the amount of recoverable water in terms of TDS. From Table 4 it is apparent that vast amounts of ground water are available in Unit #3, but the bulk of it is of poor quality.

Available data on SAR indicate that large values (in excess of 100) can be expected anywhere in Unit #3.

2.3.3 *Well Yields and Present Uses*

Except in the outcrop areas, water in Unit #3 is probably under artesian pressure throughout western South Dakota. However, no known water wells are in use, and at present there apparently is no water being withdrawn from Unit #3.

No data are available on well yields.

2.3.4 *Sustained Yield and Recharge Sites*

No data are available to allow for estimates of recharge rates or sustained yield from Unit #3.

Theoretically it is possible to artificially recharge Unit #3 about

1 mile north of Deadwood, S. D., where the Whitewood Formation crops out along Whitewood Creek. There would appear to be no need to recharge this unit, however, because there are no present withdrawals.

2.3.5 *Additional Studies*

A technological assessment of saline water conversion would be useful in establishing the development potential of Unit #3.

2.4 Unit #4 - Madison Limestone

2.4.1 *Total Ground Water in Storage*

The Madison Limestone occurs over a widespread area of the western United States. In the Black Hills area the Madison is called the Pahasapa Limestone. The Madison is well known as an excellent aquifer, although the quality of water deteriorates in the deeper basins. There are numerous reports on the hydrogeology of the Madison in South Dakota, including works by Rahn and Gries (1973), Konikow (1976), Hanshaw et al., (1977), Gries (1978), and Back et al., (in preparation).

The isopach map (Figure 7) shows that the Madison thickens from 0 in southern South Dakota to over 1300 ft in northwestern South Dakota. The total volume is 12,066 million acre-ft. It is assumed that all of Unit #4 is saturated; i.e., relatively small unsaturated zones such as near Jewel and Wind Cave are not included. This assumption does not significantly affect the calculations below.

The average porosity is fairly well documented from oil tests (see Appendix B), and is 11%; therefore the total volume of water in storage is 1,327 million acre-ft. This total porosity includes minute intergranular openings between fossils and calcite grains. Water yielded to wells is largely contained in cavernous openings or joints (see Figure 8). The effective porosity from which recoverable water can be obtained by wells is determined in Appendix B to be 5% (45% of the total porosity). Thus 605 million acre-ft of water is recoverable by wells.

2.4.2 *Water Quality*

Figure 7 shows the contours of TDS in Unit #4. In general the water has good quality (500 ppm TDS) near the outcrop areas of the Black Hills, but the TDS increases to over 3,000 ppm in northwestern South Dakota where the Madison dips down into the Williston Basin.

The water quality data (Table 5 and Appendix C) shows that 30 million acre-ft of water in Unit #4 has less than 500 ppm TDS, most of which is in basin 7A. A large part of the recoverable water in the Madison (72.6%) has greater than 3,000 ppm TDS, and hence is not good for stock or irrigation water.

The 3,000 ppm TDS contour line approximately coincides with a SAR value of 6. In general the more mineralized water in northwestern South Dakota also has high SAR. More data are needed to precisely define SAR.

2.4.3 *Well Yields and Present Uses*

Throughout most of western South Dakota the Madison is under artesian conditions, and flowing wells are common (see Figure 9). The unit yields a large amount of water to wells. Currently the U. S. Geological Survey is studying the Madison in the upper Great Plains, and three test wells are being drilled as part of this program (U. S. Geological Survey, 1976). USGS Test well #1, near Belle Fourche, S. D., is capable of being pumped at 1600 gpm.

Appendix D shows typical well yields and specific capacity data for the Madison. Because of its artesian nature, large withdrawals can cause a decline in the piezometric surface over widespread areas (Rahn, 1979).

Presently the Madison supplies water to Midland, Philip, Eagle Butte, Dupree, Edgemont, and various large ranches. Geothermal wells at Pierre, Philip, Midland, Provo, and other places are being installed (Gries, 1978). The total volume of water withdrawn from the Madison is not known, but probably is less than 20,000 acre-ft/year.

2.4.4 *Sustained Yield and Recharge Sites*

The rate of recharge to the Madison is not known. It has been identified only as "X" in a report by Rahn and Gries (1973). The recharge rate must be fairly low, because the water was determined to be about 30,000 years old at Midland and Philip (Hanshaw et al., 1977). The water presumably took 30,000 years to migrate from the recharge area, near the Black Hills, easterly to central South Dakota. Due to the low recharge rates, any large ground water withdrawals must be considered essentially as "mining" ground water because of the geologic time necessary for water replenishment.

Sites for artificial recharge to the Madison occur along the outcrop belt. Numerous streams draining the Black Hills lose water in the sinkhole zone (Rahn and Gries, 1973). Sites where supplemental recharge could be promoted include Sand, Spearfish, Whitewood, Bear Butte, Elk, Little Elk, Boxelder, Spring, Battle, Grace Coolidge, French, and Beaver Creeks.

2.4.5 *Additional Studies*

Much more work needs to be done to study recharge rates and lowering of the metric pressure due to ground-water withdrawals from the Madison. Detailed examination of sites for artificial recharge is merited.

2.5 Unit #5 - Minnelusa Formation

2.5.1 *Total Ground Water in Storage*

The Minnelusa Formation is a varied assemblage of sandstone, limestone, dolomite, and shale of Pennsylvanian and early Permian age (see Figure 10). Numerous wells utilize the Minnelusa for drinking water within a few miles of the outcrops in the Black Hills. It is occasionally drilled as a source of stock water throughout the western part of South Dakota.

Figure 11 is a map of western South Dakota showing the extent and thickness of the Minnelusa Formation. The information used to make this map was culled from an inventory of well log files made by Dr. J. P. Gries of the South Dakota School of Mines and Technology, except near the Missouri River, where the isopach maps from the Geologic Atlas of the Rocky Mountain Region (Mallory, 1972) were used.

The porosity of this unit is difficult to determine because it is so variable. Occasional well-sorted sand lenses have porosities approaching 25%, but generally the sands have porosities less than 10%, and the carbonates, which predominate, about 10% in most cases. Ten percent is used here as an estimate of the average porosity, and 5% as the effective porosity (see Appendix B). Figure 11 has been measured to derive an estimated volume of 15,320 million acre-ft for the Minnelusa Formation in western South Dakota. Assuming full saturation at 10% porosity, the total amount of water contained is 1,532 million acre-ft. About 50% of this, 766 million acre-ft, is recoverable. Table 6 summarizes the amount of water available under each of the drainage basins.

2.5.2 *Water Quality*

Appendix C shows water quality data for ground water in western South Dakota. Only data for Total Dissolved Solids (TDS) and Sodium Absorption Ratio (SAR) are included in this report, because these are the most useful parameters describing water quality for municipal and irrigation use.

In general, the better quality water is available near the Black Hills, where the Minnelusa Formation crops out and is recharged. The quality decreases rapidly away from the outcrop area. The SAR is generally low, with a few exceptions (see Appendix C, Table 6, and Figure 11).

2.5.3 *Well Yields and Present Uses*

The known pumping test data for the Minnelusa Formation are shown in Appendix D. Since the porosity is quite variable, reasonable yields can be obtained at nearly any location from somewhere in the Formation.

The present withdrawal for Unit #5 is not known, but is probably less than 20,000 acre-ft/yr. In the Red Valley the Minnelusa is typically under artesian conditions (Cox, 1962), and flowing wells are common.

2.5.4 *Sustained Yield and Recharge Sites*

There are inadequate data for assessment of sustained pumping from the Minnelusa. Recharge sites would be similar to those for the Madison Limestone.

2.5.5 *Additional Studies*

Additional water quality data are needed for central South Dakota. The recharge rate is needed in order to assess the sustained yield.

2.6 Unit #6 - Opeche Formation

2.6.1 *Total Ground Water in Storage*

Figure 12 is an isopach map of western South Dakota showing Unit #6, the Opeche Formation. The map was constructed from the inventory of South Dakota School of Mines and Technology well logs. The Opeche is typically a red shale about 100 ft thick.

The unit was judged to be 100% saturated. The total saturated volume of the unit was determined to be 1,679 million acre-ft. Table 7 shows these data broken down into the water basins.

Unit #6 was determined to have a 12% total porosity and a 2% effective porosity. The total ground water volume for this unit is therefore 200 million acre-ft with a total recoverable ground water supply of 34 million acre-ft. Essentially the Opeche Formation acts as an aquitard, being a shale unit. Some ground water has been obtained from the upper part of the Opeche Formation in the northern Black Hills, where water in the Minnekahta leaks downward and is stored within the shale (Pakkong, 1979).

2.6.2 *Water Quality*

There are few wells in this unit and no water quality data are available.

2.6.3 *Well Yields and Present Uses*

No data are available.

2.6.4 *Sustained Yield and Recharge Sites*

Unit #6 is an aquitard and is not capable of supplying ground water other than for small domestic or stock wells.

2.6.5 *Additional Studies*

No future work is recommended.

2.7 Unit #7 - Minnekahta Limestone

2.7.1 *Total Ground Water in Storage*

Figure 13 is an isopach map of western South Dakota showing Unit #7, the Minnekahta Limestone. The map was constructed from the inventory of South Dakota School of Mines and Technology well records.

The Minnekahta is a remarkably pure limestone about 40 ft thick in the Black Hills area, where it serves as a source of cement rock and aggregate. It is assumed to be 100% saturated, with a total saturated volume of 403 million acre-ft. Table 8 shows these data broken down into the water basins.

Unit #7 was determined to have an 8% total porosity and an effective porosity of 5% (Appendix B). The total volume of ground water stored in this unit is 33 million acre-ft with a total recoverable volume of 20 million acre-ft.

2.7.2 *Water Quality*

Only three reported values of TDS for Unit #7 exist, with values of 1788 ppm and 2040 ppm for Fall River County and 2162 ppm for Pennington County. Sulfate contents range from 40 to 300 ppm. High amounts of magnesium have also been noted.

2.7.3 *Well Yields and Present Uses*

The Minnekahta acts as an aquifer for certain parts of western South Dakota. In the Boulder Park area it yields about 10 to 20 gpm to wells, and is under water table conditions.

Most water wells in the Minnekahta are in the Black Hills and are shallow in depth, varying from 50 to 300 ft. At present, this water is used only for domestic and stock purposes.

2.7.4 Sustained *Yield and Recharge Sites*

No estimates of the sustained yield from Unit #7 are available.

Recharge sites are not very practical due to the fact that the unit is very thin and has only modest porosity and permeability. The unit typically crops out in high areas where it caps a dip slope, and would require water pumpage from a recharge source to the recharge sites.

2.7.5 *Additional Studies*

No additional studies are recommended at this time.

2.8 Unit #8 - Spearfish Formation

2.8.1 *Total Ground Water in Storage*

Figure 14 is an isopach map of western South Dakota showing Unit #8, the Spearfish Formation. The map was constructed from well log records of the South Dakota School of Mines and Technology. The Spearfish is Permian and Triassic in age, and consists of red silty shale with numerous gypsum lenses, dikes, and diapirs. Where it crops out around the Black Hills it forms a grass-covered lowland. Figure 15 shows the "Red Valley", about 1 mile wide, which is underlain by the Spearfish Formation.

The unit is assumed to be 100% saturated. The total saturated volume of the unit was determined to be 4,281 million acre-ft. Table 9 shows these data for the water basins.

Unit #8 was determined to have a 15% total porosity and an effective porosity of 2% (Appendix B). The total ground water volume for this unit is 642 million acre-ft, with a total recovereable volume of 86 million acre-ft.

The Spearfish, being a shale unit like the Opeche Formation, acts as an aquitard in the Black Hills area (Rahn and Gries, 1973).

2.8.2 *Water Quality*

There are no water quality data available for this unit.

2.8.3 *Well Yields and Present Uses*

No data are available since this unit acts as an aquitard. No well records are available for the Spearfish Formation in western South Dakota, although it is believed there are numerous dug wells in the Red Valley.

2.8.4 *Sustained Yield and Recharge Sites*

The unit is an aquitard; artificial recharge is impractical.

2.8.5 *Additional Studies*

No future studies are recommended.

2.9 Unit #9 - Sundance Formation

2.9.1 *Total Ground Water in Storage*

The Sundance Formation, Unit #9, is of Late Jurassic age and in western South Dakota attains a maximum thickness of over 600 ft. It is composed of gray, green, and brown shale interbedded with white, buff, or red, glauconitic, fine-grained sandstone, limestone, and red shale (U. S. Geological Survey, 1975).

An isopach map of Unit #9 is shown in Figure 16. This map is based on well-log data from the South Dakota School of Mines and Technology, and on published isopach maps of the Jurassic system from the Geologic Atlas of the Rocky Moutain Region (Mallory, 1972) and from the U. S. Geological Survey Paleotectonic Maps of the Jurassic system (McKee et al., 1956).

The saturated thickness of Unit #9 is probably variable near the outcrop area surrounding the Black Hills but is almost certainly 100% elsewhere. For the purpose of this report 100% saturation is assumed. From Figure 16, the volume of saturated Sundance Formation is 5,493 million acre-ft (see Appendix A). Table 10 shows these data broken down into the water basins.

The average porosity of the Sundance Formation was determined to be 15%; the effective porosity was judged to be 3%. Data for porosity and the methods employed to arrive at these figures are in Appendix B. Using the figures above, the total volume of ground water contained in Unit #9 in western South Dakota is approximately 824 million acre-ft. It is believed that 165 million acre-ft of water is theoretically available to wells because of the specific retention of the aquifer.

2.9.2 *Water Quality*

Water quality data for Unit #9 in western South Dakota are shown in Appendix C. Because practically no data exist on which to base conclusions about the quality of water from the Sundance Formation, no attempt was made to produce a map of TDS and SAR. In general Unit #9 appears to be quite high in TDS and SAR except very close to the outcrop area surrounding the Black Hills, and at isolated points.

2.9.3 *Well Yields and Present Uses*

No data are presently available for values of coefficients of transmissivity (T) and storage (S) for wells in Unit #9 in western South Dakota.

No known values of specific capacity exclusively for the Sundance are known. The Sundance Formation is believed capable of providing modest amounts of water for livestock and domestic wells in western South Dakota.

Apparently because of poor chemical quality and the general availability of shallower ground water sources, no cities in western South Dakota obtain their municipal water supplies solely from Unit #9. The Sundance Formation is an under-exploited source of water for domestic and stock use (U. S. Geological Survey, 1975).

2.9.4 *Sustained Yield and Recharge Sites*

No data are known to exist on the recharge rate of the Sundance Formation in South Dakota. Because of this and the lack of T and S values for Unit #9, any estimates of sustained yield would be conjectural.

Possible sites for artificial recharge of Unit #9 exist mainly along the outcrop area of the Sundance Formation surrounding the Black Hills. Probably few practical sites could be found, however, because the Sundance Formation normally lies on a steep slope beneath the resistant Cretaceous sandstone hogback, and dips rapidly under the surface away from the Black Hills area. Because streams have normally cut canyons through the resistant Jurassic and Cretaceous sandstone on the flanks of the Black Hills, the water would have to be pumped to a higher level in most instances, which could prove costly. However, the Sundance Formation crops out over a considerable area between Belle Fourche and Spearfish, South Dakota, as well as 8 miles southwest of Belle Fourche.

2.9.5 *Additional Studies*

More information is needed to thoroughly assess the ground water resources of the Sundance Formation in western South Dakota. These include:

(a) Sampling of water quality.
(b) Studies to determine the rate of recharge.
(c) Pumping tests to determine T and S and to aid in determination of maximum permissible usage.
(d) Examination of possible sites for artificial recharge.

2.10 Unit #10 - Morrison Formation and Unkpapa Sandstone

2.10.1 *Total Ground Water in Storage*

The Morrison Formation and Unkpapa Sandstone, both of nonmarine origin, are late Jurassic in age. The Morrison Formation is mainly interbedded varicolored shale with sandstone and some limestone (see Figure 17). The Unkpapa Sandstone is a massive fine-grained, white to yellow sandstone with a clayey matrix, and in recent work has been considered a member of the Morrison Formation (Szigeti, 1979). These two units comprise a maximum of over 350 ft of stratigraphic thickness in South Dakota. Where the Morrison Formation is thick, the Unkpapa Sandstone is thin, and vice versa.

Figure 18 is an isopach map of the Morrison Formation and Unkpapa Sandstone, Unit #10. This map is based on well data from the inventory of well logs at South Dakota School of Mines and Technology, and on published isopach maps from the U. S. Geological Survey Paleotectonic Maps of the Jurassic System (McKee et al., 1956).

The saturated thickness of Unit #10, as with Unit #9, is probably 100% except near the outcrop.

Using an assumed saturated thickness of 100%, and taking into account the changes in thickness, the volume of Unit #10 which is saturated is 3,154 million acre-ft (see Appendix A and Table 11).

The average porosity of Unit #10 was determined to be 12%; the effective porosity was determined to be 3%. Data for porosity and the methods employed to arrive at these figures are in Appendix B. Using the figures above, the total ground water contained in Unit #10 in western South Dakota is approximately 379 million acre-ft. It is believed that less than this, 95 million acre-ft would be theoretically available to wells, because of the aquifer's specific retention.

2.10.2 *Water Quality*

Essentially no data are available on the chemical quality of ground water from the Morrison Formation or Unkpapa Sandstone in western South Dakota. Accordingly, no tables or maps of water quality were prepared.

2.10.3 *Well Yields and Present Uses*

No data are presently available for values of coefficients of transmissivity (T) and storage (S) for wells in Unit #10 in western South Dakota.

Known values of specific capacity are shown in Appendix D. Because wells are often completed into the overlying Inyan Kara Group or underlying Sundance Formation, data on specific capacity solely for Unit #10 are limited.

No cities in western South Dakota presently obtain their water supplies exclusively from the Morrison Formation or Unkpapa Sandstone. It appears that Unit #10 may be capable of supplying modest amounts of water in western South Dakota.

2.10.4 *Sustained Yield and Recharge Sites*

Miller (1972) estimates a recharge value of 42 cfs to the Juro-Cretaceous sandstones which crop out on the eastern flanks of the Black Hills. These units include the Unkpapa Sandstone, Lakota Formation, Fall River Formation, and Newcastle Sandstone. Miller made no breakdown of estimates of recharge exclusively to the Unkpapa Sandstone. Because no other data are available on the recharge rate or T of the Morrison Formation or Unkpapa Sandstone, no estimate is made of sustained yield.

Possible sites for artificial recharge of surface water into Unit #10 exist along the outcrop area of the Morrison Formation and Unkpapa Sandstone surrounding the Black Hills. However, Unit #10, like the underlying Sundance Formation, normally lies on a steep slope beneath the resistant Cretaceous sandstone hogback, and dips rapidly under the surface away from the Black Hills area. The recharge water would have to be lifted in most cases because streams have incised canyons through the resistant Jurassic and Cretaceous sandstones on the flanks of the Black Hills.

2.10.5 *Additional Studies*

More information is necessary to thoroughly assess the ground water resources of Unit #10 in western South Dakota. These include:

(a) Sampling of water quality.
(b) Studies to accurately determine the rate of recharge.
(c) Pumping tests to determine T and S and to aid in determination of maximum permissible usage.

2.11 Unit #11 - Inyan Kara Group and Skull Creek Shale

2.11.1 *Total Ground Water in Storage*

The Inyan Kara Group consists of the Early Cretaceous Lakota Formation and the overlying Fall River Formation. The Lakota lies unconformably on the Morrison Formation, and is composed of cross-bedded channel-fill sandstone, shale and some local limestone. It attains a maximum thickness of over 500 ft in South Dakota. The Fall River Formation rests unconformably on the Lakota and consists of well bedded, fine-grained sandstone, with some siltstone and claystone. Its maximum thickness in South Dakota is about 200 ft (See Figure 19).

The Skull Creek Shale is an aquitard which conformably overlies the Fall River Formation and is a dark gray shale of marine origin. It is part of the Graneros Group and is a maximum of about 300 ft thick in western South Dakota.

The total water storage capacity of the Fall River-Lakota sandstones (Inyan Kara Group) is the subject of a South Dakota School of Mines and Technology M. S. thesis (Siok, 1972). An isopach map of the effective (saturated) thickness of Unit #11 is shown in Figure 19. This map (from Siok, 1972) was prepared through an analysis of electric logs.

The porosity of the Inyan Kara Group varies from as high as 30%

in eastern South Dakota, near an inferred source area, to as little as 12% in the extreme western part of the state. On the basis of well logs, Siok (1972, PLATE III) prepared a porosity map of the Fall River-Lakota sandstones.

The effective thickness isopach map and the isoporosity map were superimposed by Siok, (1972, PLATE IV), producing a map defining areas of known effective thickness and porosity. Enclosed areas were measured and the total volume of water stored under the area was calculated by multiplying the area, times the average thickness, times the average porosity. Siok did this for 311 such areas, arriving at a total volume of approximately 1,301,000,000 acre-ft of stored water in the Inyan Kara Group in South Dakota. For the purposes of this study, the volume of stored water east of the Missouri River was subtracted from the total, giving a volume of approximately 762 million acre-ft of stored water in the Inyan Kara Group west of the Missouri River in South Dakota.

The total amount of water in storage in the Skull Creek Shale was determined to be 43,645,000 acre-ft. For an isopach map of the Skull Creek the reader is referred to Schoon (1971, Figure 10). The Skull Creek Shale is judged to have a total porosity of 20% and an effective porosity of 1% (see Appendix B). In determining the amount of water in storage, the total area between any two thickness contours (from Schoon's isopach map) was calculated. The average thickness was then multiplied by the area, then multiplied by the effective porosity, to obtain the total volume of water (following the procedures outlined in Appendix A).

The total amount of stored water in Unit #11 is thus 804 million acre-ft. The actual amount of water that could be pumped from the unit is less and is estimated at 67% of the total porosity, or 537 million acre-ft (Table 12).

2.11.2 *Water Quality*

Water quality data for Unit #11 in western South Dakota are shown in Appendix C. Figure 18 is a map of TDS and SAR for Unit #11. Water quality for this aquifer is variable but generally poor in western South Dakota. Both TDS and SAR are lowest near the outcrop area surrounding the Black Hills, and increase greatly to the north, east, and south (down-dip from the outcrop).

2.11.3 *Well Yields and Present Uses*

The Inyan Kara aquifer is artesian over a wide area in western South Dakota. An estimated 15,000 wells have tapped one or more of the Lower Cretaceous sandstone aquifers in South Dakota (Gries et al., 1973).

Known values of specific capacity are shown in Appendix D. The specific capacity of Unit #11 averages about 3.2 gpm/ft in western South Dakota. This is the largest for any hydrogeologic unit except for alluvium.

Rahn and Gries (1973) report a coefficient of transmissivity (T) for the Fall River-Lakota aquifer of 2,165 gpd/ft at Wall, South Dakota. Rahn and Miller (1973) also report a T of 1333 gpd/ft for Box Elder, South Dakota city well #2. The Box Elder well was cased to the top of the Fall River Formation and was drilled to a total depth of 2330 ft (30 ft into the Morrison Formation). At the Tennesssee Valley Authority Burdock uranium mine at Burdock, South Dakota, a value of T = 1440 gpd/ft and S = 0.000,2 has been reported for the Lakota Sandstone and T = 800 gpd/ft for the Fall River Sandstone (Tennessee Valley Authority, 1978).

Niven (1967) calculated permeabilities for cores cut from outcrop of the Inyan Kara Group. For the Lakota Formation he calculated a mean permeability of 9115 millidarcys parallel to bedding, and 5683 millidarcys perpendicular to bedding. For the Fall River Formation, Niven reported a mean permeability of 2052 millidarcys parallel to bedding and 793 millidarcys perpendicular to bedding. He attributes these high values (relative to permeability values for the Inyan Kara in the subsurface) to removal of cement by weathering.

The Fall River-Lakota Sandstones are the source of all or part of the water supplies for many cities in western South Dakota, including Wall, Box Elder, Newell, Buffalo Gap, Rapid Valley, and Quinn.

2.11.4 *Sustained Yield and Recharge Sites*

The sustained yield of Unit #11 is determined ultimately by the recharge rate. Evidence exists which indicates that the rate of withdrawal from the Lower Cretaceous sandstones in South Dakota exceeds the rate of recharge (Schoon, 1971; Miller, 1972).

The source of recharge of the Lower Cretaceous sandstones in South Dakota is a subject of controversy. Darton (1909) believed that meteoric water is recharged into the outcrop areas on the flanks of the Black Hills, and is supplemented by leakage downward through the Pierre Shale. Russell (1928) suggested that connate water in storage could develop pressure by compaction of the sediments. Gries (1958) stated that the most likely method for recharge is water taken in at the outcrop. Swenson (1968) suggested that upward leakage from the underlying Paleozoic limestones could recharge the aquifer. Schoon (1971) presents these and other theories in a discussion on the origin of the aquifer's recharge and artesian pressure. Bredehoeft et al., (unpub., 1972) postulates that downward leakage from overlying Cretaceous shales recharges the aquifer.

Miller (1972) estimates a rate of recharge of 42 cfs to the outcrop of Juro-Cretaceous sandstone of the Black Hills area. Miller and Rahn (1974) report that more recharge is due to vertical leakage from overlying shales than by lateral recharge from outcrops.

Possible sites for artificial recharge of surface water into Unit #11 exist mainly along the outcrop area of the Cretaceous hogback ridge surrounding the Black Hills. Angostura Reservoir may be inadvertantly recharging the aquifer. Artificial recharge is not as practical elsewhere, because of pumping costs required to lift water to outcrops, and because the Fall River-Lakota Sandstone dips rapidly under the surface [redacted] outward from the Black Hills. For example, the Fall River Formation is encountered at 2,050 ft below the surface at Box Elder city well #2, only 9 miles east of the Cretaceous hogback (Rahn and Gries, 1973). Artesian conditions at most places would mean that artificial recharge wells would have to inject water under pressure. At places of declining artesian pressure artificial recharge wells would be possible.

2.11.5 *Additional Studies*

More information is necessary to thoroughly assess the ground water resources of Unit #11 in western South Dakota. These include:

(a) Detailed sampling of water quality.
(b) Determination of rate of recharge, and maximum permissible usage.
(c) Detailed, specific examination of artificial recharge sites.
(d) Locating (and plugging) present uncapped, flowing wells.

2.12 Unit #12 - Newcastle - Dakota Sandstone

2.12.1 *Total Ground Water in Storage*

The Newcastle Sandstone consists of the Lower Cretaceous Sandstone that lies below the Mowry Shale and Belle Fourche Shale, and above the Skull Creek Shale. In the outcrop it is referred to as the Newcastle Sandstone, and it has arbitrarily been called the Dakota Sandstone where it is over 50 ft thick in the subsurface (Baker, 1972). For this report, the Newcastle is considered equivalent to the Dakota Sandstone (see Figure 1). The Newcastle Sandstone is commonly porous, fine-grained, and light-gray, tan, or white. It reaches a maximum thickness of about 250 ft in western South Dakota.

The ground water capacity of the Newcastle-Dakota Sandstone (Unit #12), is the subject of a South Dakota School of Mines and Technology M. S. thesis (Baker, 1972). An isopach map of the thickness of Unit #12 is shown in Figure 20. This map (from Baker, 1972) was prepared through an analysis of electric logs. One hundred % saturation is assumed.

On the basis of well logs, Baker (1972, PLATE IV), prepared an iso-porosity map of Unit #12. The porosity of the Newcastle Sandstone varies from as high as 32% near the Missouri River in South Dakota (where the formation reaches its greatest thickness), to as little as 2% near the northeast edge of the Black Hills.

Baker (1972) determined a total water storage of 978 million acre-ft in the Newcastle Sandstone in all of South Dakota. For this study, the volume of stored water east of the Missouri River was subtracted from the total, resulting in approximately 610 million acre-ft of stored water in the Newcastle Sandstone west of the Missouri River in South Dakota (see Table 13). The amount of water actually available would be less than this total storage for several reasons (Baker, 1972), including the anisotropic nature of the formation, causing variations in permeability. The recoverable water is estimated at 67% of the total, and is 406 million acre-ft (Table 13).

2.12.2 *Water Quality*

Water quality data for Unit #12 in western South Dakota are shown in

Appendix C. Figure 20 is a map of TDS for Unit #12. Both TDS and SAR are lowest near the outcrop area surrounding the Black Hills, and increase greatly to the north, east, and south (down-dip from the outcrop). Water quality for the Newcastle-Dakota Sandstone in western South Dakota is variable but generally poorer than for the Inyan Kara Group, Unit #11.

Schoon (1971) has divided waters in the Dakota aquifer into 3 main types: sodium-chloride water, sodium-sulfate water, and calcium-sulfate water. Sodium-chloride water (believed to be connate) occurs in the northwestern two-thirds of South Dakota.

2.12.3 *Well Yields and Present Uses*

Like the Inyan Kara aquifer, the Newcastle-Dakota aquifer is artesian over a wide area in western South Dakota (see Frontispiece). In many cases flowing wells can be obtained. As mentioned above, an estimated 15,000 wells have tapped one or more of these Lower Cretaceous sandstone aquifers in South Dakota (Gries et al., 1973).

Schoon (1971) reports that 10^8 gpd (155 cfs) of water is withdrawn from the Dakota aquifer system in South Dakota. The Dakota Sandstone is much more extensively developed as a source of water in eastern South Dakota than in the western part of the state. Many private ranch wells and municipal wells such as Kadoka tap this aquifer in western South Dakota.

The specific capacity of Unit #12 is about 0.18 gpm/ft in western South Dakota. Known values of specific capacity are shown in Appendix D.

There are no known values of coefficient of transmissivity (T) determined for wells exclusively in Unit #12 in western South Dakota. Bredehoeft (unpub., 1972) computed values of hydraulic conductivity (K) for the Dakota Sandstone in eastern South Dakota, shown in Table 14.

Niven (1967) calculated permeabilities for cores cut from outcrops of the Newcastle Sandstone. He reports a mean permeability of 568 millidarcys parallel to bedding and 246 millidarcys perpendicular to bedding. These are higher than subsurface permeability values for the Newcastle-Dakota Sandstone and Niven attributes this to removal of cement by weathering.

2.12.4 *Sustained Yield and Recharge Sites*

The artesian head of the Dakota aquifer is declining (Schoon, 1971). As with the Inyan Kara aquifer, evidence exists which indicates that the rate of withdrawal exceeds the rate of recharge. Miller (1972) estimated a recharge value of 42 cfs for the Juro-Cretaceous Sandstones of the Black Hills area, far less than Schoon's (1971) estimated withdrawal rate.

As mentioned above, the source of recharge of the Cretaceous sandstones in South Dakota is a subject of controversy. The reader is referred to Darton (1909), Russell (1928), Gries (1958), Swenson (1968), Schoon (1971), Bredehoeft et al. (unpub., 1972), and Miller and Rahn (1974) for a more detailed discussion.

As with the Fall River-Lakota Sandstones, possible sites for artificial recharge of surface water into Unit #12 exist mainly along the outcrop area of the Cretaceous hogback ridge surrounding the Black Hills. Artificial recharge is impractical elsewhere, because water would have to be pumped to high elevations, and because Unit #12 dips rapidly under the surface as one goes outward from the Black Hills and is under artesian pressure.

2.12.5 *Additional Studies*

More information is necessary to thoroughly assess the ground water resources of the Newcastle Sandstone in western South Dakota. These include:

(a) Detailed sampling of water quality.
(b) Pumping tests to determine T and S.
(c) Determination of recharge values and maximum permissible usage.
(d) Detailed, specific examination of artificial recharge sites.
(e) Locating (and plugging) present uncapped, flowing wells.

2.13 Unit #13 - Cretaceous Shale

2.13.1 *Total Ground Water in Storage*

Unit #13 is made up of the marine Cretaceous interval from the base of the Mowry Shale to the top of the Pierre Shale, and includes the Belle Fourche Shale, the Greenhorn Formation, the Carlile Formation, the Niobrara Formation, and the Pierre Shale. They are lumped together for this report because they are largely marine shales with low permeability and contain highly mineralized water.

The Mowry Shale and Belle Fourche Shale are conformable members of the Graneros Group. The Mowry, as much as 250 ft thick, is generally a gray, siliceous shale with interbedded bentonite. The Belle Fourche is a soft gray shale with some bentonite, and is as much as 550 ft thick. Both units are aquitards.

The Greenhorn Formation overlies the Belle Fourche Shale and consists of interbedded calcareous shale and thin limestone. It is as much as 360 ft thick in western South Dakota. The basal beds of the Greenhorn are called the Orman Lake Limestone Member in part of western South Dakota (U. S. Geological Survey, 1975). There is as much as 30 ft of slabby, impure limestone at the top of the formation. The Greenhorn produces water at some places in western South Dakota.

The Carlile Formation, concordantly overlying the Greenhorn, is as much as 750 ft thick and consists mainly of soft, dark gray shale with some sandy zones, and is an aquitard.

The Niobrara Formation rests unconformably on the Carlile Shale (Tourtelot and Cobban, 1968) and is over 200 ft thick in western South Dakota. It is composed of calcareous shale, chalk, limestone, and thin bentonite beds.

The Pierre Shale is more than 2,000 ft thick in places in western

South Dakota, and consists mainly of gray shale, with some sand and bentonite.

An isopach map of Unit #13 in western South Dakota is shown in Figure 21. This map is based on well data from the South Dakota School of Mines and Technology, and on published isopach maps of the Cretaceous system from the Geologic Atlas of the Rocky Mountain Region (Mallory, 1972).

The average saturated thickness of Unit #13 is difficult to ascertain because of the number of formations involved and the changes in the lithology. Subjective analysis results in an approximate saturated thickness of 99%.

Using a 99% saturated thickness, and taking thickness changes into account, the volume of Unit #13 which is saturated is 55,105 million acre-ft (see Appendix A). Table 15 shows these data broken down into the 13 water basins.

The porosity of Unit #13 is quite variable, but the average porosity was determined to be 20%, and the effective porosity was judged to be 1%. Data for porosity values and the methods used to obtain these figures are in Appendix B. The total volume ground water contained in Unit #13 is thus 11,020 million acre-ft. The amount theoretically available to wells is probably less because of the aquifer's specific retention, and is estimated at 549 million acre-ft.

2.13.2 *Water Quality*

Water quality data for Unit #13 in western South Dakota are shown in Appendix C. In general, Unit #13 (especially the Pierre Shale) yields water which is quite high in TDS and SAR.

Table 15 shows water quality data for Unit #13, broken down into the 13 water basins.

2.13.3 *Well Yields and Present Uses*

No data are presently available for values of coefficients of transmissivity (T), and storage (S), or the specific capacity of Unit #13 in western South Dakota.

The major use of water from Unit #13 in western South Dakota is for livestock and domestic uses.

2.13.4 *Sustained Yield and Recharge Sites*

No data are known to exist on the recharge rate of Unit #13 in western South Dakota. Because of this and the lack of T and S values, no attempt is made to calculate a rate of sustained yield.

Unit #13 crops out over a very wide area of western South Dakota. Most of this is shale, which would allow only a slow rate of infiltration because of its low permeability, so areas suitable for recharge of surface water into Unit #13 are limited. Possible sites for recharge include sandy beds within the shale units, or limestone units in the Greenhorn and Niobrara Formations.

2.13.5 *Additional Studies*

More information is needed to thoroughly assess the ground water resources of Unit #13 in western South Dakota. These include:

(a) Sampling of water quality.
(b) Studies to determine the rate of recharge.
(c) Pumping tests to determine T and S and to aid in determination of permeability. The suggestion has been made to use this unit for high level radioactive waste disposal because of its low permeability and the general remoteness of the area (Rapid City Journal, July 16, 1979).

2.14 Unit #14 - Fox Hills Formation

2.14.1 *Total Ground Water in Storage*

The Fox Hills Formation is of Late Cretaceous age and underlies much of northwestern South Dakota (Darton, 1951). It consists mainly of grayish-white to yellow sandstone and sandy shale, and has been divided into several members (Waage, 1968).

An isopach map of the Fox Hills Formation, Unit #14, is shown in Figure 22. This map is based on well data from the South Dakota School of Mines and Technology, the South Dakota Geological Survey, and from other sources (Croft, 1978; Armstrong, 1978; Randich, 1975; Waage, 1968; Morgan and Petsch, 1945) including published geologic quadrangle reports (see references cited at the end of this section for specific quadrangles used).

The average saturated thickness of Unit #14 is variable. Values of saturated thickness are impossible to obtain from most well logs because oil and gas wells are normally cased to a point below the Fox Hills Formation to prevent contamination of this aquifer. Published reports for Adams and Bowman Counties, North Dakota (Croft, 1978), and Grant and Sioux Counties, North Dakota (Randich, 1975) indicate that 100% of the formation is saturated near the North Dakota-South Dakota border, west of the Missouri River. Available logs for South Dakota water wells in the files of the U. S. Geological Survey indicate that approximately 95% of the formation is saturated in western South Dakota.

From Figure 22, using a 95% saturated thickness and taking thickness changes into account, the volume of saturated Fox Hills Formation in this area is 1,359 million acre-ft. Table 16 shows these data broken down into the water basins.

Because the lithology of the Fox Hills Formation is variable, the porosity is also variable. No data are available for the porosity of Fox Hills beds in South Dakota, but published figures for the Fox Hills in Adams and Bowman Counties, North Dakota (Croft, 1978) and Grant and Sioux Counties, North Dakota (Randich, 1975) indicate a porosity of over 30% for the sandy beds. Unit #14 is judged to have an average porosity of 20% and an effective porosity of 5% (Appendix B). Thus, the total ground water in the Fox Hills Formation in western South Dakota is approximately 272 million acre-ft. The amount theoretically available to wells is less because of the specific retention of the water-bearing layers, and is 68 million acre-ft.

In Adams and Bowman Counties, North Dakota, the basal Hell Creek aquifer (stratigraphically above the Fox Hills Formation) is considered to form a single aquifer with the Fox Hills unit (Croft, 1978). In Grant and Sioux Counties, North Dakota (Randich, 1975) and Emmons County, North Dakota (Armstrong, 1978) the Fox Hills aquifer is considered to be separate from other aquifers.

2.14.2 *Water Quality*

Water quality data for Unit #14 in western South Dakota are shown in Appendix C. Figure 22 is a map of TDS for Unit #14. Water quality in the Fox Hills Formation is generally poor, possibly because the water comes into contact with the underlying Pierre Shale, which normally yields highly mineralized water. From Figure 22, it is apparent that better quality ground water from Unit #14 is normally available near the outcrop. In general, deeper wells from Unit #14 yield water higher in TDS and SAR.

Table 16 shows water quality for Unit #14, broken down into the water basins.

2.14.3 *Well Yields and Present Uses*

Only scattered data are available on typical pumping rates for wells in Unit #14. Armstrong (1978) reports a coefficient of transmissivity (T) of 80 ft^2/day, with a storage coefficient (S) of 0.007 for a well pumped at 7.7 gpm for 2,000 min. The well was completed in a 28 ft thick sandstone bed in the Fox Hills Formation and is located in section 19, T. 135 N., R. 76 W., Emmons County, North Dakota, just above the South Dakota border). Armstrong (1978) also reports a T of 300 ft^2/day for a well completed in 2 sandstone beds of the Fox Hills Formation, located in section 19, T. 135 N., R. 76 W., Emmons County, North Dakota. Its specific capacity was approximately 1.6 gpm/ft and it yields about 40 gpm.

Known values of specific capacity for the Fox Hills Formation in western South Dakota are shown in Appendix B. These are variable but generally low.

The cities of Lemmon, Timber Lake, and Bison, South Dakota obtain all or part of their municipal water supplies from wells in the Fox Hills Formation.

2.14.4 *Sustained Yield and Recharge Sites*

The sustained yield of Unit #14 is determined by the recharge rate. No known published reports exist which contain estimates of the rate of recharge of the Fox Hills Formation. Because it lies directly above the Pierre Shale aquitard, precipitation falling on the outcrop, supplemented by leakage from overlying formations, is the main source of recharge.

Armstrong (1978) reports that the Fox Hills aquifer and Lake Oahe are hydraulically connected in Emmons County, North Dakota.

Numerous sites for artificial recharge of surface water into Unit #14 are available along the outcrop of the Fox Hills Formation, which covers a considerable area in South Dakota (Darton, 1951).

2.14.5 *Additional Studies*

More information is necessary to thoroughly assess the ground water resources of the Fox Hills Formation in western South Dakota. These include:

(a) Detailed sampling of water quality.
(b) Determination of the rate of recharge, and permissible usage.
(c) Pumping tests to determine T and S.
(d) Detailed examination of artificial recharge sites.

2.15 Unit #15 - Hell Creek and Fort Union Formations

2.15.1 *Total Ground Water in Storage*

The Hell Creek and Fort Union Formations are combined in this report because they are both terrestrial deposits of Late Cretaceous to Paleocene age, and possess similar hydrogeologic properties. The rocks occur in northwestern South Dakota (see Figure 23).

Figure 24 shows the combined thickness of the Hell Creek and Fort Union Formations in western South Dakota. The areal distribution of this unit was obtained from the Geologic Map of South Dakota (Darton, 1951), published at a scale of 1:500,000). The basis for these isopach lines are:

1. Published quadrangle reports (see references cited for specific quadrangles used).
2. The Geologic Map of South Dakota (Darton, 1951).
3. The computerized inventory of South Dakota School of Mines and Technology well records.
4. Mineral and Water Resources of South Dakota (U. S. Geological Survey, 1975).

A comparison of this map with the information available in "Ground-Water Resources of Adams and Bowman Counties, North Dakota" (Croft, 1978) indicates that this map is fairly accurate.

No data are readily available to compute the average saturated thickness of Unit #15. Known data on total thickness and saturated thickness of Unit #15 were studied to obtain an average saturated thickness of 70% of the total thickness.

Unit #15 occurs in the northwestern part of South Dakota (see Figure 23). The Fort Union Formation has moderate potential as an aquifer (U. S. Geological Survey, 1975). The Hell Creek Formation yields small to moderate amounts of water. It has only a moderate potential for further development (McGuiness, 1962).

In order to determine the total amount of water in storage in Unit #15 a porosity value of 30% has been assumed (see Appendix A). Thus the total volume of ground water in storage in Unit #15 is 359 million acre-ft. Appendix B shows the relationship between porosity and specific yield. It is judged that about 16.6% of this, or 60 million acre-ft, would be available to well (see Table 17).

2.15.2 *Water Quality*

In general the quality of water from Hell Creek Formation is fair to highly mineralized. The Fort Union Formation yields saline water and it has high sodium sulphate and is barely potable (U. S. Geological Survey, 1975). For TDS and SAR values from Unit #15, see Appendix C. Figure 24 approximately illustrates the trend in the variation of TDS in Unit #15.

2.15.3 *Well Yields and Present Uses*

Presently, Unit #15 is a source of water for farms and ranches west of the Missouri River in Corson, Hardin, Perkins, and Ziebach Counties. The City of Lemmon obtains part of its water supply from two wells that tap the Fort Union. Unit #15 could probably support modest increases in withdrawals (U. S. Geological Survey, 1975).

No data are available on typical pumping rates for individual wells in Unit #15 except a citation by Lange (1962) "Ground-water can be readily obtained from the Hell Creek and the Fox Hill Formations throughout the area (covered by Signal Butte Quadrangle). According to local ranchers the wells can be pumped at a rate of 5-10 gpm for days without drawing the water level down appreciably."

2.15.4 *Sustained Yield and Recharge Sites*

Insufficient data are available to quantitatively define the sustained yield of Unit #15. Croft (1978) states that Hell Creek Formation is one of the most dependable sources of water in Adams and Bowman Counties, North Dakota.

Wherever it is exposed, formations of Unit #15 are recharged by direct precipitation and infiltration by seepage from streams and nearby lakes (Croft, 1978). However, recharge into Unit #15 is not appreciable due to the fact that the precipitation in the outcrop area is scanty and the outcrops are above the level of the larger streams so that the formation cannot receive recharge from them.

2.15.5 *Additional Studies*

Recharge rates and sustained yield data are needed to more fully assess the potential of Unit #15.

2.16 Unit #16 - White River Group

2.16.1 *Total Ground Water in Storage*

Unit #16 consists of the White River Group (Oligocene Age) of terrestrial origin. The Chadron and Brule Formations are claystones with local channel fill sandstones, and make up the White River Group (Figure 25). Figure 26 shows the extent and thickness of Unit #16 in western South Dakota. To draw these isopach lines, the well log inventory of South Dakota School of Mines and Technology was used.

From Appendix B, Unit #16 is judged to have a porosity of 30%. The effective porosity is 1%.

From Figure 26, the total saturated volume of Unit #16 is assessed to be 47 million acre-ft, and water in storage is 142 million acre-ft. It is estimated that 1%, i.e., 4.7 million acre-ft would theoretically be available to wells (see Table 18).

Figure 26 illustrates the trend of TDS values of Unit #16. In general, the quality of water from Unit #16 is fair to poor, apparently depending on how close the aquifer is to the Pierre Shale. Dissolved solids are known to range from 600-1,000 ppm, and probably are higher in some water from the basal sands and gravels (Ellis, 1960).

2.16.3 *Well Yields and Present Uses*

Generally Unit #16 is very impermeable and is not a source of ground water. No data are available to define yields quantitatively for individual wells in this unit.

2.16.4 *Sustained Yield and Recharge Sites*

Yields from wells in the basal 100 to 120 ft of Unit #16 are marginally adequate for domestic and stock use. But its potential as a reliable source of water is low, because of scanty precipitation, which is the only recharging agent over the outcrop area of Unit #16.

2.16.5 *Additional Studies*

No additional studies are suggested.

2.17 Unit #17 - Arikaree Formation

2.17.1 *Total Ground Water in Storage*

Figure 27 shows the extent of outcrop and the iso-thickness of Unit #17, Arikaree Formation, in western South Dakota. The references used to obtain the outcrop line and isopach lines include:

1. Geologic Map of South Dakota (Darton, 1951).
2. The inventory of South Dakota School of Mines and Technology well records (Appendix A).
3. Mineral Resources of South Dakota (U. S. Geological Survey, 1975).

The Arikaree Formation in western South Dakota consists of 0 to 500 ft of clayey silts. In Nebraska the unit is coarser-grained, and it becomes a significant aquifer.

While describing the hydrology of the Pine Ridge Indian Reservation, Ellis and Adolphson (1971) report that in the area underlain by the Arikaree Formation, there is a single continuous water table. It is assumed that Unit #17 is saturated to its full thickness of deposition. Thus the saturated volume of Unit #17 is estimated to be 410 million acre-ft. This is broken into the water basins and given in Table 19. From Appendix B, Unit #17 is judged to have a porosity value of 35% (effective, 10%). Therefore the total volume of ground water in storage in Unit #17 is 144 million acre-ft.

It is estimated that 28.5% of this, or 40 million acre-ft is available to wells.

2.17.2 *Water Quality*

TDS and SAR values for water from Unit #17 are in Appendix C. In general, water from this unit is of moderately good quality for both irrigation and domestic use (U. S. Geological Survey, 1975). TDS is generally less than 500 ppm. The few instances where it is almost 1,000 ppm may be due to contact with local mineralized strata (Ellis, 1960).

2.17.3 *Well Yields and Present Uses*

Yield from Unit #17 can be high, and large-capacity wells (more than 100 gpm) exist in Pine Ridge Indian Reservation communities (Ellis, 1960)(see Appendix D). In one pumping test, a yield of 474 gpm was observed with an indicated specific capacity of 4 gpm/ft (Gries, 1964). Harksen (1965) reports that ground water of excellent quality and in good quantity is available in nearly all parts of the area shown in the Sharps Corner Quadrangle. The primary aquifer is the Rockyford Ash member of the Arikaree Formation. A pumping rate of 10,000 gpd for over a year has resulted in a drawdown of less than 4 in. Presently this unit is used for stock and domestic wells (U. S. Geological Survey, 1975).

2.17.4 *Sustained Yield and Recharge Sites*

The Arikaree Formation has a modest potential for further development as a source of ground water. The unit is ordinarily a reliable source of water even in dry years. No data are available to predict the sustained rate of withdrawal from this unit. No information is available to describe recharge.

2.17.5 *Additional Studies*

Unit #17 has been developed on a small to moderate scale and yields water of good quality, but has not been studied sufficiently to establish its value as an aquifer. The aquifer is at shallow depth compared to other aquifers of older age. Therefore, it is suggested that more test wells be drilled and that pumping tests be conducted to establish hydraulic properties.

2.18 Unit #18 - Ogallala and Sand Hills Formations

2.18.1 *Total Ground Water in Storage*

Figure 28 shows the areal extent and thickness of hydrogeologic Unit #18, the Pliocene Ogallala Formation and the Pleistocene Sand Hills Formation. These formations crop out in Bennett, Todd, and Tripp Counties in south-central South Dakota, and consitute an aquifer of considerable potential. The sources of information for this map are the U. S. Geological Survey Hydrologic Atlases and the S. D. Geologic Quadrangles references cited at the end of this chapter.

The Ogallala Formation, a weakly consolidated sand, has been divided into members by the South Dakota Geological Survey: the Valentine Member, a medium-grained, greenish-colored, pure quartz sand; and the overlying Ash Hollow Member, similar in composition to the Valentine but containing scattered clay beds (volcanic ash or "mortar" beds). The Ogallala thickens in Nebraska and further south, and is a very important aquifer as far south as Texas. In Nebraska, the number of registered irrigation wells increased from about 7,000 in 1950 to 55,000 in 1976 (Taylor, 1978); many of these wells tap the Ogallala and Sand Hills aquifers.

The Sand Hills Formation consists of sand dunes derived from the underlying Ogallala Formation. The Sand Hills Formation is an unconsolidated, medium-grained, brownish colored quartz sand, and is a valuable aquifer in the Sand Hills area of northwestern Nebraska.

The Ogallala and Sand Hills Formations are hydraulically connected (Rahn and Paul, 1975), and hence are considered a single hydrogeologic unit for this report.

The total volume of Unit #18 in western South Dakota is 137 million acre-ft. Table 20 shows the volume in each of the water basins.

Unit #18 is flat-lying, and is eroded into buttes and mesas by the White and Niobrara Rivers and their tributaries. Due to this topography and the permeable nature of the unit, the water table typically lies at depths of about 100 ft (see Figure 29). From Figure 29 and available water well data, it is assumed that 65% of Unit #18 is saturated. Thus the volume of Unit #18 which is saturated is 89 million acre-ft (Table 20).

The total porosity of the Valentine Sand Member of the Ogallala Formation has been estimated at about 39% (Barari, 1965). Appendix B shows that the entire unit is judged to have an average porosity of 35%. Thus the total volume of water in the unit is 31 million acre-ft (Table 20).

Only an estimated 71% of the total pore water is available to wells (Appendix B). Thus the total ground water available in Unit #18 is 22 million acre-ft (Table 20).

2.18.2 *Water Quality*

In general, the ground water in Unit #18 has good to excellent quality. This is probably due to (1) the pure quartz sand composition and (2) the permeable nature of the unit, which leads to rapid ground water movement.

Appendix C shows typical TDS values. Less than 500 ppm TDS can be expected in almost all areas. One small zone tentatively drawn on Figure 27 shows greater than 500 ppm; however, more data are needed to accurately confirm these TDS contours.

In essence, nearly all the 22 million acre-ft of available ground water is suitable for drinking (Table 20).

All available SAR data for Unit #18 are less than 6.

2.18.3 *Well Yields and Present Uses*

The best pumping test available in Unit #18 is near Rosebud, S. D., where a test well and 12 observation wells were installed (Rahn and Paul, 1975). A 36-inch diameter production well was drilled to a depth of 220 ft, and pumped at 726 gpm for 5 days. The drawdown was 61.5 ft, yielding a specific capacity of 11.8 gpm/ft (see Appendix D). Transmissivity (T) was 36,860 gpd/ft, and storage (S) was 0.0419. These are typical of values reported for the Ogallala in other areas (Newport, 1969).

Additional data on specific capacity and pumping tests for Unit #18 are shown in Appendix B.

Presently, little ground water is being withdrawn from Unit #18. The cities of Winner and Gregory, S. D. obtain municipal supplies, estimated at 1 mgd from Unit #18. Numerous small stock and domestic wells occur in Unit #18, but these wells do not withdraw large amounts of water. Irrigation withdrawals are not known. A photo-interpretation of irrigation areas from a 1973 LANDSAT image shows only 2 center-pivot sprinkler locales. It is believed that in the past year many center-pivot sprinklers have been installed, especially on the Rosebud Reservation.

2.18.4 *Sustained Yield and Recharge Sites*

Although 22 million acre-ft of water is available in Unit #18, the rate of withdrawal for the best use of this resource depends on the recharge rate. If the withdrawal rate exceeds the recharge rate, ground water will be "mined", allowing for continued decline of the water table, such as occurs in Texas and other places, and land subsidence could occur (see Appendix E).

The natural ground water recharge rate of 2.5 inches/year was determined by Rahn and Paul (1975). This agrees well with other published data (Langein, 1949); Bradley, 1965; Newport, 1969; McGuiness, 1963; Havens, 1966; and Theis, 1937). This recharge rate would support irrigation on 12% of the land area.

Since the outcrop area shown in Figure 29 is about 4 x 10^{10} ft^2, the average annual recharge rate is 0.8 x 10^{10} ft^3/yr. Any ground water development and consumption equal to or exceeding this rate would cause natural ground water discharge points (such as springs and seeps along river valleys) to dry up.

Numerous excellent sites for artificial recharge occur. In general these should be on upland areas within the thickness section shown on Figure 28.

2.18 5 *Additional Studies*

Detailed hydrogeologic studies of the Ogallala and Sand Hills aquifer are needed to assess the sustained yield of the unit, and to evaluate areas favorable for supplementary recharge by surface sources.

2.19 Unit #19 - Saturated Alluvium

2.19.1 *Total Ground Water in Storage*

Figure 30 is a map of western South Dakota showing Unit #19, saturated alluvium. These areas were obtained from U. S. Geological Survey Folios and Hydrologic Atlases and from S. D. Geological Survey quadrangle reports (see references cited for specific quadrangles used). Where published maps are unavailable, LANDSAT imagery (e.g., #E-1334-17130, June 22, 1973 color infrared at 1:500,000 scale) and the South Dakota State University soils map (Westin, 1971) were used.

Figure 30 does not include terrace alluvium, which is typically unsaturated or only saturated along the basal contact; hence Figure 30 is largely alluvium underlying flood plains (see Figure 31). Numerous small valleys in western South Dakota contain narrow flood plains which would not show at the scale desired for this report, and are not included. For these reasons the following estimates of ground water stored in alluvium are minimum values.

Alluvium typically consists of coarse sand and gravel in the Black Hills areas (Figure 32). In the prairie area alluvium is largely silty, clayey sand with scattered gravel lenses.

The average saturated thickness of Unit #19 is quite variable and is difficult to precisely ascertain. The value of 20 ft used in Table 21 is determined from data compiled from: (1) the inventory of South Dakota School of Mines and Technology well records (see Appendix A), which shows an average thickness of alluvium of 35 ft, (2) U. S. Geological Survey Folio reports which describe alluvium in the Black Hills averaging 25 ft thick, (3) S. D. Geological Survey quadrangle reports, and (4) consulting reports and S. D. School of Mines and Technology M. S. theses. Because the water table is typically 5 to 10 ft below the surface in flood plain areas, the average saturated thickness is judged to be 20 ft.

From Figure 30 the area of saturated alluvium in western South Dakota totals 68×10^9 ft^2. Using a 20 ft saturated thickness, the volume of saturated alluvium is 31 million acre-ft. Table 21 shows these data broken down into the water basins.

In order to determine the total amount of ground water in storage in alluvial deposits, it is necessary to know the porosity. Appendix B shows typical porosity values for different kinds of rocks and sediments. From Appendix B, Unit #19 is judged to have a porosity of 25%. Thus the total ground water in alluvial deposits in western South Dakota is 7.8 million acre-ft. Appendix B shows the relationship between porosity and specific yield. It is judged that about 80% of the total water in Unit #19, or 6.2 million acre-ft, would be theoretically available to wells.

2.19.2 *Water Quality*

Water quality in alluvial deposits is difficult to determine due to local geology, topography, and precipitation. Appendix C shows the range in TDS and SAR for ground water in Unit #19.

In general, better quality ground water in alluvium is available in the Black Hills than in the prairie area. Black Hills communities such as Rapid City, Belle Fourche, and Hill City, which obtain their water from alluvial deposits, have less than 500 ppm TDS. The water generally becomes more mineralized away from the Black Hills. Local bedrock geology and alluvial stratigraphy have a marked influence on the quality of water in alluvium; for instance, in the White River quadrangle area, Agnew (1957) found low TDS water in wells where alluvium rests on Tertiary bedrock, but high TDS in wells where alluvium rests on the Cretaceous Pierre Shale. Figure 20 shows very generalized contours of TDS.

Table 21 shows water quality broken down into the 13 basins. It can be seen that basins 2A, 2B, 3, 7A and 7B have moderately good quality ground water in alluvium, whereas the other basins do not.

SAR data for Unit #19 is shown in Appendix C. SAR data is not shown in Figure 20 due to the extreme variability. In general, however, alluvial ground water having low SAR is found near the Black Hills areas.

2.19.3 *Well Yields and Present Uses*

Few data are available on typical pumping rates for individual wells in Unit #19. In general the alluvium is extremely permeable near the Black Hills but rapidly becomes fine-grained and hence less permeable down-valley. Davis (1979) determined a coefficient of transmissivity (T) of 900,000 gpd/ft for the alluvium at the Belle Fourche infiltration gallery along Spearfish Creek, about 1 mile north of the Black Hills; the gallery is capable of withdrawing over 3.5 mgd with only 3 ft of drawdown. In other areas alluvium scarcely produces enough water for domestic wells. The towns of Murdo (Kuchenbecker, personal communication), and Box Elder (Gries, personal communication), for instance, have reportedly abandoned attempts to develop municipal supplies from alluvium due to its fine-grained nature.

Known values of specific capacity are shown in Appendix D.

The largest present uses for ground water in alluvium in western South Dakota are for municipal supplies at Rapid City, estimated at 10 mgd, and Belle Fourche, estimated at 1.2 mgd. At both these locations water is recharged by surface water (i.e., Spearfish Creek and Rapid Creek, respectively). Some small irrigation wells occur near the Black Hills; the total withdrawal probably does not exeed 10 mgd.

2.19.4 *Sustained Yield and Recharge Sites*

The sustained yield of Unit #19 is determined by the recharge rate. Unlike most hydrogeologic units described in this report, alluvium is recharged by local stream induced-infiltration near pumping areas as well as by precipitation falling on the exposed alluvium. Therefore, no attempt is made in this report to calculate sustained pumping rates from alluvium.

Numerous sites for artifical recharge of surface water into Unit #19 are available. To be effective, all sites would require detailed evaluation of the geology and hydrology. It is doubtful, however, that any alluvium would be very receptive to large amounts of recharge water because: (1) the alluvium is not very thick, (2) at some places the alluvium has low permeability, and (3) the natural water tables have gentle slopes and would not carry much water away from the recharge site.

Areas most favorable for artifical recharge would be near the Black Hills, particularly coarse-grained terrace areas where topographic relief would allow for drainage of the recharged water. One example already in existence is the Angostura irrigation project where flood irrigation of a terrace near Oral leads to recharge of the terrace alluvium, and consequent development of springs along the Cheyenne River.

2.19.5 *Additional Studies*

Much more information is needed in order to thoroughly assess the ground water resources of alluvium in western South Dakota. Specifically, these include:

(a) Test drilling to determine thickness and permeability. This would be similar to the S. D. Geological Survey program of test drilling for outwash aquifers in eastern South Dakota.
(b) Test drilling and detailed sampling of water quality in Unit #19.
(c) Detailed, site-specific examination of artificial recharge sites.

CHAPTER III

SUMMARY

Tables 22 and Figures 33 to 35 summarize the ground water stored in western South Dakota. Figure 33 is the total ground water, Figure 34 is the recoverable ground water, and Figure 35 is the recoverable ground water having less than 1,000 ppm TDS. (Water greater than 1,000 ppm TDS is classed as saline by the U. S. Geological Survey). Table 23 and 24 show data for the water basins. Basin 7A (Cheyenne River) has more good-quality ground water (138 million acre-ft) than any basin. It can be seen, for instance, that:

(1) From Figure 33, Unit #13 (Pierre Shale, etc.) contains more water than any other unit. Most of this water is not available to wells because it is contained in minute openings in the shale.

(2) From Figure 34, the units containing the most recoverable water are, in order:
  (a) Unit #3 (Red River Formation, etc.)
  (b) Unit #5 (Minnelusa Formation)
  (c) Unit #4 (Madison Limestone)

(3) From Figure 35, the units containing the most recoverable water having less than 1,000 ppm TDS are, in order:

  (a) Unit #3 (Red River Formation, etc.)
  (b) Unit #11 (Inyan Kara Group, etc.)
  (c) Unit #14 (Fox Hills Formation)
  (d) Unit #4 (Madison Limestone)
  (e) Unit #18 (Ogallala-Sand Hills Formation)

Accordingly, the results of this investigation indicate that, in terms of moderately good quality, recoverable ground water, the Ordovician to Devonian System (e.g., the Red River Formation) is western South Dakota's most valuable aquifer.

Despite the abundance of water in these aquifers, many lie at such great depths, partially in northwestern South Dakota, that they are not presently utilized. Figures 36, 37, and 38 show structural contour maps of the top of the Deadwood, Madison, and Greenhorn Formations. From these maps, the distance required to penetrate units can be inferred as the difference between the land elevation and the elevation shown on the structural contour map. Thus Unit #18 (Ogallala-Sand Hills Formations), because of its shallow depth, has more practical value than its position in Figure 35 indicates.

Oahe Reservoir normally contains about 17 million acre-ft of water (U. S. Geological Survey, 1975). The total recoverable ground water stored in western South Dakota (4,994 million acre-ft)(Table 23) is about 294 times the volume of Oahe Reservoir.

Another parameter which affects the utilization of ground water is the yield of individual wells. From Appendix D it is shown that Unit #19 (Alluvium) has the largest specific capacity values. Thus, water can most readily be obtained from individual wells in this unit.

Ultimately, the amount of ground water capable of being utilized in a sustained manner is dependent upon the recharge rate. Except for Unit #18, only meager data are available on recharge rates. Therefore, it is conjectural to establish safe ground water yields for these 18 other units.

In summary, western South Dakota's ground water resources are vast, but much of the water is highly mineralized and at depths which presently make its utilization uneconomical. It is believed that all the aquifers presently utilized (Figure 39) can withstand modest increased withdrawals. However, in order to more fully develop the ground water resources, technical problems relating to drilling costs and desalinization will have to be overcome.

It is recommended that future detailed studies be undertaken to determine the hydraulic properties, recharge rates, and sustained yields of the more promising aquifers shown in Figure 35. The possibility of using surface water to supplement natural recharge to the Ogallala, Madison, Minnelusa, and alluvial aquifers should be investigated.

REFERENCES CITED

Adolphson, D. G., and M. J. Ellis, 1972: Basic hydrogeologic data - Pine Ridge Indian Reservation, South Dakota: S. Dak. Geol. Survey & S. Dak. Water Res. Comm. Water Resources Rept. No. 4, 75 p.

Agnew, A. G., 1957: Areal geology of the White River quadrangle: S. Dak. Geol. Survey, map and text.

___________, 1963: Geology of the Mission quadrangle, South Dakota: S. Dak. Geol. Survey, map and text.

Agnew, A. F., M. J. Tipton, and F. V. Steece, 1962: South Dakota's ground water needs and supplies: S. Dak. Geological Survey, Misc. Invest. No. 4, 8 p.

Agnew, A. F., and P. C. Tychsen, 1965: A guide to the stratigraphy of South Dakota: S. Dak. Geol. Survey, Bull. 14, 175 p.

Armstrong, C. A., 1978: Ground-water basic data for Emmons County, North Dakota: N. Dak. Geol. Survey Bull. 66, part II, 375 p.

_______________, 1978: Ground-water resources of Emmons County, North Dakota: N. Dak. Geol. Survey Bull. 66, part III, 43 p.

Back, W., *et al.*, in preparation, Chemical geohydrology of the Pahasapa Limestone, South Dakota: U. S. Geol. Survey.

Baker, C. L., 1947: Deep borings of western South Dakota: S. Dak. Geol. Survey Rept. of Inv. No. 57, 112 p.

____________, 1948: Additional well borings in South Dakota: S. Dak. Geol. Survey Rept. of Inv. No. 61, 40 p.

____________, 1951: Well borings in South Dakota, 1948-1950: S. Dak. Geol. Survey Rept. of Inv. No. 67, 67 p.

Baker, R. K., 1972: The ground water capacity of the Newcastle-Dakota sandstones in central and western South Dakota: Unpub. M. S. thesis, S. Dak. School of Mines and Tech. 130 p.

Barari, A., 1965: Ground-water supply for the City of Winner: S. Dak. Geol. Survey Special Rept. 36, 30 p.

__________, 1966: Ground-water supply for the City of Winner: S. Dak. Geol. Survey Special Rept. 36, 30 p.

__________, 1967: Ground-water supply for the City of Mission: S. Dak. Geol. Survey Special Rept. 41, 30 p.

Bradley, E., 1956: Geology and ground-water resources of the upper Niobrara River Basin, Nebraska and Wyoming: U. S. Geol. Survey Water Supply Ppaer 1368, 70 p.

Bredehoeft, J. D., *et al.*, 1972: Regional ground-water flow in the Dakota artesian aquifer: Unpub., 54 p.

Carrol, W., 1979: Depositional environments and paragenetic porosity controls, upper Red River Formation, North Dakota: N. Dak. Geol. Survey Rept. of Inv. No. 66, 51 p.

Christenson, C. M., 1962: Water supply for the City of Burke: S. Dak. Geol Survey Special Rept. 18, 13 p.

______________, 1969: Water supply for the city of Gregory: S. Dak. Geol. Survey Special Rept. 49, 47 p.

Collins, S. G., 1969: Areal geology of the Winner quadrangle: S. Dak. Geol. Survey, map and text.

Cox, E. J., 1962: Preliminary report on the artesian water supplies from the Minnelusa and Pahasapa aquifers in the Belle Fourche-Spearfish area: S. Dak. Geol. Survey Special Rept. 19, 17 p.

Croft, M. G., 1978: Ground-water basic data for Adams and Bowman Counties, North Dakota: N. Dak. Geol. Survey Bull. 65, part II, 294 p.

______________, 1978: Ground-water resources of Adams and Bowman Counties, North Dakota: N. Dak. Geol. Survey Bull. 65, part III, 54 p.

Darton, N. H., 1902: Description of the Oelrichs quadrangle: U. S. Geol. Survey Atlas, Folio No. 85, 6 p.

______________, 1909: Geology and underground water of South Dakota: U. S. Geol. Survey Water Supply Paper 227, 156 p.

______________, 1951: Geologic map of South Dakota: U. S. Geol. Survey.

Darton, N. H., and W. S. T. Smith, 1904: Description of the Edgemont quadrangle: U. S. Geol. Survey Atlas, Folio No. 108, 10 p.

Darton, N. H., and O'Harra, C. C., 1909: Description of the Belle Fourche quadrangle: U. S. Geol. Survey Atlas Folio No. 164, 9 p.

Darton, N. H., and S. Paige, 1925: Description of the central Black Hills: U. S. Geol. Survey Atlas Folio No. 219, 34 p.

Davis, A. D., 1979: Hydrogeology of the Belle Fourche water infiltration gallery area, Lawrence County, South Dakota: Unpub. M. S. thesis, S. Dak. School of Mines and Tech., 60 p.

Davis, R. W., C. F. Dyer, and J. E. Powell, 1961: Progress report on wells penetrating artestian aquifers in South Dakota: U. S. Geol. Survey Water Supply Paper 1534, 100 p.

Davis, S. N., and R. J. M. DeWiest, 1965: Hydrogeology: John Wiley and Sons, New York, 394 p.

Ellis, M. J., and D. G. Adolphson, 1971: Hydrogeology of the Pine Ridge Indian Reservation, South Dakota: U. S. Geol. Survey Hydrologic Inv. Atlas HA-357.

Ellis, M. J., J. H. Ficken, and D. G. Adolphson, 1971: Hydrology of the Rosebud Indian Reservation, South Dakota: U. S. Geol. Survey Hydrologic Inv. Atlas HA-355.

Ellis, M. J., D. G. Adolphson, and J. H. Ficken, 1972: Basic hydrologic data, Rosebud Indian Reservation, South Dakota: S. Dak. Geol. Survey Water Resources Rept. No. 6, 111 p.

Gries, J. P., 1952: Deadwood Formation: Billings Geological Society, Third Annual Field Conference Guidebook, p. 42-43.

____________, 1958: The Dakota Formation in central South Dakota: Proc. S. Dk. Acad. Sci., Vol. 37, p. 262-268.

____________, 1964: Mineral resources on Indian lands - Pine Ridge Reservation - Shannon, Washabaugh and Bennett Counties, South Dakota: U. S. Bur. Mines Rept. 153, 66 p.

____________, 1965: Mineral resources and their potential on Indian Lands - Rosebud Reservation - Gregory, Mellette, Todd, and Tripp Counties, South Dakota: U. S. Bur. Mines Prelim. Rept. 160, 66 p.

____________, 1974: Mineral resources of the Black Hills area, South Dakota and Wyoming: U. S. Bur. Mines, Info. Circ. 8660, 61 p.

____________, 1977: Geothermal application on the Madison (Pahasapa) aquifer system in South Dakota: Final Rept., South Dakota School of Mines and Technology, 96 p.

____________, 1979: Prelim. Rept. 160, Open files: S. Dak. School of Mines and Tech., 66 p.

Gries, J. P., W. J. Siok, and R. K. Baker, 1973: Determination of the total storage capacity of the Cretaceous sandstone aquifers in South Dakota: U. S. Dept. of the Interior Project No. A-031-SDAK, 13 p.

Hanshaw, B. B., et al., 1977: Hydrogeologic study of a regional carbonate-rock aquifer system: Memoires, Internat. Assoc. of Hydrologists, Vol. 13, prt. I., Birmingham Congress, p. A24-A35.

Harksen, J. C., 1965: Areal geologic map of the Sparps Corner quadrangle: S. Dak. Geol. Survey, map and text.

Harksen, J. C. and J. R. Macdonald, 1969: Guidebook to the major Cenozoic deposits of southwestern South Dakota: S. Dak. Geol. Survey Guidebook No. 2, 103 p.

Havens, J. S., 1966: Recharge studies on the high plains in northern Leo County, New Mexico: U. S. Geol. Survey Water Supply Paper 1819-F, 52 p.

Howells, L. W., 1974: Geohydrology of Crow Creek and Lower Brule Indian Reservation, South Dakota: U. S. Geol. Survey, Hydrologic Inv. Atlas HA-499.

Konikow, L. F., 1976: Preliminary digital model of ground-water flow in the Madison Group, Powder River Basin and adjacent areas, Wyoming, South Dakota, North Dakota, and Nebraska: U. S. Survey Water Resources Inv. 63-75, 44 p.

Langbein, W. B., et al., 1949: Annual runoff in the United States: U. S. Geol. Survey Circ. 52.

Lange, U., 1962: Areal geologic map of the Signal Butte quadrangle: S. Dak. Geol. Survey, map and text.

Mallory, W. W., ed., 1972: Geologic Atlas of the Rocky Mountain Region: Rocky Moutain Association of Geologists., Denver, Colo., 331 p.

McGookey, D. P., et al., 1972: Cretaceous System, In Geol. Atlas of the Rocky Moutain Region: Rocky Moutain Association of Geologists, p. 190-228.

McGuinness, C. L., 1962: Water in South Dakota: S. Dak. Geol. Survey Water Resources Report No. 2, 33 p.

_________________, 1963: The role of ground water in the national water situation: U. S. Geol. Survey Water Supply Paper 1800, 1121 p.

McKee, E. D., et. al., 1956: Paleotectonic maps of the Jurassic System: U. S. Geol. Survey Misc. Geol. Inv. Map I-175, 6 p.

Miller, R. H., 1972: Possible recharge to the Dakota Sandstone aquifer from outcrops of Juro-Cretaceous sandstones, Black Hills area: Unpub. M. S. thesis, S. Dak. School of Mines and Tech., 65 p.

Morgan, R. E., and B. C. Petsch, 1945: A geological survey in Dewey and Corson Counties, South Dakota: S. Dak. Geol. Survey Rept. of Inv. No. 47, 118 p.

Newport, T. G., 1969: Ground-water resources of the lower Niobrara River and Ponca Creek Basins, Nebraska and South Dakota: U. S. Geol. Survey Water Supply Paper 1460-G, 50 p.

Niven, D. W., 1967: Determination of porosity and permeability of selected sandstone aquifers in South Dakota: Unpub. M. S. thesis, S. Dak. School of Mines and Tech., 31 p.

Peterson, J. A., 1972: Jurassic System, In Geologic Atlas of Rocky Mountain Region: Rocky Mountain Association of Geologists, p. 177-189.

Petsch, B. C., 1946: Geology of the Missouri Valley in South Dakota: S. Dak. Survey Rept. of Inv. No. 53, 78 p.

Powell, J. E., J. J. Norton, and D. G. Adolphson, 1973: Water resources and geology of Mount Rushmore National Memorial, South Dakota: U. S. Geol. Survey Water Supply Paper 1865, 50 p.

Rahn, P. H., 1975: Ground water in coal strip mine spoils, Powder River Basin: 35th Ann. Meeting, Proc. Montana Acad. Sci. and Fort Union Coal Field Symposium, p. 348-361.

___________, 1979: Effect of the proposed ETSI coal slurry pipeline on water resources in Wyoming, South Dakota, and Nebraska: In press, Proc. S. Dak. Acad. Sci., Vol. 58.

Rahn, P. H. and J. P. Gries, 1973: Calculation of permeability of Cretaceous sandstones from pumping and static level data in selected areas of western South Dakota: U. S. Dept. of the Interior Project No. A-034-SDAK, 15 p.

______________________, 1973: Large springs in the Black Hills, South Dakota and Wyoming: S. Dak. Geol. Survey Rept. of Inv. No. 107, 46 p.

Rahn, P. H. and H. A. Paul, 1975: Hydrogeology of a portion of the Sand Hills and Ogallala aquifer, South Dakota and Nebraska: Ground Water Jour., V. 13, p. 428-437.

Randich, P. G., 1975: Ground-water basic data for Grand and Sioux Counties, North Dakota: N. Dak. Geol. Survey Bull. 67, part II, 303 p.

Rapid City Journal, July 12, 1979.

Roadifer, J. E., 1962: A subsurface study of the Dakota Sandstone in South Dakota: Unpub. M. S. thesis, S. Dak. School of Mines and Tech., 35 p.

Russell, W. L., 1928: The origin of artesian pressure: Econ. Geol., V. 23, p. 132-157.

Schoon, R. A., 1972: Geology and hydrology of the Dakota Formation in South Dakota: S. Dak. Geol. Survey Rept. of Inv. No. 104, 55 p.

Sevon, W. D., 1960: Geology of the Spring Creek quadrangle, South Dakota: S. Dak. Geol. Survey, map and text.

___________, 1960: Geology of the Ring Thunder Quadrangle: S. Dak. Geol. Survey, map and text.

Siok, W. J., 1972: Total water storage capacity of the Fall River-Lakota sandstones, and of the Dakota Formation east of the zero Skull Creek Shale line in South Dakota: Unpub. M. S. thesis, S. Dak. School of Mines and Tech., 130 p.

South Dakota Department of Environmental Protection, 1976: South Dakota Public Water Supply, Chemical Data: Department of Environmental Protection, Pierre, S.D.

South Dakota Department of Natural Resources, 1975: South Dakota Water Plan: S. Dak. Dept. of Nat. Resources, Vol. II-B, Section B.

South Dakota Geological Survey: Areal geologic maps of 15' quadrangles: Akaska, Artichoke, Bison, Black Horse Butte, Buffalo, Bull Head, Butte, Camp Crook & Midland, Cash, Castle Rock Butte, Cedar Canyon, Change, Cheyenne Agency, Coal Spring, Dallas, Date, Deer's Ears Buttes, Ellingson, Faith, Fort Bennett, Glad Valley, Glencross, Gopher, Govert, Gregory, Haynes, Little Eagle, Ludlow, Mahto, Martin, Meadow, Midland, Miscol, Mobridge, Morristown, Mouth of Bull Creek, Mouth of Moreau, Murchison, No Heart, Okobojo, Okreek, Patricia, Pollack, Procupine, Ralph, Red Elm, Redig, Rousseau Creek, Sorum, Standing Butte, Strol, Thunder Hawk, Timber Lake, Wakpala, Wewela, Willett, and Witten.

______________, 1979: Open files.

Steece, F. V., 1978: Deadwood Formation in the Williston Basin, South Dakota: Montana Geological Society, Williston Basin Symposium, p. 63-69.

Swenson, F. A., 1968: New theory of recharge to the artesian basin of the Dakotas: Geol. Soc. America Bull., v. 79, p. 163-182.

Szigeti, G. J., 1979: Sedimentology and paleontology of the upper Jurassic Unkpapa Sandstone and Morrison Formation, east flank of the Black Hills, South Dakota: Unpub. M. S. thesis, S. Dak. School of Mines and Tech., 78 p.

Taylor, J. O., 1978: Summary appraisals of the nation's ground-water resources - Missouri Basin Region: U. S. Geol. Survey Prof. Paper 813-Q, 41 p.

Theis, C. V., 1935: The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Trans. Am. Geophysical Union, p. 519-524.

____________, 1937: Amount of ground-water recharge in the southern High Plains: Trans. Am. Geophys. Union, v. 18, p. 564-568.

Thornbury, W. D., 1965: Regional geomorphology of the United States: John Wiley & Sons, New York, N. Y., 609 p.

Tipton, M. J., 1960: Shallow water supply for the City of Ft. Pierre: S. Dak. Geol. Survey Special Rept. 11, 11 p.

Toeppelman, 1923: The possibility of oil in eastern Harding County: S. Dak. Geol. and Nat. History Survey.

Tourtelot, H. A., and W. A. Cobban, 1968: Stratigraphic significance and petrology South Dakota: U. S. Geol. Survey Prof. Paper 594-L, 22 p.

Tullis, E. H., J. P. Gries, and J. H. Cope, 1954: Inventory of published and unpublished data of the characteristics of saline surface and ground water of South Dakota: Eng. and Mining Exp. Stat., S. Dak. School of Mines and Tech.

Tennessee Valley Authority, 1978: Draft environmental statement, Edgemont uranium mine, South Dakota: Tenn. Valley Authority, Chattanooga, Tenn., 201 p.

U. S. Bureau of Mines, 1978: Minerals in the economy of South Dakota: U. S. Dept. of the Interior, 12 p.

U. S. Geological Survey, 1964: Mineral and water resources of South Dakota: U. S. Govt. Printing Office, Washington, 295 p.

________________________, 1975: Mineral and water resources of South Dakota: U. S. Govt. Printing Office, Washington, 313 p.

________________________, 1975: Plan of study of hydrology of the Madison Limestone and associated rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U. S. Geol. Survey Open File Report 75-631.

________________________, 1979: Open files.

Waage, K. M., 1968: The type Fox Hills Formation, Cretaceous (Maestrichtian), South Dakota: Part 1. Stratigraphy and paleoenvironments: Peabody Museum of Natural History, Yale University, Bull. 27, p. 1-171.

Walton, W. C., 1962: Selected analytical methods for well and aquifer evaluation: Illinois State Water Survey Bull. 49, 81 p.

Westin, F. C., et al., 1971: Soil associations of South Dakota: S. Dak. Agr. Exp. Sta. Info. Series No. 3, Brookings, South Dakota.

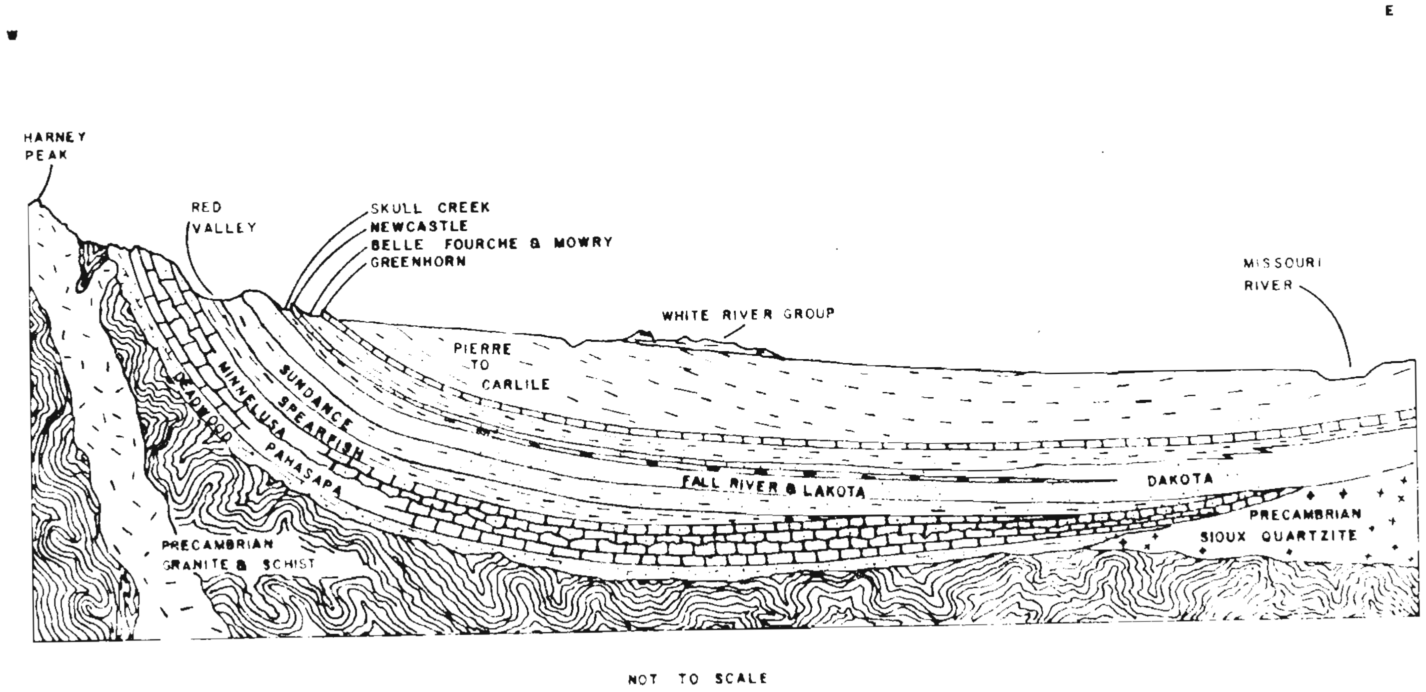


Figure 1. Generalized east-west geologic cross-section of western South Dakota.

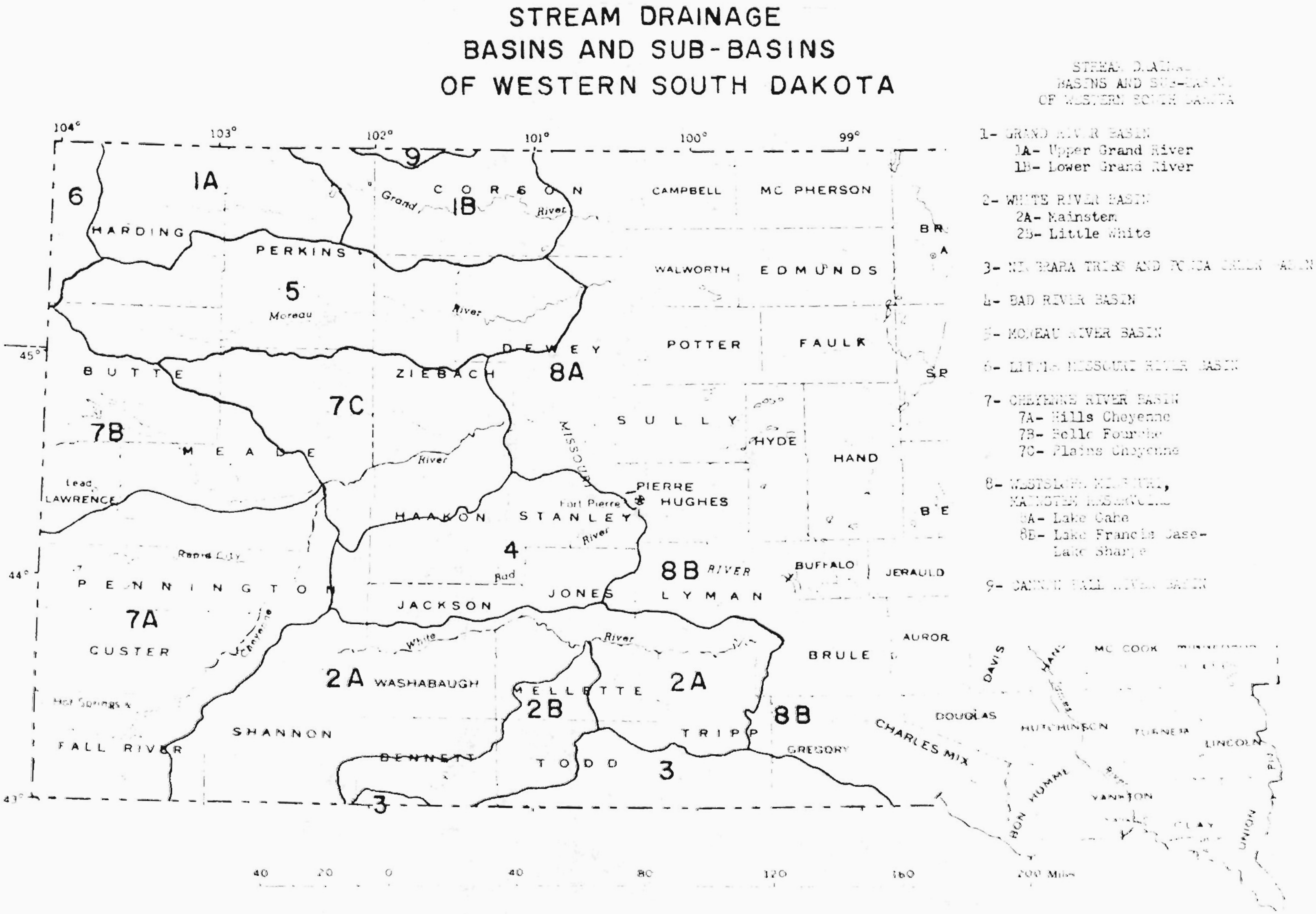


Figure 2. Map of western South Dakota showing 13 water basins.

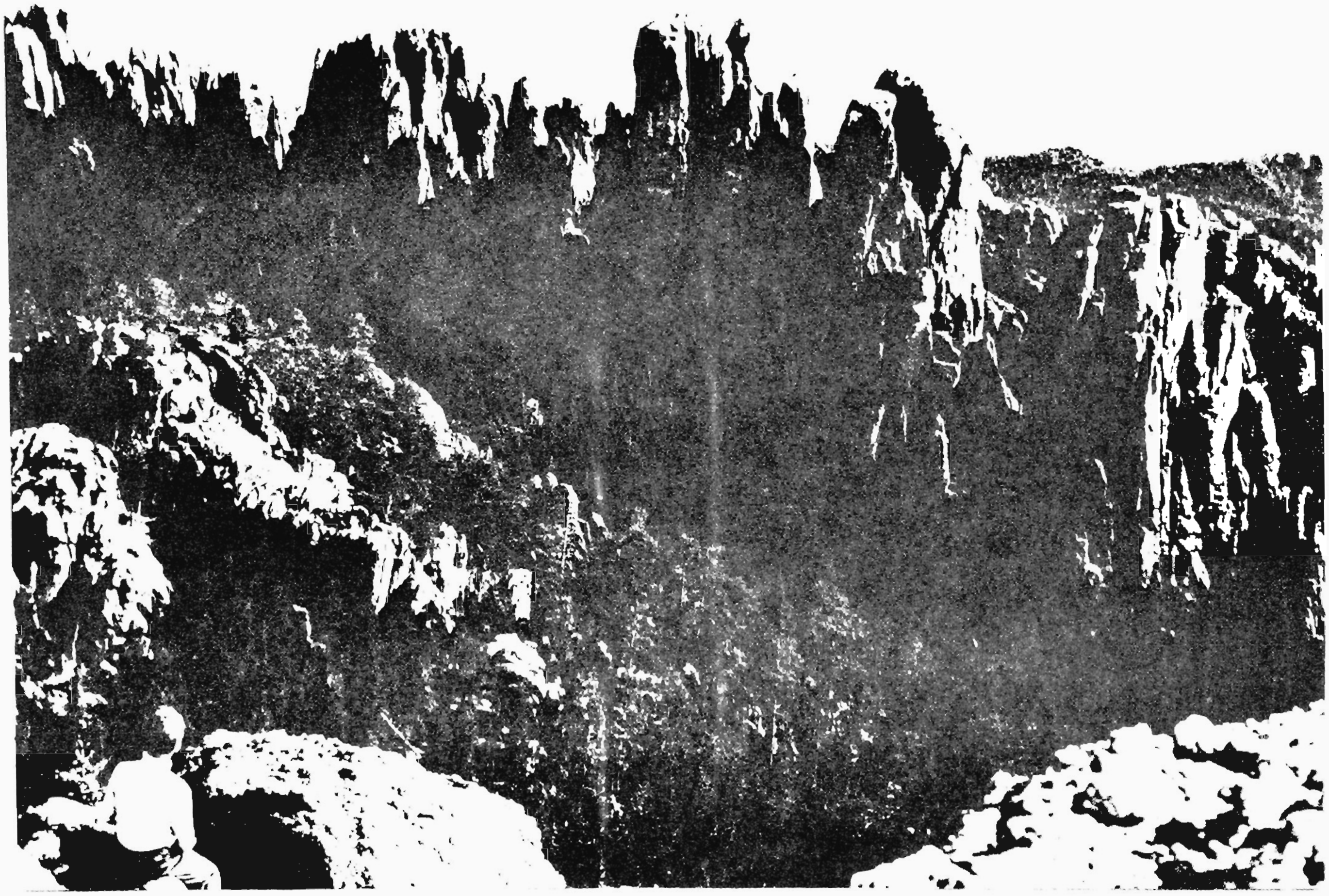


Figure 3. Outcrops of Precambrian rocks in the Black Hills. Granite areas such as "The Needles" are not very productive for ground water. Photo by P. H. Rahn.

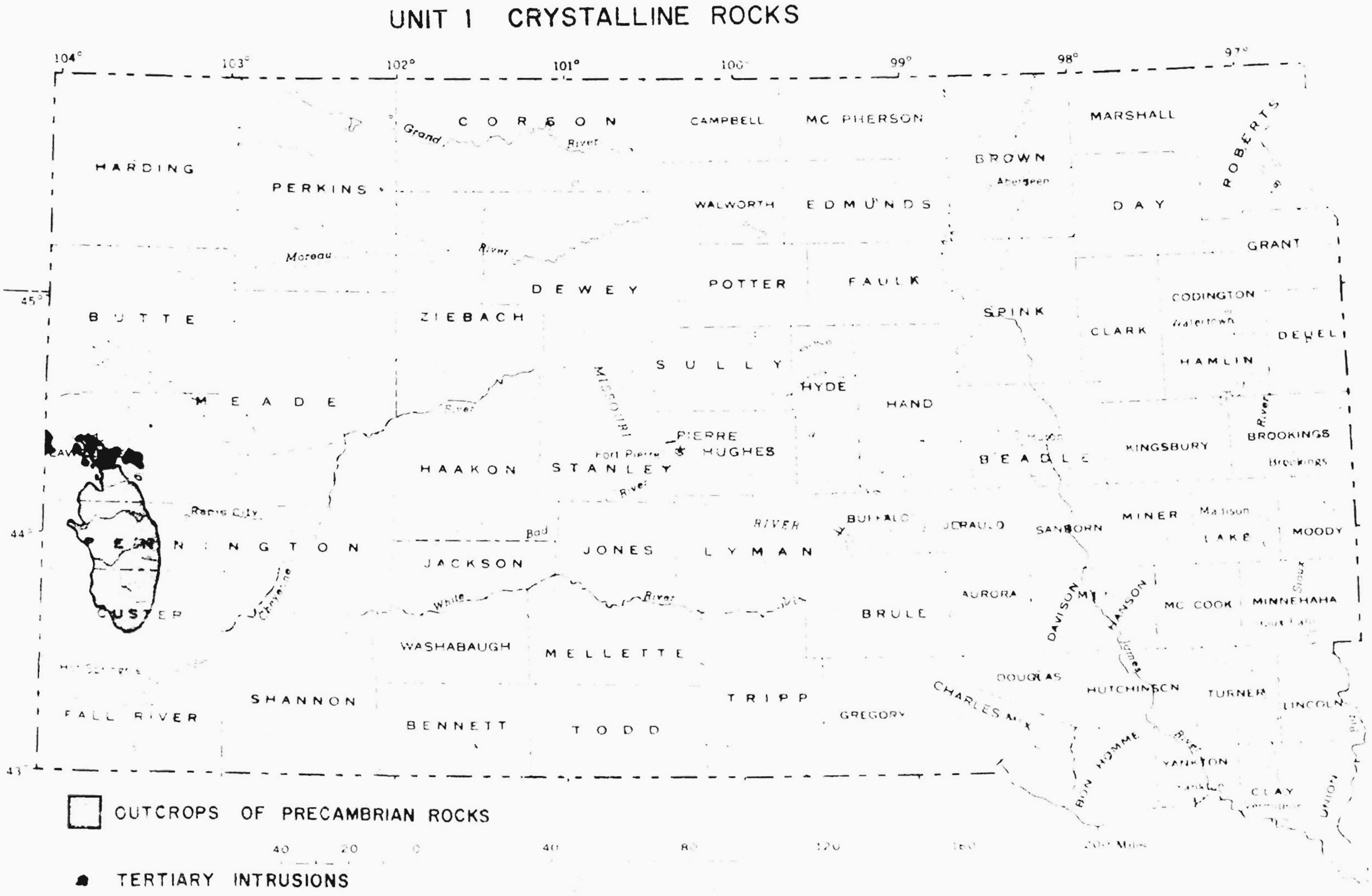
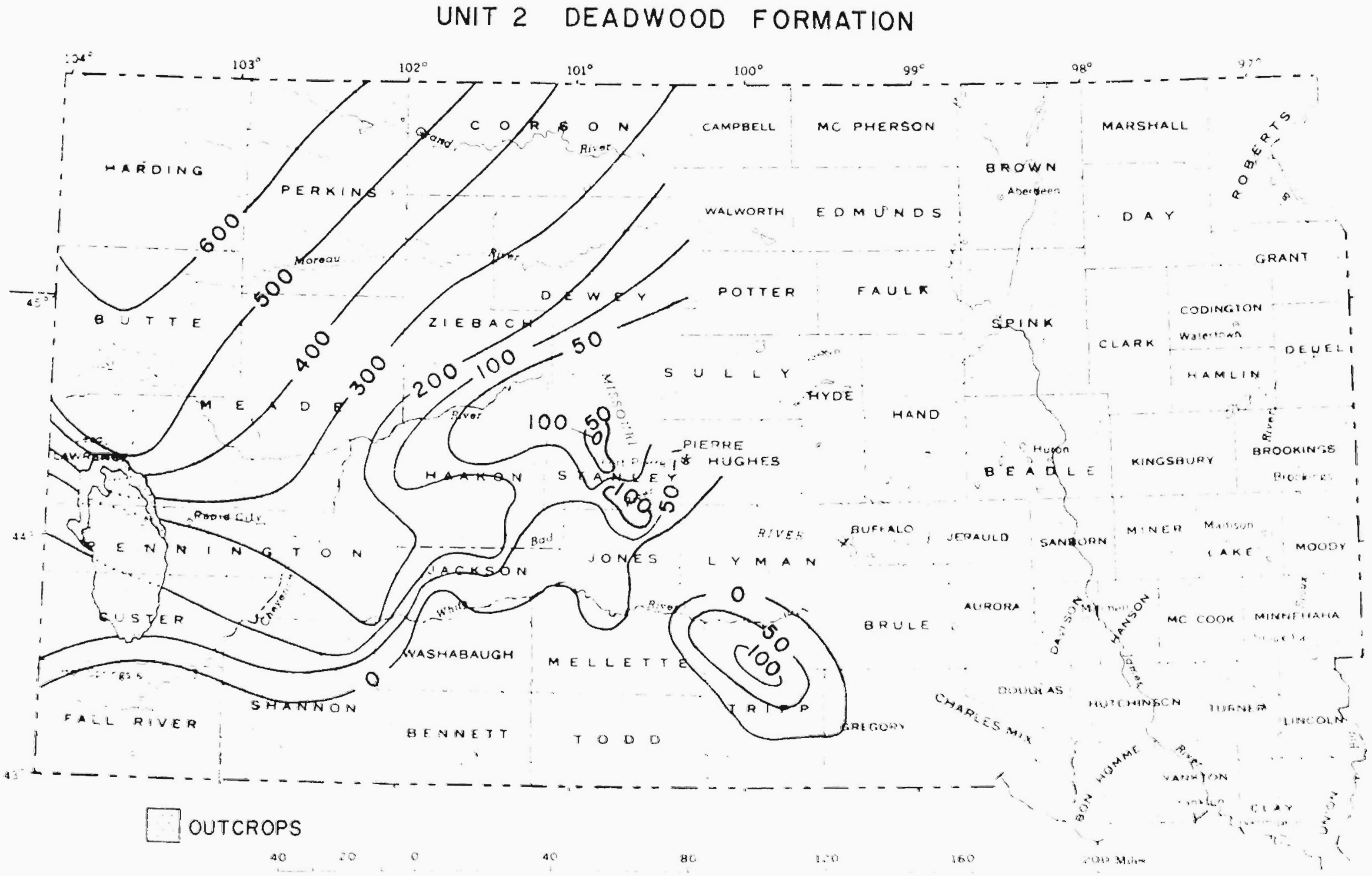


Figure 4. Unit #1 - Crystalline Rocks. Outcrop area of Precambrian igneous and metamorphic rocks and Tertiary intrusive rocks are shown. All ground water in these rocks are believed to have less than 500 ppm TDS.



UNIT 2 DEADWOOD FORMATION

Figure 5. Unit #2 - Deadwood Formation. Isopach map shows thickness (ft) of the Deadwood Formation (from Steece, 1978). No TDS contours are drawn due to inadequate data.

UNIT 3 ORDOVICIAN, SILURAN, & DEVONIAN SYSTEMS

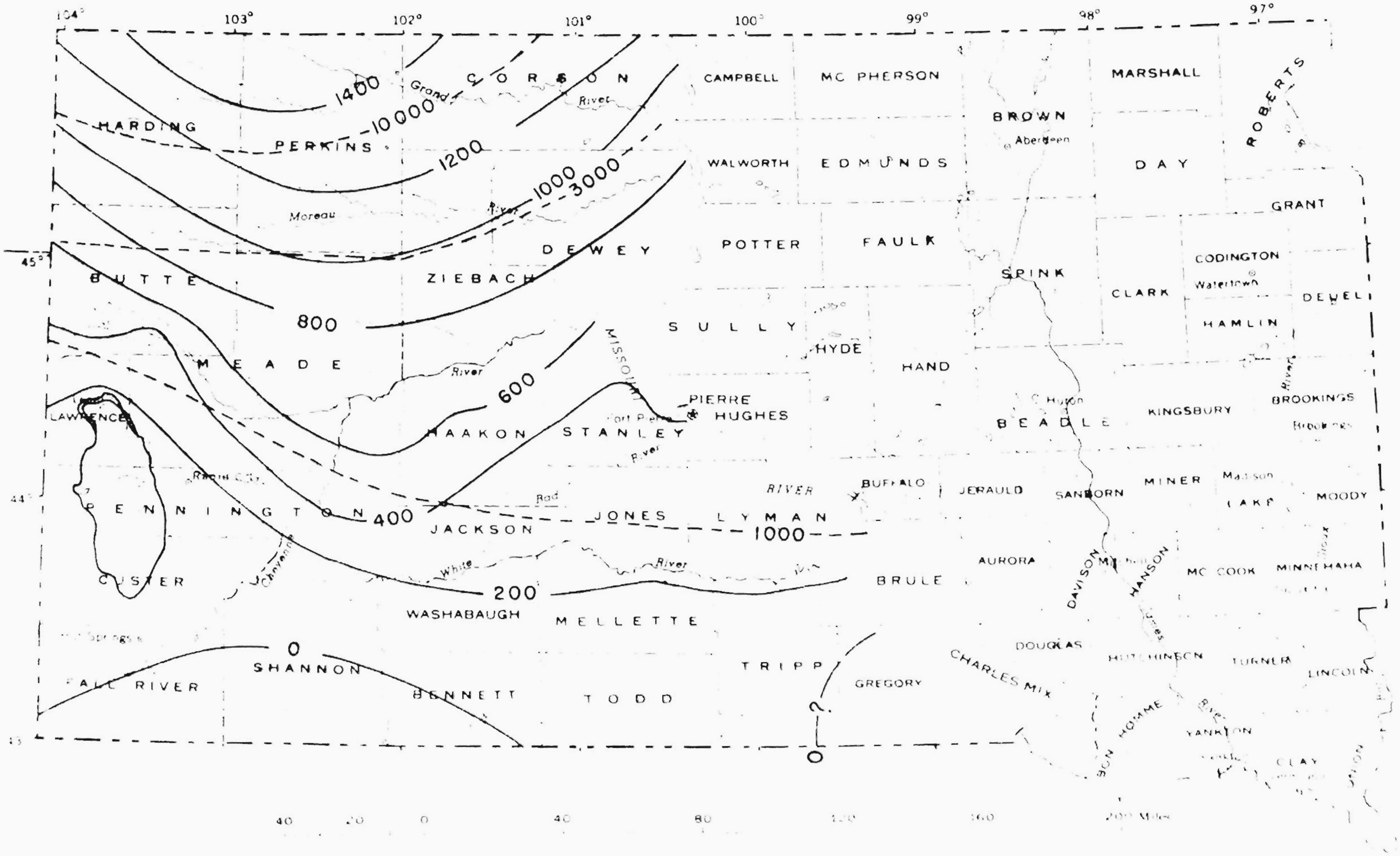


Figure 6. Unit #3 - Ordovician to Devonian Systems. Isopach map shows thickness (ft) of these strata. (Modified from Mallory, 1972). TDS (in ppm) contours (dashed lines) are very schematic.

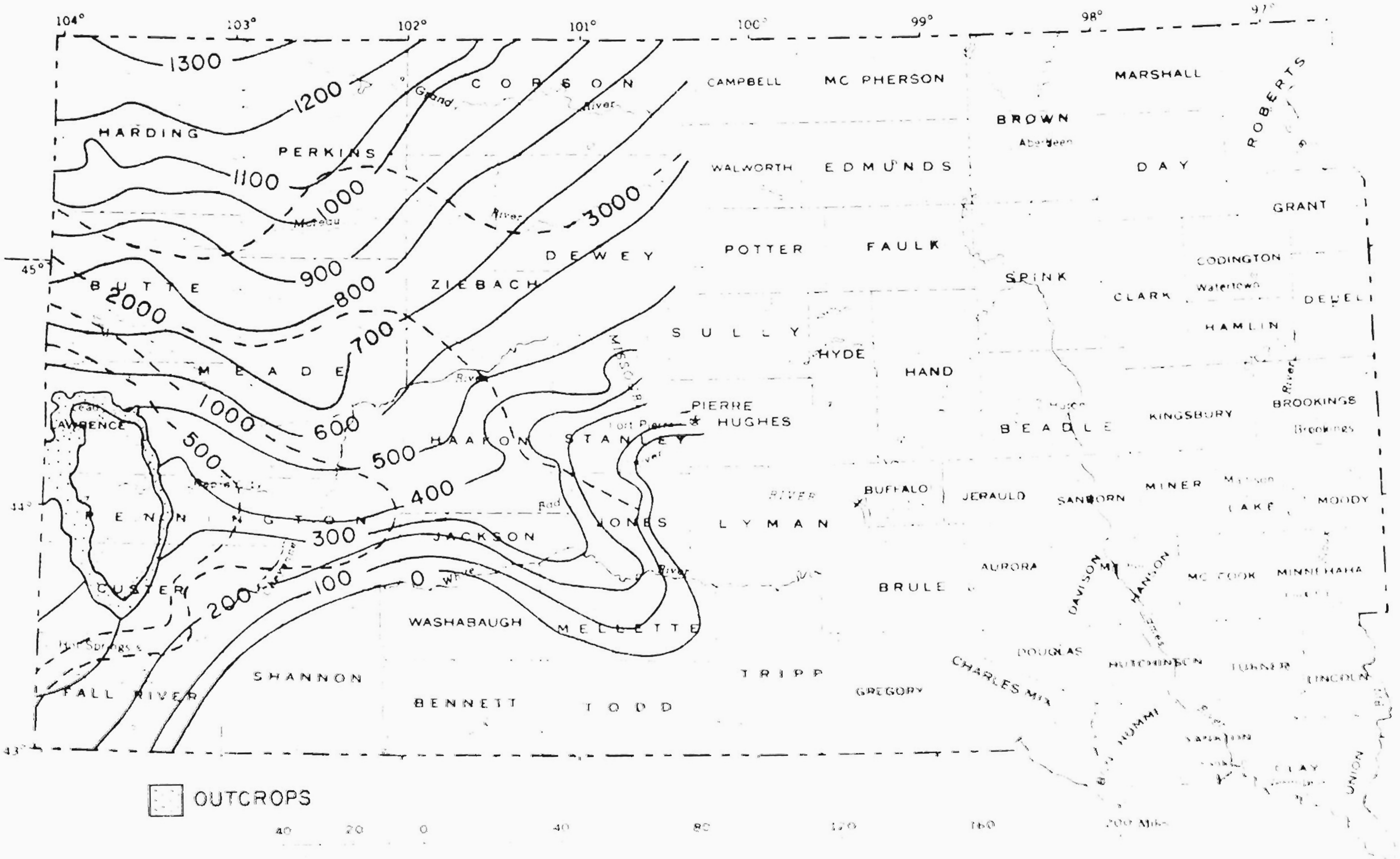

UNIT 4 MADISON (PAHASAPA) FORMATION

Figure 7. Unit #4 - Madison Limestone. Isopach map shows thickness (ft) of the Madison (Pahasapa) Limestone. TDS contours (in ppm) are dashed. (From Gries, 1977).

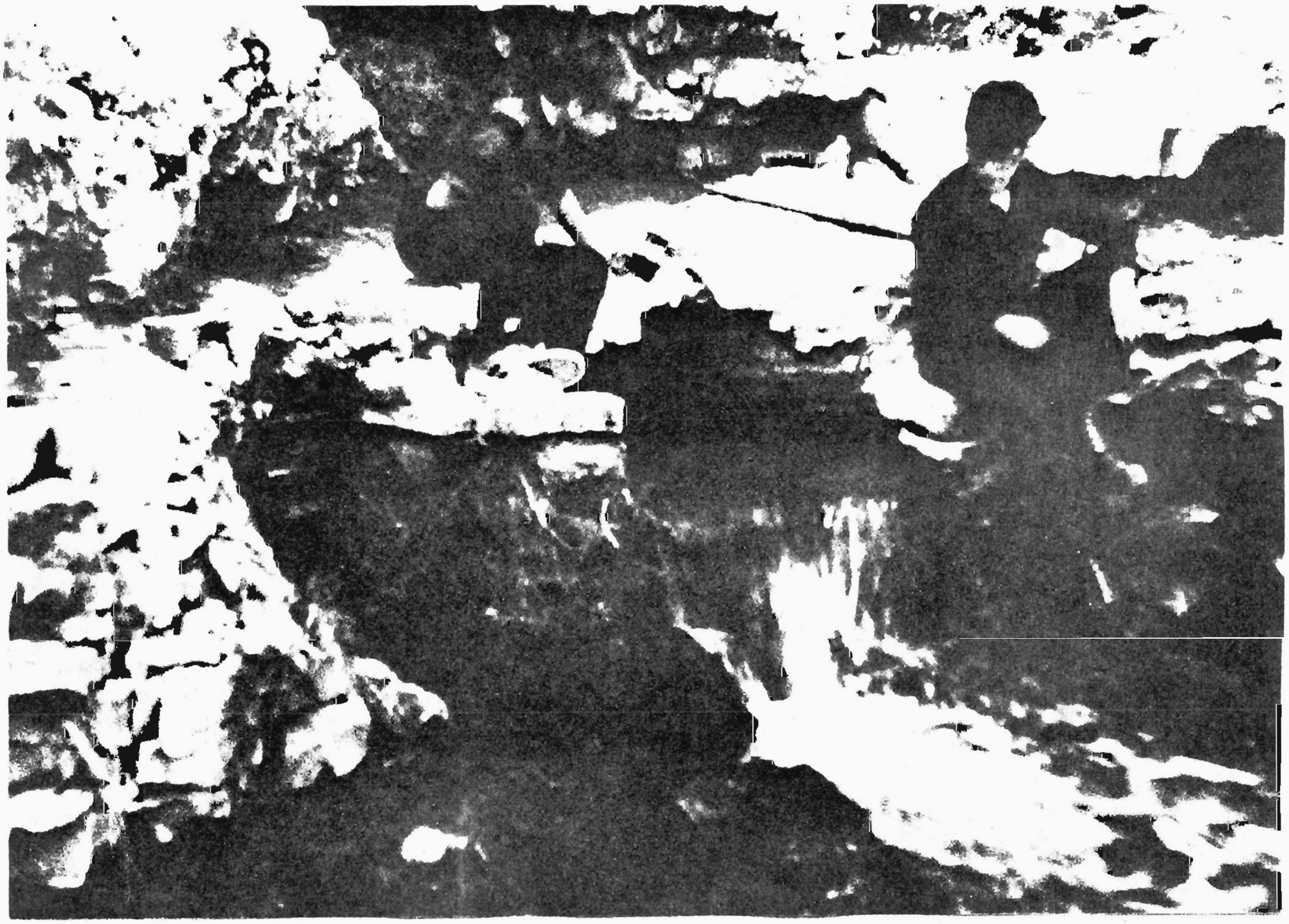


Figure 8. Springs in the Madison Limestone. Note ground water travels in solution cavities in this excellent aquifer. Photo by P. H. Rahn.

Figure 9. Flowing artesian well near Belle Fourche, S.D. The water discharges from the Madison Limestone. Photo by P. H. Rahn.

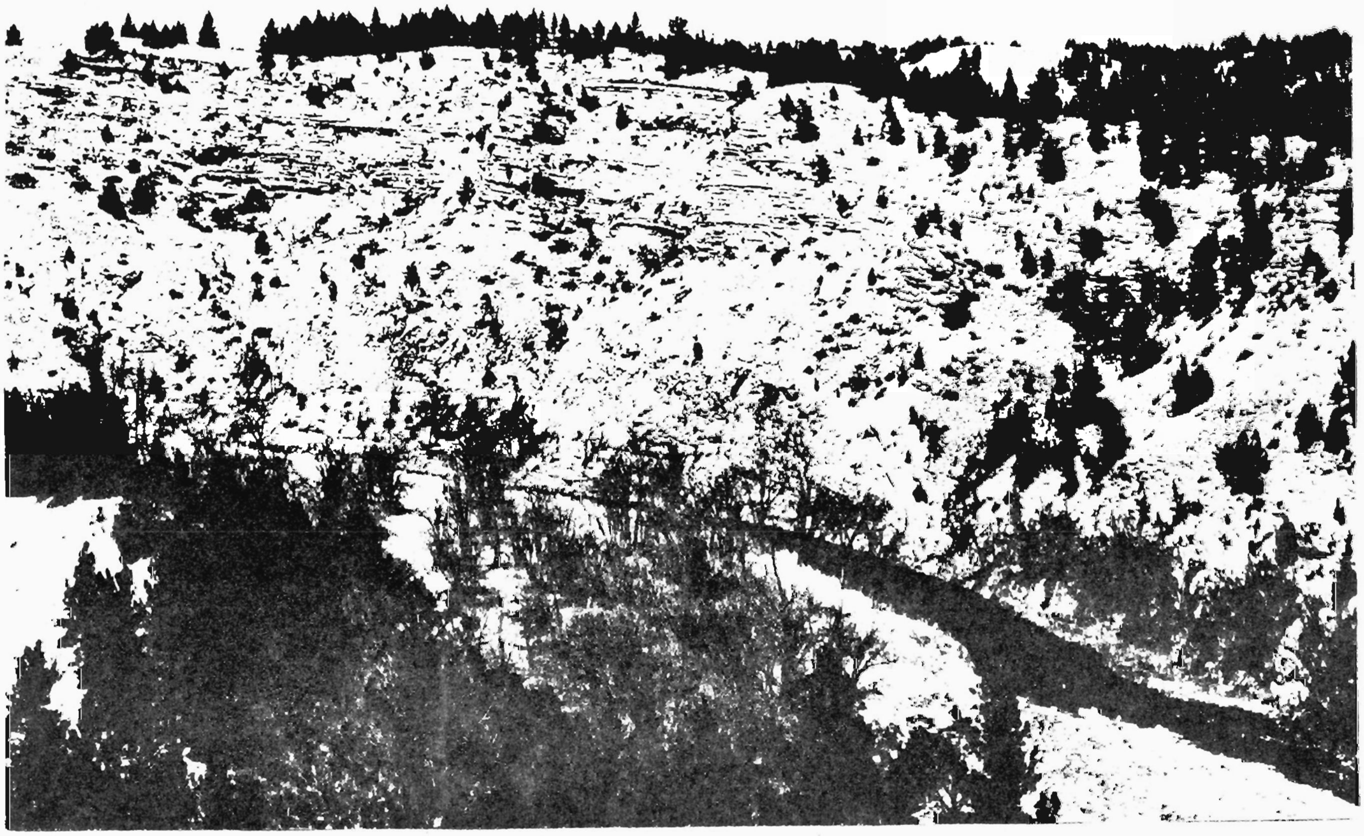


Figure 10. Minnelusa Formation exposed in Dark Canyon, 2 miles west of Rapid City, S.D. "Minnelusa" is the Sioux word for "rapid water." The Minnelusa Formation is the bedded unit overlying the massive Pahasapa (Madison) Limestone. Photo by P. H. Rahn.

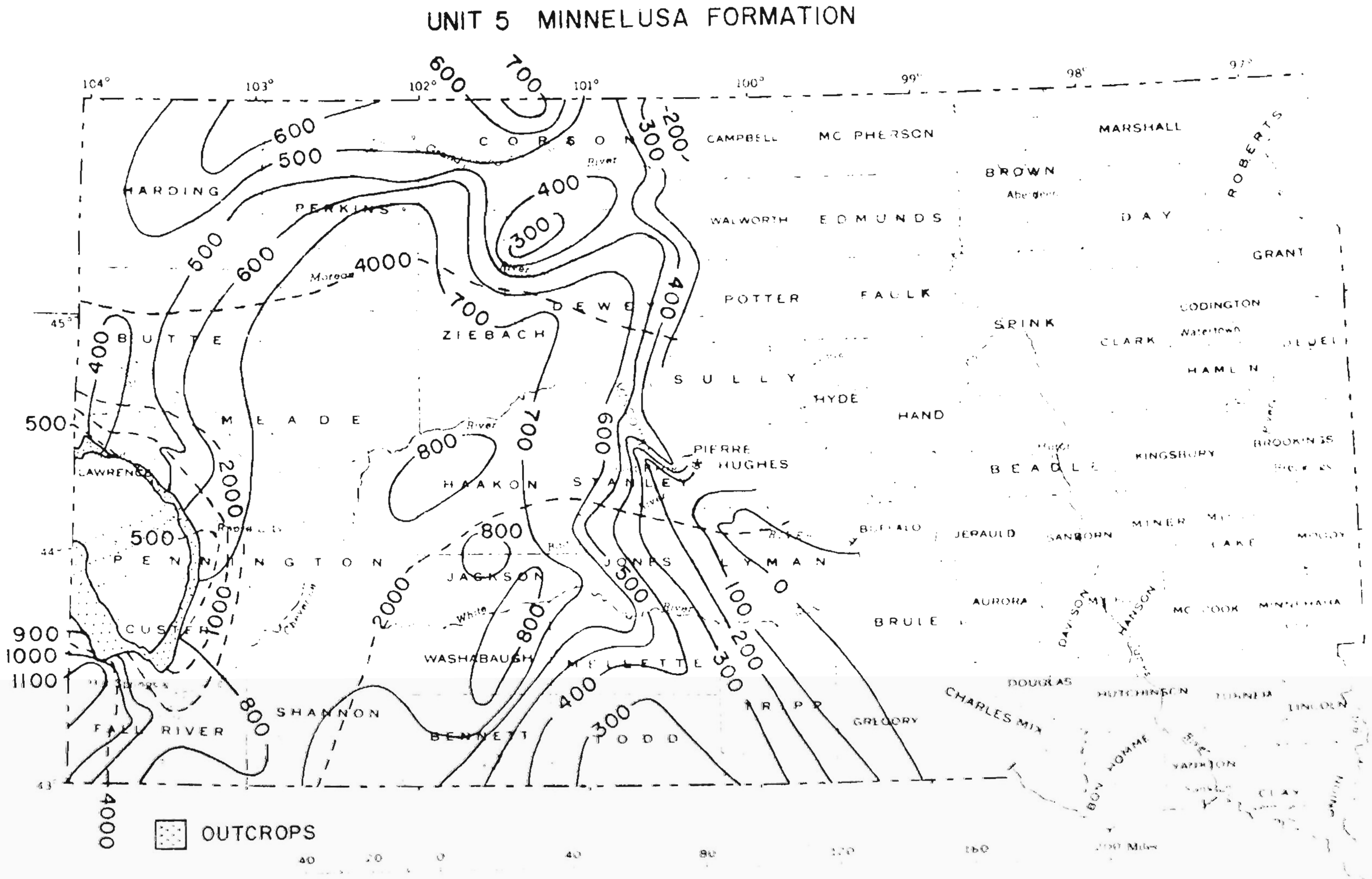


Figure 11. Unit #5 - Minnelusa Formation. Isopach map shows thickness (ft) of the Minnelusa Formation and equivalent. TDS contours (in ppm) are dashed.

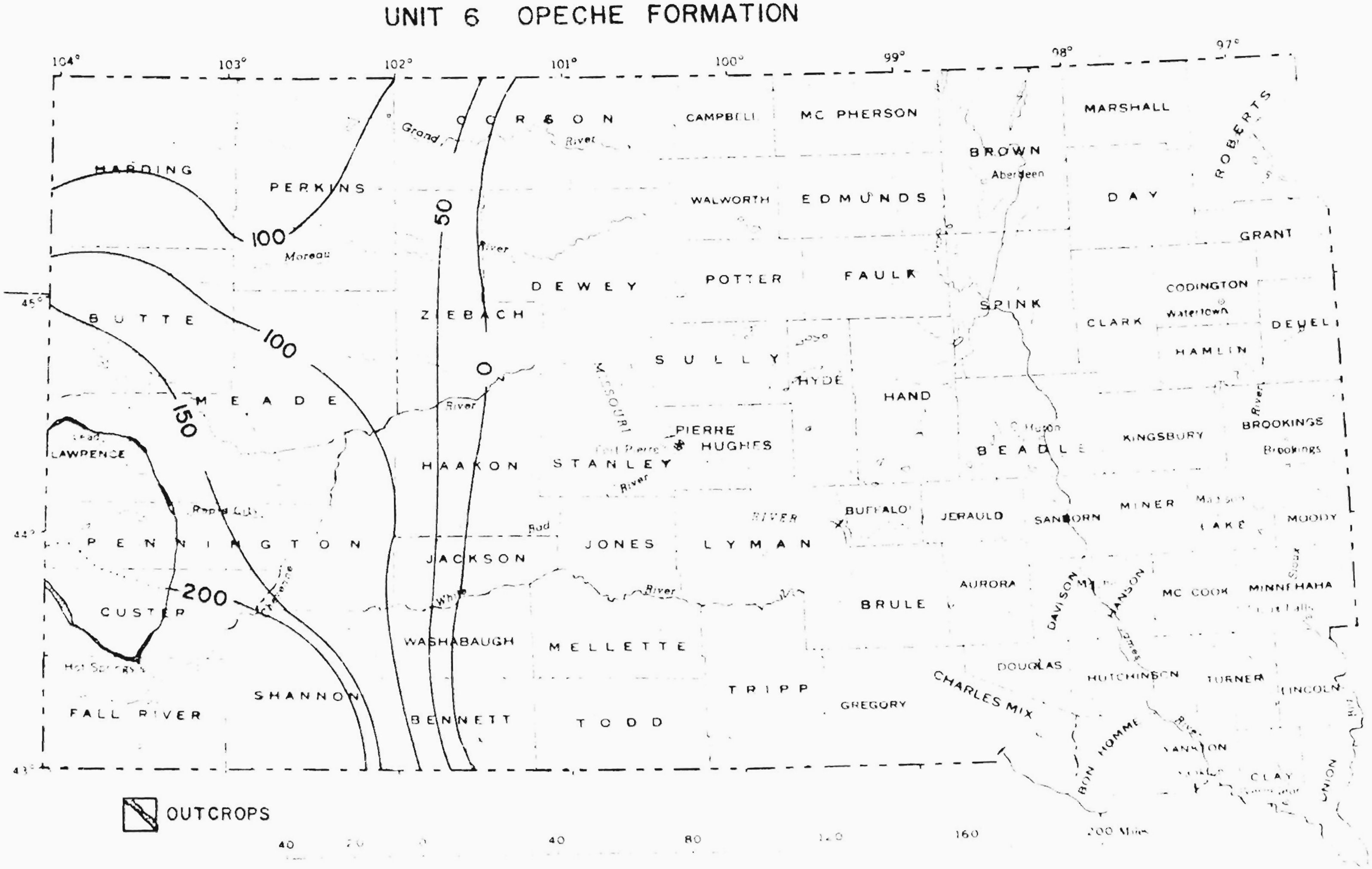


Figure 12. Unit #6 - Opeche Formation. Isopach map shows thickness (ft) of the Opeche Formation.

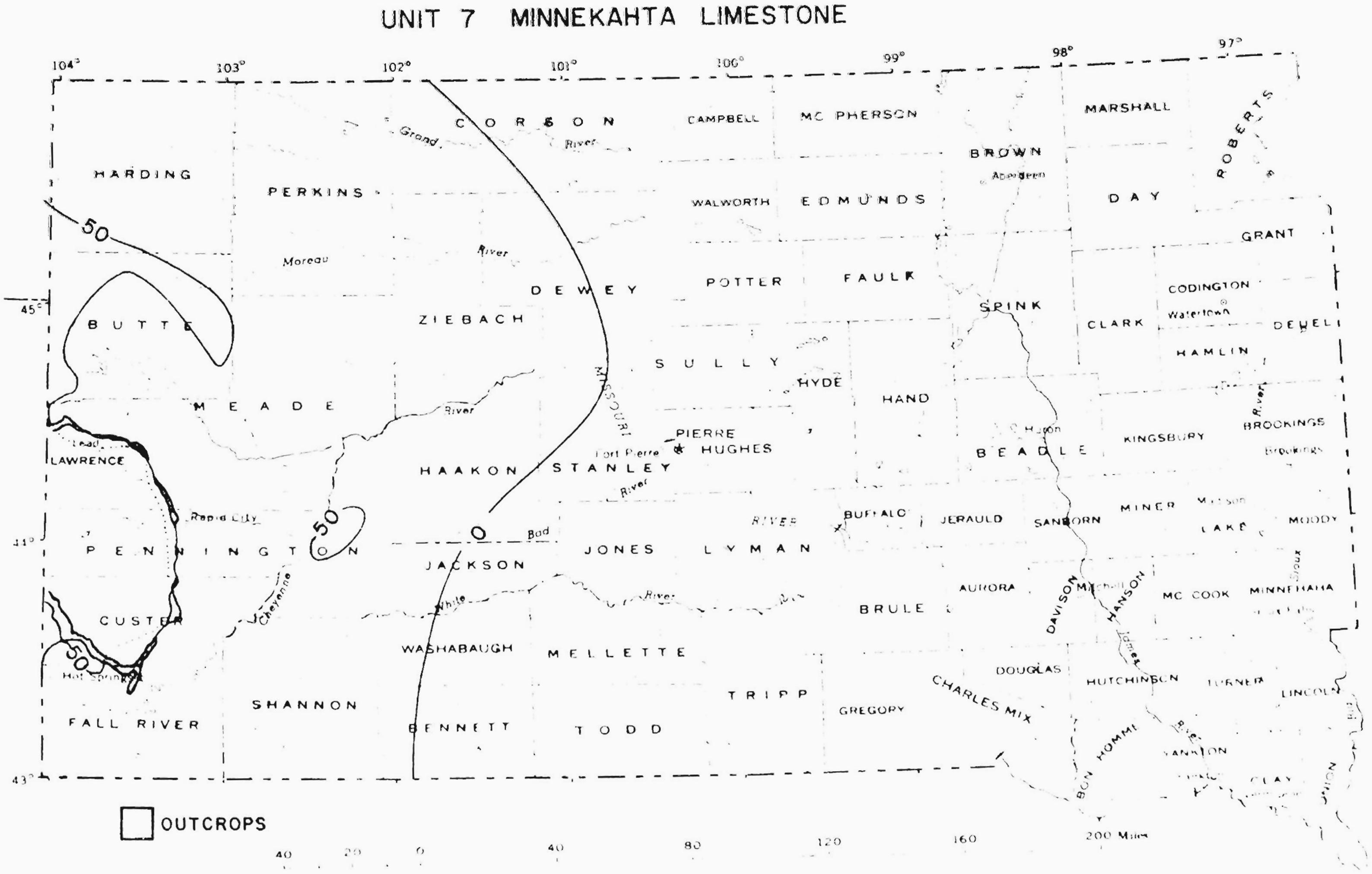
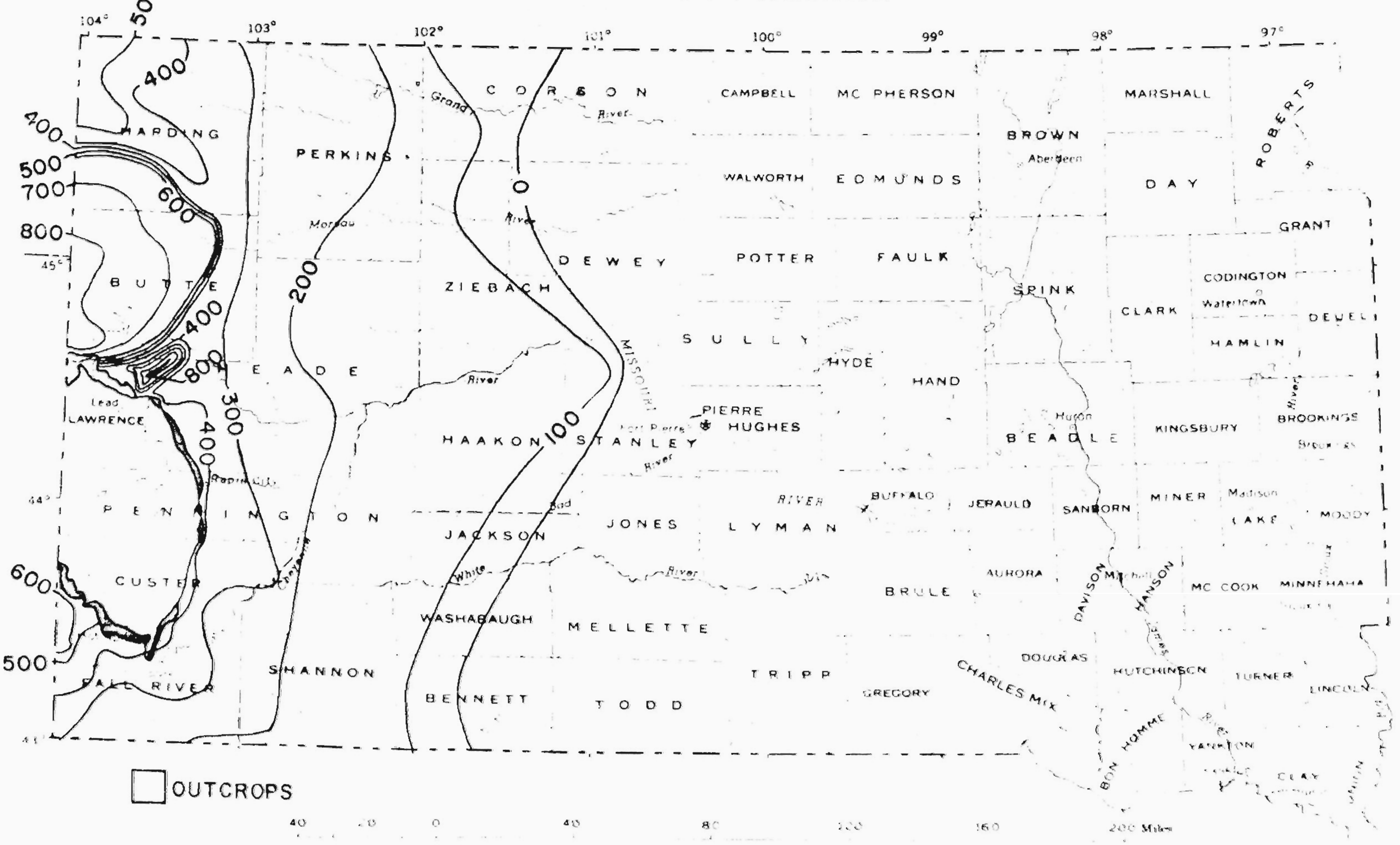


Figure 13. Unit #7 - Minnekahta Formation. Isopach map shows thickness (ft) of the Minnekahta Formation.



UNIT 8 SPEARFISH FORMATION

Figure 14. Unit #8 - Spearfish Formation. Isopach map shows thickness (ft) of the Spearfish Formation.

Figure 15. Spearfish Formation is eroded to make the "Red Valley" or "racetrack" around the Black Hills. This oblique aerial view was taken looking north from 3 miles north of Rapid City. The Paleozoic carbonate rocks (left) and the Cretaceous Sandstone hogback (right) separate the red valley. Photo by P. H. Rahn.

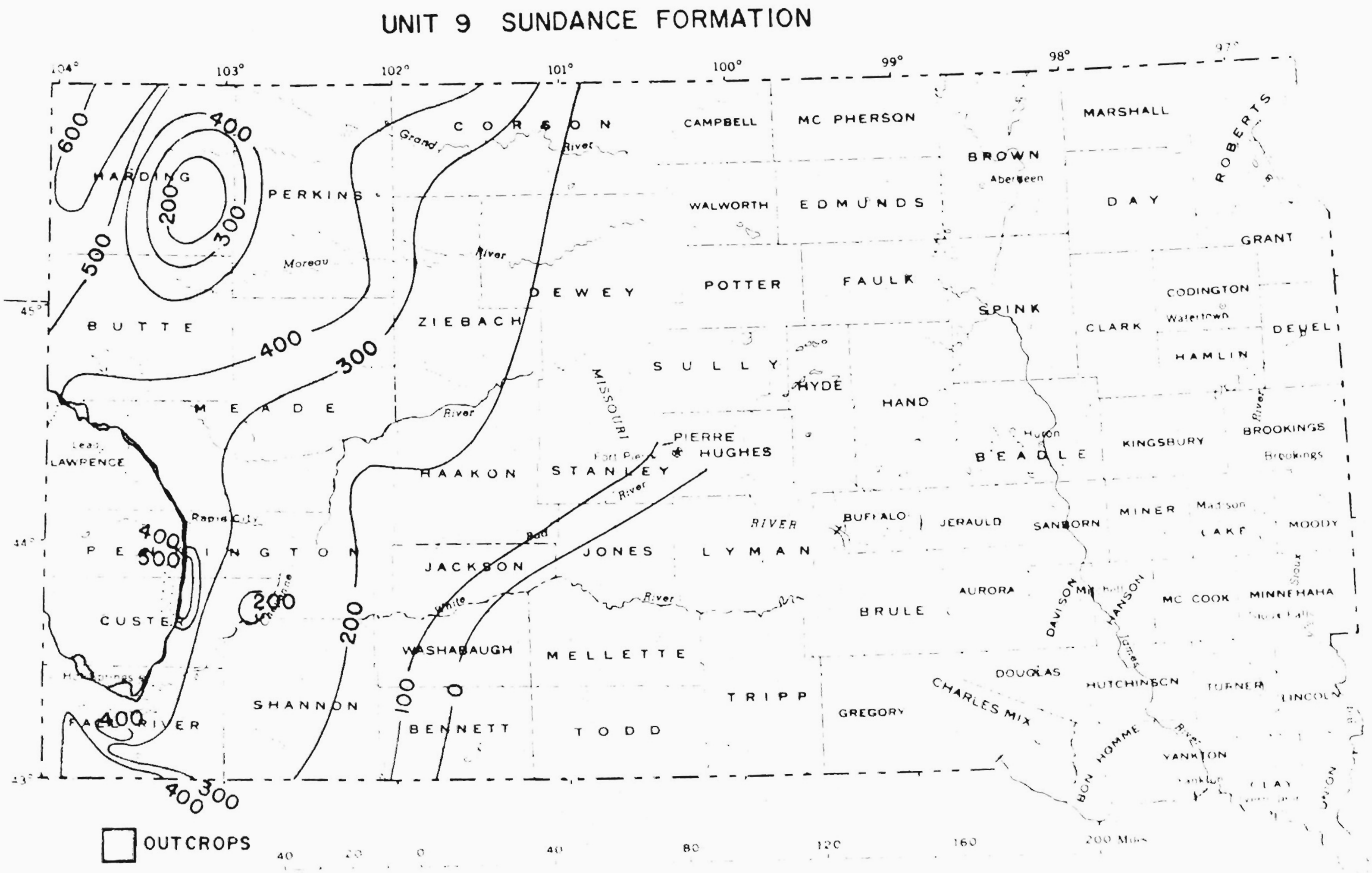
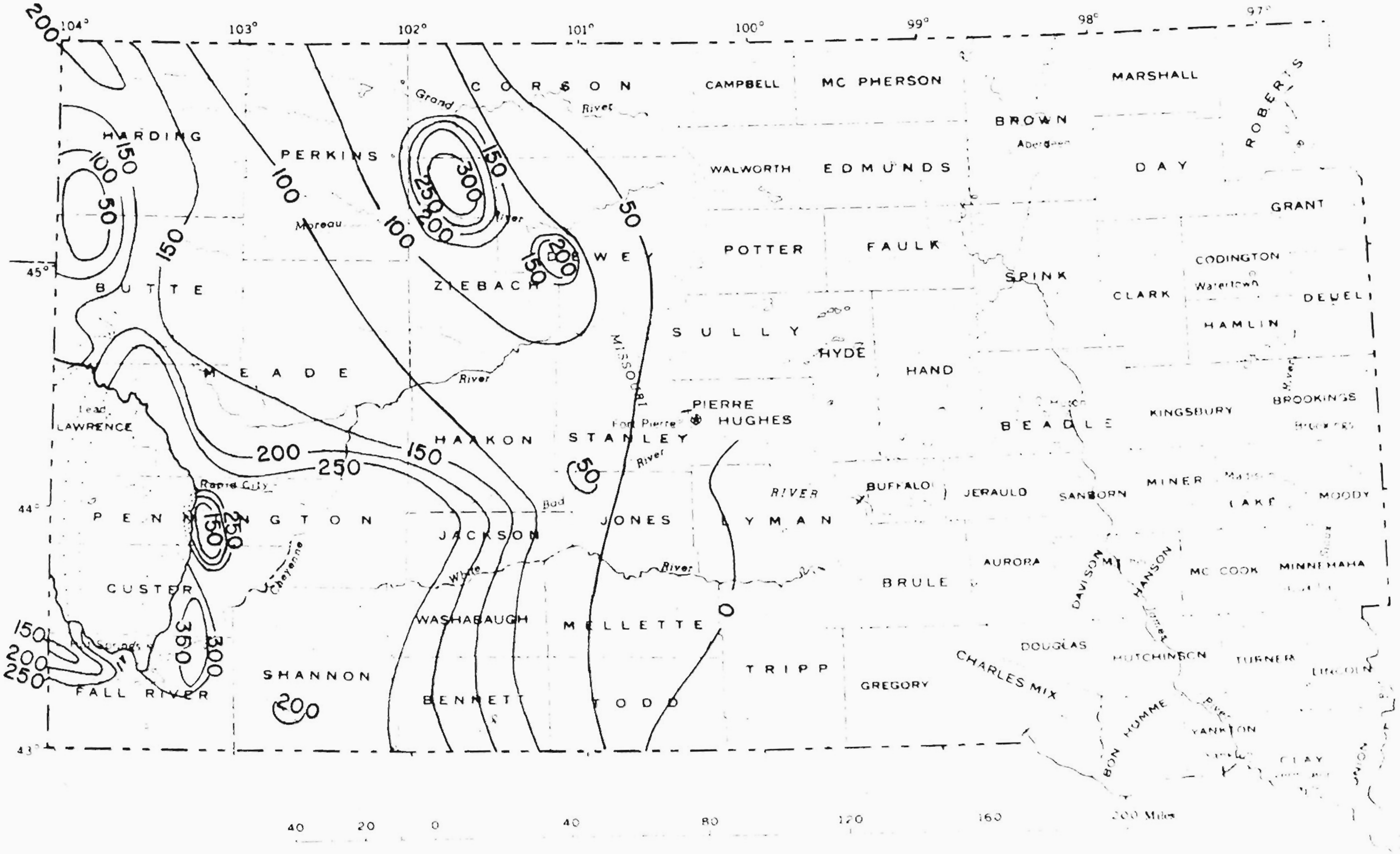


Figure 16. Unit #9 - Sundance Formation. Isopach map shows thickness (ft) of the Sundance and Gypsum Springs Formation.

Figure 17. Unkpapa Sandstone exposed on "M Hill" in Rapid City, S.D. The pure white sand is mixed as an additive for the manufacture of cement. The top of the hogback forming M Hill is the Lakota Formation. These rocks dip [redacted] at about 20° easterly under the prairie.



UNIT 10 MORRISON & UNKPAPA

Figure 18. Unit #10 - Morrison and Unkpapa Formations. Isopach map shows thickness (ft) of the Morrison Formation (including Unkpapa Sandstone).

UNIT 11 INYAN KARA GROUP

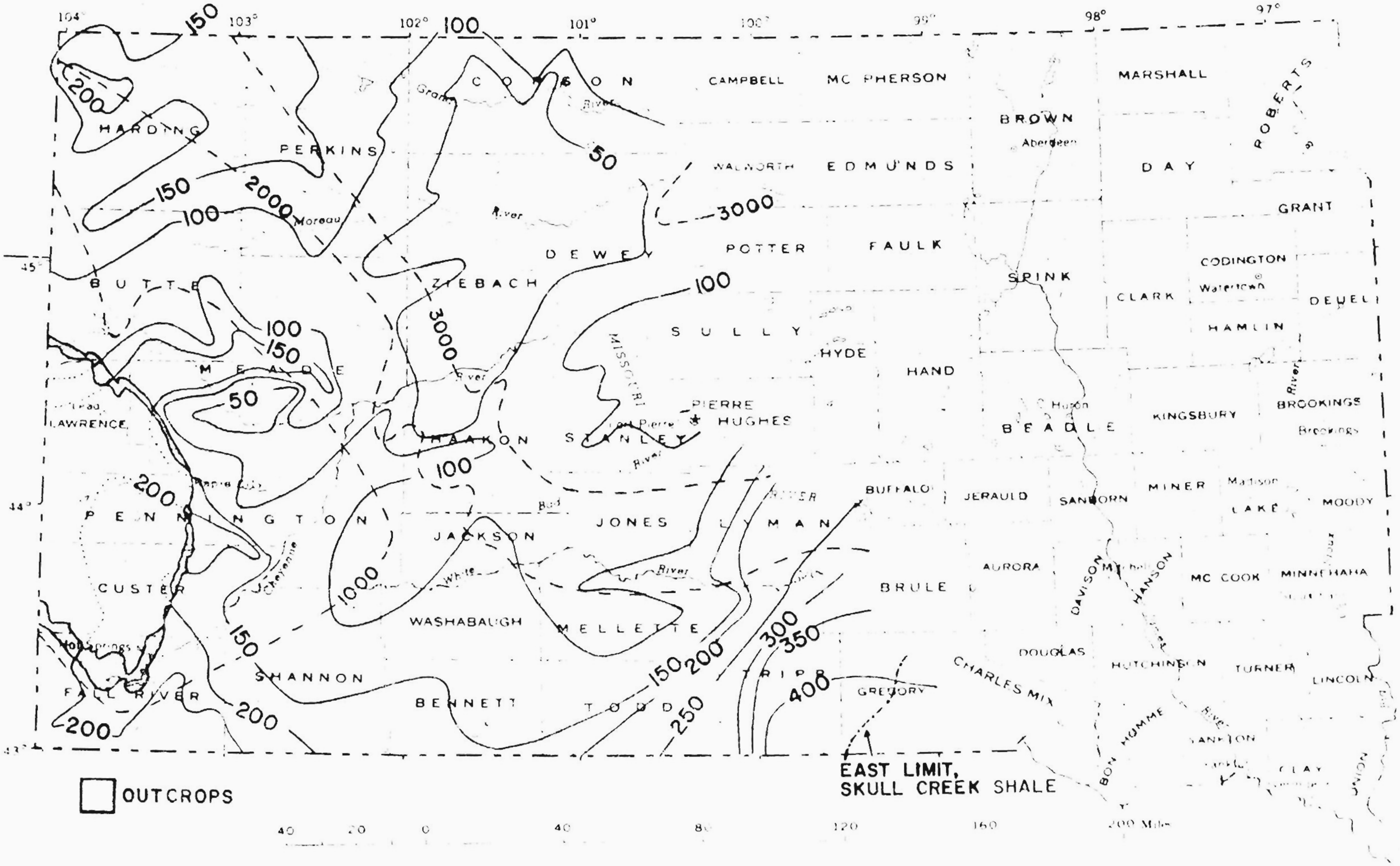


Figure 19. Unit #11 - Inyan Kara Group. Isopach map shows the thickness (ft) of the Lakota Formation, Fall River Sandstone, and Skull Creek Shale. TDS contours (dashed lines) are approximately located.

UNIT 12 NEWCASTLE - DAKOTA SANDSTONE

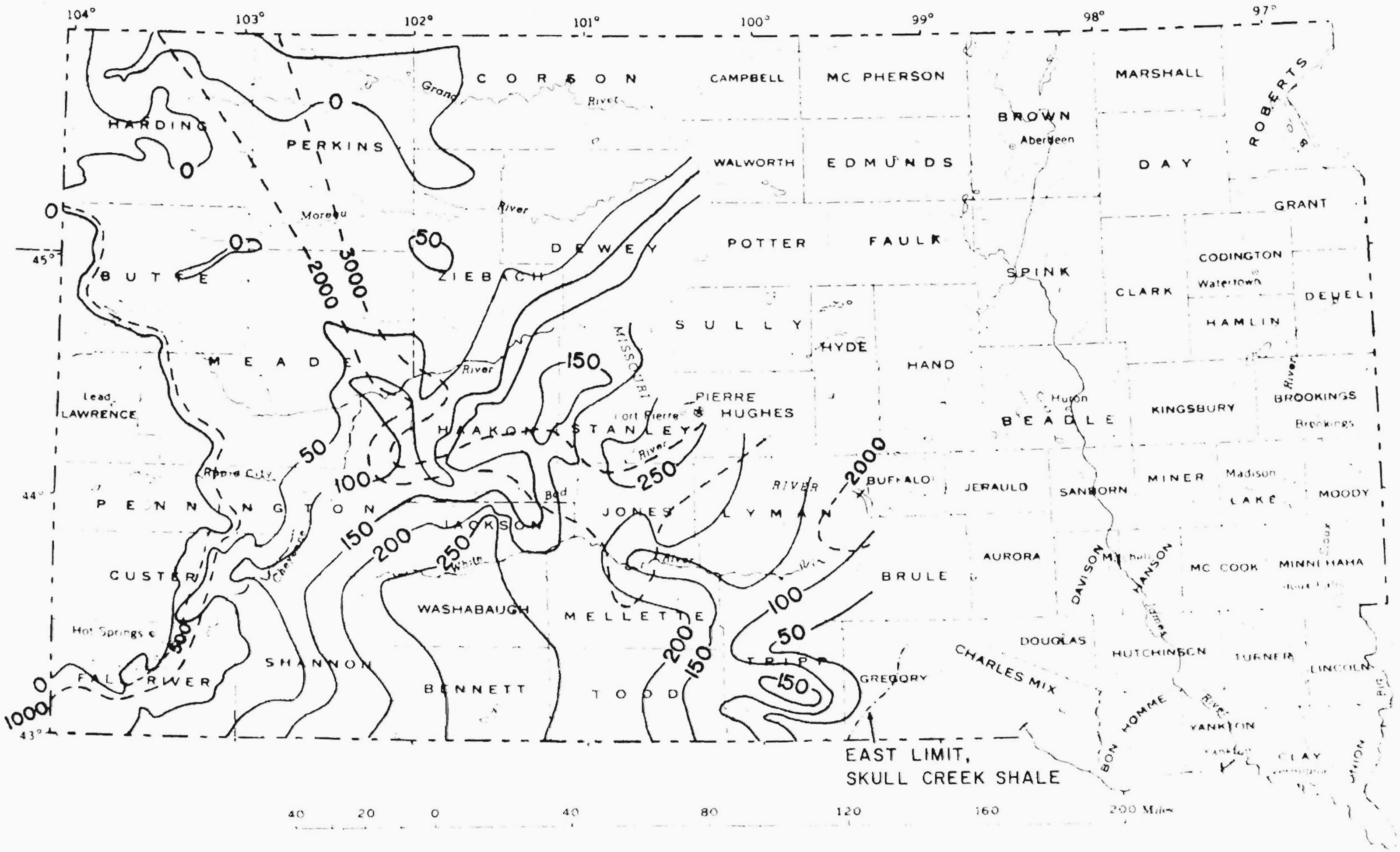


Figure 20. Unit #12 - Newcastle Sandstone. Isopach map shows the thickness (ft) of this formation. TDS contours (dashed lines) are approximately located.

UNIT 13 PIERRE SHALE THRU MOWRY SHALE

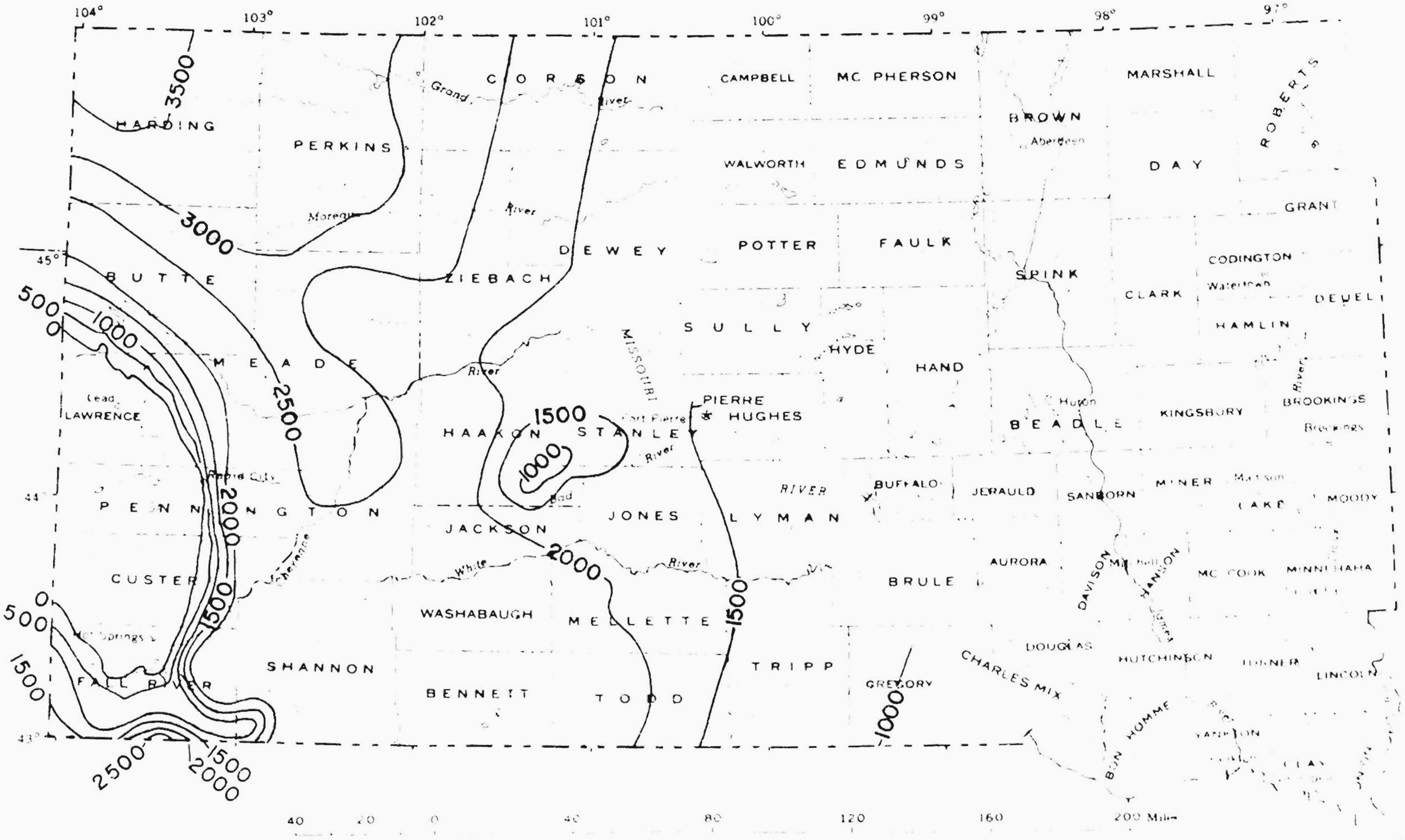


Figure 21. Unit #13 - Cretaceous shales. Isopach map shows the aggregate thickness of lower to upper Cretaceous marine shales and limestone between the Fox Hills Formation and the Newcastle Sandstone.

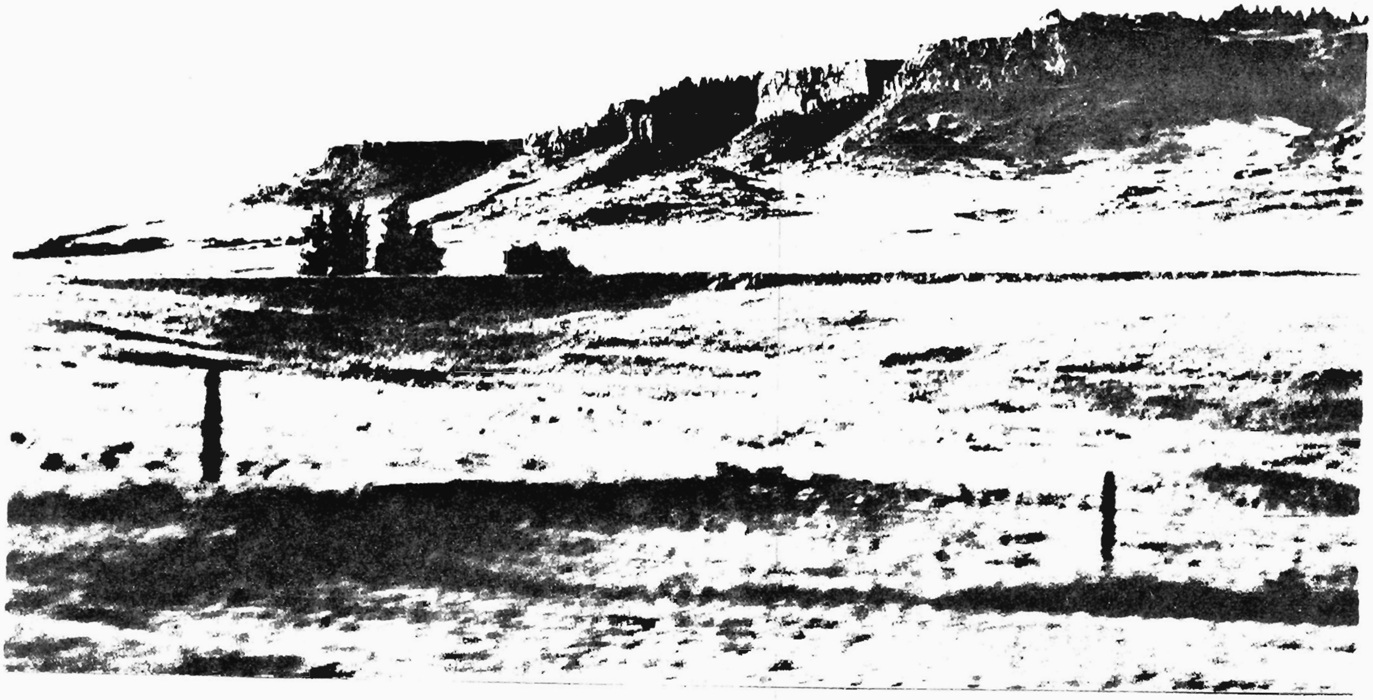


Figure 23. Outcrop of the Fort Union Formation (Tongue River sandstone member above Ludlow shale member) overlying the Hell Creek Formation in the valley. Cave Hills area, S.D. Photo by P. H. Rahn.


UNIT 15 HELL CREEK & FORT UNION FORMATIONS

Figure 24. Unit #15 - Early Tertiary System. Isopach map shows the thickness (ft) of the Hell Creek (Cretaceous (?) to Paleocene) and Fort Union Formations (Paleocene).

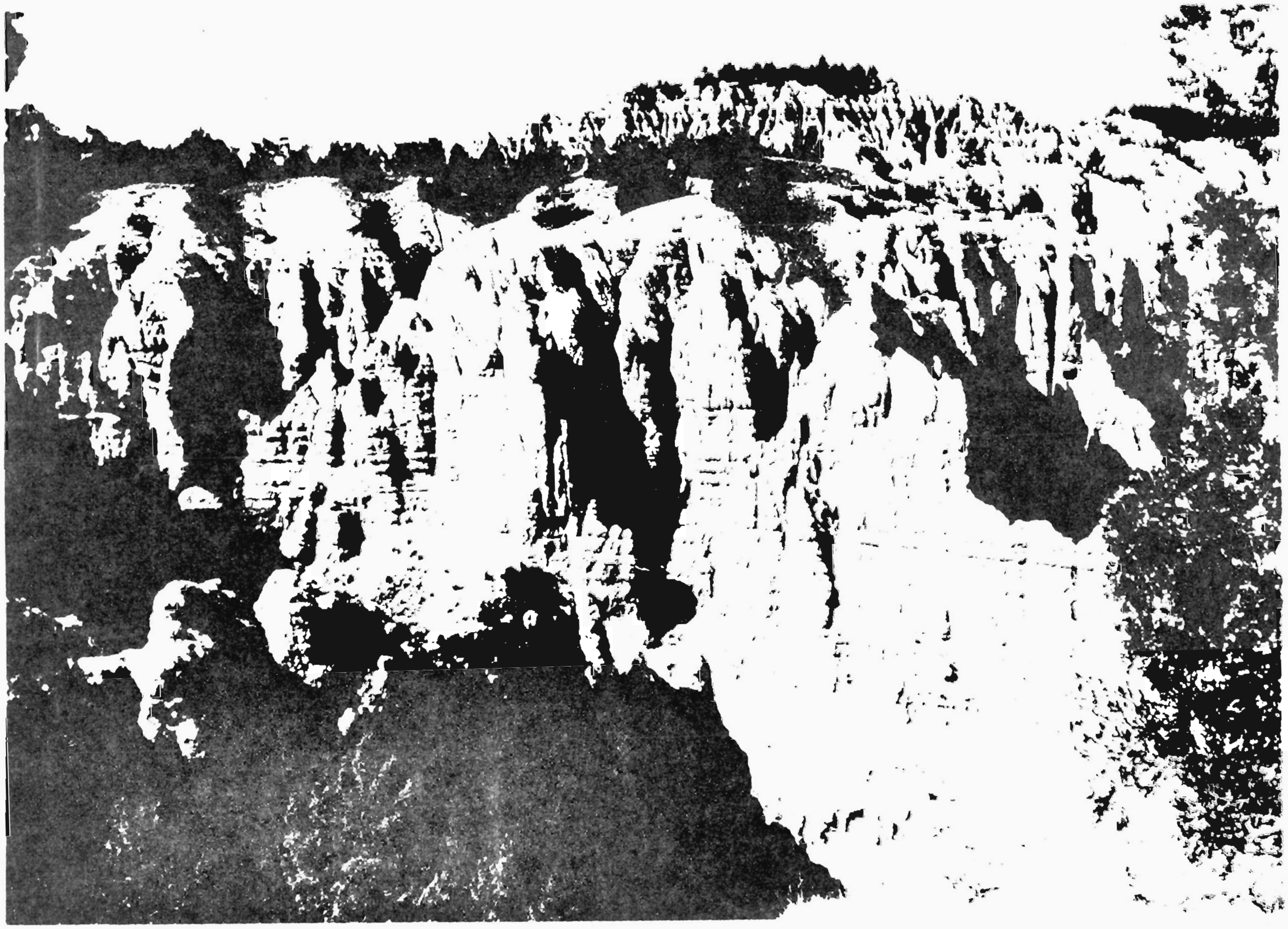


Figure 25. White River Group exposed at Sheep Mountain Table. Photo by P. H. Rahn.

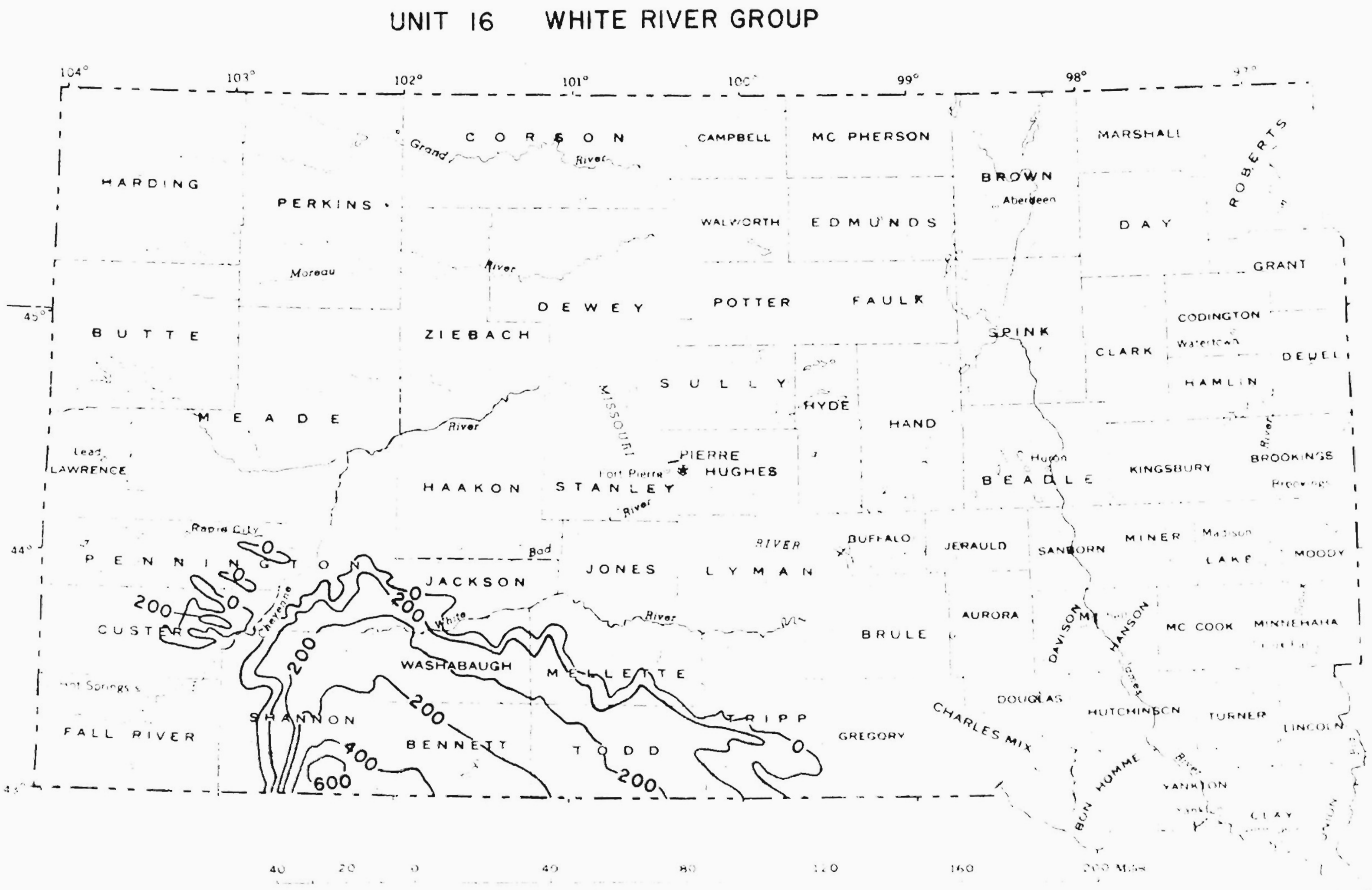


Figure 26. Unit #16 - White River Group. Isopach map shows the thickness (ft) of the Oligocene White River Group.

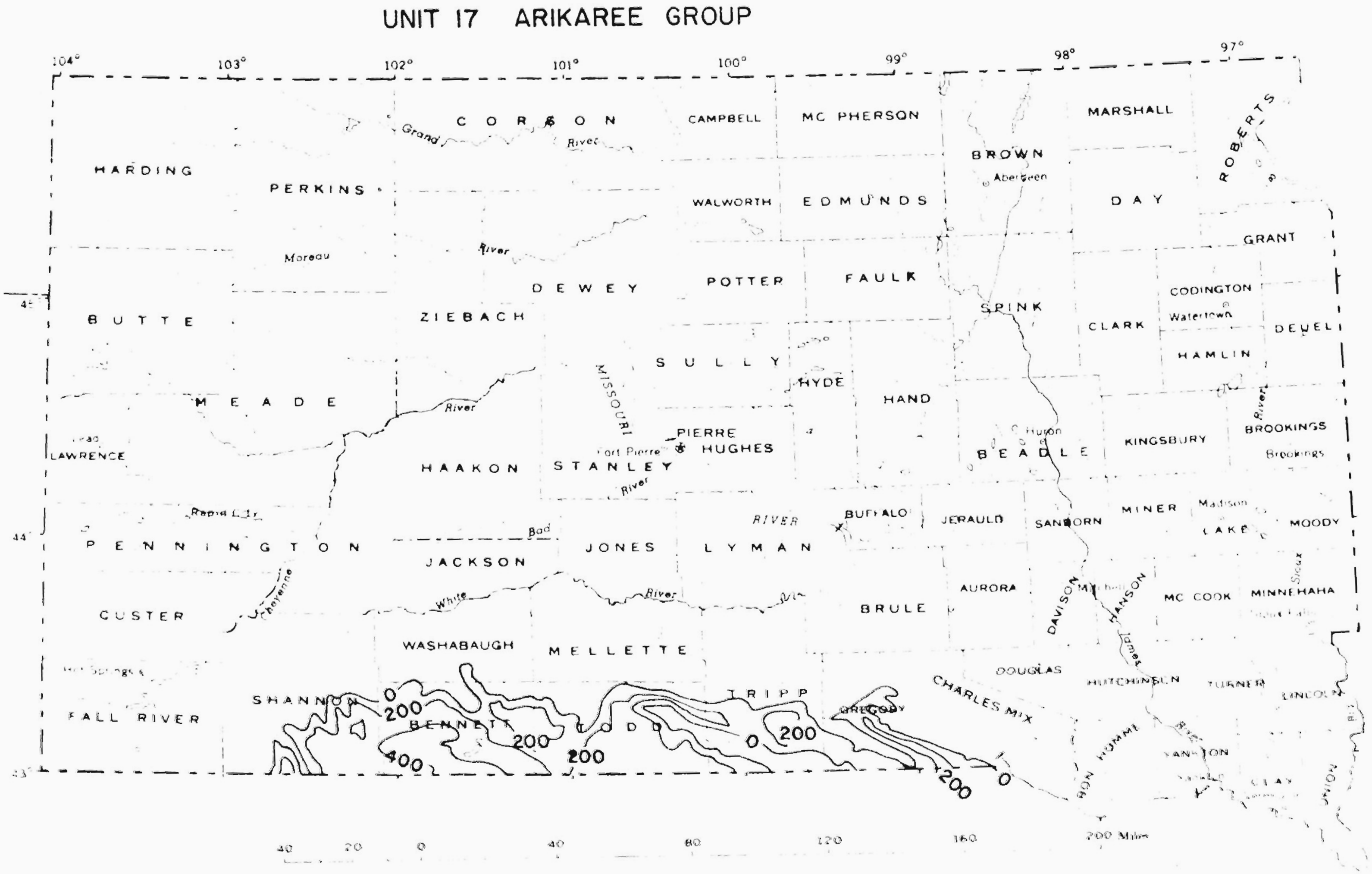


Figure 27. Unit #17 - Arikaree Group. Isopach map shows the thickness (ft) of the Miocene Arikaree Group and equivalents.

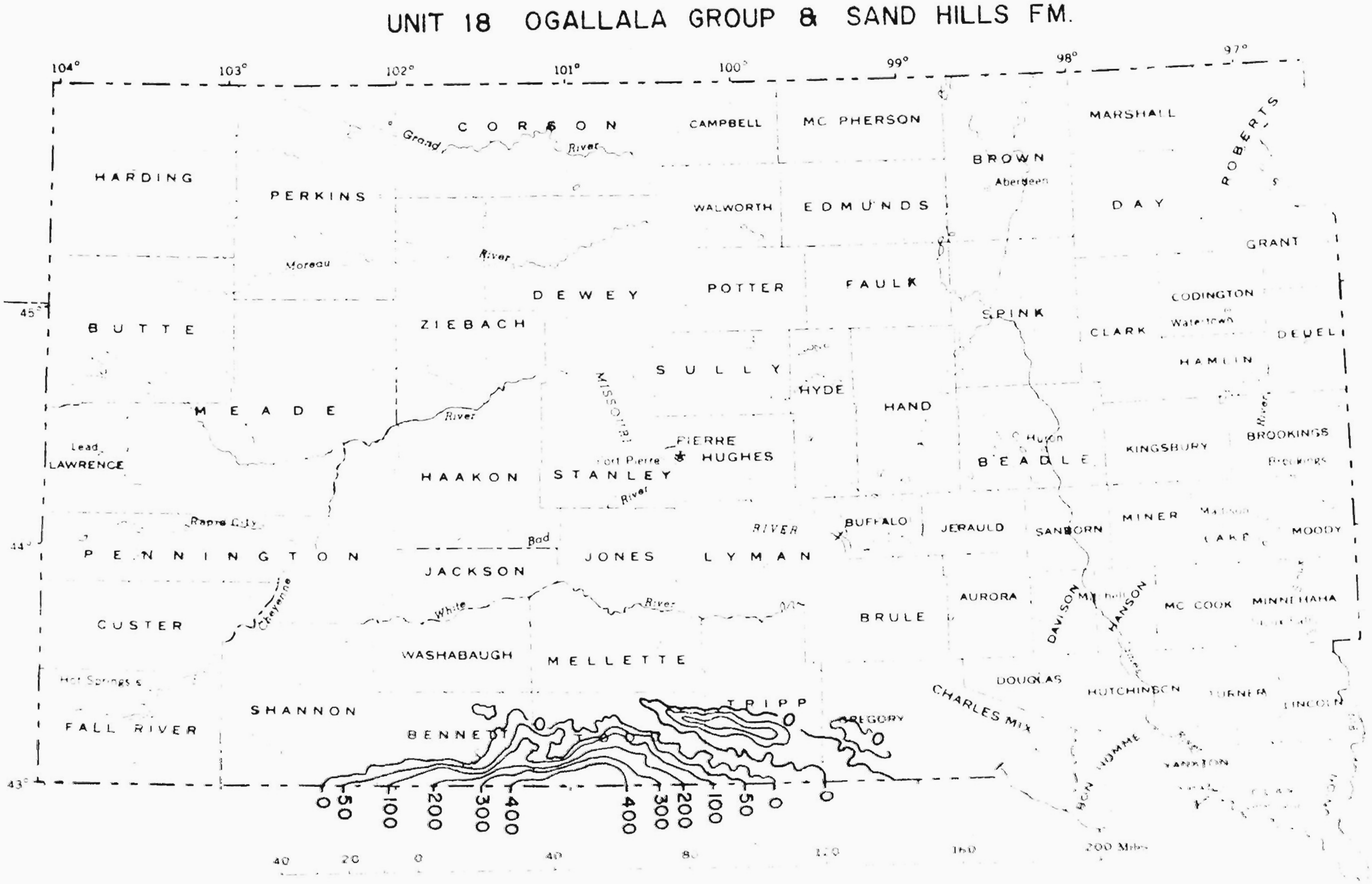

UNIT 18 OGALLALA GROUP & SAND HILLS FM.

Figure 28. Unit #18 - Ogallala and Sand Hills Formations. Isopach map shows the thickness (ft) of the Pliocene Ogallala Formation and the Pleistocene Sand Hills Formation. Compiled from numerous sources (see text).

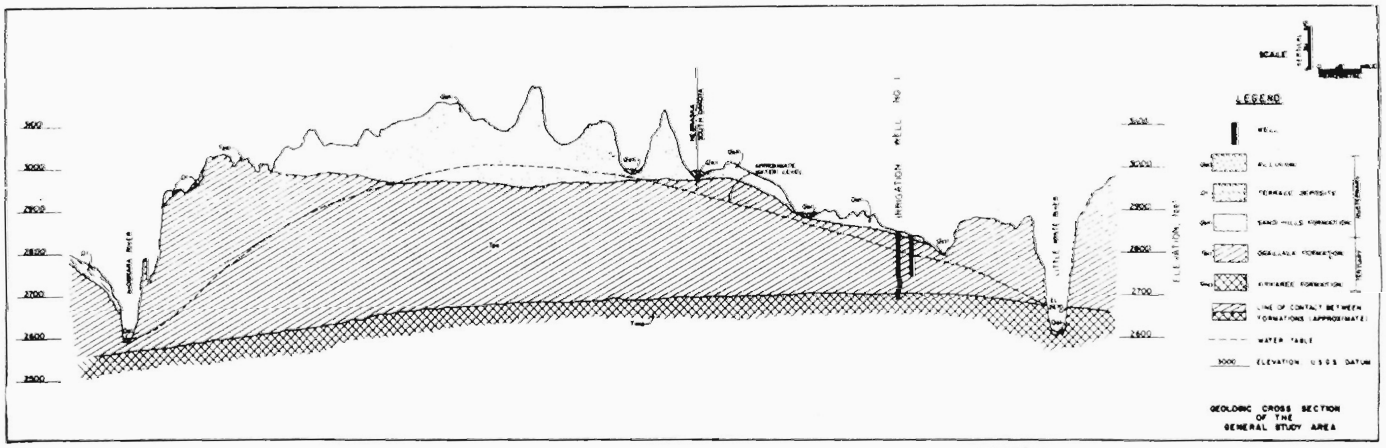


Figure 29. Cross section of Unit #18 (from Rahn and Paul, 1975).

UNIT 19 ALLUVIUM

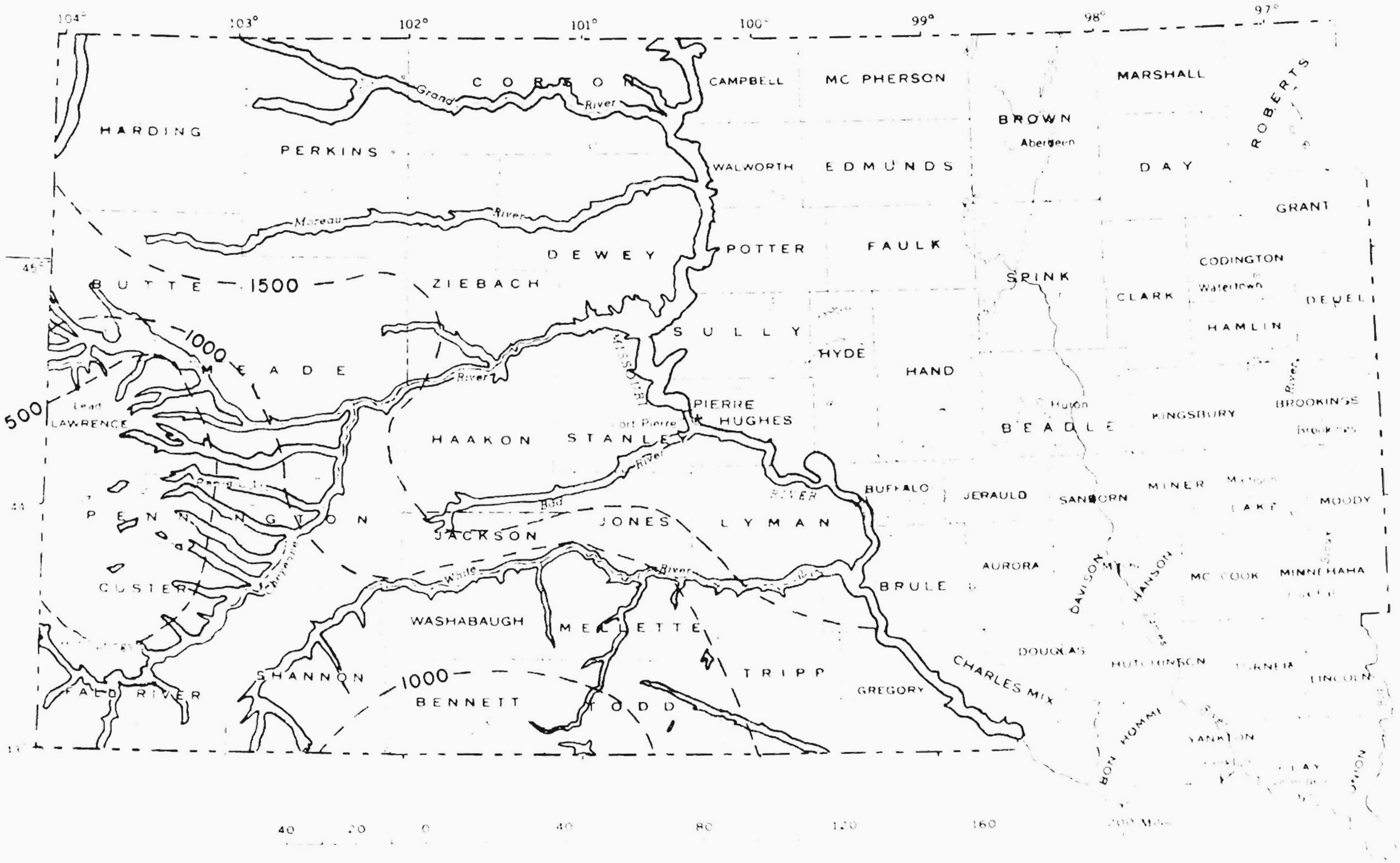


Figure 30. Unit #19 - Alluvium. Map shows deposits of saturated alluvium. Compiled from numerous sources (see text). TDS contours (in ppm), shown as dashed lines, are approximately located.

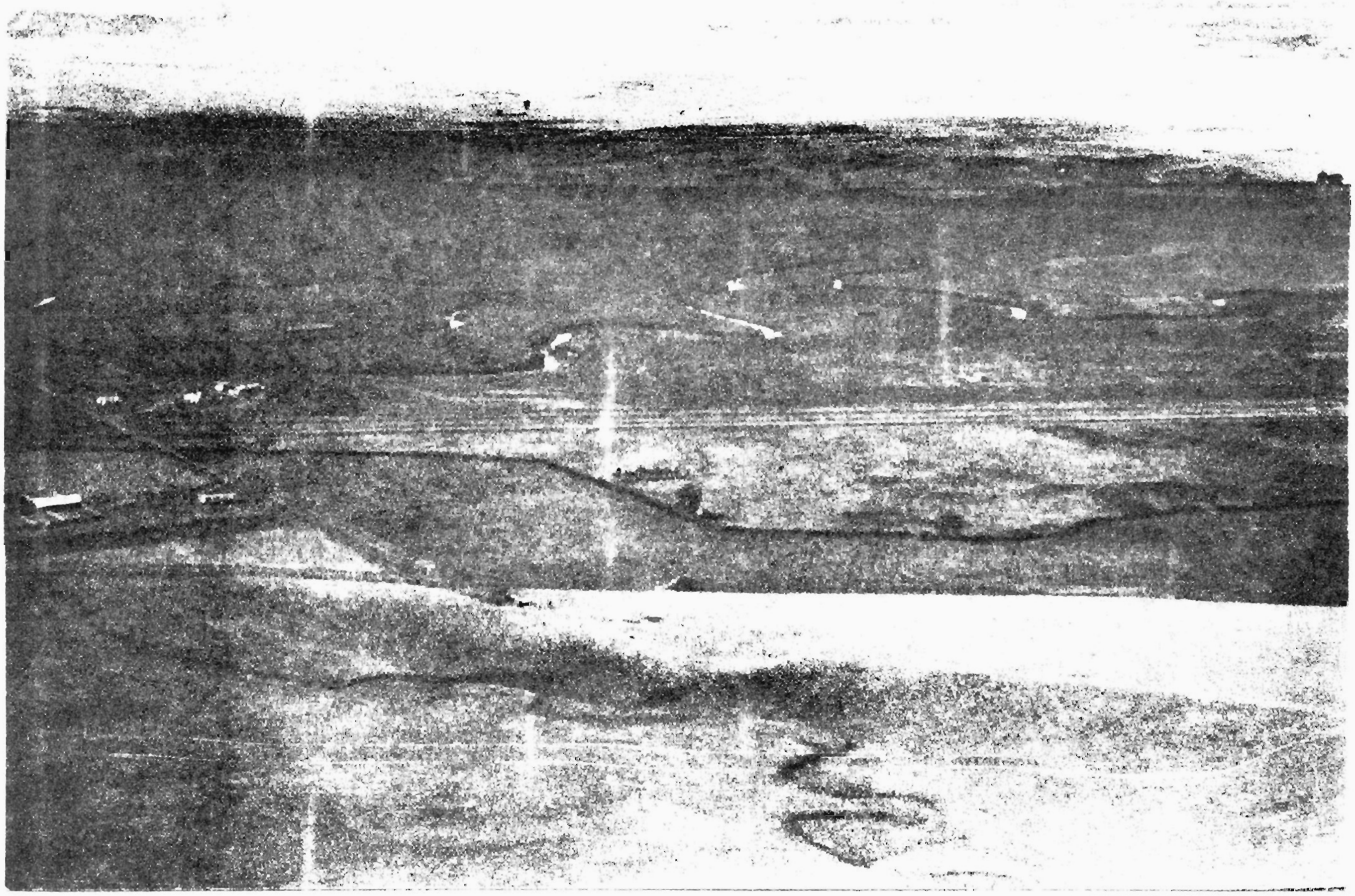


Figure 31. Alluvium underlies the valley of Rapid Creek near Caputa, S.D. Because of abundant ground water at shallow depth, vegetation has a distinct darker tone on this photograph. Photo by P. H. Rahn.

Figure 32. Exposure of alluvium 1 mile northwest of Spearfish, S.D. Photo by P. H. Rahn.

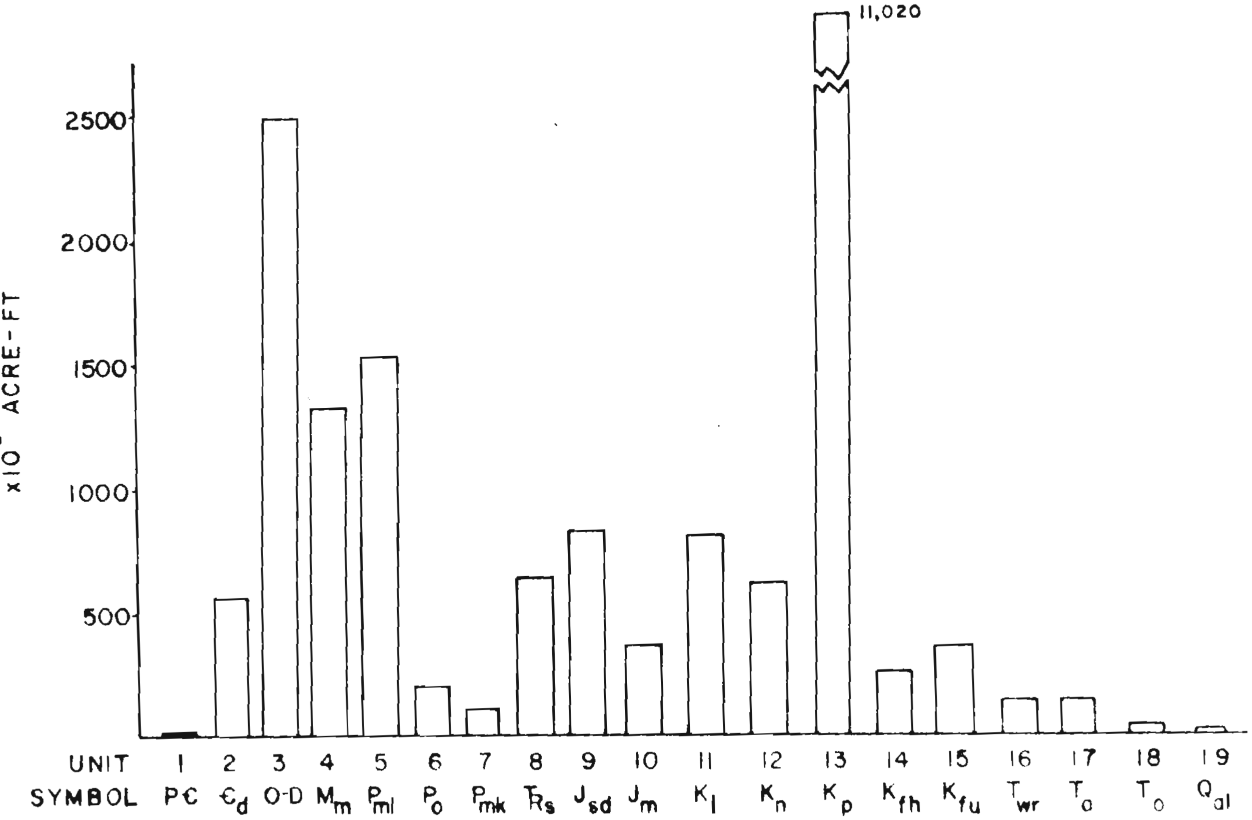


Figure 33. Histogram of total ground water stored in western South Dakota.

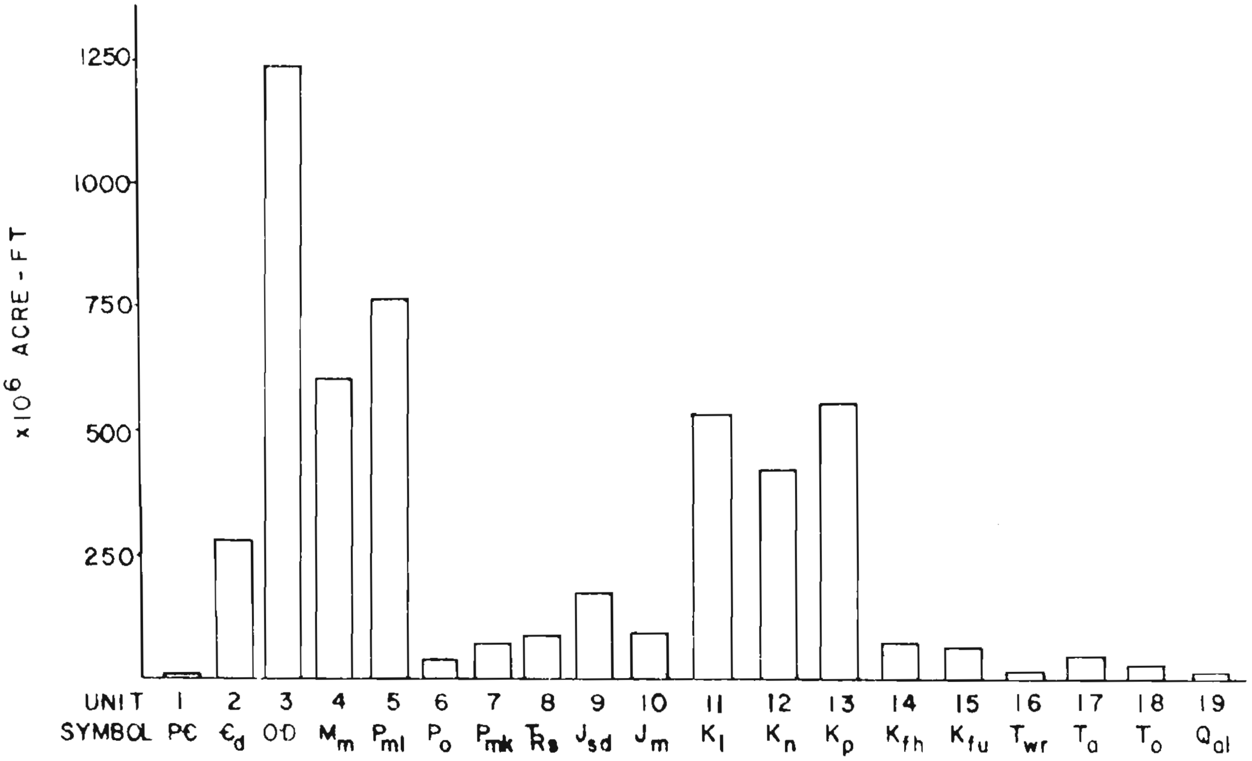


Figure 34. Histogram of recoverable ground water stored in western South Dakota.

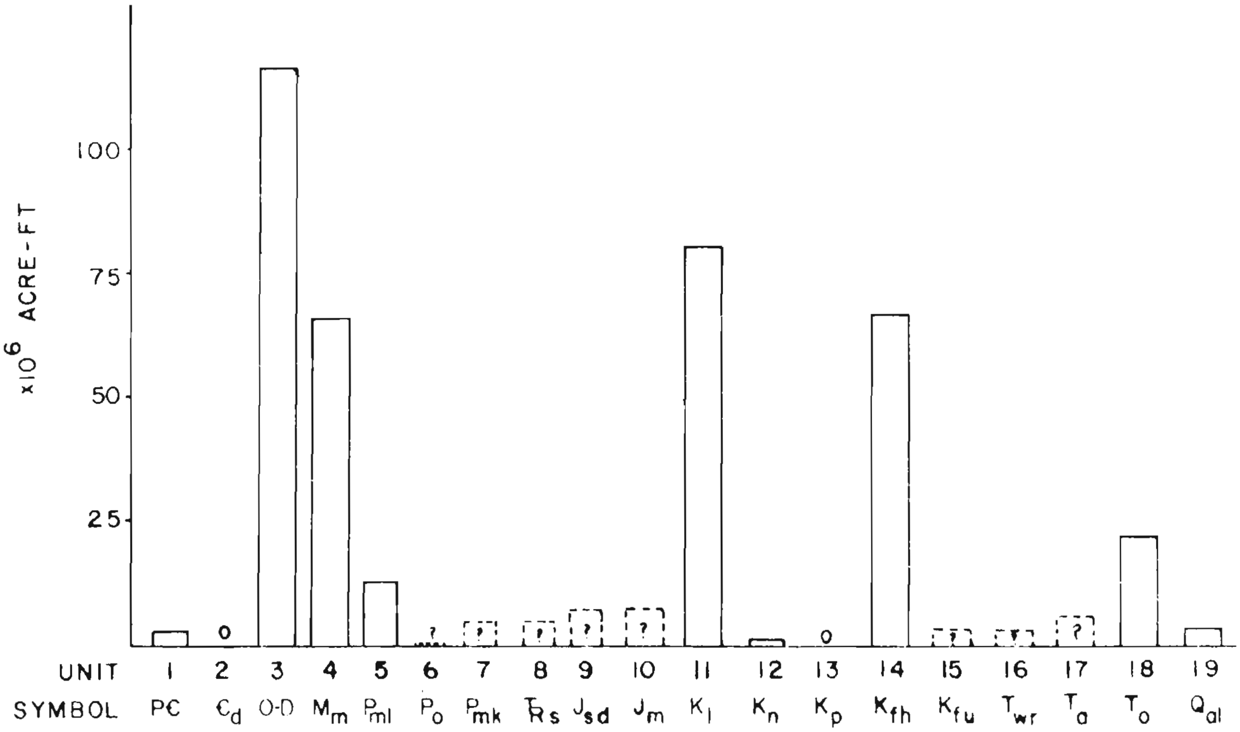


Figure 35. Histogram of recoverable ground water stored in western South Dakota having less than 1,000 ppm TDS.

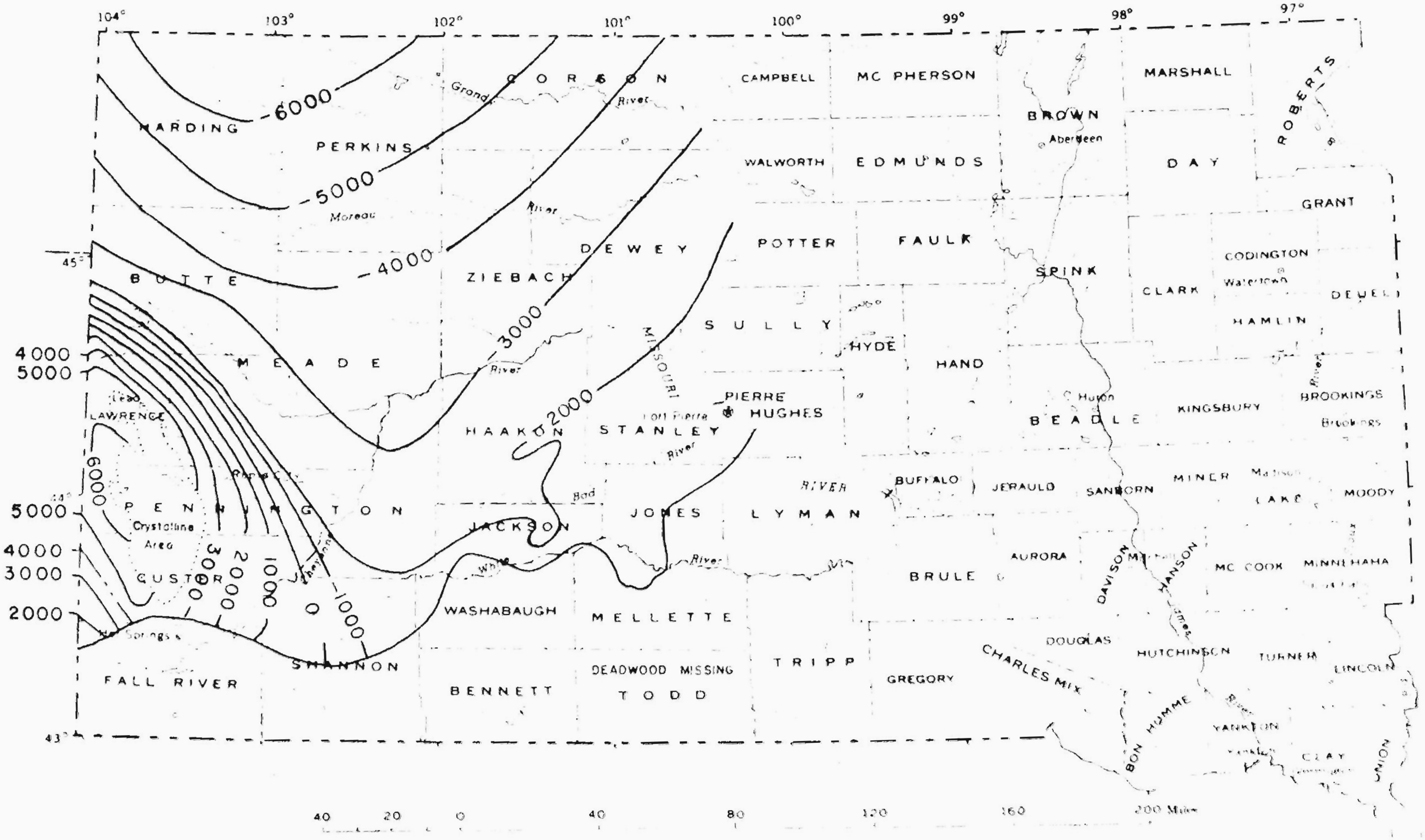


Figure 36. Structural contour map on the top of the Deadwood Formation (from Steece, 1978). Contours are feet above sea level.

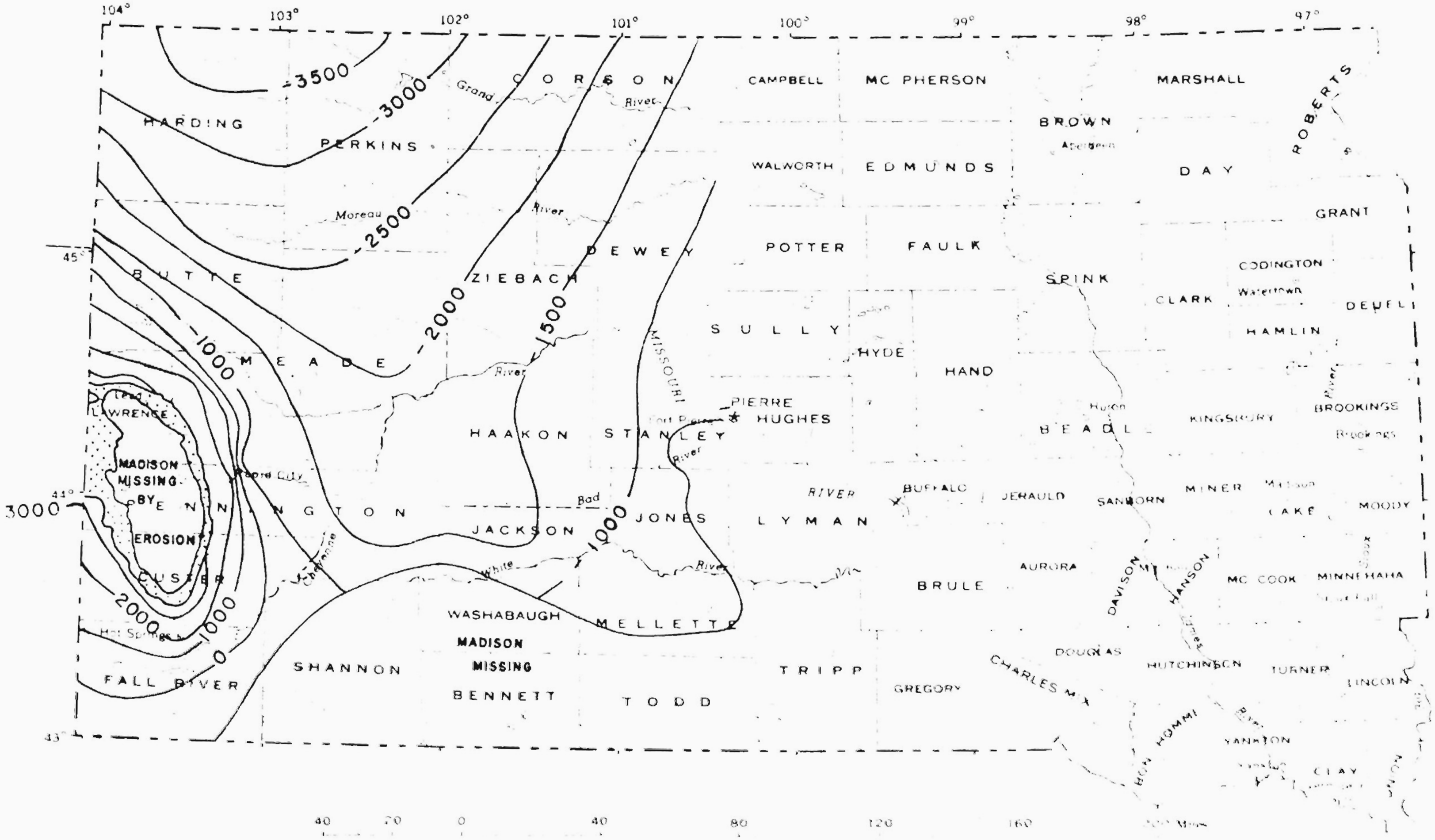


Figure 37. Structural contour map on the top of the Madison Limestone (from Gries, 1978). Contours are feet above sea level.

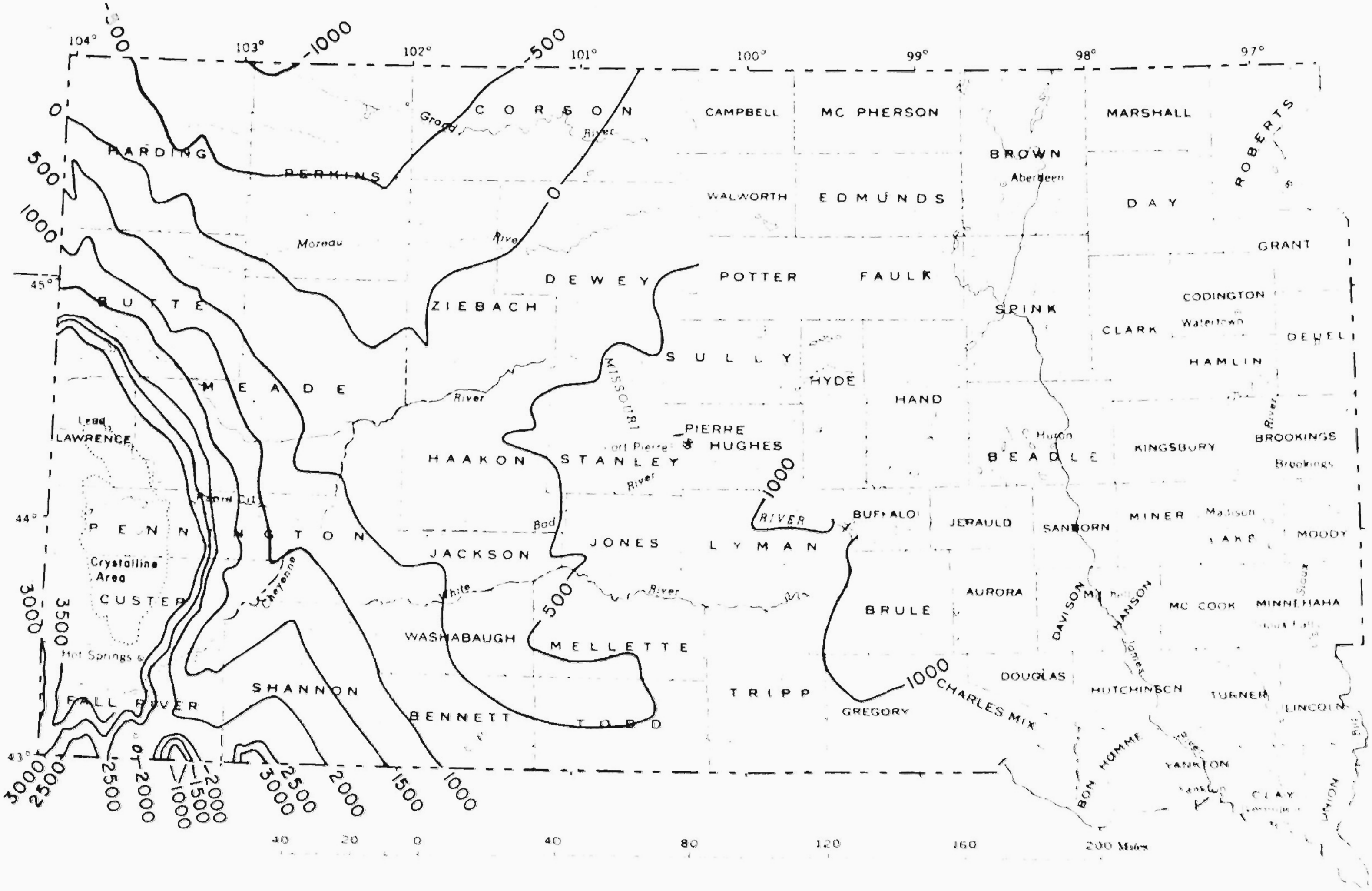


Figure 38. Structural contour map on the top of the Greenhorn Formation (from Schoon, 1971). Contours are feet above sea level.

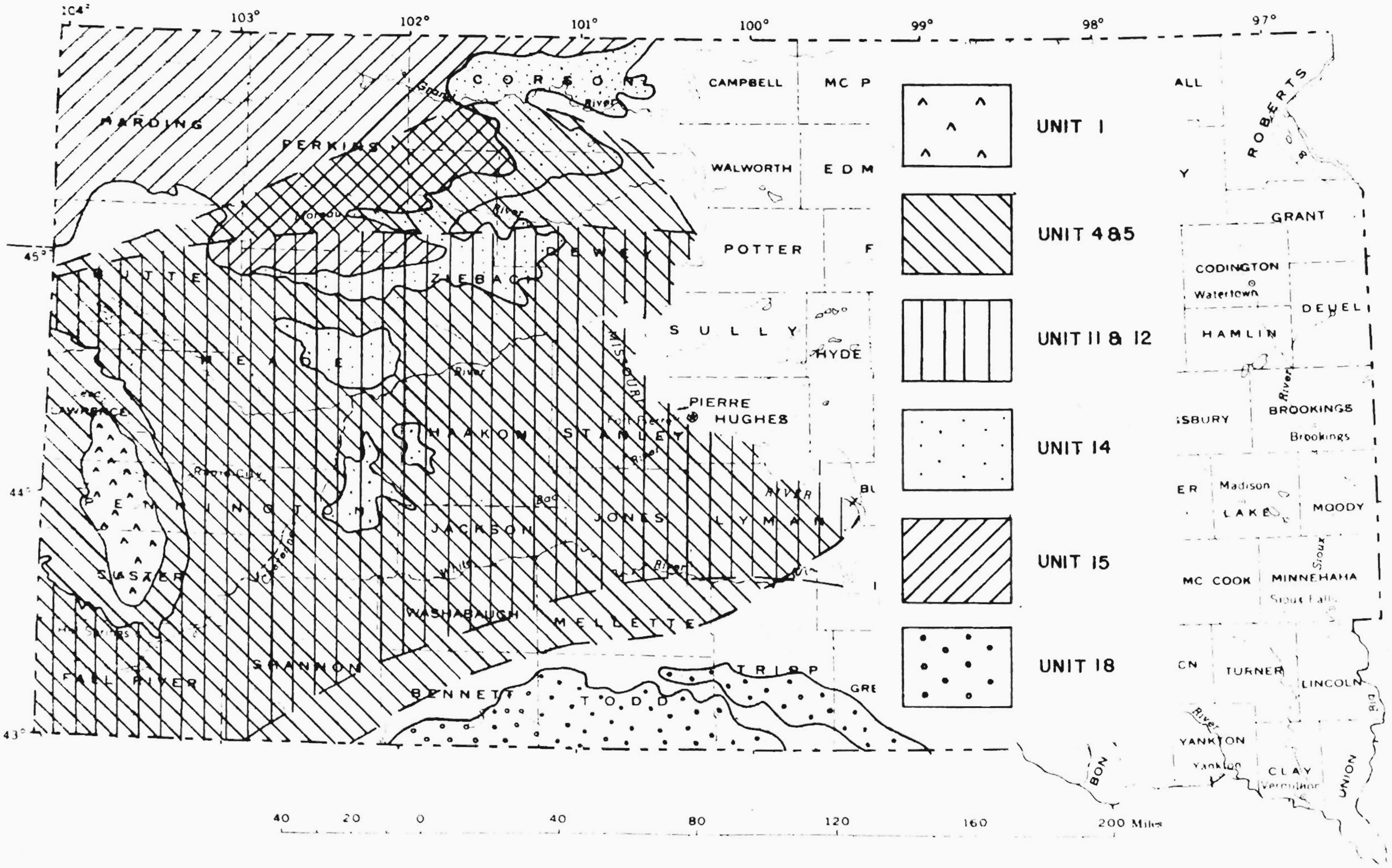
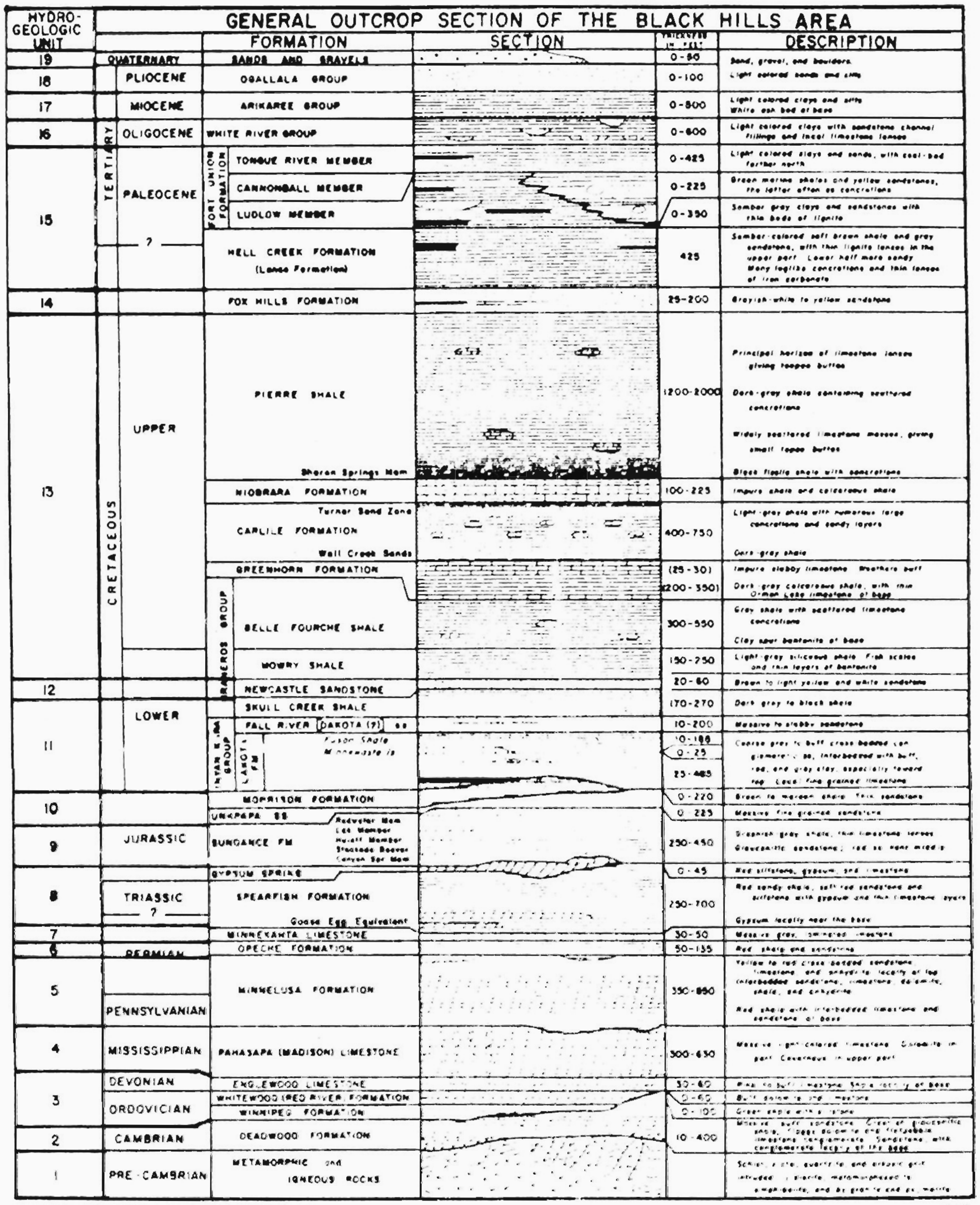


Figure 39. Aquifers presently utilized in western South Dakota.



GENERAL OUTCROP SECTION OF THE BLACK HILLS AREA

HYDRO-GEOLOGIC UNIT			FORMATION		THICKNESS IN FEET	DESCRIPTION
19	QUATERNARY		SANDS AND GRAVELS		0-50	Sand, gravel, and boulders
18	TERTIARY	PLIOCENE	OGALLALA GROUP		0-100	Light colored sands and silts
17		MIOCENE	ARIKAREE GROUP		0-500	Light colored clays and silts White ash bed at base
16		OLIGOCENE	WHITE RIVER GROUP		0-600	Light colored clays with sandstone channel fillings and local limestone lenses
15		PALEOCENE	FORT UNION FORMATION	TONGUE RIVER MEMBER	0-425	Light colored clays and sands, with coal-bed farther north
				CANNONBALL MEMBER	0-225	Green marine shales and yellow sandstones, the latter often as concretions
				LUDLOW MEMBER	0-350	Somber gray clays and sandstones with thin beds of lignite
		?	HELL CREEK FORMATION (Lance Formation)		425	Somber-colored soft brown shale and gray sandstone, with thin lignite lenses in the upper part. Lower half more sandy. Many loglike concretions and thin lenses of iron carbonate
14	CRETACEOUS		FOX HILLS FORMATION		25-200	Grayish-white to yellow sandstone
13		UPPER	PIERRE SHALE	Sharon Springs Mem	1200-2000	Principal horizon of limestone lenses giving teepee buttes Dark-gray shale containing scattered concretions Widely scattered limestone masses, giving small teepee buttes Black fissile shale with concretions
			NIOBRARA FORMATION		100-225	Impure chalk and calcareous shale
			CARLILE FORMATION	Turner Sand Zone Wall Creek Sands	400-750	Light-gray shale with numerous large concretions and sandy layers Dark-gray shale
			GREENHORN FORMATION		(25-30)	Impure slabby limestone. Weathers buff
			GRANEROS GROUP		(200-350)	Dark gray calcareous shale, with thin Orman Lake limestone at base
				BELLE FOURCHE SHALE	300-550	Gray shale with scattered limestone concretions Clay spur bentonite at base
				MOWRY SHALE	150-250	Light-gray siliceous shale. Fish scales and thin layers of bentonite
12				NEWCASTLE SANDSTONE	20-60	Brown to light yellow and white sandstone
11		LOWER		SKULL CREEK SHALE	170-270	Dark gray to black shale
			INYAN KARA GROUP	FALL RIVER [DAKOTA (?)] SS	10-200	Massive to slabby sandstone
				LAKOTA FM: Fuson Shale Minnewaste ls	10-188 0-25 25-485	Coarse gray to buff cross-bedded conglomeratic ss, interbedded with buff, red, and gray clay, especially toward top. Local fine-grained limestone
10			MORRISON FORMATION		0-220	Green to maroon shale. Thin sandstone
	JURASSIC		UNKPAPA SS		0-225	Massive fine-grained sandstone
9			SUNDANCE FM	Redwater Mem Lak Member Hulett Member Stockade Beaver Canyon Spr Mem	250-450	Greenish gray shale, thin limestone lenses Glauconitic sandstone; red ss near middle
8			GYPSUM SPRING		0-45	Red siltstone, gypsum, and limestone
	TRIASSIC		SPEARFISH FORMATION	Goose Egg Equivalent	250-700	Red sandy shale, soft red sandstone and siltstone with gypsum and thin limestone layers Gypsum locally near the base
7	?		MINNEKAHTA LIMESTONE		30-50	Massive gray, laminated limestone
6	PERMIAN		OPECHE FORMATION		50-135	Red shale and sandstone
5	PENNSYLVANIAN		MINNELUSA FORMATION		350-850	Yellow to red cross-bedded sandstone, limestone, and anhydrite locally at top Interbedded sandstone, limestone, dolomite, shale, and anhydrite Red shale with interbedded limestone and sandstone at base
4	MISSISSIPPIAN		PAHASAPA (MADISON) LIMESTONE		300-630	Massive light-colored limestone. Dolomite in part. Cavernous in upper part
3	DEVONIAN		ENGLEWOOD LIMESTONE		30-60	Pink to buff limestone. Shale locally at base
	ORDOVICIAN		WHITEWOOD (RED RIVER) FORMATION		0-60	Buff dolomite and limestone
			WINNIPEG FORMATION		0-100	Green shale with siltstone
2	CAMBRIAN		DEADWOOD FORMATION		10-400	Massive buff sandstone. Green glauconitic shale, flaggy dolomite and flatpebble limestone conglomerate. Sandstone, with conglomerate locally at the base
1	PRE-CAMBRIAN		METAMORPHIC and IGNEOUS ROCKS			Schist, slate, quartzite, and arkosic grit intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite

1953

DEPARTMENT OF GEOLOGY AND GEOLOGICAL ENGINEERING
SOUTH DAKOTA SCHOOL OF MINES AND TECHNOLOGY
RAPID CITY, SOUTH DAKOTA

Table 1. Stratigraphic section of the Black Hills area showing 19 hydrogeologic units.

This p. should follow ~~p. 24~~ Table 24

APPENDICES

APPENDIX A. VOLUMETRIC CALCULATIONS

APPENDIX B. POROSITY CALCULATIONS

APPENDIX C. GROUND WATER QUALITY

APPENDIX D. AQUIFER TEST AND WELL YIELD DATA

APPENDIX E. ANALYSIS OF LAND SUBSIDENCE

Table 2 - Hydrogeologic Unit # 1   Crystalline Rock

(all values are 10^6 acre-ft)
except where noted

	Unit # 1		Water in Unit # 1					
					Recoverable Water Volume Having TDS values as shown (ppm)			
basin no.	Total rock area (10^9 ft^2)	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	< 500	500 to 1000	1000 to 2000	> 2000
1A	0	0	0	0	0	0	0	0
1B	0	0	0	0	0	0	0	0
2A	0	0	0	0	0	0	0	0
2B	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7A	23	263	7.9	2.6	2.6	0	0	0
7B	2.2	25	.8	.3	.3	0	0	0
7C	0	0	0	0	0	0	0	0
8A	0	0	0	0	0	0	0	0
8B	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
Total (% total)	25.2	288	8.7	2.9	2.9 (100%)	0	0	0

(1) Assumes Unit #1 at 500 ft thickness
(2) Assumes a total porosity of 3% and all 500 ft is saturated.
(3) Assumes an effective porosity of 1%.

County	Population			Water Required at 100gpc/day for 20 years. (acre-ft)
	4-1-1970	7-1-1977	7-1-1997	
Bennett	3088	3193	3162	7174
Butte	7825	8355	8963	20178
Corson	4994	4914	5597	12555
Custer	4698	5376	7044	15694
Dewey	5170	6026	8217	18384
Fall River	7505	8737	11914	26680
Gregory	6710	6258	7199	16142
Haakon	2802	2893	3329	7399
Harding	1855	1801	7071	4708
Jackson	1531	1551	1446	3139
Jones	1882	1711	1969	4417
Lawrence	17453	17229	19821	44391
Lyman	4060	4025	4631	10380
Mellette	2420	2199	2503	5614
Pennington	59349	70955	104819	235002
Perkins	4769	4627	5323	11934
Shannon	8198	8494	8411	18857
Stanley	2457	2686	3090	6950
Todd	6606	7165	8000	17936
Tripp	8171	7961	9159	20534
Washabaugh	1389	1518	1746	3915
Ziebach	2221	2247	2096	4699
Western S.D.	182173	199506	256172	574301
South Dakota	666257	689051		

Table E-1. Population.

Unit #	Maximum formation thickness. (ft)	Percentage of saturation.	Anticipated depletion in water level. (ft)	Maximum subsidence expected.* (ft)	Subsidence expressed as % of total thickness.
15	800	70	560	16	2
16	600	50	300	13	2
17	400	100	400	16	4
18	400	65	265	10	2.5
19	25	80	20	-	-

* Values of ratio of water-level decline to land subsidence range from 35/1 to 23/1 (Utgard, 1978, p.84)

Table E-2. Land subsidence data.

Table 3 - Hydrogeologic Unit # 2 Deadwood Fm.
(all values are 10^6 acre-ft)

	Unit # 2		Water in Unit # 2					
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	Recoverable Water Volume Having TDS values as shown (ppm)			
					< 500	500 to 1000	1000 to 2000	>2000
1A	960	960	96	48	0	0	0	48
1B	580	580	58	29	0	0	0	29
2A	110	110	11	5.5	0	0	0	5.5
2B	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	160	160	16	8	0	0	0	8
5	1390	1390	139	69	0	0	0	69
6	250	250	25	13	0	0	0	13
7A	470	470	47	23	0	0	0	23
7B	910	910	91	46	0	0	0	46
7C	540	540	54	27	0	0	0	27
8A	220	220	22	11	0	0	0	11
8B	0	0	0	0	0	0	0	0
9	30	30	3	1.5	0	0	0	1.5
Total (% total)	5620	5620	562	281	0	0	0	281 (100%)

(1) Assumes Unit # 2 is 100% saturated.
(2) Assumes a total porosity of 10%.
(3) Assumes an effective porosity of 5%.

Table 4 - Hydrogeologic Unit # 3 [illegible]
(all values are 10^6 acre-ft)

	Unit # 3		Water in Unit # 3					
Basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	Recoverable Water Volume Having TDS values as shown (ppm)			
					< 1000	1000 to 3000	3000 to 10000	> 10000
1A	1843	1843	369	185	0	0	10	175
1B	1499	1499	300	150	0	0	93	57
2A	430	430	86	43	43	0	0	0
2B	117	117	23	12	12	0	0	0
3	80	80	16	8	8	0	0	0
4	645	645	129	65	7	58	0	0
5	2949	2949	590	295	0	51	229	15
6	485	485	97	49	0	0	18	31
7A	387	387	77	39	31	8	0	0
7B	1130	1130	226	113	12	98	3	0
7C	1585	1585	317	159	0	159	0	0
8A	1130	1130	226	113	0	67	46	0
8B	37	37	7.4	3.7	3.7	0	0	0
9	104	104	21	11	0	0	0	11
Total (% total)	12421	12421	2484.4	1245.7	116.7 (9.3%)	441 (35.5%)	399 (32.1%)	289 (23.2%)

(1) Assumes Unit #3 is 100% saturated.
(2) Assumes a total porosity of 20%.
(3) Assumes an effective porosity of 10%.

Table 5 - Hydrogeologic Unit # 4 Pahasapa (Madison) Fm.
(all values are 10^6 acre-ft)

	Unit # 4		Water in Unit # 4					
					Recoverable Water Volume Having TDS values as shown (ppm)			
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	< 500	500 to 1000	1000 to 2000	> 2000
1A	1775	1775	195	89	0	0	0	89
1B	1288	1288	142	65	0	0	0	65
2A	131	131	14	6.6	0	0	6.6	0
2B	18	18	2	0.9	0	0	0.9	0
3	0	0	0	0	0	0	0	0
4	523	523	58	26	0	2	18	6
5	2764	2764	304	138	0	0	0	138
6	448	448	48	23	0	0	0	23
7A	1157	1157	128	58	21	22	15	0
7B	1313	1313	144	66	9	12	30	15
7C	1547	1547	171	77	0	0	29	48
8A	1017	1017	112	51	0	0	0	51
8B	0	0	0	0	0	0	0	0
9	85	85	9.4	4.3	0	0	0	4.3
Total (% total)	12066	12066	1327.4	604.8	30 (5.0%)	36 (5.9%)	99.5 (16.6%)	439.3 (72.8%)

(1) Assumes Unit #4 is 100% saturated.
(2) Assumes a total porosity of 11%.
(3) Assumes an effective porosity of 5%.

Table 6 - Hydrogeologic Unit # 5 Minnelusa Fm.

(all values are 10^6 acre-ft)

	Unit # 5		Water in Unit # 5					
					Recoverable Water Volume Having TDS values as shown (ppm)			
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	< 500	500 to 1000	1000 to 2000	> 2000
1A	870	870	87	43	0	0	0	43
1B	790	790	79	39	0	0	0	39
2A	2630	2630	263	132	0	0	115	17
2B	470	470	47	24	0	0	24	0
3	300	300	30	15	0	0	15	0
4	1310	1310	131	66	0	0	35	31
5	1990	1990	199	100	0	0	0	100
6	200	200	20	10	0	0	0	10
7A	2800	2800	280	140	3	7	17	113
7B	1140	1140	114	57	1	2	8	46
7C	1880	1880	188	94	0	0	0	94
8A	850	850	85	42	0	0	0	42
8B	50	50	5	2.5	0	0	2	0.5
9	40	40	4	2	0	0	0	2
Total (% total)	15320	15320	1532	766.5	4 (.5%)	9 (1.2%)	216 (28.2%)	537.5 (70.1%)

(1) Assumes Unit #5 is 100% saturated.
(2) Assumes a total porosity of 10%.
(3) Assumes an effective porosity of 5%.

Table 7 - Hydrogeologic Unit # 6 Opeche Fm.
(all values are 10^6 acre-ft)

	Unit # 6		Water in Unit # 6					
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	Recoverable Water Volume Having TDS values as shown (ppm)			
1A	150	150	18	3				
1B	60	60	7	1.2				
2A	300	300	36	6				
2B	20	20	2	0.4				
3	6	6	0.7	0.1				
4	40	40	5	0.8				
5	220	220	26	4.4				
6	40	40	5	0.8				
7A	420	420	50	8.4				
7B	260	260	31	5.2				
7C	160	160	19	3.2				
8A	0	0	0	0				
8B	0	0	0	0				
9	3	3	0.4	0.1				
Total (% total)	1679	1679	200.1	33.6				

(1) Assumes Unit #6 is 100% saturated.
(2) Assumes a total porosity of 12%.
(3) Assumes an effective porosity of 2%.

Table 8 - Hydrogeologic Unit # 7 Minnekahta L.S.
(all values are 10^6 acre-ft)

	Unit # 7		Water in Unit # 7					
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	Recoverable Water Volume Having TDS values as shown (ppm)			
1A	46	46	3.7	2.3				
1B	12	12	1.0	.6				
2A	48	48	3.8	2.4				
2B	1.8	1.8	.1	.1				
3	.6	.6	0	0				
4	7.6	7.6	.6	.4				
5	73	73	5.8	3.7				
6	10	10	.8	.5				
7A	92	92	7.3	4.6				
7B	57	57	4.6	2.8				
7C	54	54	4.3	2.7				
8A	0	0	0	0				
8B	0	0	0	0				
9	.6	.6	0	0				
Total (% total)	402.6	402.6	32.2	20.1				

(1) Assumes Unit #7 is 100% saturated.
(2) Assumes a total porosity of 8%.
(3) Assumes an effective porosity of 5%.

Table 9 - Hydrogeologic Unit # 8 Spearfish Fm.

(all values are 10^6 acre-ft)

	Unit # 8		Water in Unit # 8					
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	Recoverable Water Volume Having TDS values as shown (ppm)			
1A	489	489	73	9.8				
1B	92	92	14	1.8				
2A	313	313	47	6.3				
2B	9	9	1.4	0.2				
3	2	2	0.3	0				
4	114	114	17	2.3				
5	805	805	121	16				
6	203	203	30	4.1				
7A	940	940	141	19				
7B	894	894	134	18				
7C	399	399	60	8.0				
8A	18	18	2.7	0.5				
8B	0	0	0	0				
9	3	3	0.5	0.1				
Total (% total)	4281	4281	641.9	86.1				

(1) Assumes Unit #8 is 100% saturated.
(2) Assumes a total porosity of 15%.
(3) Assumes an effective porosity of 2%.

Table 10- Hydrogeologic Unit #9 Sundance

(all values are 10^6 acre-ft)

	Unit #9		Water in Unit # 9					
					Recoverable Water. Volume Having TDS values as shown (ppm)			
basin no.	Total rock volume	Saturated volume (1)	Total water volume (2)	Total recoverable water volume (3)				
1A	608	608	91	18				
1B	436	436	65	13				
2A	353	353	53	11				
2B	5	5	0.7	0.2				
3	2	2	0.3	0.1				
4	197	197	30	5.9				
5	1087	1087	163	33				
6	246	246	37	7.4				
7A	934	934	140	28				
7B	657	657	99	20				
7C	645	645	97	19				
8A	298	298	45	8.9				
8B	0	0	0	0				
9	25	25	3.7	0.8				
Total (% total)	5493	5493	824.7	165.3				

(1) Assumes Unit #9 is 100% saturated.
(2) Assumes a total porosity of 15%.
(3) Assumes an effective porosity of 3%.

Table11 - Hydrogeologic Unit #10 Morrison Fm.
(all values are 10^6 acre-ft)

	Unit #10		Water in Unit # 10					
					Recoverable Water Volume Having TDS values as shown (ppm)			
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)				
1A	178	178	21	5.3				
1B	126	126	15	3.8				
2A	688	688	83	21				
2B	89	89	11	2.7				
3	15	15	1.8	0.5				
4	249	249	30	7.5				
5	399	399	48	12				
6	55	55	6.6	1.6				
7A	750	750	90	22				
7B	283	283	34	8.5				
7C	249	249	30	7.5				
8A	70	70	8.4	2.1				
8B	0	0	0	0				
9	3	3	0.4	0.1				
Total (% total)	3154	3154	379.2	94.6				

(1) Assumes Unit #10 is 100% saturated.
(2) Assumes a total porosity of 12%.
(3) Assumes an effective porosity of 3%.

Table 12 - Hydrogeologic Unit # 11 Inyan Kara Group
(all values are 10^6 acre-ft)

	Unit # 11		Water in Unit # 11					
					Recoverable Water Volume Having TDS values as shown (ppm)			
basin no.	Total rock volume	Saturated volume(1)	Total water volume	Total recoverable water volume (2)	< 500	500 to 1000	1000 to 2000	> 2000
1A	246	246	64	43	0	0	5	38
1B	98	98	25	17	0	0	0	17
2A	648	648	169	113	0	3	97	13
2B	120	120	31	21	0	0	20	1
3	295	295	77	51	0	0	0	51
4	184	184	48	32	0	0.6	5.4	26
5	240	240	63	42	0	0.7	22.3	19
6	61	61	16	11	0	0.4	6.9	3.7
7A	387	387	101	67	11	38	18	0
7B	184	184	48	32	3.2	24	4.8	0
7C	151	151	39	26	0	0	15	11
8A	160	160	42	28	0	0	0	28
8B	304	304	79	53	0	0	29	24
9	6.2	6.2	1.6	1.1	0	0	0	1.1
Total (% total)	3084.2	3084.2	803.6	537.1	14.2 (2.6%)	66.7 (12.5%)	223.4 (41.5%)	232.8 (43.4%)

(1) Assumes Unit #11 is 100% saturated.

Table 13– Hydrogeologic Unit # 12 Newcastle S.S.
(all values are 10^6 acre-ft)

basin no.	Unit # 12		Water in Unit # 12					
	Total rock volume	Saturated volume(1)	Total water volume	Total recoverable water volume (2)	Recoverable Water Volume Having TDS values as shown (ppm)			
					< 500	500 to 1000	1000 to 2000	> 2000
1A	25	25	6.8	4.3	0	0	4.3	0
1B	0	0	0	0	0	0	0	0
2A	796	796	221	147	0	0	5	142
2B	236	236	66	44	0	0	43	1.0
3	123	123	34	23	0	0	23	0
4	396	396	110	73	0	0	20	53
5	12	12	3.4	2.2	0	0	0.4	1.8
6	21	21	5.9	3.9	0	0	0	3.9
7A	101	101	28	19	0.5	0.5	17.5	0.5
7B	3.1	3.1	0.9	0.6	0	0	0.6	0
7C	147	147	41	27	0	0	3.1	24
8A	184	184	51	34	0	0	0	34
8B	151	151	42	28	0	0	5	23
9	0	0	0	0	0	0	0	0
Total (% total)	2195.1	2195.1	610	406	0.5 (.1%)	0.5 (.1%)	121.8 (29.8%)	283.2 (70.0%)

(1) Assumes Unit # 12 is 100% saturated.
(2) Assumes a specific retention of 33%.

County	Number of Wells	Mean Hydraulic Conductivity (Ft $Sec^{-1}x10^{-5}$)	Standard Deviation (Ft $Sec^{-1}x10^{-5}$)
Beadle	112	6.7×10^{-5}	6.0×10^{-5}
Brown	110	5.4	6.2
Clark	6	3.0	2.2
Edmunds	5	3.0	1.4
Faulk	75	7.0	7.1
Hand	11	11.0	8.8
Kingsbury	41	2.1	2.9
Marshall & Day	20	3.5	3.5
Sandborn & Miner	10	3.9	5.5
Spink	88	11.0	11.0
Stanley & Hughes	7	5.7	6.4
Sully	9	2.1	3.0
SUMMARY			
ALL DATA	494	6.4×10^{-5}	7.1×10^{-5}

Table 14. Dakota Sandstone aquifer data (from Bredehoeft, unpubl., 1972).

Table15 - Hydrogeologic Unit # 13 Pierre Shale
(all values are 10^6 acre-ft)

	Unit # 13		Water in Unit # 13					
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	Recoverable Water Volume Having TDS values as shown (ppm)			
1A	5391	5337	1067	53				
1B	3717	3680	736	37				
2A	9139	9048	1810	90				
2B	2150	2129	426	21				
3	1643	1627	325	16				
4	3686	3649	730	36				
5	9292	9199	1840	92				
6	1259	1246	249	12				
7A	4853	4805	961	48				
7B	3348	3315	663	33				
7C	6021	5961	1192	60				
8A	3333	3300	660	33				
8B	1643	1627	325	16				
9	184	182	36	1.8				
Total (% total)	55659	55105	11020	548.8				

(1) Assumes Unit #13 is 99% saturated.
(2) Assumes a total porosity of 20%.
(3) Assumes an effective porosity Of 1%.

Table 16 - Hydrogeologic Unit # 14 Fox Hills Fm.

(all values are 10^6 acre-ft)

	Unit # 14		Water in Unit # 14					
					Recoverable Water Volume Having TDS values as shown (ppm)			
basin no.	Total rock volume	Saturated volume (1)	Total water volume (2)	Total recoverable water volume (3)	< 500	500 to 1000	1000 to 2000	> 2000
1A	316	301	60	15	0	15	0	0
1B	313	298	60	15	2	13	0	0
2A	0	0	0	0	0	0	0	0
2B	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	12	11	2.4	0.6	0.3	0.3	0	0
5	510	484	97	24	2	22	0	0
6	65	61	12	3.1	0.5	2.6	0	0
7A	6.2	5.9	1.2	0.3	0.1	0.2	0	0
7B	9.2	8.7	1.7	0.4	0.2	.2	0	0
7C	126	120	24	6	4	2	0	0
8A	58	55	11	2.8	1.4	1.4	0	0
8B	0	0	0	0	0	0	0	0
9	15	14	2.9	0.7	0	0.7	0	0
Total (% total)	1430.4	1358.6	272.2	67.9	10.5	57.4	0	0

(1) Assumes Unit #14 is 95% saturated.
(2) Assumes a total porosity of 20%.
(3) Assumes an effective porosity of 5%.

Table 17 - Hydrogeologic Unit # 15 Fort Union and Hell Creek Fms.
(all values are 10^6 acre-ft)

	Unit # 15		Water in Unit # 15					
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	Recoverable Water. Volume Having TDS values as shown (ppm)			
1A	875	612	184	31				
1B	246	172	52	8.6				
2A	0	0	0	0				
2B	0	0	0	0				
3	0	0	0	0				
4	0	0	0	0				
5	457	320	96	16				
6	104	73	22	3.7				
7A	0	0	0	0				
7B	0	0	0	0				
7C	0.9	0.6	0.2	0				
8A	0.5	0.3	0.1	0				
8B	0	0	0	0				
9	25	17	5.2	0.9				
Total (% total)	1708.4	1194.9	359.5	60.2				

(1) Assumes Unit #15 is 70% saturated.
(2) Assumes a total porosity of 30%.
(3) Assumes an effective porosity of 5%.

Table 18- Hydrogeologic Unit # 16 White River Group
(all values are 10^6 acre-ft)

	Unit # 16		Water in Unit # 16					
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	Recoverable Water Volume Having TDS values as shown (ppm)			
1A	0	0	0	0				
1B	0	0	0	0				
2A	553	276	83	2.8				
2B	215	107	32	1.1				
3	135	68	20	0.7				
4	12	6	1.9	0.1				
5	0	0	0	0				
6	0	0	0	0				
7A	31	15	4.6	0.2				
7B	0	0	0	0				
7C	0	0	0	0				
8A	0	0	0	0				
8B	0	0	0	0				
9	0	0	0	0				
Total (% total)	946	472	141.5	4.9				

(1) Assumes Unit #16 is 50% saturated.
(2) Assumes a total porosity of 30%.
(3) Assumes an effective porosity of 1%.

Table 19 - Hydrogeologic Unit # 17 Arikaree Group
(all values are 10^6 acre-ft)

	Unit # 17		Water in Unit # 17					
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	Recoverable Water Volume Having TDS values as shown (ppm)			
1A	0	0	0	0				
1B	0	0	0	0				
2A	104	104	37	10				
2B	171	171	60	17				
3	123	123	43	12				
4	0	0	0	0				
5	0	0	0	0				
6	0	0	0	0				
7A	0	0	0	0				
7B	0	0	0	0				
7C	0	0	0	0				
8A	0	0	0	0				
8B	12	12	4.3	1.2				
9	0	0	0	0				
Total (% total)	410	410	144.3	40.2				

(1) Assumes Unit #17 is 100% saturated.
(2) Assumes a total porosity of 35%.
(3) Assumes an effective porosity of 10%.

Table 20 - Hydrogeologic Unit # 18 Ogallala and Sand Hills Fms.
(all values are 10^6 acre-ft)

	Unit # 18		Water in Unit #18					
basin no.	Total rock volume	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	Recoverable Water Volume Having TDS values as shown (ppm)			
					< 500	500 to 1000	1000 to 2000	> 2000
1A	0	0	0	0	0	0	0	0
1B	0	0	0	0	0	0	0	0
2A	4.9	3.2	1.1	0.8	0.8	0	0	0
2B	46	30	11	7.5	7.5	0	0	0
3	86	56	19	14	13	1	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7A	0	0	0	0	0	0	0	0
7B	0	0	0	0	0	0	0	0
7C	0	0	0	0	0	0	0	0
8A	0	0	0	0	0	0	0	0
8B	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
Total (% total)	136.9	89.2	31.1	22.3	21.3 (95.4%)	1 (4.6%)	0	0

(1) Assumes Unit #18 is 65% saturated.
(2) Assumes a total porosity of 35%.
(3) Assumes an effective porosity of 25%.

Table 21 - Hydrogeologic Unit # 19 Saturated Alluvium
(all values are 10^6 acre-ft)
except where noted

	Unit # 19		Water in Unit # 19					
					Recoverable Water Volume Having TDS values as shown (ppm)			
basin no.	Total rock area (10^9 ft^2)	Saturated volume(1)	Total water volume (2)	Total recoverable water volume (3)	< 500	500 to 1000	1000 to 2000	> 2000
1A	2.9	1.3	0.3	0.3	0	0	0	0.3
1B	3.5	1.6	0.4	0.3	0	0	0	0.3
2A	11	5	1.3	1	0	0.7	0.1	0.2
2B	2.1	1	0.2	0.2	0.1	0.1	0	0
3	1.9	0.9	0.2	0.2	0	0.1	0.1	0
4	3.4	1.6	0.4	0.3	0	0	0	0.3
5	5.9	2.7	0.7	0.5	0	0	0	0.5
6	1.3	0.60	0.2	0.1	0	0	0	0.1
7A	18	8.1	2	1.6	0.1	1.3	0.2	0
7B	12	5.4	1.4	1.1	0.1	0.9	0.1	0
7C	4.5	2.1	0.5	0.4	0	0	0.2	0.2
8A	0.8	0.4	0.1	0.1	0	0	0	0.1
8B	1	0.5	0.1	0.1	0	0	0	0.1
9	0	0	0	0	0	0	0	0
Total (% total)	68.3	31.2	7.8	6.2	0.3 (5.2%)	3.1 (50%)	0.7 (11.1%)	2.1 (33.7%)

(1) Assumes Unit #19 averages 20 ft saturated thickness.
(2) Assumes a total porosity of 25%.
(3) Assumes an effective porosity of 20%.

TABLE 22. Summary of ground water in storage in western South Dakota (all values are million acre-ft).

Unit #		Unit Volume	Saturated Volume	Total Water	Recoverable Water	Recoverable Water <1000 ppm
1	PC	288	288	8.7	2.9	2.9
2	C_d	5620	5620	562	281	0
3	Ord-Dev	12421	12421	2484.4	1245.7	116.7
4	M_p	12066	12066	1327.4	604.8	66
5	P_{ml}	15320	15320	1532	766.5	13
6	P_o	1679	1679	200.1	33.6	*
7	P_{mk}	402.6	402.6	32.2	20.1	*
8	T_{re}	4281	4281	641.9	86.1	*
9	J_{ad}	5493	5493	824.7	165.3	*
10	J_m	3154	3154	379.2	94.6	*
11	K_1K_{sc}	3084.2	3084.2	803.6	537.1	80.9
12	K_n	2195.1	2195.1	610	406	1
13	K_p	55659	55105	11020	548.8	*
14	K_{fh}	1430.4	1358.6	272.2	67.9	67.9
15	K_{hc} K_{fu}	1708.4	1194.9	359.5	60.2	*
16	T_{wr}	946	472	141.5	4.9	*
17	T_a	410	410	144.3	40.2	*
18	T_o Q_{sh}	136.9	89.2	31.1	22.3	22.3
19	Q_{al}	68.3	31.2	7.8	6.2	3.4
TOTAL		126362.9	124664.8	21382.6	4994.2	374.1

*All estimated at <0.1 million acre-ft (see Figure 35)

Table 23

Total Ground Water in Storage

By Basin

(all values are 10^6 acre-ft)

Basin no.	Total Water Volume	Total Recoverable Water Volume	Recoverable Water Volume Having TDS Values as Shown(ppm)	
			< 1000	> 1000
1A	2335.8	550.0	15	535
1B	1554.4	381.3	15	366.3
2A	2929.2	598.4	47.5	550.9
2B	713.4	152.3	19.7	132.6
3	567.3	140.6	22.1	118.5
4	1309.3	323.9	10.2	313.7
5	3695.9	847.8	24.7	823.1
6	574.5	143.6	3.5	140.1
7A	2066.0	480.7	138.3	342.4
7B	1593.4	403.9	64.9	339.0
7C	2237.0	516.8	6	510.8
8A	1265.3	326.4	2.8	323.6
8B	462.8	104.5	3.7	105.8
9	88.1	24.4	0.7	23.7
Total	21382.6	4994.2	374.1	4620.5

TABLE 24

BASIN UNIT	1A	1B	2A	2B	3	4	5	6	7A	7B	7C	8A	8B	9	TOTAL
1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	2.6/0	.3/0	0/0	0/0	0/0	0/0	2.9/0
2	0/48	0/29	0/5.5	0/0	0/0	0/8.0	0/69	0/13	0/23	0/46	0/27	0/11	0/0	0/1.5	0/281
3	0/185	0/150	43/0	12/0	8/0	7/58	0/295	0/49	31/8.0	12/101	0/159	0/113	3.7/0	0/11	116.7/1129
4	0/89	0/65	0/6.6	0/0.9	0/0	2/24	0/138	0/23	43/15	21/45	0/77	0/51	0/0	0/4.3	66/538.8
5	0/43	0/39	0/132	0/24	0/15	0/66	0/100	0/10	10/130	3.0/54	0/94	0/42	0/2.5	0/2.0	13/753.5
6	0/3.0	0/1.2	0/6.0	0/0.4	0/.1	0/.8	0/4.4	0/.8	0/8.4	0/5.2	0/3.2	0/0	0/0	0/.1	0/33.6
7	0/2.3	0/.6	0/2.4	0/.1	0/0	0/.4	0/3.7	0/.5	0/4.6	0/2.8	0/2.7	0/0	0/0	0/0	0/20.1
8	0/9.8	0/1.8	0/6.3	0/.2	0/0	0/2.3	0/16	0/4.1	0/19	0/18	0/8.0	0/.5	0/0	0/.1	0/86.1
9	0/18	0/13	0/11	0/.2	0/.1	0/5.9	0/33	0/7.4	0/28	0/20	0/19	0/8.9	0/0	0/.8	0/165.3
10	0/5.3	0/3.8	0/21	0/2.7	0/0.5	0/7.5	0/12	0/1.6	0/22	0/8.5	0/7.5	0/2.1	0/0	0/0.1	0/94.6
11	0/43	0/17	3/110	0/21	0/51	.5/31.4	.7/41.3	.4/10.6	49/18	27.2/4.8	0/26	0/28	0/53	0/1.1	80.9/456.2
12	0/4.3	0/0	0/147	0/44	0/23	0/73	0/2.2	0/3.9	1/18	0/.6	0/27	0/34	0/28	0/0	1/405
13	0/53	0/37	0/90	0/21	0/16	0/36	0/92	0/12	0/48	0/33	0/60	0/33	0/16	0/1.8	0/548.8
14	15/0	15/0	0/0	0/0	0/0	.6/0	24/0	3.1/0	.3/0	.4/0	6.0/0	2.8/0	0/0	.7/0	67.9/0
15	0/31	0/8.6	0/0	0/0	0/0	0/0	0/16	0/3.7	0/0	0/0	0/0	0/0	0/0	0/.9	0/60.2
16	0/0	0/0	0/2.8	0/1.1	0/.7	0/.1	0/0	0/0	0/.2	0/0	0/0	0/0	0/0	0/0	0/4.9
17	0/0	0/0	0/10	0/17	0/12	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/1.2	0/0	0/40.2
18	0/0	0/0	.8/0	7.5/0	14/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	22.3/0
19	0/.3	0/.3	.7/.3	.2/0	.1/.1	0/.3	0/.5	0/.1	1.4/.2	1/.1	0/.4	0/.1	0/.1	0/0	3.4/2.8
TOTAL	15/535	15/366.3	47.7/550.9	19.7/132.6	22.1/118.5	10.2/313.7	24.7/823.1	3.5/140.1	138.3/342.4	64.9/339.0	6/510.8	2.8/323.6	3.7/100.8	.7/23.7	374.1/4620.5

TABLE 24. Basin Summary of recoverable ground water, by Hydrogeologic Unit. Ratio is:
<100 ppm/>1000 ppm TDS.
All data are in million acre-feet.

APPENDIX A

VOLUMETRIC CALCULATIONS

- by Jeffrey A. Sussman

The purpose of this appendix is to explain the method of determining the volumes of the units described in this study.

The areal distribution of Units #1 and #19 were planimetered. The area was multiplied by 20 ft (the saturated thickness for Unit #19) and by 500 ft for Unit #1, to yield a volume that would produce water.

The volumes for Units #2 through #18 were determined as follows. Using the 1:500,000 scale isopach maps, a three-dimensional contour map was constructed with a thickness of paper representing a contour interval. Succeeding layers of paper (i.e. contour intervals) were then sparsely glued onto each other to form a layered scale model of each unit. By then weighing the layered contour map a volume could be calculated by simply multiplying by an appropriate weight constant. The error introduced by the weight of the glue is less than 3%.

Having calculated a total volume, the layered contour map was then cut into the 14 designated drainage basins and a volume calculated for each basin. Data thus acquired is found in the respective tables for each hydrogeologic unit. On each table, the total rock volume represents the values obtained (as described above). The saturated volume was found by multiplying the total volume by a saturation percentage. These values are found in each unit report and in the table as footnote 1. The total water volume was calculated by multiplying the saturated volume by the total porosity for each unit (see Appendix B). These values are found in the tables as footnote 2. The total recoverable water volume was calculated by multiplying the total water volume by the ratio of effective porosity to total porosity (see Appendix B). These values are found as footnote 3 in the tables. If enough water quality information was available, the recoverable water was [redacted] further broken down into TDS ranges. Finally, the TDS volumes are shown as a percent of the total recoverable water for each unit.

APPENDIX B

POROSITY CALCULATIONS

- by Charles S. Harris

A brief discussion of porosity is necessary to facilitate understanding of the terms used in this appendix. Porosity is the percentage of the total volume of material that is occupied by pores or interstices (Bouwer, 1978). Freeze and Cherry (1979) discuss two types of porosity. Primary porosity is due to the nature of the soil or rock matrix. Secondary porosity is due to such phenomena as secondary solution or structurally controlled regional fracturing. Figure 1 illustrates primary and secondary porosity. The letters a, b, c, and d illustrate primary porosity. Secondary porosity is illustrated by e (resulting from solution) and f (resulting from fracturing).

Because of the forces of adhesion and cohesion, not all the water in the interstices of a rock can be withdrawn. The amount which can be removed is some percent of the total porosity and is referred to as the effective porosity or specific yield. Walton (1970) defines effective porosity as "a measure of the water-yielding capacity of the rock and is expressed quantitatively as the percentage of the total volume of rock occupied by the ultimate volume of water released from or added to storage in a watertable aquifer per unit (horizontal) area of aquifer and per unit decline or rise of the water table". Hence the amount of water retained by the rock is the specific retention. The relation between total porosity, effective porosity, and specific retention is best illustrated by the following equation:

Total Porosity = Effective Porosity + Specific Retention.

For this study it is assumed that theoretically any aquifer would act as a water-table aquifer in terms of its water-yielding properties as it is pumped to depletion.

Appendix B has been prepared to evaluate and summarize porosity and effective porosity values for each of the 19 hydrogeologic units of western South Dakota. These values were based on ~~previous works of~~ laboratory analyses of samples, electric well-log analyses, and bulk-density log analyses, documented in the literature. For units having no published porosity value, an average value based on lithology was used. These porosity values were calculated from porosity ranges given by Freeze and Cherry (1979), illustrated in Table B-1. Similarly the effective porosity for clastic material was calculated from the graphic relationship of specific yield and grain size given by Davis and DeWiest (1965), where published values were lacking.

Where a hydrogeologic unit consists of more than one rock type, the porosity value for that unit was calculated using a weighted value for each rock type. A calculation of the porosity·feet product was determined by multiplying the porosity value of a given formation by its thickness. The sum of the porosity·feet products for all the formations in a unit, divided by the total thickness of that unit, gave a weighted porosity value for the hydrogeologic unit. The same method was used to obtain a weighted value for the effective porosity.

The values used for porosity and effective porosity are undoubtedly subject to bias. With the exception of Units #11, #12, and #15, most porosity values were based on a few samples in an isolated area. In a few cases porosity and effective porosity values were taken from data collected outside the study area. Here porosity and effective porosity values may have been subject to error due to lateral change in lithology. Many of the values for porosity were taken from oil-well logs. It is probable that these values represent the more porous zones of rock investigated for their oil-bearing potential. In such cases the porosity value given for that zone is probably higher than the value for the entire thickness of the formation. In an attempt to correct for these sources of bias, the porosity and effective porosity value for most units were adjusted. These adjustments were made upon subjective evaluation by Dr. Perry H. Rahn and Dr. J. P. Gries. Adjusted total and effective porosity values for the 19 hydrogeologic units are given in Table B-2.

Unit #1

Unit #1 consists of Precambrian metamorphic, igneous, and Tertiary intrusive rocks. Only the upper 500 ft of outcrops are studied. Freeze and Cherry (1979) give a range from 0 - 10% total porosity for fractured crystalline rocks. Based on the secondary porosity (joints and fractures), Rahn and Gries made a subjective evaluation of 3% for the total porosity and 1% for effective porosity. Thus the effective porosity is 33% of the total porosity.

Unit #2

Unit #2 consists of Cambrian and lower Ordovician rocks of the Deadwood Formation. The Deadwood Formation can be divided into 3 lithologic subdivisions: sandstone (200 ft thick), shale (30 ft thick), and limestone (200 ft thick). The range of porosity for these lithologies given by Freeze and Cherry (1979) are: sandstone 5 - 30%, shale 0 - 10%, and limestone 0 - 20%. Using an average porosity from these ranges and weighting these values by the thicknesses of rocks they represent, the porosity value for Unit #2 is calculated to be 13%. Upon subjective evaluation by Rahn and Gries, the porosity value for Unit #2 is given as 10% for the total porosity and 5% for the effective porosity.

Unit #3

Unit #3 consists partly of Ordovician rocks of the Winnipeg Formation and Whitewood (Red River) Formation. The remainder of this unit consists of Devonian rocks of the Englewood Limestone.

The Winnipeg Formation is composed of green shale and siltstone. Freeze and Cherry (1979) give a total porosity range for shale of 0 - 10%, and a range of 35 - 50% for silt. Average values of 5% and 42.5% are calculated for shale and silt, respectively.

The Whitewood (Red River) Formation is a buff dolomite and limestone. A range of 0 - 20% total porosity is given by Freeze and Cherry (1979) for limestone and dolomite. An average value of 10% is calculated from this range.

The Englewood Limestone is pink to buff limestone with shale locally at the base. Freeze and Cherry (1979) give a range of 0 - 20% total porosity for limestone. An average value of 10% is calculated from this range.

Using an average value from the ranges given for each formation, the total porosity of Unit #3 is calculated as 20%. Subjective evaluation by Rahn and Gries gives a total porosity value of 20% with an effective porosity of 10%.

Unit #4

Unit #4 consists of Mississippian rocks of the Pahasapa (Madison) Limestone, with a maxiumum thickness of 630 ft in South Dakota. An average total porosity value of 13% is calculated from oil-well logs from Wyoming (Wyo. Geol. Assoc., 1957). An average value of 11.4% is calculated from well-log analyses taken from Gries (1977). These values did not include porosity values less than 7%. Upon subjective evaluation by Rahn and Gries, the total porosity is given as 11% and the effective porosity as 5%.

Unit #5

Unit #5 consists of Pennsylvanian and Permian rocks of the Minnelusa Formation, having a maxiumum thickness of 805 ft in South Dakota. The Minnelusa Formation is composed of sandstones, shales, limestones, and anhydrites. An average of 14% for the total porosity is calculated from Wyoming oil-well logs (Wyo. Geol. Assoc., 1957). Subjective evaluation by Rahn and Gries gives a total porosity of 10% and an effective porosity of 5% for Unit #5.

Unit #6

Unit #6 consists of Permian rocks of the Opeche Formation, composed of red shale and sandstone. Freeze and Cherry (1979) give a range for total porosity of 0 - 10% for shale and 5 - 30% for sandstone. Using the average of these ranges, a total porosity for Unit #6 is calculated as 11.2%. Subjective evaluation by Rahn and Gries gives a total porosity of 12% and an effective porosity of 2%. Thus the effective porosity is 17% of the total porosity.

Unit #7

Unit #7 consists of Permian rocks of the Minnekahta Limestone, having a maximum thickness of 50 ft in South Dakota. The Minnekahta Limestone is gray, massive, laminated limestone. An average total porosity value of 13% is calculated for Unit #7 from Wyoming oil-well logs (Wyo. Geol. Assoc., 1957). Subjective evaluation by Rahn and Gries gives a total porosity value for Unit #7 of 8% and an effective porosity of 5%.

Unit #8

Unit #8 consists of Permian?, Triassic, and Jurassic rocks of the Spearfish Formation and Gypsum Spring Formation. The Spearfish is composed of shale, sandstone, siltstone, and gypsum. Its maximum thickness is about 700 ft in South Dakota. An average value for the total porosity of 16% is calculated from Wyoming oil-well logs (Wyo. Geol. Assoc., 1957). The Gypsum Spring Formation is composed of siltstone, gypsum, and limestone. Using an average value for the ranges given by Freeze and Cherry (1979), the total porosity of the Gypsum Spring Formation is calculated as 26%. Weighting the total porosity values by the thicknesses of rock they represent, a total porosity value of 16.6% is calculated. Subjective evaluation by Rahn and Gries gives a total porosity value of 15% and an effective porosity value of 2%.

Unit #9

Unit #9 consists of Jurassic rocks of the Sundance Formation, with a maximum thickness of 450 ft in South Dakota. The Sundance Formation is composed of shale and sandstone, with thin lenses of limestone. An average value of 18% for the total porosity is calculated from Wyoming oil-well logs (Wyo. Geol. Assoc., 1957). Subjective evaluation by Rahn and Gries gives a total porosity of 15% and an effective porosity of 3%.

Unit #10

Unit #10 consists of Jurassic rocks of the Morrison Formation and Unkpapa sandstone. The Unkpapa Sandstone consists of massive, fine-grained sandstone with a maximum thickness of 225 ft in South Dakota. The Morrison Formation is a shale with little sandstone, having a maximum thickness in South Dakota of 220 ft. A total porosity value of 12% is calculated from Wyoming oil-well logs (Wyo. Geol. Assoc., 1957). The total porosity value for the Unkpapa Sandstone is calculated as 17.5% from the range given by Freeze and Cherry (1979). These values are weighted by the thicknesses they represent, yielding a total porosity for Unit #10 of 14.8%. Subjective evaluation by Rahn and Gries gives a total porosity of 12% with an effective porosity of 3%.

Unit #11

Unit #11 consists of Lower Cretaceous rocks of the Lakota Formation, Fall River Sandstone, and Skull Creek Shale. The Lakota and Fall River Formations are composed of sandstone, having a combined maximum thickness of 898 ft in South Dakota.

Siok (1972) determined the porosity of the Lakota and Fall River Formations through an analysis of sonic and bulk density logs. He found that the porosity of this aquifer varies laterally, from 12% in northwestern South Dakota to 30% near the Missouri River. The average value of porosity for this sandstone is 20% (Siok, 1972). The reader is referred to Siok's South Dakota School of Mines and Technology M. S. thesis (1972, pl. III) for an isoporosity map of the Lakota and Fall River sandstones.

The Skull Creek Shale is a dark gray marine shale, approximately 270 ft thick in South Dakota. Freeze and Cherry (1979) give a porosity range of 0 - 10% for shale. ~~Subjective evaluation by Rahn and Gries for Unit #11 gives a total porosity of 12% and an effective porosity of 3%~~.

Unit #12

Unit #12 consists of Lower Cretaceous Newcastle Sandstone and its equivalent Dakota Sandstone. The porosity of the Newcastle Sandstone was determined by Baker (1972) through an analysis of sonic, bulk density, and gamma ray well logs. He reports that the porosity of this aquifer varies laterally, from 2% in Meade County to 32% near the Missouri River. An average porosity value is given as 23% total porosity (Baker, 1972). For an isoporosity map of the Newcastle Sandstone the reader is referred to Baker's South Dakota School of Mines and Technology M. S. thesis (1972, pl. IV). ~~Subjective evaluation by Rahn and Gries gives a total porosity for Unit #12 of 15% and an effective porosity of 10%.~~

Unit #13

Unit #13 consists of Lower and Upper Cretaceous rocks, including the Mowry Shale, Belle Fourche Shale, Greenhorn Formation, Carlile Formation, Niobrara Formation, and Pierre Shale. The Mowry Shale, Belle Fourche Shale, Carlile Formation, and Niobrara Formation are composed mainly of shale, and together represent a total thickness of up to 1775 ft in South Dakota. An average total porosity value of 5% is calculated from the 0 - 10% range given by Freeze and Cherry (1979). The Greenhorn Formation is composed of 30 ft of limestone and 250 ft of shale. An average total porosity value of 10% for limestone and 5% for shale is calculated from ranges given by Freeze and Cherry (1979). Weighting these values by the interval of rocks they represent, a total porosity value of 5.4% is calculated for the total thickness of the Greenhorn Formation. The Pierre Shale is composed dominantly of shale with minor limestone lenses. In South Dakota it has a maximum thickness of about 2000 ft. An average total porosity of 33.4% is calculated from data taken from Croft (1974) and Russell (1925) for this formation. An average total porosity of 19% is calculated for Unit #13 by weighting the total porosity value for each formation by its thickness. Subjective evaluation by Rahn and Gries gives a total porosity value of 20% and an effective porosity value of 1%.

Unit #14

Unit #14 consists of Upper Cretaceous rocks of the Fox Hills Formation, having a maximum thickness of over 300 ft in South Dakota. The Fox Hills Formation is composed of grayish-white to yellow sandstone, with some shale. An average value of 39% for the total porosity was calculated from data taken from Croft (1974) and Randich (1975). Subjective evaluation by Rahn and Gries gives a total porosity value of 20% and an effective porosity value of 5%. This assumes an effective porosity of 25% of the total porosity.

Unit #15

Unit #15 consists of Upper Cretaceous and Paleocene rocks of the Hell Creek Formation and the Fort Union Formation. The Hell Creek Formation consists of shale and sandstone and attains a maximum thickness of about 425 ft in South Dakota. A total porosity value of 36.5% is calculated from data taken from Croft (1974) and Randich (1975). The Fort Union Formation can be divided into three members: The Ludlow Member (350 ft thick), the Cannonball Member (225 ft thick), and the Tongue River Member (425 ft thick). The total porosity for these members is calculated as: 33.5% for the Ludlow Member, 35.5% for the Cannonball Member, and 35.1% for the Tongue River Member. These calculations are based on data from Croft (1974) and Randich (1975). Weighting these values by the thickness each represents, a total porosity value of 35.2% is calculated. Subjective evaluation by Rahn and Gries gives a total porosity value of 30% and an effective porosity value of 5%.

Unit #16

Unit #16 consists of Oligocene sedimentary rocks of the White River Group. The White River Group is composed of clay with some sandstone and limestone. The maximum thickness of Unit #16 in South Dakota is 600 ft. The total porosity is calculated to be 30%, averaged from data taken from Rothrock (1942). Subjective evaluation by Rahn and Gries gives a total porosity value of 30% and an effective porosity of 1%.

Unit #17

Unit #17 consists of Miocene rocks of the Arikaree Group. This unit is composed of sands and silts, having a maximum thickness of 100 ft in South Dakota. The total and effective porosities are calculated as 36.1% and 21.5%, respectively, based on data taken from Whitcomb (1965). Subjective evaluation by Rahn and Gries gives a total porosity value of 35% and an effective porosity value of 10%.

Unit #18

Unit #18 consists of Pliocene sands and silts of the Ogallala Group. The total and effective porosities of the sands and of the silts of the Ogallala Group are calculated as 38.8% and 32.7%, respectively. These values are based on data taken from Barari (1966). Subjective analysis by Rahn and Gries gives a total porosity of 35% and an effective porosity of 25%.

Unit #19

Unit #19 consists of Quaternary sands and gravels. A total porosity of 35% is calculated from the averages of the ranges for unconsolidated sands and gravels. Freeze and Cherry (1979) give a range for total porosity of 35 - 40% for sands and 30 - 40% for gravels that are unconsolidated. Subjective evaluation by Rahn and Gries gives a total porosity value of 25% and an effective porosity of 20%.

REFERENCES CITED

Baker, R. K., 1972: The ground water capacity of the Newcastle-Dakota Sandstone in central and western South Dakota: Unpub. M. S. thesis, S. Dak. School of Mines and Tech., 130 p.

Barari, A., 1966: Ground water supply for the City of Winner: S. Dak. Geol. Survey Special Rept. 36, 12 p.

Bouwer, H., 1978: Groundwater hydrology: McGraw-Hill, New York, 480 p.

Croft, M. G., 1978: Ground-water basic data for Adams and Bowman Counties, North Dakota: N. Dak. Geol. Survey Bull. 65, part II, 294 p.

Davis, S. N., 1969: Porosity and permeability of natural materials, In Flow through porous media (R. J. M. DeWiest, ed.): Academic Press, New York, p. 54-89.

Davis, S. N. and DeWiest, R. J. M., 1966: Hydrogeology: John Wiley and Sons, New York, 463 p.

Gries, J. P., 1977: Geothermal applications on the Madison (Pahasapa) aquifer system in South Dakota, Appendix B: National Technical Information Service, U. S. Dept. of Commerce, Springfield, Virginia, 95 p.

Keene, J. R., 1973: Ground-water resources of the western half of Fall River County, South Dakota: Unpub. M. S. thesis, S. Dak. School of Mines and Tech., 36 p.

Niven, D. W., 1967: Determination of porosity and permeability of selected sandstone aquifers in South Dakota: Unpub. M. S. thesis, S. Dak. School of Mines and Tech., 31 p.

Randich, P. G., 1975: Ground-water basic data for Grant and Sioux Counties, North Dakota: N. Dak. Geol. Survey Bull. 67, part II, 303 p.

Rothrock, E. P., 1942: A hydrologic study of the White River valley: S. Dak. Geol. Survey Rept. of Inv. No. 41, 17 p.

Russell, W. L., 1925: Well log in north Ziebach County: S. Dak. Geol. and Nat. History Survey Circ. 18, 6 p.

Schoon, R. A., 1971: Geology and hydrology of the Dakota Formation in South Dakota: S. Dak. Geol. Survey Rept. of Inv. No. 104, 55 p.

Siok, W. J., 1972: Total water storage capacity of the Fall River-Lakota Sandstones, and of the Dakota Formation east of the zero Skull Creek Shale line in South Dakota: Unpub. M. S. thesis, S. Dak. School of Mines and Tech., 130 p.

Walton, W. C., 1970: Groundwater Resource Evaluation: McGraw-Hill, New York, 664 p.

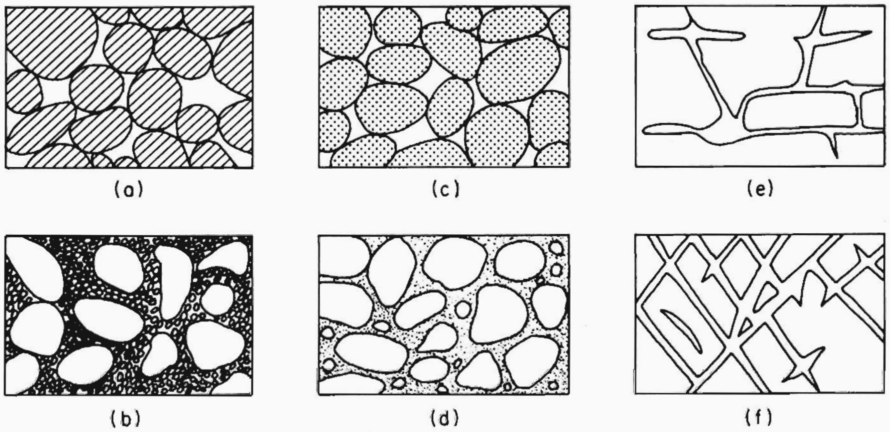
Whitecomb, H. A., 1965: Ground-water resources and geology of Niobrara County, Wyoming: U. S. Geol. Survey Water Supply Paper 1788, 44 p.

Whitecomb, H. A. and Morris, D. A., 1964: Ground-water resources and geology of northern and western Crook County, Wyoming: U. S. Geol. Survey Water Supply Paper 1698, 17 p.

Wyoming Geological Association, 1957: Wyoming oil and gas fields symposium: Wyo. Geol. Assoc., Casper, 579 p.

Figure B-1

Relation between texture and porosity.
(from Freeze and Cherry, 1978)



Relation between texture and porosity. (a) Well-sorted sedimentary deposit having high porosity; (b) poorly sorted sedimentary deposit having low porosity; (c) well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity; (d) well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices; (e) rock rendered porous by solution; (f) rock rendered porous by fracturing.

TABLE B-1

Range of Values of porosity.

Unconsolidated deposits	n (%)
Gravel	25-40
Sand	25-50
Silt	35-50
Clay	40-70
Rocks	
Fractured basalts	5-50
Karst limestone	5-50
Sandstone	5-30
Limestone, dolomite	0-20
Shale	0-10
Fractured crystalline rock	0-10
Dense crystalline rock	0-5

Freeze and Cherry, 1979, Table 2.4

Table B-2

Adjusted total and effective porosity values.

Unit	Total Porosity %	Effective Porosity %
1	3	1
2	10	5
3	20	10
4	11	5
5	10	5
6	12	2
7	8	5
8	15	2
9	15	3
10	12	3
11	26	17
12	27	18
13	20	1
14	20	5
15	30	5
16	30	1
17	35	10
18	35	25
19	25	20

APPENDIX C

GROUND WATER QUALITY

by Larry Van Stone

Table C-1 presents 384 measurements of ground water quality in western South Dakota. These data were compiled from a number of sources, as noted in the references cited in the text.

Figure C-1 shows histograms of TDS for the ten units with fifteen or more determinations, and Figure C-2 shows cumulative curves derived from the histograms. Note that the data are weighted equally. Although we have, in effect, a "presenting sample", it is not random because the locations occur in clusters; no one intentionally will drill for water in a rock unit that is known to contain saline water in their area. Fortunately, saline water in oil and gas wells has been analyzed in enough cases to give us a more complete spectrum of data.

To assess the effect of data-point clustering, area-weighting of measurements was done for three units. For each of the three, well locations were plotted and a "polygon of influence" drawn about each point. Cumulative curves made with the unweighted data were only a little different from those made with the unweighted data.

Of more immediate interest is the statistical presentation of the data used for the histograms, in Figure C-2. The geometric (log-normal) mean and standard deviation for each of those ten units can be inferred there. (NOTE: the geometric standard deviation is a multiplying factor, not an additive term). The general decrease in both quantities with decreasing age is clear, with equally clear variations resulting from lithology: sandstones have better water than limestones and shales. Part of the age trend is due to the depth of burial; Units #3 and #4 lie deep enough to encounter hydrothermal brines. However, the Paleozoic and Cenozoic rocks are marine, and originally contained as much as 1% connate salt, which concentrates downward in time. The Tertiary and younger rocks, starting with Unit #14 (Fox Hills) are terrestrial sediments, having no need to be flushed of connate salt (except near old playas). The relatively higher dissolved solids content of the Quaternary and Recent gravels is partly due to down-river increases in ground water contributions from sediments containing soluble minerals.

TABLE C-1 Water Quality in Western South Dakota

Hydrogeologic Unit 01 - Precambrian Rocks

Location		County	TDS	SAR
3S 4E	15	Custer	205	.6
1S 5E	30	Pennington	295	.6

Hydrogeologic Unit 02 - Cambrian Deadwood Formation

Location		County	TDS	SAR
22N 19E	11	Corson	39670	92.9
4S 2E	2	Custer	278	.10
1N 7E	31	Pennington	313	.2
17N 15E	7	Perkins	1750	23.4

Hydrogeologic Unit 03 - Ordovician Rocks

Location		County	TDS	SAR
22N 19E	11	Corson	131000	127.1
22N 19E	11	Corson	76900	---
12N 22E	8	Dewey	2510	1.2
13N 22E	21	Dewey	2856	4.0
13N 22E	29	Dewey	12542	23.7
17N 1E	1	Harding	3300	7.9
20N 4E	11	Harding	5527	29.0
21N 3E	23	Harding	14212	40.0
21N 4E	4	Harding	19590	61.0
21N 4E	6	Harding	11828	43.0
21N 4E	7	Harding	14348	43.8
21N 4E	8	Harding	13315	54.0
21N 4E	12	Harding	16404	65.8
21N 4E	12	Harding	33381	99.0
21N 4E	28	Harding	7233	31.8
22N 3E	20	Harding	16647	63.0
17N 15E	7	Perkins	31000	62.8
17N 15E	7	Perkins	150000	117.0
20N 12E	13	Perkins	200000	132.2
20N 12E	13	Perkins	19000	61.8
21N 16E	19	Perkins	1290	17.0
7N 28E	18	Stanley	2029	1.4

TABLE C-1 Water Quality in Western South Dakota

Hydrogeologic Unit 04 - Mississippian Pahasapa Limestone

Location		County	TDS	SAR
8N 2E	22	Butte	2518	.03
9N 3E	27	Butte	2018	.4
21N 19E	8	Corson	16000	340.0
22N 19E	11	Corson	140000	222.8
22N 19E	11	Corson	7238	10.1
22N 19E	23	Corson	11800	21.9
6S 6E	15	Custer	865	18.1
6S 6E	15	Custer	999	18.0
12N 24E	17	Dewey	2080	.7
13N 22E	32	Dewey	2244	.4
16N 22E	25	Dewey	5000	10.6
16N 22E	25	Dewey	7330	--
9S 2E	1	Fall River	2980	28.1
9S 2E	2	Fall River	836	--
10S 2E	3	Fall River	1070	4.6
10S 2E	3	Fall River	1154	4.5
10S 2E	3	Fall River	1340	5.6
10S 2E	3	Fall River	1600	3.1
1N 20E	1	Haakon	1040	--
5N 24E	31	Haakon	2087	1.1
18N 1E	35	Harding	4097	6.3
20N 3E	7	Harding	25000	50.0
21N 7E	23	Harding	3882	16.1
1S 22E	1	Jackson	1681	--
5N 4E	5	Lawrence	290	--
5N 4E	15	Lawrence	195	.10
2N 9E	1	Meade	490	.2
5N 5E	11	Meade	3086	--
6N 6E	19	Meade	1213	--
42N 25W	32	Mellette	1270	.5
42N 26W	34	Mellette	1185	.5
2N 7E	34	Pennington	266	.07
17N 15E	7	Perkins	124000	128.5
20N 12E	13	Perkins	6600	9.5
5N 27E	22	Stanley	2064	.8
6N 27E	26	Stanley	2037	.6
7N 28E	18	Stanley	2247	1.0
41N 26W	8	Todd	1260	--
42N 25W	32	Todd	1170	--
13N 21E	31	Ziebach	2300	1.3

TABLE C-1 Water Quality in Western South Dakota

Hydrogeologic Unit 05 - Penn-Permian Minnelusa Formation

Location			County	TDS	SAR
7N	2E	3	Butte	2710	.9
8N	2E	22	Butte	2518	.03
8N	3E	2	Butte	2530	.6
9N	3E	27	Butte	1811	0
9N	5E	24	Butte	1581	1.1
4S	8E	25	Custer	2174	.5
6S	2E	34	Custer	5500	6.8
14N	29E	36	Dewey	4320	8.3
7S	5E	14	Fall River	1421	2.1
7S	5E	14	Fall River	1390	--
7S	5E	24	Fall River	1040	6.2
9S	5E	29	Fall River	2415	.7
3S	22E	31	Jackson	1870	50.7
6N	4E	21	Lawrence	324	.10
7N	1E	14	Lawrence	1644	.01
7N	1E	19	Lawrence	2630	.2
7N	1E	26	Lawrence	1210	--
7N	1E	32	Lawrence	410	.06
7N	1E	32	Lawrence	451	.10
7N	2E	15	Lawrence	1300	0
7N	2E	18	Lawrence	1680	.10
7N	3E	7	Lawrence	1298	.06
3N	7E	19	Meade	1045	.7
5N	5E	11	Meade	1060	.7
5N	7E	18	Meade	1026	--
5N	7E	19	Meade	2114	--
6N	6E	18	Meade	1213	.03
41N	26W	8	Mellette	1640	.6
42N	26W	21	Mellette	1270	.7
42N	26W	34	Mellette	1180	.5
1N	7E	2	Pennington	662	--
1N	7E	9	Pennington	230	1.6
1N	7E	10	Pennington	2542	--
2N	7E	23	Pennington	208	.1
4N	27E	9	Stanley	2372	1.3
42N	16W	21	Todd	1130	--
42N	26W	34	Todd	1060	--

Hydrogeologic Unit 07 - Permian Minnekahta Limestone

Location			County	TDS	SAR
7N	1E	11	Butte	2270	.10
4S	7E	25	Custer	2174	--
21N	19E	8	Corson	14550	--
7S	4E	19	Fall River	1788	--

TABLE C-1 Water Quality in Western South Dakota

Hydrogeologic Unit 07 - Permian Minnekahta Limestone

Location		County	TDS	SAR
7S 5E	13	Fall River	2040	--
6N 2E	5	Lawrence	280	--
7N 1E	30	Lawrence	410	--
7N 1E	30	Lawrence	942	.08
7N 2E	10	Lawrence	2130	.03
1N 7E	9	Pennington	2162	.10

Hydrogeologic Unit 08 - Triassic Spearfish Formation

Location		County	TDS	SAR
4S 7E	25	Custer	2174	--
7S 4E	19	Fall River	1788	--

Hydrogeologic Unit 09 - Jurassic Sundance Formation

Location		County	TDS	SAR
3S 7E	16	Custer	212	1.6
3S 8E	22	Custer	432	--
3S 8E	22	Custer	398	--
7S 2E	12	Fall River	1790	11.3
8S 5E	26	Fall River	1770	--
3S 14E	28	Pennington	7255	88.1
7N 28E	18	Stanley	2020	5.7
12N 24E	27	Ziebach	7620	15.5

Hydrogeologic Unit 10 - Jurassic Morrison Formation

Location		County	TDS	SAR
2N 9E	7	Meade	502	--

Hydrogeologic Unit 11+12 - Lower Cret., Newcastle thru Lakota

Location		County	TDS	SAR
8N 5E	6	Butte	733	190.0
8N 5E	7	Butte	605	15.4

ABLE C-1 Water Quality in Western South Dakota

Hydrogeologic Unit 11+12 - Lower Cret., Newcastle thru Lakota

Location			County	TDS	SAR
8N	5E	7	Butte	830	34.8
8N	5E	8	Butte	733	0
8N	8E	11	Butte	620	3.9
9N	2E	36	Butte	492	11.5
9N	4E	19	Butte	1107	1.4
9N	5E	24	Butte	616	32.9
9N	5E	24	Butte	1061	56.3
9N	5E	24	Butte	1104	41.8
22N	19E	11	Corson	4487	168.1
3S	8E	9	Custer	447	4.7
15N	26E	12	Dewey	3640	93.9
7S	1E	3	Fall River	955	--
7S	1E	3	Fall River	978	3.2
7S	1E	5	Fall River	1034	6.3
7S	1E	9	Fall River	947	--
7S	1E	9	Fall River	968	6.2
7S	1E	9	Fall River	1194	6.2
7S	1E	11	Fall River	1833	.9
7S	1E	16	Fall River	1180	--
7S	1E	16	Fall River	1199	50.0
7S	1E	17	Fall River	1090	8.5
7S	1E	19	Fall River	1099	6.4
7S	1E	23	Fall River	1840	.9
7S	2E	32	Fall River	2175	30.0
8S	1E	1	Fall River	1252	--
8S	2E	5	Fall River	2094	4.1
8S	2E	6	Fall River	1539	17.1
8S	2E	6	Fall River	1619	19.9
8S	2E	6	Fall River	1635	190.0
8S	2E	8	Fall River	1515	190.0
8S	2E	17	Fall River	1444	24.1
8S	2E	28	Fall River	2288	15.2
8S	2E	36	Fall River	1010	--
8S	6E	14	Fall River	1608	--
9S	2E	1	Fall River	1396	--
9S	2E	4	Fall River	1450	--
9S	5E	27	Fall River	2588	--
1N	20E	12	Haakon	1733	56.8
1N	20E	13	Haakon	1900	--
1N	20E	13	Haakon	2080	17.1
1N	20E	13	Haakon	2573	3.3
1N	21E	13	Haakon	3154	5.9
1N	22E	13	Haakon	2818	--
1N	23E	13	Haakon	2107	58.7
1N	25E	6	Haakon	2686	--
5N	23E	7	Haakon	7445	144.0
5N	23E	8	Haakon	6770	139.3

TABLE C-1 Water Quality in Western South Dakota

Hydrogeologic Unit 11+12 - Lower Cret., Newcastle thru Lakota

Location		County	TDS	SAR
6N 18E	31	Haakon	1980	124.9
6N 21E	11+12	Haakon	7870	66.5
6N 21E	12	Haakon	6963	141.3
6N 23E	31	Haakon	3370	108.0
7N 20E	20	Haakon	5717	185.8
7N 22E	21	Haakon	6211	19.1
8N 23E	26	Haakon	384	3.6
3N 24E	35	Haakon	2120	--
15N 2E	29	Harding	8894	100.6
15N 7E	4	Harding	4393	--
16N 3E	26	Harding	7154	117.0
20N 5E	22	Harding	9954	29.0
1S 21E	19	Jackson	2110	--
1S 22E	15	Jackson	4860	--
1S 22E	34	Jackson	2816	--
2S 18E	16	Jackson	1388	--
2S 22E	28	Jackson	1780	15.9
2S 22E	32	Jackson	1778	--
3S 22E	32	Jackson	1870	--
1S 30E	27	Jones	1992	66.3
2N 26E	22	Jones	2848	--
104N 72W	9	Lyman	2192	--
3N 8E	32	Meade	460	--
6N 5E	21	Meade	783	.10
6N 11E	20	Meade	728	--
9N 17E	16	Meade	2183	45.4
40N 25W	12	Mellette	1727	15.2
40N 25W	20	Mellette	1640	23.0
40N 29W	8	Mellette	1846	3.0
41N 25W	27	Mellette	1320	--
41N 25W	31	Mellette	1380	32.0
41N 25W	35	Mellette	1580	9.3
41N 26W	27	Mellette	1950	5.8
41N 26W	30	Mellette	1910	20.0
41N 26W	30	Mellette	1690	--
41N 27W	15	Mellette	1772	44.4
41N 27W	25	Mellette	2030	49.0
42N 25W	34	Mellette	1450	.4
42N 26W	27	Mellette	1600	--
42N 26W	27	Mellette	1740	30.0
42N 27W	1	Mellette	1820	66.0
42N 27W	2	Mellette	1900	53.0
42N 27W	23	MEllette	1890	30.0
42N 27W	23	Mellette	1750	--
42N 28W	22	Mellette	1960	1.6
42N 28W	30	Mellette	2390	14.0
42N 29W	7	Mellette	2560	33.0

TABLE C-1 Water Quality in Western South Dakota

Hydrogeologic Unit 11+12 - Lower Cret., Newcastle thru Lakota

Location		County	TDS	SAR
42N 30W	12	Mellette	2780	54.0
42N 30W	13	Mellette	1870	51.0
42N 30W	15	Mellette	3860	45.0
42N 31W	34	Mellette	1730	8.4
43N 25W	24	Mellette	1810	--
43N 26W	33	Mellette	1990	1.4
43N 27W	3	Mellette	1998	45.0
43N 27W	14	Mellette	1880	54.0
43N 28W	36	Mellette	1770	55.0
43N 30W	5	Mellette	1910	65.0
43N 30W	29	Mellette	3000	60.0
44N 30W	5	Mellette	1910	--
44N 31W	20	Mellette	1800	52.0
44N 31W	23	Mellette	1700	--
45N 32W	36	Mellette	4180	65.0
1N 8E	10	Pennington	1031	12.6
1N 15E	36	Pennington	738	27.7
2N 8E	13	Pennington	898	6.7
2N 12E	13	Pennington	895	--
4N 17E	7	Pennington	2330	109.6
4N 17E	3	Pennington	756	104.2
1S 16E	6	Pennington	671	--
1S 17E	6	Pennington	3902	--
2S 22E	32	Pennington	1847	--
17N 15E	7	Perkins	3850	108.5
20N 12E	13	Perkins	4260	103.2
3N 29E	5	Stanley	3587	42.9
5N 27E	14	Stanley	2080	3.0
5N 31E	15	Stanley	1405	55.1
109N 77W	17	Stanley	2100	1.0
8N 22E	32	Ziebach	4510	140.8
9N 19E	06	Ziebach	6337	147.0
10N 19E	12	Ziebach	3860	122.2
12N 24E	27	Ziebach	7190	--

Hydrogeologic Unit 13 - Upper Cretaceous, Pierre thru Mowry

Location		County	TDS	SAR
9N 5E	24	Butte	8152	--
19N 25E	5	Corson	1433	10.7
16N 25E	31	Dewey	1084	8.0
17N 26E	9	Dewey	2974	20.0
8S 6E	16	Fall River	1887	34.5
12S 5E	5	Fall River	4740	--

TABLE C-1 Water Quality in Western South Dakota

Hydrogeologic Unit 13 - Upper Cretaceous, Pierre thru Mowry

Location		County	TDS	SAR
97N 73W	16	Gregory	1470	3.4
15N 3E	21	Harding	49309	186.0
18N 1E	23	Harding	14524	82.0
40N 26W	18	Mellette	3748	92.0
2S 14E	1	Pennington	10587	91.3
96N 76W	33	Tripp	518	2.5
100N 76W	14	Tripp	3010	4.1
100N 77W	34	Tripp	1810	4.5
100N 77W	35	Tripp	3460	6.3

Hydrogeologic Unit 14 - Cretaceous Fox Hills Formation

Location		County	TDS	SAR
18N 23E	23	Corson	1368	20.6
18N 24E	3	Corson	376	2.1
18N 27E	3	Corson	916	7.0
18N 27E	31	Corson	348	.7
19N 26E	24	Corson	644	5.6
19N 26E	26	Corson	274	2.3
12N 23E	9	Dewey	2670	18.0
15N 24E	8	Dewey	1994	15.3
15N 23E	24	Dewey	624	1.2
16N 26E	2	Dewey	4268	32.6
17N 22E	32	Dewey	1260	--
17N 24E	14	Dewey	236	.4
10N 16E	3	Meade	3700	22.9
14N 13E	24	Perkins	1506	5.8
14N 14E	14	Perkins	1172	38.9
15N 15E	23	Perkins	1754	16.3
13N 18E	8	Ziebach	780	--
14N 19E	18	Ziebach	1395	--
15N 18E	4	Ziebach	296	1.1
15N 20E	30	Ziebach	1930	51.6

Hydrogeologic Unit 15 - Paleocene Fort Union & Hell Creek Fms.

Location		County	TDS	SAR
18N 17E	13	Corson	1070	32.0
21N 17E	14	Corson	3300	15.7
21N 19E	6	Corson	803	2.8
21N 19E	18	Corson	314	9.3

TABLE C-1 Water Quality in Western South Dakota

Hydrogeologic Unit 15 - Paleocene Fort Union & Hell Creek Fms.

Location			County	TDS	SAR
23N	22E	28	Corson	2000	42.4
12N	14E	8	Meade	384	.10
12N	15E	3	Meade	1120	27.7
12N	15E	10	Meade	1064	10.2
13N	11E	13	Perkins	1232	36.7
13N	11E	13	Perkins	1256	32.4
13N	11E	26	Perkins	340	1.2
13N	12E	33	Perkins	542	--
15N	13E	22	Perkins	1546	157.9
15N	14E	20	Perkins	874	24.8
17N	19E	29	Ziebach	1510	44.3
23N	16E	20	Perkins	2561	47.9

Hydrogeologic Unit 16 - Oligocene White River Group

Location			County	TDS	SAR
40N	27W	5	Mellette	672	2.0
40N	30W	22	Mellette	690	9.3
40N	30W	22	Mellette	778	17.3
41N	27W	19	Mellette	383	.5
41N	31W	5	Mellette	309	3.4
41N	45W	18	Shannon	324	1.6
96N	75W	17	Tripp	634	.5
98N	77W	33	Tripp	630	.2
98N	79W	9	Tripp	567	1.9
41N	34W	18	Washabaugh	481	15.7

Hydrogeologic Unit 17 - Miocene Arikaree Group

Location			County	TDS	SAR
36N	37W	8	Bennett	696	.6
36N	37W	12	Bennett	494	.3
38N	35W	31	Bennett	340	1.0
38N	36W	1	Bennett	356	.3
39N	35W	18	Bennett	396	5.6
39N	36W	28	Bennett	260	.14
40N	33W	3	Mellette	425	7.9
41N	31W	5	Mellette	268	.9
35N	41W	4	Shannon	934	.3
36N	43W	32	Shannon	207	.2
37N	26W	9	Todd	288	.5

TABLE C-1 Water Quality in Western South Dakota

Hydrogeologic Unit 17 - Miocene Arikaree Group

Location			County	TDS	SAR
38N	28W	5	Todd	303	4.3
38N	28W	5	Todd	370	--
38N	28W	16	Todd	272	.5
38N	30W	27	Todd	311	.7
38N	30W	34	Todd	499	5.5
38N	31W	1	Todd	228	1.3
38N	32W	11	Todd	177	.4
38N	32W	30	Todd	288	.7
39N	26W	33	Todd	272	.3
39N	28W	3	Todd	248	4.7
39N	28W	32	Todd	420	--
39N	29W	26	Todd	322	2.9
39N	29W	31	Todd	298	1.1
39N	31W	9	Todd	285	4.0
39N	32W	6	Todd	411	.9
40N	36W	2	Washabaugh	367	.6
41N	36W	25	Washabaugh	570	--
41N	37W	26	Washabaugh	340	--

Hydrogeologic Unit 18 - Pliocene Ogalalla Group

Location			County	TDS	SAR
36N	36W	13	Bennett	479	1.4
36N	38W	24	Bennett	144	.4
95N	72W	34	Gregory	266	.4
35N	28W	10	Todd	286	.2
36N	28W	7	Todd	272	--
36N	28W	7	Todd	448	--
36N	30W	34	Todd	298	.2
37N	30W	32	Todd	261	.4
37N	33W	27	Todd	194	.15
37N	33W	23	Todd	230	.14
38N	26W	8	Todd	244	.2
38N	27W	31	Todd	264	.4
96N	74W	22	Tripp	1484	.4
96N	74W	30	Tripp	794	.11
96N	76W	13	Tripp	497	.2
96N	79W	36	Tripp	239	.4
98N	76W	33	Tripp	350	.2

TABLE C-1 Water Quality in Western South Dakota

Hydrogeologic Unit 19 - Quaternary Sands and Gravels

Location			County	TDS	SAR
38N	37W	27	Bennett	412	.8
20N	28E	35	Corson	597	2.3
16N	27E	27	Dewey	1920	7.6
96N	72W	10	Gregory	581	.8
97N	72W	31	Gregory	246	.19
4S	28E	8	Jones	771	5.6
107N	74W	5	Lyman	520	2.3
40N	25W	5	Mellette	336	.7
40N	28W	7	Mellette	2620	5.0
41N	27W	12	Mellette	3150	2.8
42n	29W	34	Mellette	232	1.0
43N	26W	14	Mellette	2000	3.8
43N	28W	2	Mellette	1430	3.4
43n	28W	18	Mellette	3380	12.0
2S	5E	11	Pennington	98	.5
35N	32W	3	Todd	269	.9
36N	32W	1	Todd	324	2.7
36N	33W	10	Todd	182	.8
38N	30W	17	Todd	199	.9
98N	76W	28	Tripp	237	--
98N	77W	17	Tripp	424	2.0

APPENDIX D

AQUIFER TEST AND WELL YIELD DATA

by S. Dash

Table D-1 shows aquifer test and specific capacity data for individual wells in western South Dakota. The data were collected from the files of Dr. J. P. Gries and Dr. P. H. Rahn of the South Dakota School of Mines and Technology, as well as from published sources. The specific capacity of a pumped well is defined as the pump rate (gpm) divided by the drawdown (ft). Most tests were run for 1 or 2 hours. No correction was made for feet of aquifer penetrated.

Unit #1 - Crystalline Rocks

Data from 5 aquifer tests are available for Unit #1. In general, the metamorphic and igneous rocks have low permeability. Permeability is mainly due to fracturing and is confined to within a few hundred feet of the surface. Available data (Table D-1) show that the average specific capacity of this unit is 0.78 gpm/ft. There are undoubtedly many other producing wells in the Black Hills, but they have low yields and data are not available.

Unit #2 - Deadwood Formation

Limited data are available for Unit #2 in western South Dakota. In general, the Deadwood Formation yields a small to moderate amount of fresh to saline water for stock and domestic purposes. Table D-1 shows that the pumping rate varies from 25 gpm to 85 gpm. The only specific capacity datum for this formation is 0.1 gpm/ft for a well in Pennington County. Some wells in Pennington, Custer, and Corson Counties are reported to have higher yields. Most of the counties in western South Dakota have no well yield data for Unit #2.

Unit #3 - Ordovician-Devonian System

Unit #3 has no aquifer test or well yield data. According to the U. S. Geological Survey (1975), near the North Dakota border the sandstone in the Winnipeg Formation yields saline water under artesian pressure, and the Red River Formation (Whitewood) has a excellent potential.

Unit #4 - Madison Limestone

Unit #4 is a major hydrogeologic unit. The average yield for the Madison Limestone (Table D-1) is 218 gpm. The range of the yield is from 10 gpm to 2050 gpm. Most of the wells are in Lawrence, Fall River, Meade, Pennington, Dewey, and Haakon Counties. Rahn (1979) determined a coefficient of transmissivity (T) of 6400 gpd/ft and a coefficient of storage (S) of 0.000,065 for the Madison near Fall River County. The average specific capacity of this unit (Table D-1) is 1.05 gpm/ft. Water from the Madison Limestone has considerable potential for domestic, irrigation, and stock supplies (USGS, 1975).

Unit #5 - Minnelusa Formation

This Unit is a major water-bearing unit. Most of the Minnelusa wells are in Lawrence, Pennington, Fall River, and Butte Counties. Well yields vary from 6 gpm to 1000 gpm, with a mean of 153 gpm. The average specific capacity of this Unit is 1.06 gpm/ft (Table D-1). A well near Sturgis had an inital flow of 4,000 gpm. Many ranches close to the Black Hills outcrop area obtain water from this formation for stock and domestic uses (USGS, 1975).

Unit #6 - Opeche Formation

The Opeche Formation has no aquifer test or well yield data as it is primarily shale, having a low permeability.

Unit #7 - Minnekahta Limestone

Limited data are available for Unit #7. The average well yield and specific capacity of this Unit are 86 gpm and 0.4 gpm/ft., respectively.

Unit #8 - Spearfish Formation

There are no aquifer test or well yield data available for Unit #8.

Unit #9 - Sundance Formation

The Sundance Formation, Unit #9, yields some water in western South Dakota which is used for domestic and stock purposes. There are no known aquifer test or pumping data exclusively for the Sundance Formation.

Unit #10 - Morrison Formation

There are no aquifer test or well yield data for Unit #10.

Units # 11 & #12 - Cretaceous Sandstones

Units #11 and #12 are a major source of water in South Dakota. The average well yield and specific capacity of these Cretaceous sandstones (Table D-1) are 118 gpm and 0.2 gpm/ft, respectively. Well flows as large as 1500 gpm have been measured by U. S. Geological Survey personnel. Rahn and Gries (1973) determined an average coefficient of transmissivity (T) and storage (S) of 2165 gpd/ft and 0.000,0233, respectively, for the Fall River-Lakota Sandstones at Wall. The coefficient of transmissivity (T) is 1333 gpd/ft for the Fall River-Lakota Sandstones at Box Elder city well #2 (Miller and Rahn, 1974). Numerous wells in Jackson, Haakon, Fall River, Pennington, and Todd Counties yield water from this unit for domestic and livestock supplies.

Unit #13 - Cretaceous Shale

Unit #13 has no aquifer test or well yield data.

Unit #14 - Fox Hills Formation

For Unit #14, the Fox Hills Formation, data are available only in

Perkins and Harding Counties (Table D-1), but it is known that this formation is a good source of water in other areas. The average specific capacity is 0.29 gpm/ft. Armstrong (1978) estimated the coefficients of transmissivity (T) and storage (S) to be 598.4 gpd/ft and 0.007, respectively, for a well in section 19, T. 135 N, R. 76 W, Emmons County, North Dakota, just north of the North Dakota-South Dakota border.

Unit #15 - Hell Creek Formation, etc.

No aquifer test data are available for Unit #15. Much of the Hell Creek Formation is unsaturated, but the lower part of this formation appears to be very permeable. Armstrong (1978) determined yields of 3 to 4 gpm in section 10, T. 136 N, R. 77 W, Emmons County, North Dakota. In general, the Hell Creek Formation yields a small to moderate amount of water in Corson, Harding, Perkins, and Ziebach Counties for irrigation use.

Unit #16 - White River Group & Unit #17 - Arikaree Group

There are no aquifer test or well yield data for Units #16 or #17.

Unit #18 - Ogallala Formation

The Ogallala Formation is greenish-colored, medium-grained pure quartz sandstone which is poorly indurated. It has high permeability. Usually this formation is deemed to be under water-table conditions. Rahn and Paul (1975) pumped a well at 726 gpm over 5-day test period in section 22, T. 36 N, R. 32 W, Todd County, South Dakota, and determined the cofficient of transmissivity (T) to be 26,570 gpd/ft and the coefficient of storage (S) to be 0.0548. Wells in Gregory, Tripp, Mellette, and Todd Counties produce water from this formation. This aquifer has considerable potential for development.

Unit #19 - Alluvium

Limited data are available on pumping rates for individual wells in Unit #19. In general, the alluvium is extremely permeable near the Black Hills but rapidly becomes fine -grained and hence less permeable down-valley. For example, the city of Belle Fourche obtained an average of 1.2 million gallons per day in 1977 from an infiltration gallery in alluvium near Spearfish, while the towns of Murdo and Box Elder, farther from the Black Hills, could not obtain adequate municipal supplies from alluvium.

Table D-1 is a bar graph showing the average specific capacity for each hydrogeologic Unit.

REFERENCES CITED

Armstrong, C. A., 1978: Ground-water resources of Emmons County, North Dakota: N. Dak. Geol. Survey Bull. 66, part III.

Davis, A. D., 1979: Hydrogeology of the Belle Fourche water infiltration gallery area, Lawrence County, South Dakota: Unpub. M. S. thesis, S. Dak. School of Mines & Tech., 60 p.

Miller, R. H., and Rahn, P. H., 1974: Recharge to the Dakota Sandstone from outcrops in the Black Hills, South Dakota: Association of Eng. Geologists Bull., Vol. XI, No. 3, 230 p.

Rahn, P. H., 1979: Effect of the proposed ETSI coal slurry pipeline on water resources in Wyoming, South Dakota and Nebraska: Proc. S. Dak. Acad. Sci., Vol. 58.

Rahn, P. H., and Gries, J. P., 1973: Calculation of permeability of Cretaceous sandstones from pumping and static level data in selected areas of western South Dakota: U. S. Dept. of Interior Project No. A-034-SDAK.

Rahn, P. H., and Paul, H. A., 1975: Hydrogeology of a portion of the Sand Hills and Ogallala aquifer, South Dakota and Nebraska: Ground Water, Vol. 13, No. 5.

U. S. Geological Survey, 1975: Mineral and water resources of South Dakota: U. S. Govt. Printing Office, Washington, 313 p.

TABLE D-1 PUMPING DATA

Location	Hydrogeologic Unit	Pumping Data		
		Pumping Rate (gpm)	Drawdown (ft)	Sp. Capacity (gpm/ft)
Pennington,S.8,T.1N,R.5E	01 Precambrian	3	10	0.3
Pennington,S.13,T.1S,R.6E	01 Precambrian	10	13.8	0.7
Custer,S.24,T.5S,R.4E	01 Precambrian	5	---	---
Mount Rushmore, Well #3	01 Precambrian	52.5	30.15	1.74
Mount Rushmore, Well #4	01 Precambrian	46	125.2	0.38
Pennington,S.13,T.1N,R7E	02 Deadwood	85	---	---
Pennington,S.31,T.1N,R.7E	02 Deadwood	25	250	0.1
Meade,S.16,T.5N,R.5E	04 Mississippian	10	---	---
Lawrence,S.22,T.6N,R.2E	04 Mississippian	10	520	0.019
Lawrence,S.22,T.6N,R.2E	04 Mississippian	20	600	0.03
Fall River,S.2,T.9W,R.2E	04 Mississippian	300	---	---
Meade,S.1,T.6N,R.6E	04 Mississippian	19.7		2.7
Meade,S.21,T.5N,R.5E	04 Mississippian	300	105	2.85
Lawrence,S.15,T.5N,R.4E	04 Mississippian	30	260	0.11
Lawrence,S.14,T.5N,R.4E	04 Mississippian	10	235	0.04
Lawrence,S.14,T.5N,R.4E	04 Mississippian	16	335	0.048
Meade,S.19,T.6N,R.6E	04 Mississippian	2050	---	---
Dewey,S.17,T.12N,R.24E	04 Mississippian	110	---	---
Haakon,S.1,T.1N,R.29E	04 Mississippian	100	920	1.09
Pennington,S.12,T.1N,R.6E	04 Mississippian	11	---	---
Lawrence,S.15,T.6N,R.2E	04 Mississippian	540	560	0.96
Pennington,S.35,T.2N,R.6E	04 Mississippian	24	400	0.06
Pennington,S.35,T.2N,R.6E	04 Mississippian	48	480	0.1
Pennington,S.35,T.2N,R.6E	04 Mississippian	60	640	0.09
Fall River,S.3,T.10S,R.2E	04 Mississippian	400	112	3.6
Fall River,S.3,T10S,R.2E	04 Mississippian	506	165	3.07
Pennington,S.34,T.2N,R.7E	04 Mississippian	20	---	---
Pennington,S.12,T.1N,R.6E	04 Mississippian	11	---	---
Meade,S.30,T.3N,R.6E	05 Minnelusa	45	140	0.32
Meade,S.30,T.3N,R.6E	05 Minnelusa	100	260	0.38
Meade,S.30,T.3N,R.6E	05 Minnelusa	120	360	0.33
Lawrence,S.14,T.6N,R.3E	05 Minnelusa	50	100	0.5
Lawrence,S.29,T.7N,R.2E	05 Minnelusa	1000	---	---
Fall River,S.4,T.8S,R.5E	05 Minnelusa	15	---	---
Butte,S.10,T.7N,R.1E	05 Minnelusa	7	---	---
Butte,S.12,T.7N,R.1E	05 Minnelusa	800	---	---
Meade,S.4,T.2N,R.7E	05 Minnelusa	35	---	---
Meade,S.6,T.2N,R.7E	05 Minnelusa	10	---	---
Meade,S.6,T.2N,R.7E	05 Minnelusa	15	---	---
Meade,S.7,T.2N,R.7E	05 Minnelusa	45	---	---
Meade,S.30,T.3N,R.6E	05 Minnelusa	45	140	0.32
Meade,S.30,T.3N,R.6E	05 Minnelusa	100	260	0.38
Meade,S.30,T.3N,R.6E	05 Minnelusa	120	360	0.33
Meade,S.32,T.4N,R.6E	05 Minnelusa	40	---	---
Meade,S.32,T.4N,R.6E	05 Minnelusa	10	---	---
Meade,S.6,T.5N,R.5E	05 Minnelusa	50	325	0.15

Location	Hydrogeologic Unit	Pumping Data		
		Pumping Rate (gpm)	Drawdown (ft)	Sp. Capacity (gpm/ft)
Meade,S.6,T.5N,R.5E	05 Minnelusa	100	450	0.22
Meade,S.5,T.5N,R.5E	05 Minnelusa	30	130	0.23
Meade,S.25,T.5N,R.5E	05 Minnelusa	15	20	0.75
Meade,S.25,T.5N,R.5E	05 Minnelusa	70	420	0.17
Meade,S.9,T.5N,R.5E	05 Minnelusa	250	26	9.6
Lawrence,S.14,T.5N,R.4E	05 Minnelusa	80	20	4
Lawrence,S.14,T.5N,R.4E	05 Minnelusa	18	---	---
Lawrence,S.15,T.5N,R.4E	05 Minnelusa	6	---	---
Lawrence,S.15,T.5N,R.4E	05 Minnelusa	60	55	1.1
Lawrence,S.6,T.6N,R.1E	05 Minnelusa	15	121	0.123
Lawrence,S.6,T.6N,R.1E	05 Minnelusa	45	225	0.2
Lawrence,S.8,T.6N,R.1E	05 Minnelusa	20	74	0.27
Lawrence,S.15,T.6N,R.2E	05 Minnelusa	15	151	0.1
Lawrence,S.10,T.6N,R.2E	05 Minnelusa	275	---	---
Lawrence,S.14,T.6N,R.3E	05 Minnelusa	50	100	0.5
Lawrence,S.15,T.6N,R.3E	05 Minnelusa	25	90	0.28
Lawrence,S.17,T.6N,R.3E	05 Minnelusa	55	301	0.18
Lawrence,S.22,T.6N,R.4E	05 Minnelusa	10	40	0.25
Pennington,S.23,T.2N,R.7E	05 Minnelusa	150	---	---
Lawrence,S.15,T.7N,R.2E	05 Minnelusa	550	---	---
Lawrence,S.19,T.7N,R.2E	05 Minnelusa	750	---	---
Lawrence,S.21,T.7N,R.2E	05 Minnelusa	725	---	---
Lawrence,S.22,T.7N,R.2E	05 Minnelusa	700	---	---
Lawrence,S.29,T.7N,R.2E	05 Minnelusa	1000	---	---
Lawrence,S.32,T.7N,R.2E	05 Minnelusa	25	102	0.24
Lawrence,S.7,T.7N,R.3E	05 Minnelusa	550	90	6.1
Pennington,S.3,T.1S,R.7E	05 Minnelusa	70	35	2
Pennington,S.33,T.1N,R.7E	05 Minnelusa	60	---	---
Pennington,S.21,T.1N,R.7E	05 Minnelusa	17	---	---
Pennington,S.23,T.1N,R.7E	05 Minnelusa	8	---	---
Pennington,S.27,T.1N,R.7E	05 Minnelusa	40	---	---
Pennington,S.28,T.1N,R.7E	05 Minnelusa	20	---	---
Pennington,S.15,T.1N,R.7E	05 Minnelusa	75	300	0.25
Pennington,S.16,T.1N,R.7E	05 Minnelusa	12	30	0.4
Pennington,S.16,T.IN,R.7E	05 Minnelusa	30	50	0.6
Pennington,S.8,T.1N,R.7E	05 Minnelusa	30	12	2.5
Pennington,S.15,T.1N,R.7E	05 Minnelusa	10	255	0.039
Fall River,S.4,T.8S,R.5E	05 Minnelusa	15	---	---
Meade,S.26,T.3N,R.6E	07 Minnekahta	30	106	0.28
Meade,S.6,T.5N,R.5E	07 Minnekahta	25	75	0.33
Meade,S.7,T.2N,R.7E	07 Minnekahta	30	---	---
Lawrence,S.30,T.7N,R.1E	07 Minnekahta	93	---	---
Pennington,S.8,T.2N,R.7E	07 Minnekahta	250	385	0.65
Custer,S.22,T.3S,R.8E	11 Lakota	250	285	0.88
Custer,S.22,T.3S,R.8E	11 Lakota	200	19	10.53
Custer,S.22,T.3S,R.8E	11 Lakota	250	23	10.87
Jackson,S.34,T.1S,R.22E	11 Lower Cretaceous	43	220	0.19
Todd,S.7,T.38N,R.31W	11&12 Lower Cretaceous	300	---	---

Location	Hydrogeologic Unit	Pumping Data		
		Pumping Rate (gpm)	Drawdown (ft)	Sp. Capacity (gpm/ft)
Pennington,S.6,T.1S,R.16E	11 Lower Cretaceous	160	93	1.7
Pennington,S.18,T.2N,R.9E	11 Lower Cretaceous	200	107	1.87
Pennington, Wall #1	11 Lower Cretaceous	120	14.7	7.9
Jackson,S.28,T.1S,R.22E	12 Lower Cretaceous	30	90	0.33
Jackson,S.16,T.2S,R.18E	12 Lower Cretaceous	7	1000	0.007
Jackson,S.32,T.2S,R.24E	12 Lower Cretaceous	20	95	0.21
Jackson,S.28,T.2S,R.19E	12 Lower Cretaceous	25	130	0.19
Haakon,S.13,T.1N,R.22E	12 Lower Cretaceous	40	---	---
Fall River, S.16,T.7S,R.1E	11 Lower Cretaceous	15	---	---
Perkins,S.17,T.17N,R.16E	14 Fox Hills	10	55	0.2
Perkins,S.13,T.18N,R.13E	14 Fox Hills	8	35	0.23
Perkins,S.13,T.18N,R.13E	14 Fox Hills	6	30	0.2
Perkins,S.13,T.18N,R.13E (City Well)	14 Fox Hills	6	75	0.08
Perkins,Bison City Well#6	14 Fox Hills	25	275	0.09
Perkins,S.20,T.23N,R.16E	14 Fox Hills	80	90	0.9
Harding,S.2,T.15N,R.3E	14 Fox Hills	1.25	41	0.03
Harding,S.12,T.16N,R.1E	14 Fox Hills	18	20	0.9
Harding,S.13,T.16N,R.1E	14 Fox Hills	30	180	0.17
Harding,S.22,T.16N,R.2E	14 Fox Hills	5	63	0.08
Todd,S.22,T.36N,R.32W	18 Ogallala	726	61.5	11.8
Haakon,S.32,T.7N,R.23E	19 Alluvium	9	40	0.225
Pennington,S.32,T.1N,R.4E	19 Alluvium	30	0.458	65.5
Pennington,S.13,T.1S,R.6E	19 Alluvium	10	0.67	15
Pennington,S13,T.1S,R.6E	19 Alluvium	12	4	3

APPENDIX E

ANALYSIS OF LAND SUBSIDENCE

by S. Balakrishnan

Consequences of withdrawal of large amounts of water from an aquifer may be:

1. depletion of the water,
2. migration of water from other strata having poor quality of water, leading to contamination of the aquifer,
3. land subsidence, and
4. reduction of porosity of the permeable medium due to compaction.

Of these, land subsidence poses the greatest environmental risk.

Downward movement of ground surface is called subsidence (Bouwer, 1978). Subsidence is likely to develop when large amounts of water are removed from an unconsolidated artesian aquifer (Utgard, 1978). As ground water is pumped out, the 'effective stress' on the granular structure of the sediments increases, which causes settlement (Bolt, 1977).

Western South Dakota depends largely on ground water as a source of domestic, stock, and municipal supply. It is expected that large-scale withdrawal of ground water due to population growth and irrigation is likely in the near future. Therefore, a doubt may arise whether western South Dakota will also experience subsidence problems as in Arizona, California, or Venice, Italy. In Mexico City land has subsided by as much as 8.5 meters over a period of 50 years to 90 years (Bolt, 1977; Bouwer, 1978). Even though the known history of ground-water management in western South Dakota does not indicate any subsidence problem so far, this Appendix assesses any future possibility.

Total water withdrawal due to population growth in western South Dakota can be assessed and compared with the total water in storage in all the aquifers.

A trend in population growth in western South Dakota is calculated country-wise based on population growth that took place between 1970 and 1977 (S. D. Dept. Health, 1977). It is assumed that this growth is in exponential order, that is,

$$\frac{\text{population of 1977}}{\text{population of 1970}} = e^{\lambda t}$$

where t = the time interval
λ = a constant dictating the trend in growth.

Knowing the value of t, it may be possible to predict the population after any number of years. In this study a 20-year period is assumed. Relevant calculations are shown in Table E-1.

Assuming a per capita consumption rate of 100 gallons per day, it may be expected that in the next 20 years the total withdrawal of ground water in western South Dakota, having a population of 0.26 million, would not exceed 0.6 million acre-feet. This is a very small fraction of the total water in storage in different aquifers identified to exist in western South Dakota. It is believed, therefore, that there would not be any subsidence problem associated with future withdrawal of ground water.

In another approach, to study future land subsidence possibility under any conceivable future ground water use, a hypothetical case of complete withdrawal of water from certain aquifers has been considered. Units #15, #16, #17, #18, and #19 are the only semiconsolidated or unconsolidated sediments and hence the only units which could deform due to fluid withdrawal.

Maximum saturated thicknesses of Units #15 through #19 have been calculated (via isopach maps of these units and their percentages of saturation). The calculations are presented in Table E-2. The locations of these units are shown in the main text of this report. From this study it is noticed that a maximum subsidence of 16 ft could occur in Todd, Bennett, Perkins, and Harding Counties. If recharge and possible structural strength of some of the members of Units #15 through #18 are considered, the potential for subsidence will be much less.

REFERENCES CITED

Bolt, B. A., Horn, W. L., Macdonald, G. A., and Scott, R. F., 1977: Geological hazards: Springer-Verlag, New York, 330p.

Bouwer, Herman, 1978: Groundwater hydrology: John Wiley and Sons, New York, 480 p.

South Dakota Department of Health, 1977: South Dakota-vital statistics - annual report.

Utgard, R. O., McKenzie, G. D., Foley, D., 1978: Geology in urban environment: Burgess Publ. Co., New York, 480 p.

TASK I-B

IMPACT OF WEATHER MODIFICATION UPON SURFACE WATER SUPPLIES IN WESTERN SOUTH DAKOTA

by

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1 Introduction

Assessment of the possible effects of weather modification upon water supplies in any region is a two-part problem. The first part is the assessment of the changes in precipitation that would result from the application of cloud seeding technology. The second part is to use the expected changes in precipitation to estimate hydrological changes. Points to be considered include changes in runoff, ground water storage, and evaporation, as well as in such secondary factors as soil erosion.

A study of the possible hydrological effects of weather modification was included as part of a large scale study conducted at South Dakota State University (SDSU) on the "Effects of Additional Precipitation on Agricultural Production, the Environment, the Economy and Human Society in South Dakota" (Special Study Team, 1973). This report draws heavily on the material assembled by the Special Study Team, but uses more recent information on the probable effects of cloud seeding in South Dakota.

Weather modification projects have been conducted in many countries, and results have been presented in hundreds of reports, scientific papers, and review documents. However, there is a general agreement among meteorologists that the effects of cloud seeding vary with geographic location, with season, and with the types of clouds treated. Therefore, we shall rely principally upon the experience gained in weather modification experiments and operations in the northern Great Plains region in attempting to estimate probable effects of cloud seeding in western South Dakota. In order to assist the reader in identifying the sources of information quoted, we begin with a brief history of weather modification activities in South Dakota.

2 History of Weather Modification Activities in South Dakota

Weather modification began in South Dakota in about 1950, following the basic discoveries of Langmuir, Schaefer, and Vonnegut on the ability of dry ice, silver iodide, and water spray to hasten the formation of precipitation in clouds (e.g., Schaefer, 1976). The history of weather modification programs in South Dakota since 1950 is shown in Figure 1, which draws upon historical records on cloud seeding in the Dakotas and Minnesota as compiled by Schock (1977).

In the early 1950's many South Dakota farmers and ranchers made voluntary contributions to local organizations to launch "rain making" projects. All of these projects use networks of silver iodide (AgI) generators on the ground to release AgI crystals. The crystals were carried aloft by air currents to serve as ice nuclei around which (it was hoped) additional snowflakes and small hail would form. These particles would then melt to rain while falling to earth. Commercial cloud seeding was wide spread for several years, but in the late 50's discontentment increased and the operational activities diminished (Fig. 1).

The first extensive experimental seeding in the state was conducted

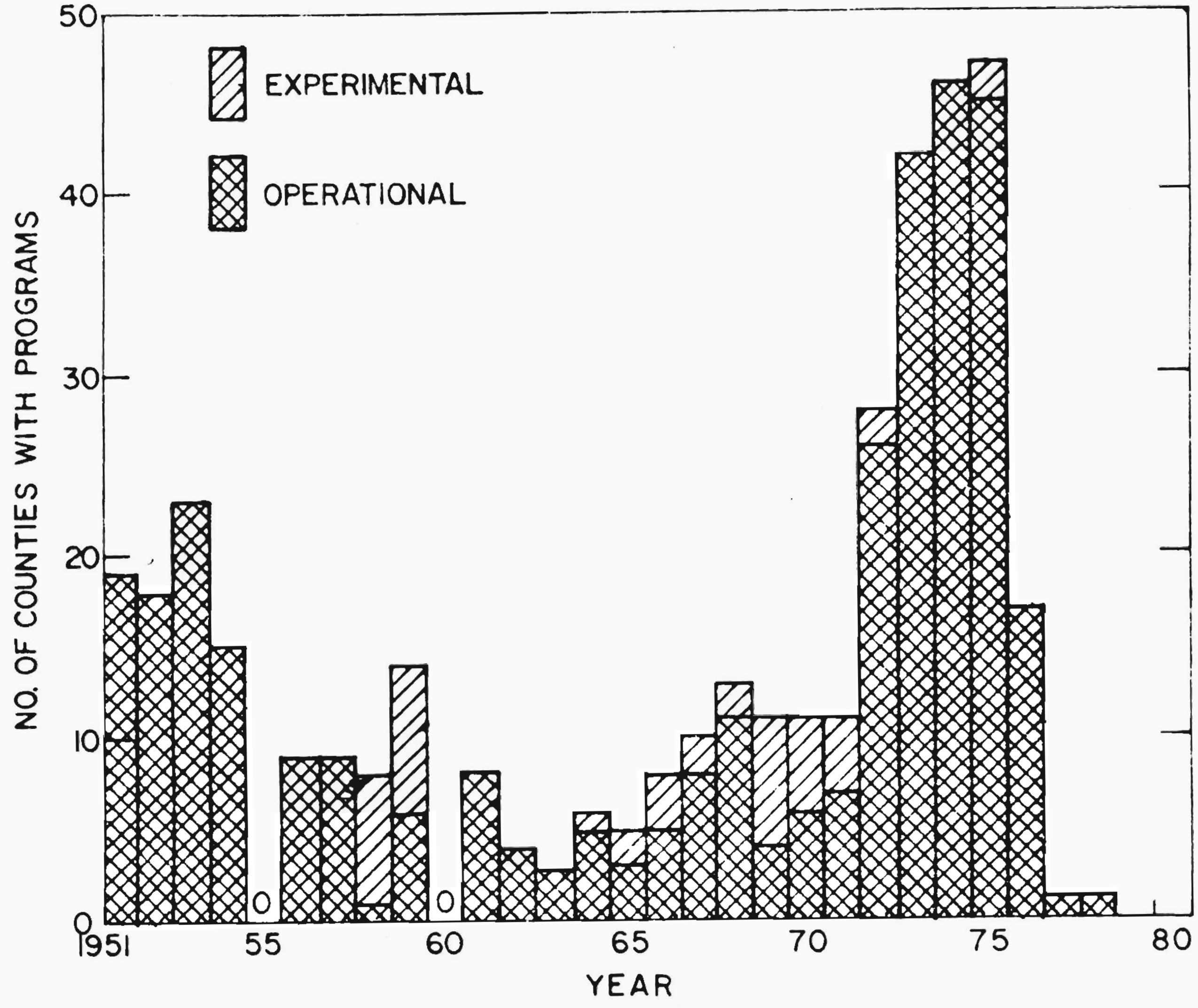

Fig. 1. History of weather modification in programs in South Dakota.

by SDSU in 1958 and 1959 (Schock, 1977). In 1959, the Board of Regents created the Institute of Atmospheric Sciences (IAS) at the South Dakota School of Mines and Technology to carry out weather modification research. Several years elapsed before the IAS launched its first field experiments. One very small, short experiment was conducted near Rapid City in 1962. The first IAS randomized experiment took place in 1964. Dr. Richard Schleusener became the first full-time director of the IAS in early 1965, and several experimental programs were conducted over the next eight summers. One of those programs, the North Dakota Pilot Project, was conducted in west central North Dakota.

Operational activities also increased, but in an irregular fashion, during the 1960's. While the programs of the 1950's had relied on ground based generators and had rainfall stimulation as their objective, several programs in the 1960's used airplanes for seeding and were intended to suppress hail as well as to increase rainfall.

In 1970, Mr. Marion Bruce, Chairman of the South Dakota Weather Modification Commission, asked the IAS to prepare a plan for a statewide cloud seeding program. Mr. Merlin Williams was hired as the state's first weather modification director in 1971. A cost-sharing program was funded by the state and participating counties beginning in 1972. From 1973 to 1975 this program, operated by the state's Division of Weather Modification, covered about two thirds of the state's 67 counties (Fig. 1). However, opposition developed following the dry summers of 1973 and 1974. The legislature declined to support the program beyond 30 June 1976. Only one county (Harding) had a program in 1977, 1978, and 1979.

3 Current and Future State-of-the-Art

3.1 Summertime Convective Clouds

Western South Dakota has a continental climate with about 60% of the annual precipitation concentrated in the growing season (May - August inclusive). Cloud seeding in the Dakotas has tended to concentrate upon convective clouds, which bring to the region most of its growing season rainfall.

Considerable research has been conducted on convective cloud processes, including cloud dynamics and precipitation formation. The research has involved the use of numerical cloud models, laboratory studies of cloud condensation nuclei and ice nuclei, and cloud seeding experiments in the field. The results of the various studies support the concept that one can change convective clouds and the precipitation that falls from them.

Cloud seeding affects convective clouds in two principal ways. First, the introduction of large particles to promote coalescence of liquid droplets of of materials to form ice crystals in supercooled clouds hastens the conversion of cloud water to precipitation. Second, the artificial freezing of supercooled water releases latent heat, which affects the dynamics of clouds and causes some clouds to grow larger. In field experiments, it is very difficult to distinguish the changes in precipitation due to the purely microphysical effects from those related to changes in cloud dynamics, so the material to follow simply reports the apparent changes in precipitation.

As noted above, the effects of weather modification must be evaluated on a regional basis, so we shall limit our discussion to projects which have been conducted in the northern Great Plains. Table 1 shows the projects to which reference will be made below and whose results form the basis for the conclusions presented.

Some of the IAS randomized experiments are not included in Table 1 because they ran for very short periods of time. One project (the Grand River Randomized Project of 1969-70) is omitted because of strong evidence of uncontrolled background variations which influenced the apparent results (Gelhaus et al., 1974).

Operational projects present a special problem in evaluation because ordinarily no cases are reserved as no-seed (control) cases. In some situations, notably orographic seeding projects, this difficulty can be overcome by use of nearby untreated areas as controls (e.g., Thom, 1957a). However, in the case of convective precipitation in South Dakota, target-control correlations are so low that target-control evaluations are of very limited value (e.g., Schleusener and Grant, 1964). Although attempts have been made over the years to evaluate operational cloud seeding projects in South Dakota (e.g., Boyd, 1971), we have included in Table 1 only the state supported operational program of 1972 to 1976. In that case, the large area seeded, amounting in some years to over half of the state, lends a stability to the results which is not found in the isolated small projects of previous years.

The data presented in Table 1 leave little doubt that some convective clouds can be seeded to produce additional rainfall. The Rapid Project results indicated increases in rainfall from moderate showers but were inconclusive regarding larger storms (Dennis and Koscielski, 1969; Chang, 1976). Studies of single clouds or cloud clusters in the Rapid City area in 1969-70 under the name of Project Cloud Catcher indicated that seeding effects (on a percentage basis) were most pronounced in small and medium sized clouds (Dennis et al., 1975a). The North Dakota Pilot Project (NDPP) results indicated large increases (∿70%) in area rainfall due to seeding during the final two years of the project (NDPP II), when an improved silver iodide solution was used in the cloud seeding generators. There were indications that the increases in rainfall were concentrated on days when cloud seeding with silver iodide would lead to dynamic effects (Dennis et al., 1975b).

One of the more interesting results of the NDPP analysis was the indication that cloud seeding increased the number of rainfall events at a point as well as the amount of rain per event. This change could be due to the initiation of showers which would not otherwise have occurred, to the expansion of the area covered by existing showers at a given moment, or to increases in shower lifetimes. All three possibilities are supported by the Cloud Catcher radar data (Dennis et al., 1975a).

The results of randomized experiments on convective clouds vary widely due to natural variability. Striking a balance, we estimate that precipitation

TABLE 1

Results of Cloud Seeding Projects in Northern Great Plains

Project		
Rapid	1966-68	Increases from shower clouds. Possible decreases for some large storms.[a]
Cloud Catcher I	1969-70	More rain from seeded clouds than from unseeded clouds of same depth.[b] AgI more effective than hygroscopic agent (NaCl); effects decrease with increasing cloud depth.[c]
North Dakota Pilot Project:		
NDPP I	1969-70	None.[d]
NDPP II	1971-72	Substantial increases, concentrated on days with possible dynamic effects (generally days with cloud tops in -10 to -30°C range). Chance of decreases on days with low upper-air temperatures.[d]
South Dakota State Operational Project	1972-76	7% increase.*[e]

a. Dennis and Koscielski (1969).
b. Cloud depth was determined by subtracting height of cloud base from maximum height of radar echo in each test case.
c. Dennis, _et_ _al._, (1975a).
d. Dennis _et_ _al._, (1975b).
e. Pellett _et_ _al._, (1977).

*Data suggest better results for May and June than for July and August.

in the western Dakotas during the growing season might be increased by as much as 10% per growing season. Schleusener and Boyd (1972) made a variety of target-control evaluations of one experiment and one operational project in western South Dakota. They found indications of rainfall increases averaging somewhere between 8 and 12% in IAS experiment and 7% in the operational project. The results of the South Dakota operational program, which covered much of the state from 1972 to 1976, indicate a 7% increase in rainfall (Pellett et al., 1977). A preliminary analysis of operational seeding in North Dakota indicates a similar result in that state (Eddy, 1979).

Possible reasons for the smaller indicated increases in the operational programs as opposed to the IAS experiments are: (1) the inclusion of unfavorable seeding opportunities in the data base, (2) requirement to cover large target areas with a limited number of seeding aircraft, and (3) inclusion of nocturnal rainfall in the evaluation.

There are some rain situations which are unfavorable for cloud seeding, for example, where continuous light rain falls from stratiform cloud decks with abundant ice crystals already present in their upper parts. On other occasions, light rain or drizzle forms by the coalescence process so that silver iodide seeding would again have no effect. In two of the randomized experiments, Rapid and Cloud Catcher, these cases were simply not declared as seeding opportunities, and so the rainfall on such days did not dilute the results. However, the NDPP design included such days in the evaluation, and the NDPP II results were as good as for the other experiments.

It may be that the larger areas covered in the operational programs meant that the seeding aircraft were "stretched thin" and that some favorable seeding opportunities were lost as a result.

Nighttime seeding operations involve both of the above possibilities. They may be less effective than daylight seeding because of differences in cloud characteristics between day and night, or because of the greater difficulties in conducting seeding operations by aircraft at night.

Taking a conservative posture, one can estimate that renewed operational seeding programs in western Dakotas would produce increases in precipitation similar to those experienced during 1972 to 1976, that is, an average increase of 7% in growing season rainfall. This figure might be increased slightly by a program with more seeding aircraft available than were used previously. However, we consider it highly unlikely that a seasonal increase of more than 10% could be produced by presently known seeding techniques.

There are no research breakthroughs in sight which would indicate any dramatic increase in the effectiveness of cloud seeding technology. Plans are underway in the National Oceanic and Atmospheric Administration and elsewhere for dynamic seeding experiments to influence the dynamics of thunderstorms, squall lines, and other mesoscale systems which contribute much of the summer rainfall in the northern Great Plains. However, recent workshops connected with such projects have shown that the proposed seeding concepts have not been reduced to a quantitative form that could be tested in numerical models or in field experiments. Therefore, it appears to us unrealistic to expect any dramatic breakthroughs in cloud seeding technology applicable to convective clouds in this region within the next 20 years.

3.2 Wintertime Orographic Systems

The most successful application of cloud seeding technology in the United States over the past 25 years have been the orographic seeding programs in the western states. Repeated evaluations of orographic seeding operations by commercial operators and experiments by research groups have indicated increases in annual snowpack in the range of 10 to 15% (e.g., Thom, 1957b; Panel, 1966; Panel, 1973). Investigations have shown that in certain favorable storms increases of as much as 50% of natural snowfall are possible, but the frequency of occurrence of such storms is such that only 10 to 15% seasonal increases should be anticipated (Vardiman and Moore, 1978; Elliott *et al.*, 1978).

Supercooled orographic cloud systems occur quite frequently over the Black Hills in the wintertime. There are also situations where upslope (easterly) winds cause the formation of supercooled straticumulus clouds over large areas of the state. Whiteman (1973) has studied the frequency of occurrence of these supercooled upslope clouds over the northern Great Plains by analyzing radiosonde data for the months of September through April over a 10-yr period. He estimated about 10 such occurrences per winter for Rapid City and 25 at Bismarck, North Dakota. As each occurrence is based on a radiosonde observation, and radiosonde observations are normally taken at 12-hr intervals, we can estimate 120 seedable hours per winter at Rapid City Regional Airport.

Orographic cloud seeding attempts in South Dakota have been very limited. During one winter the Terry Peak Ski Association contracted with Mr. Alexander Koscielski (formerly of the IAS) to seed with ground generators to increase snowpack at Terry Peak in the northern Black Hills. No formal evaluation of this operation was conducted, but Mr. Koscielski believed on the basis of visual observations that his efforts were successful.

On the basis of the results obtained elsewhere in similar cloud systems, it is the present authors' opinion that snowpack increases of up to 15% could be realized over the Black Hills. It is also possible that small increases could be produced over the plains on occasion, but the seeding opportunities there would be less frequent than over the Black Hills (say 120 hours per winter over the plains compared to perhaps 200 to 250 hours in the Hills).

In summary, it is believed that an average of 8% increase in annual precipitation can be achieved by a combined orographic and summer convective weather modification program in western South Dakota.

4 Assessment of Likely Hydrologic Changes Due to Increased Precipitation

The Special Study Team (1973) report developed various models of rainfall changes that might result from future weather modification programs and assessed hydrologic, economic, ecological, and sociological impacts of the precipitation increases.

The three models of seeding effects which they used (A, B, and C) are shown in Table 2. The models differ not only in the overall or expected increase in growing season precipitation, but in the way in which the increase is distributed over storms of different sizes as expressed in daily rainfall amounts. Also shown are a model K, which consists of a 15% increase on all types of storms, and a natural increase model N, which expresses the changes required to change rainfall distribution for a normal year into that characteristic of wet years.

We leave aside for the moment the question of which of these models is most appropriate in view of the information presented in Section 3, and move on to present the results of runoff modeling studies by Chu, which are included in Special Study Team (1973) report. The Special Study Team based their results for small watersheds on a paper by Lumb and Linsley (1971). Lumb and Linsley (1971) developed rainfall increase model which is more sophisticated than those of Table 2. It provided for a systematic decrease in the percentage increase in rainfall of storms of different sizes, somewhat like Model A., but with the proviso that only the upper one percentile of storms had a zero rainfall increase. The model also provided an element of randomness, with a substantial fraction of the increase consisting of a random element which could be positive or negative. Therefore, it was not necessary that all storms in a given category show an increase, but only that the expected value for all storms in a given size category show an increase.

Lumb and Linsley (1971) combined their rainfall increase model with output of the Stanford Watershed Model as calibrated by four streams in California and one in Australia to derive a figure showing how much of the added annual precipitation would runoff from small watersheds. One of the Lumb and Linsley curves was used by the Special Study Team to estimate what fraction of additional annual precipitation at various stations in South Dakota would appear as runoff in small water sheds of less than 50 mi^2. The curve is produced here as Fig. 2. The results for three locations in western South Dakota with widely varying runoff/precipitation ratios are reproduced in Table 3. We have extended the calculations beyond the end point in the Special Study Team report to show the expected increase in runoff for a 10% increase in rainfall in absolute terms and also as a percentage increase in annual runoff. It should be understood that these results are applicable to a typical season and would vary from year to year. What is impressive in Table 1 is the indication that a 10% increase in rainfall translates into an increase in small watershed runoff of 50 to 70% and that this percentage does not vary nearly as widely as the runoff precipitation ratio. We defer further discussion of this point until the results of the Special Study Team for medium sized and large watersheds have been presented.

4.1 Results for Intermediate Watersheds (50 m^2 - 1000 mi^2)

The Special Study Team analyzed intermediate sized and large watersheds by regression methods. For the intermediate watersheds, a step-wise multiple regression analysis was applied to estimate increases in runoff during the growing season (May to August). The monthly rainfall amounts for May to August were used as independent variables and the seasonal runoff was the dependent variable. The result indicated that 6 to 15% of the additional rainfall would run off.

TABLE 2

Rainfall Increase Models:
Percent Increase in Daily Rainfall Amounts

Daily Rainfall (in.)	Model A	Model B	Model C	Model K	Model N
≤ .10	100	75	50	15	0
.11 to .50	50	30	20	15	5
.51 to 1.00	20	10	0	15	15
>1.00	0	-10	-20	15	26
10-station average increase in growing season precipitation	3.14	1.55	.40	1.66	--
Average growing season increase	28.4%	14.0%	3.6%	15%	--

TABLE 3

Estimated Increase in Annual Runoff for Small Watersheds Due to 10% Increase in Annual Precipitation Following the Lumb and Linsley Rainfall Increase Model[a]

	Mobridge	Cottonwood	Newell
Average annual precipitation (in)	17.0	15.0	15.5
Present Average annual runoff (in)	0.3	0.5	0.9
Runoff/precipitation ratio	0.002	0.003	0.006
Increase in annual precipitation (in)	1.70	1.50	1.55
Fraction of increase converted to runoff	0.13	0.24	0.36
Increase in runoff (in)	0.2	0.36	0.56
Percentage increase in annual runoff	70	70	60

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a. Based on Special Study Team (1973).

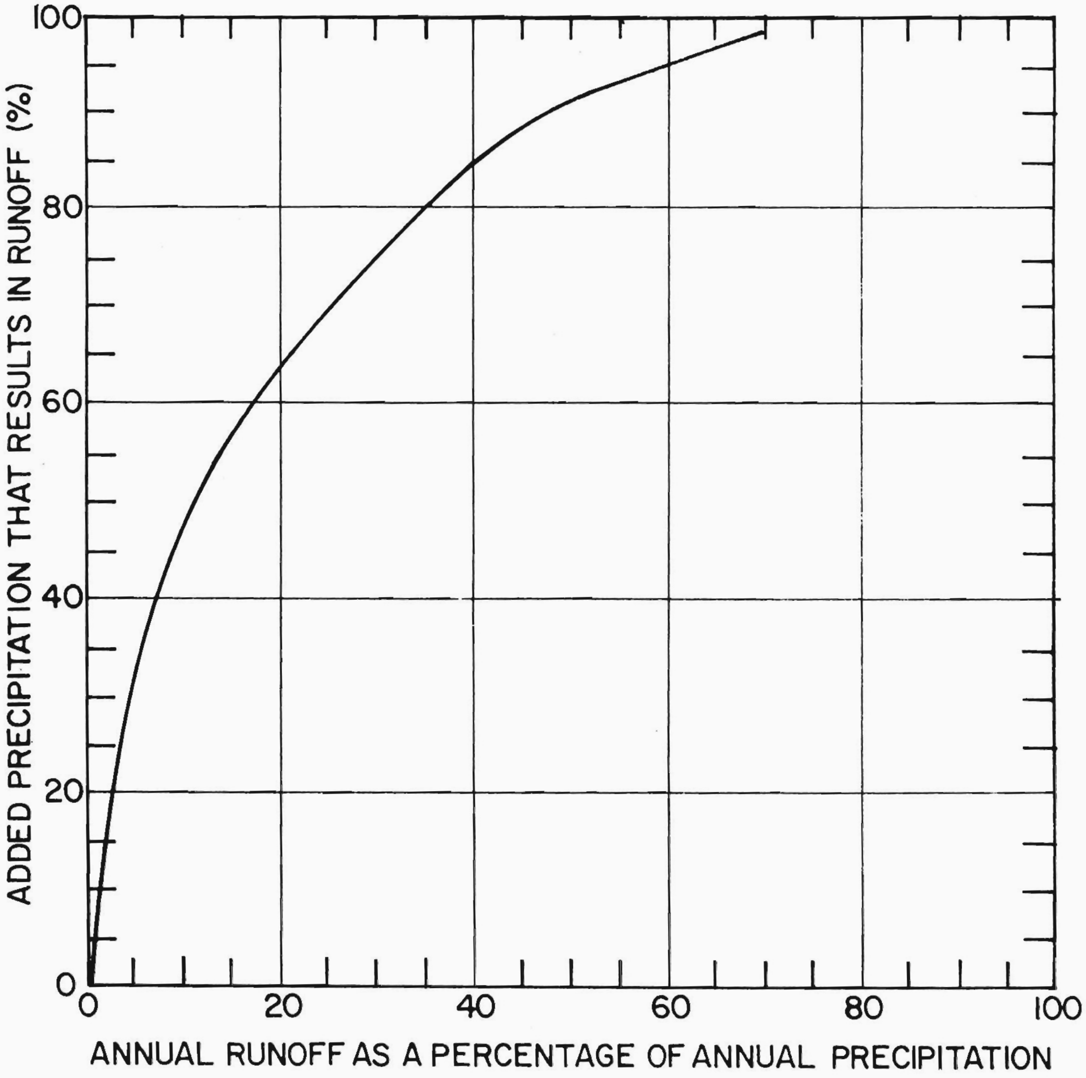

Fig. 2. Added annual precipitation that results in runoff.
Source: Lumb & Linsley, 1971.

4.2 Results for Large Watersheds (>1000 mi^2)

The Special Study Team's (1973) analysis of large watersheds followed yet another approach. It was assumed that the growing season runoff was of the form

$$Q = AX^B ,$$

where Q is seasonal runoff, X is the seasonal rainfall, and A and B are fitted constants. The

$$\Delta Q/\Delta X = B \cdot AX^{B-1} = BQ/X .$$

Results for the three large streams draining into the Missouri from western South Dakota are summarized in Table 4. It is seen that from 6 to 15% of the added seasonal rainfall should run off from the large watersheds. (This corresponds to a 25 to 30% increase in runoff as a function of current runoff measurements (Table 4).

4.3 Discussion

The calculated runoff increases expressed as a percentage of the natural runoff are less for the intermediate and large watersheds than for the small watersheds. Possible reasons include the use of different models and the comparison of growing season results in one case to annual results in the other. Due to reduced evaporation and evapotranspiration, the fraction of the increase in precipitation converted into runoff would be greater in winter than in the growing season. Nevertheless, it does appear that the percentage impact of additional rainfall would be greater in the small streams where the runoff represents a very small difference between rainfall and evaporation.

The increases calculated for both the intermediate and large watersheds are based on the assumption that cloud seeding causes the rainfall pattern in dry years to shift in a direction to make the rainfall statistics resemble more closely those of wet years. In other words, model N of Table 2 is assumed to apply. This model places the largest percentage increases in rainfall in the largest storms. Elementary reasoning suggests that the impact of rainfall upon precipitation would be maximized by concentrating the rainfall increases on the wettest days.

The results of the experiments in this region show the largest percentage increases in rainfall to be concentrated in the small storms. In many such cases, the soil would not become sufficiently wet to provide much runoff. Therefore, it appears that the runoff increases for a 10% rainfall increase due to seeding are overestimated in Tables 3 and 4.

Hanson and Woolhiser (1978) also studies the effects that changes in summertime rainfall would have on runoff on small watersheds in western South Dakota. They used numerous "simulated" changes in May through September precipitation ascribed to cloud seeding to predict changes in runoff. May and June tended to give greater "runoff" return than did the July-September period. Assuming a 10% growing season precipitation increase, their models predict that summertime runoff may increase 8-10%. But Hanson and Woolhiser suggest that in the long run, with increased vegetation, runoff could again decrease, even with continued "extra" precipitation.

TABLE 4

Expected Increase in May - August Runoff for Large Watersheds in Western South Dakota Due to 10% Increase in Seasonal (May - August) Rainfall Following the Natural Rainfall Increase Model[a]

	Cheyenne	Grand	White
Average seasonal rainfall, X (in)	11.6	13.5	12.4
Average seasonal runoff, Q (in)	0.60	0.31	0.63
Runoff/rainfall ratio, Q/X	0.052	0.023	0.051
Regression coefficients, A(10^{-4})	6.32	5.70	3.80
B	2.70	2.49	2.88
Postulated rainfall increase (10% of natural), ΔX (in)	1.16	1.35	1.24
$\Delta Q/ X$	0.14	0.06	0.15
Expected runoff increase, ΔQ (in)	0.16	0.08	0.19
Expected percentage increase in runoff, 100 (ΔQ)/Q	27	∿26	30

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a. Based on Special Study Team (1973).

Orr(1959) using Rapid Creek data (1915-42) in the Black Hills found that the annual runoff (Y) could be predicted from the annual precipitation by using the equation

$$\hat{Y} = 0.2042X_1 - 1.0831$$

where $\hat{Y}$ = estimated runoff in inches and X_1 = annual precipitation in inches. This relationship suggests that runoff varies from ∿13% of annual rainfall for low precipitation years to ∿17% for higher rainfall years; with the minimum yield of ∿6% in 1930 to a maximum yield of ∿26% in 1920, with an average yield of ∿14%.

5 Other Hydrologic Effects

5.1 Ground water

The effect of added precipitation is not expected to cause additional recharge to deep aquifers. Some additional recharge may result on water table aquifers such as alluvium, Tertiary strata, and Precambrian rocks.

5.2 Stockwater

Computer simulation studies indicate that 1 to 5% of rainfall increases would show up in stock dams. The 1% was for rainfall increase model B (Table 1), where it is assumed the large storms would actually be suppressed by seeding, the 5% for model N. The actual case should be between, suggesting increases of 10-20% in the runoff caught. Although this sounds small, ranchers would likely be tempted to add additional stock dams which would result in a further increase in available water for livestock.

5.3 Evaporation

The primary response to additional rainfall in western South Dakota appears to be in the form of increased evaporation. The annual increase in evaporation appears to fall in the range of 86 to 92% of the added rainfall. A potential benefit of increased evapotranspiration may be that the added water vapor would act to increase the liklihood of rainfall on subsequent days; this idea is somewhat supported by South Dakota climatological data which suggests wet periods breed more precipitation and dry periods hinder future wet periods.

5.4 Erosion

In the short term runoff may slightly increase stream erosion and subsequent dam siltation problems. One sidelight of "wetter" soils appears to be that some reduction in wind erosion would be a likely result. This, along with a long term increase in vegetation and subsequent reduction in water erosion could help in improving the western South Dakota grasslands. Soil erosion would only increase if precipitation was increased from large storms over cultivated lands.

6 Conclusions:

6.1 Assessment of the Modeling of Summertime Precipitation Increases

Most of the results presented were based on an "optimistic" 10% rainfall increase model. The best guess of current state-of-the-art potential is based on the five-year State of South Dakota operational cloud seeding program (1972-76) which suggests a 7% rainfall augmentation. Thus, all hydrological effects mentioned above (which assume a 10% precipitation increase) would have to be reduced somewhat to compensate.

6.2 Assessment of Precipitation Enhancement over the Black Hills

There is a lack of Black Hills runoff versus precipitation studies; some studies have been done by the U.S. Forest Service research station (Orr, 1959). These have involved changes in runoff due to forest management practices, e.g., 30-40% runoff increases follow a timbering under current Black Hills National Forest guidelines (Yamamoto, personal communication).

A conservative estimate would be a 10% increase in wintertime orographic precipitation could be realized. Much of this would evaporate, but percentage increases in runoff would be at least 10%. There would be some additions to ground water as the streams carrying the extra runoff crossed the permeable outcroppings around the periphery of the Hills.

Increases in Black Hills snowpack and runoff would most likely increase available water to hills towns and help stabilize recreation programs (i.e., summer boating and winter skiing).

6.3 Summary

It is believed that using current weather technology, that an 8% increase in annual precipitation in western South Dakota could be realized; this would allow for an approximate increase in surface runoff of 10% to 50% over current runoff experience. Technological advances over the next 10 to 20 years are not likely to change this precipitation enhancement assessment by any appreciable amount.

REFERENCES

Boyd, E. I., 1971; South Dakota cloud seeding evaluation, 1965-71. Report 71-23, Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City. 32 pp.

Chang, L.-P., 1976: Re-evaluation of Rapid Project data. M. S. Thesis, Department of Meteorology, South Dakota School of Mines and Technology, Rapid City. 58 pp.

Dennis, A. S., 1970: Modifying precipitation by cloud seeding. Journal of Soil and Water Conservation, 25, 3, May-June 1970, 88-92.

Dennis, A. S., and A. Koscielski, 1969: Results of a randomized cloud seeding experiment in South Dakota. J. Appl. Meteor., 8, 4, 556-565.

Dennis, A. S., A. Koscielski, D. E. Cain, J. H. Hirsch, and P. L. Smith, Jr., 1975a: Analysis of radar observations of a randomized cloud seeding experiments. J. Appl. Meteor., 14, 5, 897-908.

Dennis, A. S., J. R. Miller, Jr., D. E. Cain, and R. L. Schwaller, 1975b: Evaluation by Monte Carlo tests of effects of cloud seeding on growing season rainfall in North Dakota. J. Appl. Meteor., 14, 5, 959-969.

Eddy, Amos and Ellen Cooter, 1979: The evaluation of operational cloud seeding in North Dakota: Some Preliminary Findings, Amos Eddy, Inc., Norman, Okla., 43 pp.

Elliott, R. D., R. W. Shaffer, A. Court, and J. F. Hannaford, 1978: Randomized cloud seeding in the San Juan Mountains, Colorado. J. Appl. Meteor., 17, 9, 1298-1318.

Gelhaus, J. W., A. S. Dennis, and M. R. Schock, 1974: Possibility of a Type I statistical error in analysis of a randomized cloud seeding project in South Dakota. J. Appl. Meteor, 13, 3, 383-386.

Hanson, C. L., and D. A. Woolhisher, 1978: Probable effect of summer weather modification on runoff. Journal of the Irrigation and Drainage Division, ASCE, 104, No. 1R1, Proc. Paper 13608, March 1978, 1-11.

Lumb, A. M., and R. K. Linsley, 1971: Hydrologic consequences of rainfall augmentation. Journal of the Hydraulics Division, ASCE, 97, No. HY7, July 1971.

Orr, H. K., 1959: Precipitation and Streamflow in the Black Hills, Rocky Mountain Forest and Range Experiment Station, Forest Service, USDA, August, 25 pp.

Panel on Weather and Climate Modification (T. F. Malone, chairman), 1973: Weather and climate modification: Problems and progress. National Academy of Sciences, Washington. xxi + 258 pp.

Panel on Weather and Climate Modification (G. J. F. McDonald, chairman), 1966: Weather and climate modification: Problems and prospects. Vol. I. Summary and recommendations; Vol. II. Research and development. Publication No. 1350, National Academy of Sciences/National Research Council, Washington, cii + 28 pp. + 198 pp.

Pellett, J. L., R. S. Leblang, and M. R. Schock, 1977: Evaluation of recent operational weahter modification projects in the Dakotas. North Dakota Weather Modification Board, Box 1833, Bismarck, North Dakota 58505. 54 pp.

Possible Effects of Weather Modification on the Hydrologic Cycle, by Meteorology 445, Class of 1970-71, Department of Meteorology, Pennsylvania State University, April 1979. 81 pp. Report to the Bureau of Reclamation.

Schaefer, V. J., 1976: After 29 1/2 years. Journal of Weather Modification, 8, 2, September 1976, 5-7.

Schleusener, R. A., and E. I. Boyd, 1972: Weather modification program for South Dakota. J. Hydraulics Div., ASCE, 98, No. HY9, 1515-1526.

Schock, M. R., 1977: Upper midwest weather modification activities. University of North Dakota, Grand Forks, North Dakota 58202. 85 pp.

Special Study Team, 1973: Effects of Additional Precipitation on Agricultural Production, the Environment, the Economy, and Human Society in South Dakota. Agriculture Experiment Station, South Dakota State University, Brookings, South Dakota 57006, June 1973, Two volumes, 177 pp. and 242 pp., respectively.

Thom, H. C. S., 1957a: In "Final Report of the Advisory Committee on Weather Control," Vol. II, pp. 5-25. U. S. Government Printing Office, Washington.

Thom, H. C. S., 1957b: In "Final Report of the Advisory Committee on Weather Control," Vol. II, pp. 25-50. U. S. Government Printing Office, Washington.

Vardiman, L., and J. A. Moore, 1978: Generalized criteria for seeding winter orographic clouds. J. Appl. Meteor., 17, 12, 1769-1777.

Whiteman, C. D., 1973: Some climatological characteristics of seedable upslope cloud systems in the High Plains. NOAA Tech Report ERL268-APCL27, U. S. Department of Commerce, Boulder, Colorado. 43 pp.

TASK 1-C

TERRAIN ANALYSIS FOR GRAVITY DISTRIBUTION

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TASK I-C

TERRAIN ANALYSIS FOR GRAVITY DISTRIBUTION

Introduction

The purpose of this study is to identify any potential gravity-feed water distribution areas in western South Dakota.

All the land west of the Missouri River in South Dakota was examined on available maps with 50, 100, and 200 foot contour intervals. The map scales used were 1:500,000 and 1:250,000. The distribution areas were studied for land use (rangeland, farming, forest, or badland), possible water source(s), and major towns located within the area.

Procedure

The highest elevation points in western South Dakota were located and noted on Plate 1. (The points were located originally on a larger scale map, not included in this report.) The following data were collected on each area: size, major land use, possible water source(s), distance to source, elevation of storage facility, and towns. See Table 1. All areas are referenced on Plate 1 for location. See references cited at the end of this chapter for maps used in this study.

The distribution areas were examined to determine the possibility of connecting the high points in two or more area by a gravity-feed aqueduct. The topography along possible routes was examined between adjoining high points. The areas were regressively ranked with the maximum area served by the minimum length of aqueduct. See Table 2. All areas are referenced on Plate 1 for location.

The aqueduct distribution areas and the Black Hills were examined to determine the possibility of connecting the existing areas by pumping from one area to another. The topography was examined and the aqueducts requiring pumping noted and the elevation changes calculated. The aqueducts with pumping stations were marked and the elevation differences noted at the approximate place on the aqueduct. See Table 3. All areas are referenced on Plate 3 for location.

Problems Encountered

The largest map scale available completely covering western South Dakota is 1:250,000, with contour intervals varying from 50 to 200 feet. The contour error for all maps must be based on the largest error encountered, thus decreasing the accuracy in the distribution area.

The majority of the maps were compiled in the early 1950's, then updated. The updates were widespread, limited, and not all were done in the same decade, decreasing the accuracy of some maps. The lack of current updated maps decreased the accuracy of all the maps.

With unknown water requirements, the capacity of pumping stations to connect the areas cannot be determined. Other problems include: (1) the quantity of water is unknown, (2) the pipe diameter cannot be determined, and (3) the elevation difference is taken from the contour intervals. The necessity of pumping stations to connect the areas created problems beyond the scope of this study.

This study is strictly a reconnaissance effort and the distribution areas were derived using the procedure outlined. A distribution area will vary somewhat depending on the individual conducting the reconnaissance.

Conclusion

This is a preliminary study of possible gravity-feed water distribution areas and gravity-feed aqueduct distribution areas in western South Dakota.

Since this is a preliminary study, the economic feasibility of individual areas was not determined. The exact number of feasible distribution areas will have to be determined by a more in-depth study.

It is recommended that a more in-depth study be conducted to determine the feasibility of establishing gravity-feed water distribution areas and/or gravity-feed aqueduct distribution areas in western South Dakota. This study should include an assessment of the reliability of the water source, a benefit cost ratio, use of the water, exact area boundaries, environmental effects, pumping feasibility, and costs.

REFERENCES CITED

Land Use Map of South Dakota, State of South Dakota Planning Bureau; Pierre, South Dakota, 1973.

Official Highway Map of South Dakota, Department of Transportation; Pierre, South Dakota, 1979.

South Dakota Public Water Supply Data, Department of Environmental Protection; Pierre, South Dakota, 1979.

U.S. Geological Survey, 2° Topography Maps, Lemmon, Hot Springs, Rapid City, Pierre, McIntosh, Martin, Mitchell; Denver, Colorado.

TABLE 1

GRAVITY-FEED DISTRIBUTION AREAS

		AREA	STORAGE FACILITY							
AREA	**COUNTY**	**SQ. MILE**	**ELEVATION**	**LOCATION**	**POSSIBLE WATER SOURCE**	**DISTANCE**	**MAJOR LAND USE**	**TOWN**	**POPULATION***	**WATER SOURCE**
1	Northeast Dewey, Southeast Corson	760	2,842 ft.	Sec. 9, T[illegible], R26E	Spring Lake	3 miles	Rangeland	Timber Lake	625	Ground Water
2	South Central Corson	254	2,212 ft.	Sec. 15, T[illegible], R23E	Lake Walton	7 miles	Rangeland	None		
3	Northwest Dewey	366	2,500 ft.	Sec. 17, T[illegible], R21E	Isabel Lake	7 miles	Rangeland	Isabel	394	Isabel Lake
4	East Dewey	325	2,235 ft.	Sec. 3, T[illegible], R30E	Lake Oahe	5 miles	Rangeland	None		
5	Northeast Corson	297	2,270 ft.	Sec. 20, T[illegible], R29E	Lake Oahe	10 miles	Rangeland	Wakpala	195	Ground Water
6	East Central Corson	266	2,193 ft.	Sec. 11, T[illegible], R27E	Grand River	2 miles	Rangeland	McLaughlin Bulhead	863 219	Ground Water Ground Water
7	North Central Corson	382	2,240 ft.	Sec. 29, T[illegible]N, R84W	Tatanka Lake	3 miles	Farmland	McIntosh	561	Ground Water
8	Northwest Corson, Northeast Perkins	653	2,180 ft.	Sec. 5, T22N, R17E	Lemmon Lake	9 miles	Rangeland	Lemmon Morristown	1,997 144	Ground Water Ground Water
9	Southwest Corson, North Ziebach	724	2,755 ft.	Sec. 26, T16N, R18E	Glad Valley Lake	9 miles	Farmland	None		
10	Northwest Ziebach, East Central Perkins	102	2,443 ft.	Sec. 22, T15N, R18E	Moreau River	2 miles	Rangeland	None		
11	West Central Corson, Northeast Perkins	256	2,630 ft.	Sec. 15, T[illegible], R16E	Grand River	9 miles	Rangeland	None		
12	North Central Perkins	349	2,900 ft.	Sec. 22, T21N, R12E	South Fork Grand River	7 miles	Rangeland	None		
13	North Central Perkins	178	2,920 ft.	Sec. 21, T22N, R14E	North Fork Grand River	3 miles	Rangeland	None		
14	Southwest Corson, East Central Perkins	86	2,570 ft.	Sec. 29, T15N, R18E	Coal Creek	3 miles	Rangeland	None		
15	Central Perkins	405	2,805 ft.	Sec. 3, T19N, R13E	Thunder Butte Creek	1 mile	Rangeland	Bison	406	Ground Water
16	Northwest Perkins, Northeast Harding	289	3,000 ft.	Sec. 19, T22N, R3E	Big Nasty Creek	4 miles	Rangeland	None		
17	Southeast Central Perkins	185	2,750 ft.	Sec. 22, T[illegible], R15E	Thunder Butte Creek	4 miles	Rangeland	None		
18	West Central Perkins, East Central Harding	514	3,635 ft.	Sec. 23, T[illegible], R2E	South Fork Grand River	7 miles	Farmland	None		
19	North Central Harding	193	3,485 ft.	Sec. 3, T21N, R5E	Bull Creek	1 mile	Farmland	None		
20	Northeast Harding, Northwest Perkins	116	3,250 ft.	Sec. 4, T21N, R8E	Skull Creek	1 mile	Farmland	None		
21	Northwest Harding	116	3,200 ft.	Sec. 15, T[illegible], R1E	Little Missouri River	3 miles	Rangeland	Camp Crook	150	Unknown
22	Northwest Central Harding	144	3,500 ft.	Sec. 19, T21N, R5E	Jones Creek	2 miles	Rangeland	None		
23	North Central Harding	139	3,640 ft.	Sec. 8, T22N, R4E	Little Missouri River	12 miles	Rangeland	None		
24	North Central Harding	47	3,240 ft.	Sec. 16, T21N, R7E	North Fork Grand River	5 miles	Farmland	None		
25	West Central Harding	223	3,495 ft.	Sec. 21, T[illegible], R5E	Jones Creek	1 mile	Rangeland	Buffalo	393	Ground Water
26	West Central Harding	48	3,475 ft.	Sec. 28, T19N, R3E	South Fork Grand River	7 miles	Rangeland	None		
27	Central Harding	164	3,273 ft.	Sec. 5, T17N, R6E	North Fork Moreau River	5 miles	Rangeland	None		
28	Southeast Central Harding	282	3,685 ft.	Sec. 8, T16N, R8E	North Fork Moreau River	7 miles	Farmland	None		
29	West Central Perkins, Southeast Harding	182	3,200 ft.	Sec. 28, T17N, R10E	Rabbit Creek	5 miles	Rangeland	None		
30	South Central Perkins	347	2,945 ft.	Sec. 18, T15N, R11E	Antelope Creek	3 miles	Rangeland	None		
31	Southwest Harding	542	4,015 ft.	Sec. 10, T16N, R3E	North Fork Moreau River	8 miles	Rangeland	None		
32	South Central Harding, North Central Butte	121	3,190 ft.	Sec. 16, T14N, R5E	South Fork Moreau River	1 mile	Rangeland	None		
33	Southeast Harding, Northeast Butte, Southwest Perkins	303	3,150 ft.	Sec. 33, T15N, R7E	North Fork Moreau River	5 miles	Rangeland	None		
34	East Central Dewey	103	2,150 ft.	Sec. 28, T15N, R28E	Swan Lake	3 miles	Rangeland	None		
35	Southeast Dewey	618	2,355 ft.	Sec. 10, T13N, R27E	Moreau River	11 miles	Rangeland	None		
36	South Central Dewey	278	2,335 ft.	Sec. 33, T13N, R25E	Brueschke Dam	7 miles	Rangeland	None		

		AREA	STORAGE FACILITY							
AREA	COUNTY	SQ. MILE	ELEVATION	LOCATION	POSSIBLE WATER SOURCE	DISTANCE	MAJOR LAND USE	TOWN	POPULATION*	WATER SOURC
37	Southeast Ziebach, Southwest Dewey	1,378	2,555 ft.	Sec. 28, T12N, R20E	Lantry Lake	12 miles	Rangeland	Eagle Butte	530	Lak ahe
								Dupree	523	Gro Wat
38	Northeast Meade, Southeast Perkins, Central Ziebach	179	2,618 ft.	Sec. 17, T12N, R18E	Moreau River	12 miles	Rangeland	Faith	576	Durkee Lak
39	North Central Meade, South Central Perkins	1,155	3,165 ft.	Sec. 14, T12N, R13E	Maurine Lake	7 miles	Rangeland	None		
40	Stanley	1,152	2,255 ft.	Sec. 35, T7N, R25E	Hermaphrodite Creek	4 miles	Rangeland	Fort Pierre	1,448	Gro Wat
41	Northeast Haakon	191	2,383 ft.	Sec. 28, T6N, R24E	Hermaphrodite Creek	5 miles	Rangeland	None		
42	Southeast Haakon, Northwest Jones, Southwest Stanley	901	2,500 ft.	Sec. 28, T4N, R22E	Ottumwa Lake	7 miles	Rangeland	Midland	270	Gro Wat
43	Northwest Butte, Southwest Harding	104	3,665 ft.	Sec. 21, T15N, R2E	South Fork Moreau River	21 miles	Rangeland	None		
44	West Center Butte	48	3,400 ft.	Sec. 4, T12, R1E	Indian Creek	8 miles	Rangeland	None		
45	East Central Butte	185	3,070 ft.	Sec. 17, T12N, R8E	South Fork Moreau River	4 miles	Rangeland	None		
46	Northwest Butte	237	3,690 ft.	Sec. 34, T14N, R2E	Indian Creek	22 miles	Rangeland	None		
47	Central Butte	482	3,775 ft.	Sec. 13, T12N, R5E	South Fork Moreau River	7 miles	Farmland	Newell	664	Gro Wat
48	Southeast Butte, West Central Meade	664	3,094 ft.	Sec. 10, T10N, R7E	Belle Fourche River	14 miles	Rangeland	None		
49	Southwest Ziebach, Central Meade	1,376	3,200 ft.	Sec. 34, T8N, R12E	White Owl Creek	3 miles	Rangeland	None		
50	West Central Haakon, Northeast Pennington	709	2,810 ft.	Sec. 9, T3N, R18E	North Fork Bad River	8 miles	Rangeland	Philip	983	Ground Wate Lake Wagner
[illegible]	Southwest Haakon, Northeast Pennington	529	2,945 ft.	Sec. 29, T2N, R17E	Cheyenne River	8 miles	Farmland	None		
52	Southwest Lyman, Southeast Jones	518	2,295 ft.	Sec. 2, T2S, R30E	Medicine Creek	2 miles	Farmland	Fresno	922	Gro Wat
53	Northwest Lyman, Northeast Jones, Southeast Stanley	1,304	2,253 ft.	Sec. 13, T106N, R30E	Medicine Creek	7 miles	Farmland	Draper	200	Gro Wat
								Vivian	162	Unknown
								Murdo	865	Ground Wate Murdo Lake
54	Center Jones	264	2,279 ft.	Sec. 20, T2S, R28E	White River	5 miles	Farmland	None		
55	East Jackson, West Jones, Southeast Haakon	266	2,515 ft.	Sec. 32, T1S, R26E	White River	4 miles	Rangeland	None		
56	East Jackson, Southeast Haakon	312	2,455 ft.	Sec. 33, T2S, R22E	Kadoka Lake	3 miles	Rangeland	Kadoka	815	Gro Wate
57	Central Jackson	312	2,626 ft.	Sec. 36, T2S, R19E	South Fork Bad River	6 miles	Rangeland	None		
58	East Pennington	765	3,255 ft.	Sec. 16, T2S, R16E	Cajn Creek	5 miles	Rangeland	Wall	786	Ground Wate
								Quinn	105	Unknown
59	Southeast Butte	315	3,290 ft.	Sec. 34, T11N, R2E	Indian Creek	2 miles	Farmland	Nisland	157	Gro Wate
								Belle Fourche	4,236	Gro Wate
60	North Lawrence, Southwest Butte	296	3,898 ft.	Sec. 4, T6N, R4E	Whitewood Creek	8 miles	Farmland	None		
61	Central Lawrence	19	4,000 ft.	Sec. 23, T6N, R3E	Whitewood Creek	5 miles	Rangeland	Whitewood	689	Gro Wate
62	Southwest Meade	924	4,426 ft.	Sec. 17, T6N, R6E	Bear Butte Lake	2 miles	Farmland	Sturgis	4,536	Ground Wate
								Vale	138	Ground Wate

		AREA	STORAGE FACILITY							
AREA	COUNTY	SQ. MILE	ELEVATION	LOCATION	POSSIBLE WATER SOURCE	DISTANCE	MAJOR LAND USE	TOWN	POPULATION*	WATER SOURC
63	South Meade, North Central Pennington	448	3,276 ft.	Sec. 20, R11E, T2N	Box Elder Creek	2 miles	Rangeland	EAFB	6,207	Ground Wa
								Box Elder	607	Ground Wa
								New Underwood	416	Ground Wa
								Wasta	127	Ground Wa
64	Central Pennington	542	3,820 ft.	Sec. 22, T1N, R7E	Rapid Creek	5 miles	Rangeland	Rapid City	43,836	Ground Wa
65	Northeast Custer	162	3,418 ft.	Sec. 24, T2S, R8E	Battle Creek	3 miles	Rangeland	Hermosa	150	Ground Wa
66	East Custer	380	3,300 ft.	Sec. 14, T5S, R8E	Cheyenne River	4 miles	Rangeland	Buffalo Gap	155	Ground Wa
67	Black Hills	2,739	7,241 ft.	Sec. 21, T2S, R5E	Sylvan Lake	2 miles	Forest			
68	Southwest Fall River	389	4,005 ft.	Sec. 19, T10S, R55W	Hat Creek	9 miles	Rangeland	Provo	108	Ground Wa
69	South Central Fall River	348	3,855 ft.	Sec. 36, T10S, R53W	Angostura Reservoir	12 miles	Rangeland	None		
70	Southeast Pennington, North Central Shannon	289	3,282 ft.	Sec. 21, T41N, R11E	Cheyenne River	9 miles	Rangeland	None		
71	Northwest Shannon	474	3,252 ft.	Sec. 21, T41N, R47W	White River	10 miles	Rangeland	None		
72	Northeast Fall River, West Central Shannon	404	3,460 ft.	Sec. 9, T9S, R49W	White River	11 miles	Rangeland	None		
73	Southeast Fall River, Southwest Shannon	330	3,695 ft.	Sec. 6, T12S, R50W	White River	20 miles	Farmland	None		
74	Southwest Shannon	176	3,250 ft.	Sec. 9, T35N, R45W	White Clay Creek	4 miles	Rangeland	None		
75	Central Shannon	393	3,680 ft.	Sec. 5, T37N, R45W	Oglala Dam	2 miles	Rangeland	Pine Ridge	2,768	Ground Wa
76	Northwest Mellette	450	2,533 ft.	Sec. 31, T3S, R32W	White River	4 miles	Rangeland	None		
77	Northeast Bennett, Southeast Washabaugh, Southwest Mellette, Northwest Todd	893	3,195 ft.	Sec. 1, T37W, R33W	Little White River	8 miles	Rangeland	None		
78	Northeast Washabaugh	208	2,560 ft.	Sec. 28, T42N, R33W	Harris Lake	2 miles	Badlands	None		
79	Central Washabaugh	458	3,410 ft.	Sec. 2, T40N, R37W	Bear-In-The-Lodge Creek	7 miles	Badlands	Wanblee	193	Ground Wa
80	Northeast Bennett, West Washabaugh East Shannon	1,424	3,710 ft.	Sec. 3, T38N, R42W	Porcupine Creek	5 miles	Rangeland	Martin	1,248	Ground Wa
								Batesland	125	Ground Wa
81	South Bennett, Southwest Todd, Southeast Shannon	479	3,680 ft.	Sec. 14, T35N, R43W	Alkali Lake	1 mile	Farmland	None		
82	East Mellette, Northeast Todd, Northwest Tripp	1,410	2,760 ft.	Sec. 22, T39N, R27W	Antelope Creek	4 miles	Rangeland	White River	617	Ground Wa
								Mission	739	Ground Wa
								Wood	13[illegible]	Unknown
								Witten	10[illegible]	Ground Wa
83	Southeast Todd, Southwest Tripp	1,015	3,025 ft.	Sec. 32, T37N, R30W	Little White River	5 miles	Farmland	Rosebud	327	Ground Wa
								St. Francis	300	Ground Wa
84	Southeast Lyman	469	1,850 ft.	Sec. 29, T105N, R73W	Reliance Lake	1 mile	Rangeland	Reliance	204	Ground Wa

AREA	COUNTY	AREA SQ. MILE	STORAGE FACILITY ELEVATION	STORAGE FACILITY LOCATION	POSSIBLE WATER SOURCE	DISTANCE	MAJOR LAND USE	TOWN	POPULATION*	WATER SOURC
85	Northwest Gregory, Northwest Tripp, Southwest Brule	1,223	2,355 ft.	Sec. 6, T100N, R75W	Old Lodge Creek	3 miles	Rangeland	Gregory	1,756	Ground wat
								Dallas	233	Ground wat
								Burke	890	Ground wat
								Herrick	126	Ground wat
								Bonesteel	354	Ground wat
								Fairfax	199	Ground wat
86	North Central Tripp	65	1,886 ft.	Sec. 16, T102N, R76W	Dog Ear Creek	2 miles	Farmland	None		
87	Central Tripp	72	2,315 ft.	Sec. 7, T100N, R76W	Dog Ear Creek	2 miles	Farmland	Winner	3,789	Ground wat
88	Southeast Tripp, Southwest Gregory	610	2,520 ft.	Sec. 3, T97N, R77W	Dog Ear Lake	5 miles	Rangeland	Colome	375	Ground wat
89	Central Gregory	230	2,195 ft.	Sec. 24, T98N, R72W	South Fork Whetstone Creek	4 miles	Rangeland	None		

*1970 Census

TABLE 2

GRAVITY-FEED AQUEDUCT DISTRIBUTION AREAS

AQUEDUCT AREA	AREAS COMPILING AQUEDUCT AREA	AREA SQUARE MILE	AQUEDUCT LENGTH (MI.)	AQUEDUCT LENGTH/ AREA SIZE	RANK
A	68,69,71,72,73	1,945	29	0.0149	1
B	82,83	2,425	43	0.0177	2
C	45,47,48	1,331	29	0.0218	3
D	40,41,42,50,51	3,482	87	0.0250	4
E	76,77,78	1,551	42	0.0271	5
F	85,88,89	2,063	59	0.0286	6
G	56,57	624	18	0.0288	7
H	52,53,54,55,84	2,821	91	0.0323	8
I	4,34,35,36,37	2,702	99	0.0366	9
J	1,2,3,9,11,14,15, 18,28,29,30	4,176	177	0.0424	10
K	27,31,32,33	1,130	56	0.0496	11

TABLE 3

DISTRIBUTION AREAS CONNECTED BY PUMPS

PUMP AQUEDUCT AREA NUMBER	AREAS COMPILING PUMP AREA	AREA SQ. MILE	AREA PUMPED FROM	TO	ELEVATION DIFFERENCE (FT.)
I	J,C,K,I,49,39,17,10	12,157	C	49	300
			49	39	565
			39	38	158
			K	J	412
			J	17	150
			K	C	775
II	G,H	3,445	G	H	60
III	B,F	4,488	B	F	170

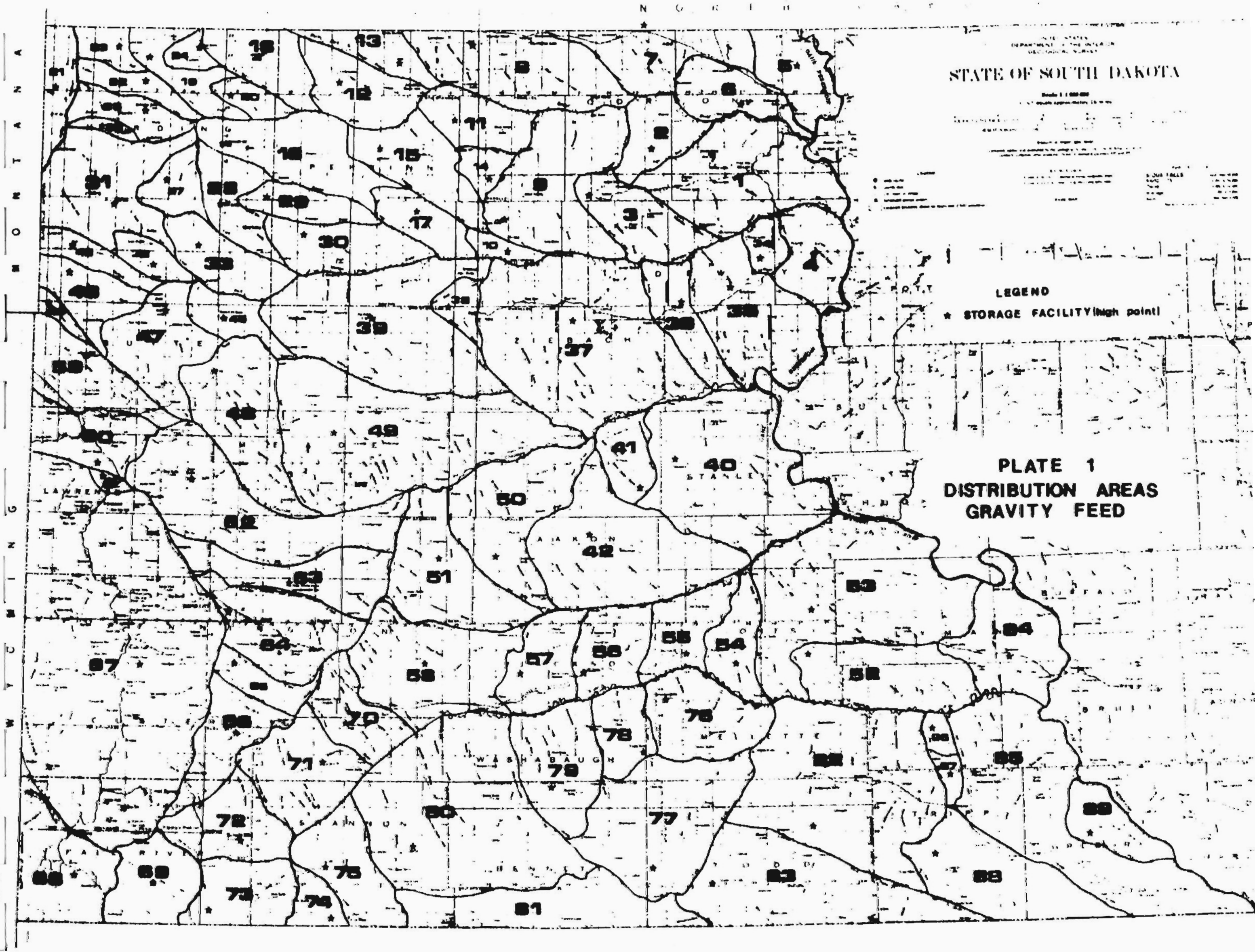


PLATE 1
DISTRIBUTION AREAS
GRAVITY FEED

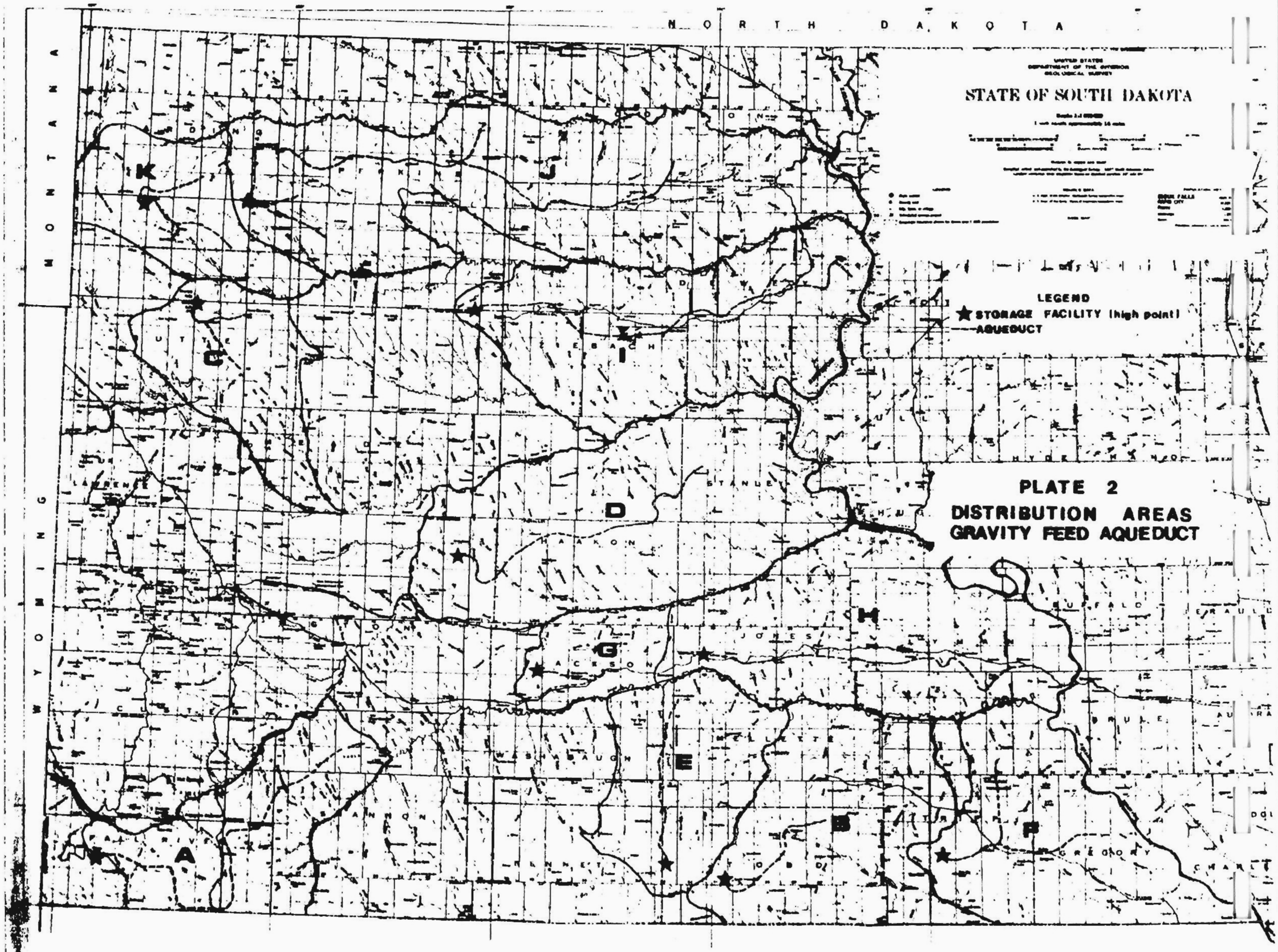


PLATE 2
DISTRIBUTION AREAS
GRAVITY FEED AQUEDUCT

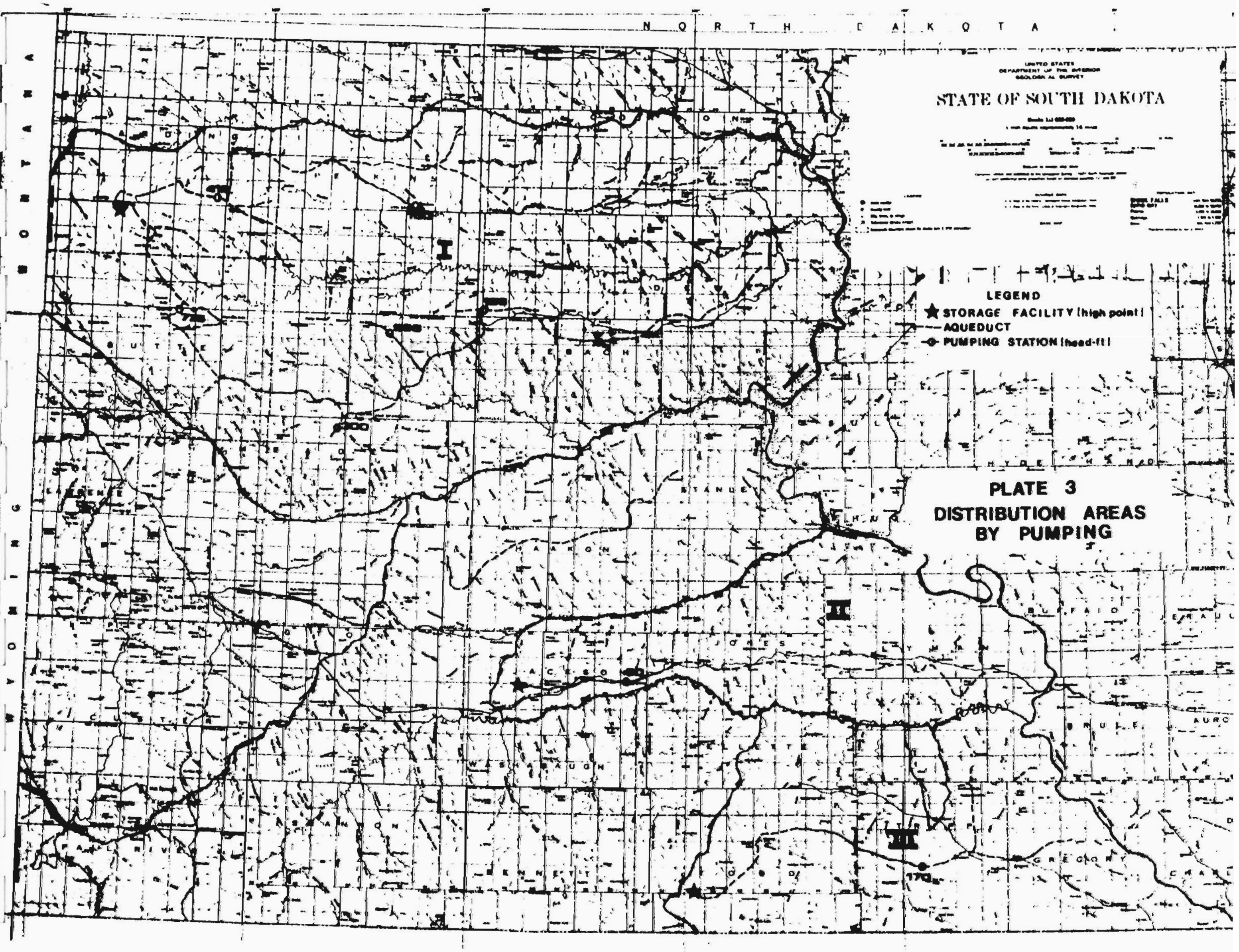


PLATE 3
DISTRIBUTION AREAS BY PUMPING

APPENDIX A Total Aqueduct Project

A.1. Introduction

A preliminary conceptual study was conducted to examine the possibility of transporting good quality water from the Black Hills easterly to municipalities located on the plains.

The majority of the water supplies for municipalities located in Western South Dakota is groundwater. Most of this groundwater is of poor quality, which contributes to the limited growth encountered by many of the municipalities. The route for T.A.P. Was chosen to provide water to the maximum number of communities possible.

The main objective of this study is to investigate possible means of solving the water quality problem of some municipalities in Western South Dakota. Some of the information used was obtained from the 1978 West River Aqueduct Study.

A.2. Route Selection

The route for T.A.P. was selected based on the following considerations: water needs, distribution effects, topography, soils, existing interference, ease of trenching, logistics, land use, and environmental factors. A route paralleling Interstate 90 was selected. The water would flow down gradient by gravity from west to east. The I-90 route serves a maximum number of municipalities while being feasible from an engineering standpoint. T.A.P. would be located within the I-90 right-of-way when possible to minimize land requirements. The secondary distribution systems from the main aqueduct are not within the scope of this study.

A.3. Water Needs

The municipalities located along T.A.P. were identified and the water needs for the year 2000 were calculated.

TABLE 1 WATER PROJECTIONS FOR THE YEAR 2000

TOWN	MGD*	TOWN	MGD*
Murdo	0.66	Wasta	0.04
White River	0.28	New Underwood	0.10
Okaton	0.01	Box Elder	0.50
Belvidere	0.04	Rapid Valley	1.62
Kadoka	0.95	Hermosa	0.08
Wall	0.80	Piedmont-Sturgis Valley	1.14
Philip	1.14		

Total 7.36 MGD @ 2000 (excluding Ellsworth Air Force Base)
* Million gallons per day

The total flow was used as the design flow for the T.A.P. system.

Secondary distribution systems from T.A.P. to the municipalities should be left to the individual municipality, based on their criteria.

A.4. Engineering Considerations

Before any route for T.A.P. could be evaluated a source of sufficient quality water in the Black Hills must be located. Several options were investigated, and Box Elder Creek is judged the most feasible based on proximity, size of basin, and the fact that the basin presently has no diversions or flood water storage structures. It is estimated, from hydrologic records, that Box Elder Creek will supply approximately 13,000 to 15,000 Acre-Feet/year at the proposed impoundment area. Based on geology and topography it is believed that an impoundment located on Box Elder Creek about 4 miles below Nemo is feasible. The stream below "School Section Bridge" is normally dry due to a sinkhole zone. The impoundment will be capable of providing the water necessary for T.A.P. beyond the year 2000.

The dam would store high-quality flood water, and divert this when need to an aqueduct. Low flow discharges to the stream would be provided, however, to recharge the sinkhole zone.

The exact acreage disturbed by the impoundment area is unknown and will be determined by an in-depth study of the area. It is estimated that the following number of structures will be directly effected: twenty (20) residential buildings, one (1) State campground, one (1) church camp, and two (2) ranches. Five to six miles of paved road will have to be relocated around the impoundment area to connect Nemo to Rapid City.

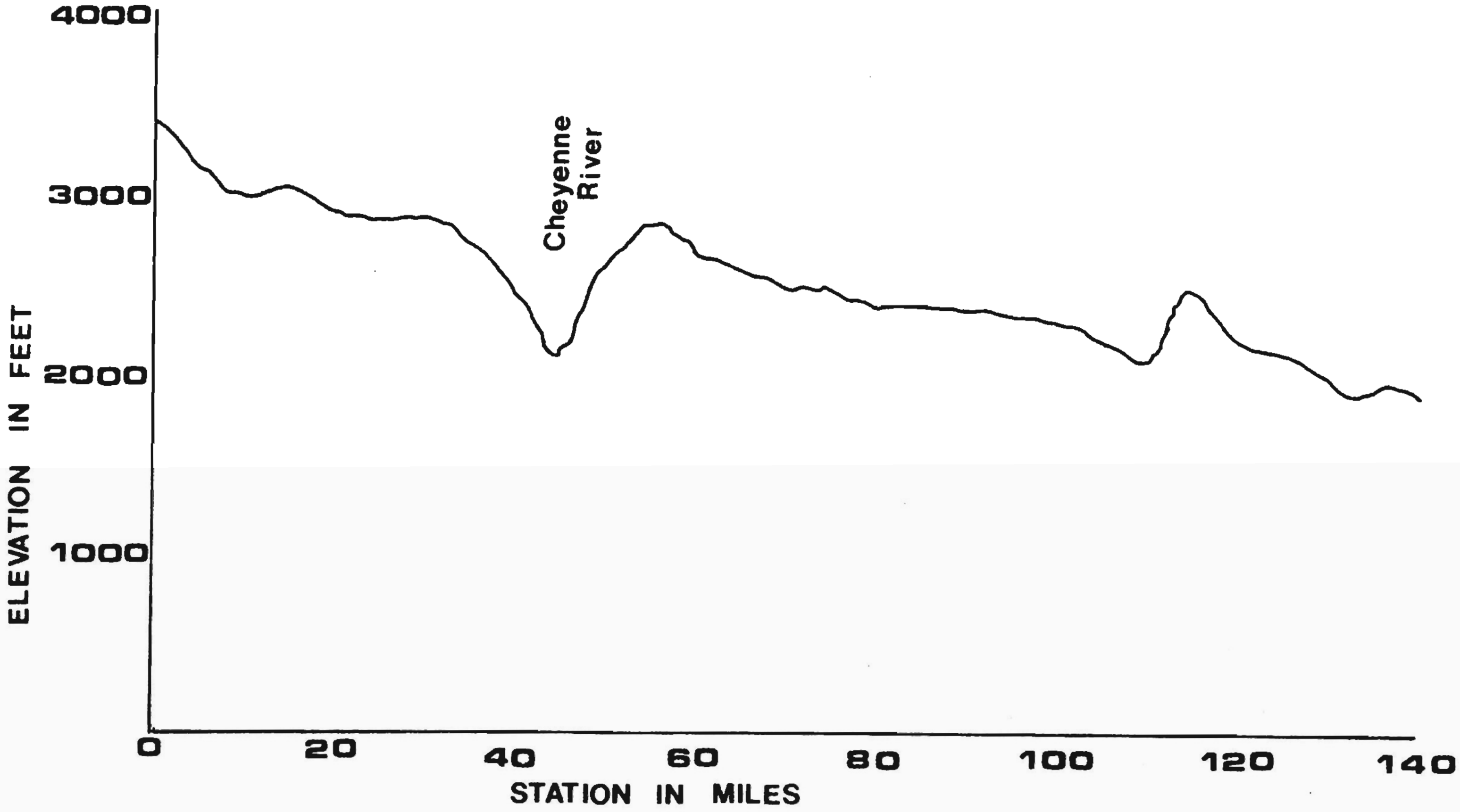
The route for T.A.P. from the impoundment area to I-90 is parallel to Box Elder Creek. Although this may not be the most feasible route without a permanent location for the impoundment area a route to I-90 cannot be determined. Where Box Elder Creek crosses Interstate 90 to Murdo, South Dakota a detailed profile of the terrain is available. See Figure 1. T.A.P. parallels I-90 to Murdo utilizing the I-90 right-of-way whenever possible.

Three alternative T.A.P. systems were examined, (1) no pumping stations, (2) one pumping station, and (3) two pumping stations to determine whether further in-depth examination is warranted (all impoundment area costs are excluded). See Table 2 for comparison.

A.5. Conclusion

This report is a conceptual study of T.A.P. and should be viewed in that context. The data are preliminary and subject to change at a later date when precise data are available.

FIGURE 1



PIPELINE [T.A.P.] PROFILE

TABLE 2 T.A.P. ALTERNATIVE COSTS

T.A.P.	Pipe Cost	Capital Cost	O & M/yr.	Ave. Cost/yr.	Total Cost
2 pump station	$ 23,467,040	$ 42,244,540	$ 456,900	$ 3,560,900	$ 69,740,380
1 pump station	$ 24,274,440	$ 43,487,640	$ 408,940	$ 3,592,800	$ 71,763,820
No pump station	$ 31,121,600	$ 53,521,500	$ 109,880	$ 3,901,400	$ 88,654,380

1. Life expectancy of T.A.P. system is 50 years.

Based on available information and data, T.A.P. is feasible and a necessity if the municipalities to be served are to experience any large growth. The need of quality water by municipalities located on the plains is present and formeable. T.A.P. is a viable means of providing quality water to municipalities located along its' route. Three alternative designs for T.A.P. were listed as possible means of transporting the water.

It is recommended that an in-dept study be conducted on the impoundment area and T.A.P. utilizing all alternatives for providing quality water to municipalities on the plains. That this study investigate in-depth the feasibility of T.A.P. based on water needs, distribution effects, topography, soils, existing interference, obstruction to burial, logistics, land use, and environmental factors.

REFERENCES CITED

CH2M Hill, Inc.; Francis-Meador-Gellhaus; Team Four, Inc.; and Kaiser and Company; West River Aqueduct, Technical Report, December, 1978.

U.S. Geological Survey, 7.5 Minute/Topography Maps, Piedmont Quadrangle, South Dakota.

TASK II

INPUT/OUTPUT MODEL OF THE GRAND RIVER AND WHITE RIVER BASINS

by

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SDSM&T Project
#2533-30

TASK II

INPUT/OUTPUT MODEL FOR THE GRAND RIVER AND WHITE RIVER BASINS

1. Introduction

The purpose of this study is to construct water resources input/output models of the Grand River and White River basins of western South Dakota (Figure 1).

The models were constructed following the description of the mechanics of water resources input/output modeling (Goldlach, 1977).

All data for the study are reported in 10^3 acre-ft/year. Basin data were supplied by the Water Resources Research Institute at South Dakota State University.

2. Grand River Basin

Simplified hydrologic budgets for the Grand River basin and its component subbasins are illustrated in Figure 2 and Figure 3. The water resources input/output model for the Grand River basin is presented in Figure 4. The various source/destination* entries of the model are explained as follows:

"Sources" (or inputs) of water shown are shown on the left column on Figure 4 and "Destinations" (or outputs) along the top. A major source is precipitation falling on the basin (Total 4549 x 10^3 acre-ft/year). (Also see Figure 2).

Beginning with Transport entries on Figure 4, the Avg. Atmosphere/Bowman-Haley Subbasin, etc., represent the total annual volume of water precipitated on each of the three component subbasins of the Grand River less the amount that is precipitated directly on the surface of the wastewater stabilization ponds of the towns within each subbasin. The entries Avg. Atmosphere/Buffalo, etc., separately account for the latter process.

In the second row, the entries Ground Water/Buffalo, etc., represent the ground water annual volumes diverted to consumptive uses by each use sector within the basin.

Entries to the Transport to Transport Sectors include Bowman-Haley Subbasin, etc./Upper Grand Subbasins, etc. These are the annual volumes of surface water flowing from one subbasin to the next. The entries Shadehill Reservoir/Irrigation, represent the diversion of surface water from Shadehill Reservoir to consumptive irrigation uses within each of the identified subbasins. The entry Lower Grand Subbasin/Isobel represents the annual

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*In the following discussions, a slash (/) is used to separate the source (to left of slash) from the destination (to right of slash).

volume of surface water diverted from Lake Isobel to consumptive uses within the town. The entries Bowman-Haley Subbasin, etc./Atmosphere represent the annual water volumes returned to the atmosphere from each component subbasin via the evapotranspiration process. The entry Lower Grand Subbasin/Missouri River represents the annual volume of surface water flowing from the Grand River into the Missouri River.

The final rows are "Use Sectors". The entries Irrigation/Atmosphere represent the annual water volumes returned to the atmosphere via the evapotranspiration process from consumptive irrigation uses within each of the identified subbasins.

The entries Buffalo, etc./Ground Water represents the annual volumes of seepage from the wastewater stabilization ponds of each use sector within the basin.

The entries Buffalo, etc./Atmosphere represent the annual water volumes returned to the atmosphere from each basin use sector via the evapotranspiration process.

The entry Lemmon/Out-Basin Discharge represents the annual volume of effluent from the Lemmon wastewater stabilization pond that flows across the basin boundary and into the Cannonball basin of North Dakota.

3. White River Basin

Simplified hydrologic budgets for the White River basin and its component subbasins are illustrated in Figure 5 and Figure 6. The water resources input/output model for the White River basin is presented in Figure 7. The various source/destination entries of the model are explained as follows:

The entries Avg. Atmosphere/White River Subbasin, etc., represent the total annual volume of water precipitated on each of the two component subbasins of the White River.

The entries Ground Water/Irrigation, White River, etc., represent the annual volumes of ground water diverted to consumptive irrigation uses within each of the identified subbasins.

The entries Ground Water/Hyle, etc., represent the annual volumes of ground water diverted to consumptive uses by each identified use sector within the basin.

The entries Little White Subbasin/White River Subbasin represents the annual volume of surface water that flows from the Little White into the White River.

The entries White River Subbasin, etc.,/Atmosphere represent the annual water volumes returned to the atmosphere via the evapotranspiration process from each component subbasin.

The entry White River Subbasin/Missouri River represents the annual volume of surface water flowing from the White River into the Missouri River.

The entries Irrigation,White River, etc.,/Atmosphere represent the annual water volumes returned to the atmosphere via the evapotranspiration process from consumptive irrigation uses within each of the identified subbasins.

The entries Kyle, etc.,/Atmosphere represent the annual water volumes returned from each basin use sector to the atmosphere via the evapotranspiration process.

REFERENCE CITED

Goldbach, Joseph C., 1977: Water Supply Management Analysis and Alternative Development for the South Platte River Basin, Volume 7, Technical Appendix - A Guide to Imput/Output Modeling and Users Manual for IQPLOT. Prepared by the Environmental Engineering Program, Department of Civil Engineering, Colorado State University, for U. S. Army Engineers District, Omaha Corps of Engineers, Omaha, Nebraska, April, 1977.

FIGURES

Figure 1. Map of South Dakota showing location of Grand and White River Basins.

Figure 2. Simplified hydrologic budget for the Grand River Basin.

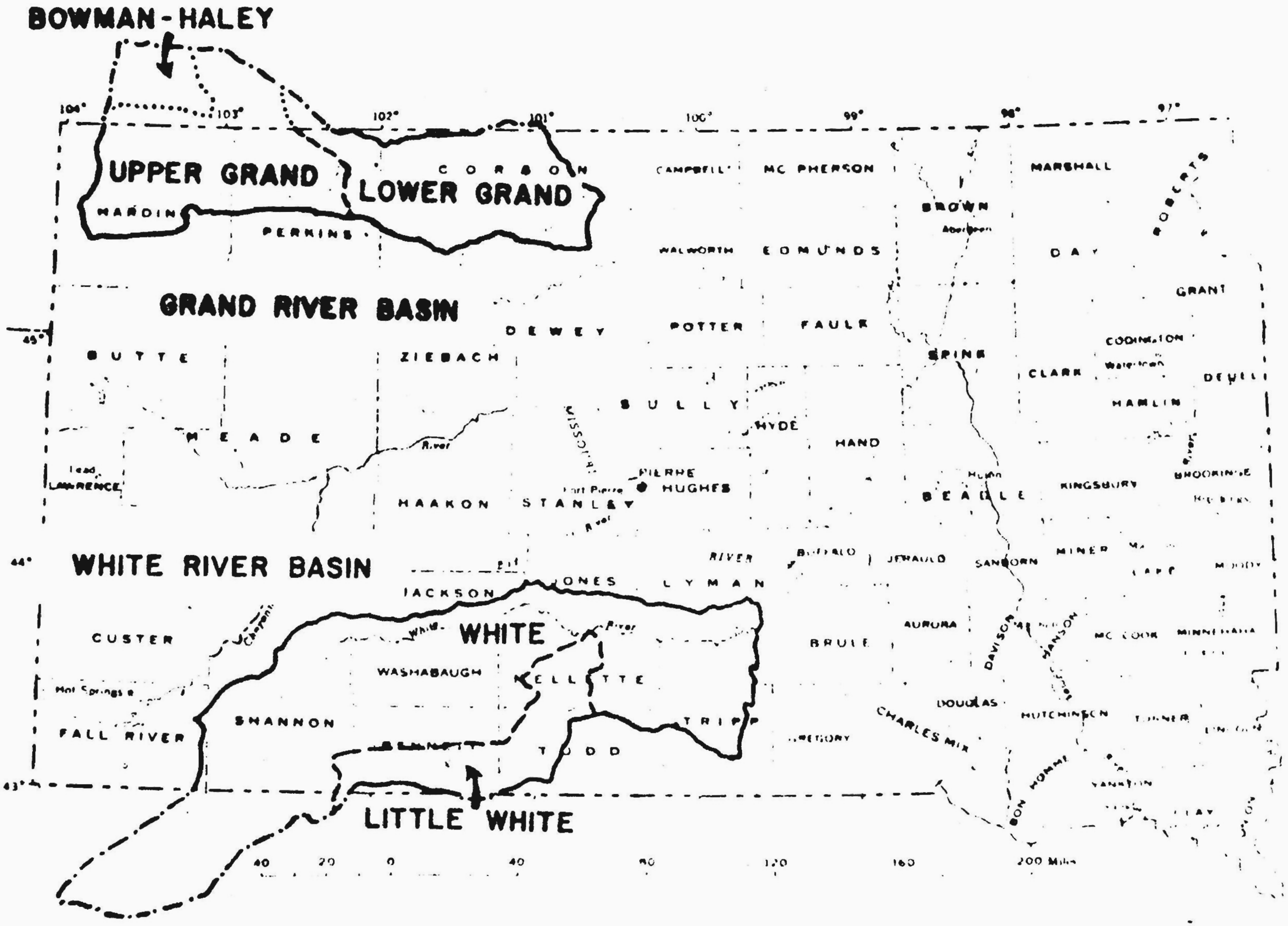
Figure 3. Simplified hydrologic budget for subbasins of the Grand River Basin.

Figure 4. Input/Output model for the Grand River Basin.

Figure 5. Simplified hydrologic budget for the White River Basin.

Figure 6. Simplified hydrologic budget for subbasins of the White River Basin.

Figure 7. Input/Output model for the White River Basin.


BOWMAN - HALEY
UPPER GRAND
LOWER GRAND
GRAND RIVER BASIN
WHITE RIVER BASIN
WHITE
LITTLE WHITE
104°
103°
102°
101°
100°
99°
98°
97°
45°
44°
43°
HARDING
PERKINS
CORSON
CAMPBELL
MC PHERSON
BROWN
Aberdeen
MARSHALL
ROBERTS
WALWORTH
EDMUNDS
DAY
GRANT
DEWEY
POTTER
FAULK
SPINK
CODINGTON
Watertown
CLARK
DEUEL
BUTTE
ZIEBACH
SULLY
HAMLIN
MEADE
HYDE
HAND
River
Lead
LAWRENCE
PIERRE
Fort Pierre
HUGHES
MISSOURI
HAAKON
STANLEY
River
BEADLE
Huron
KINGSBURY
BROOKINGS
RIVER
BUFFALO
JERAULD
SANBORN
MINER
LAKE
MOODY
JACKSON
JONES
LYMAN
CUSTER
Cheyenne
White
River
AURORA
BRULE
DAVISON
HANSON
MC COOK
MINNEHAHA
WASHABAUGH
MELLETTE
Hot Springs
SHANNON
DOUGLAS
CHARLES MIX
HUTCHINSON
TURNER
UNION
FALL RIVER
BENNETT
TODD
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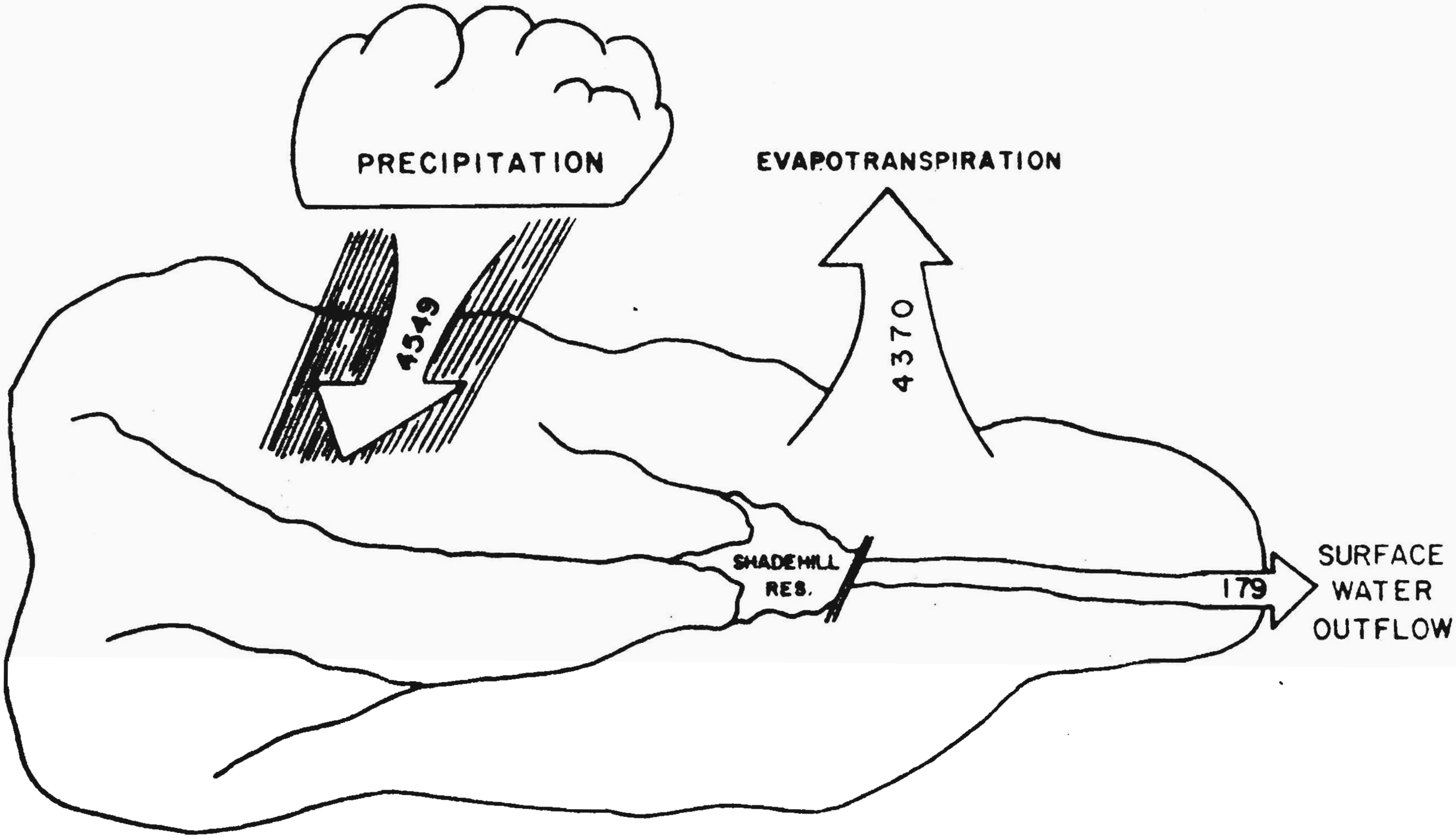
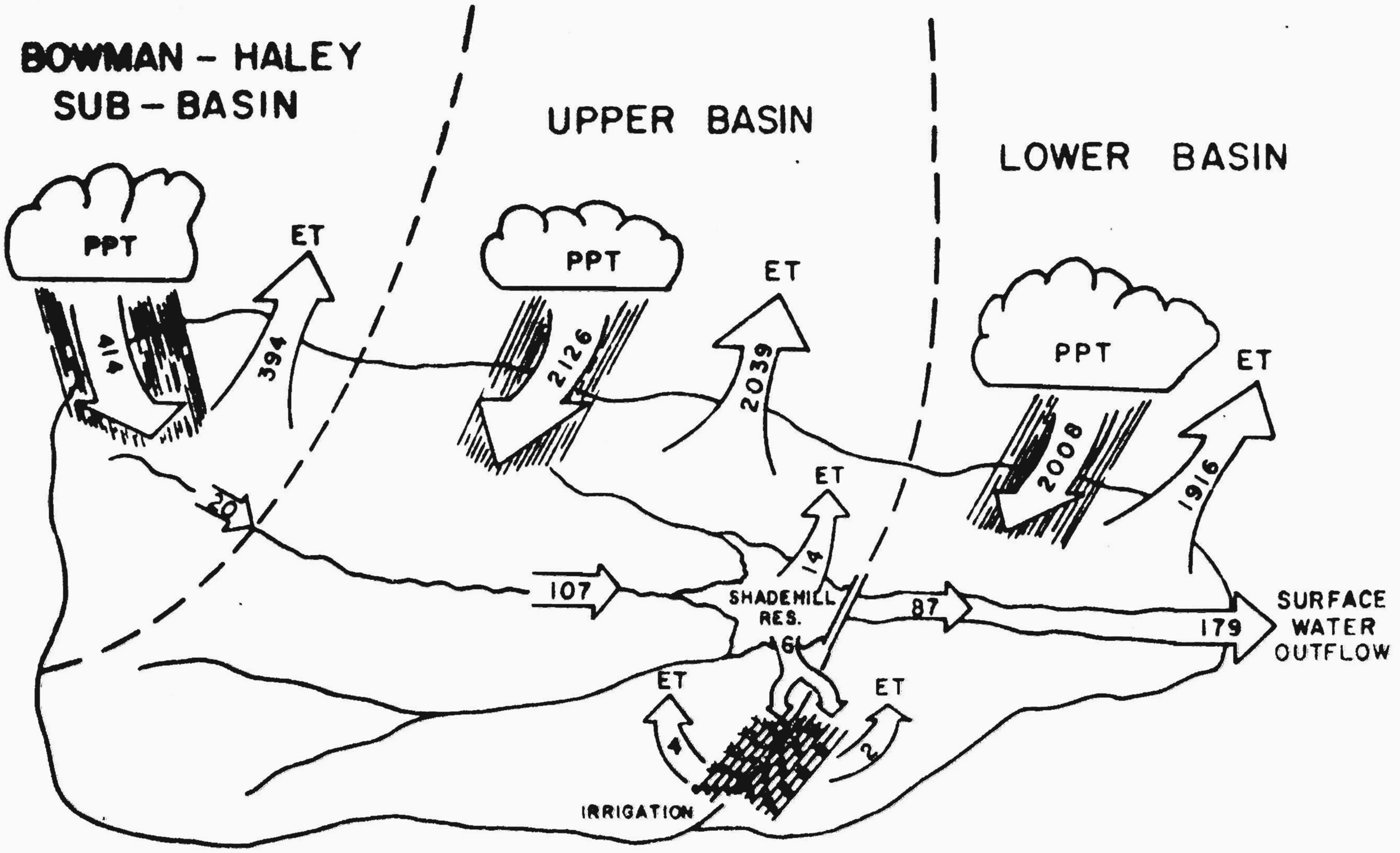
0
40
80
120
160
200 Miles



GRAND RIVER BASIN
SIMPLIFIED HYDROLOGIC BUDGET
(IN 1000 ACRE-FT/YR)



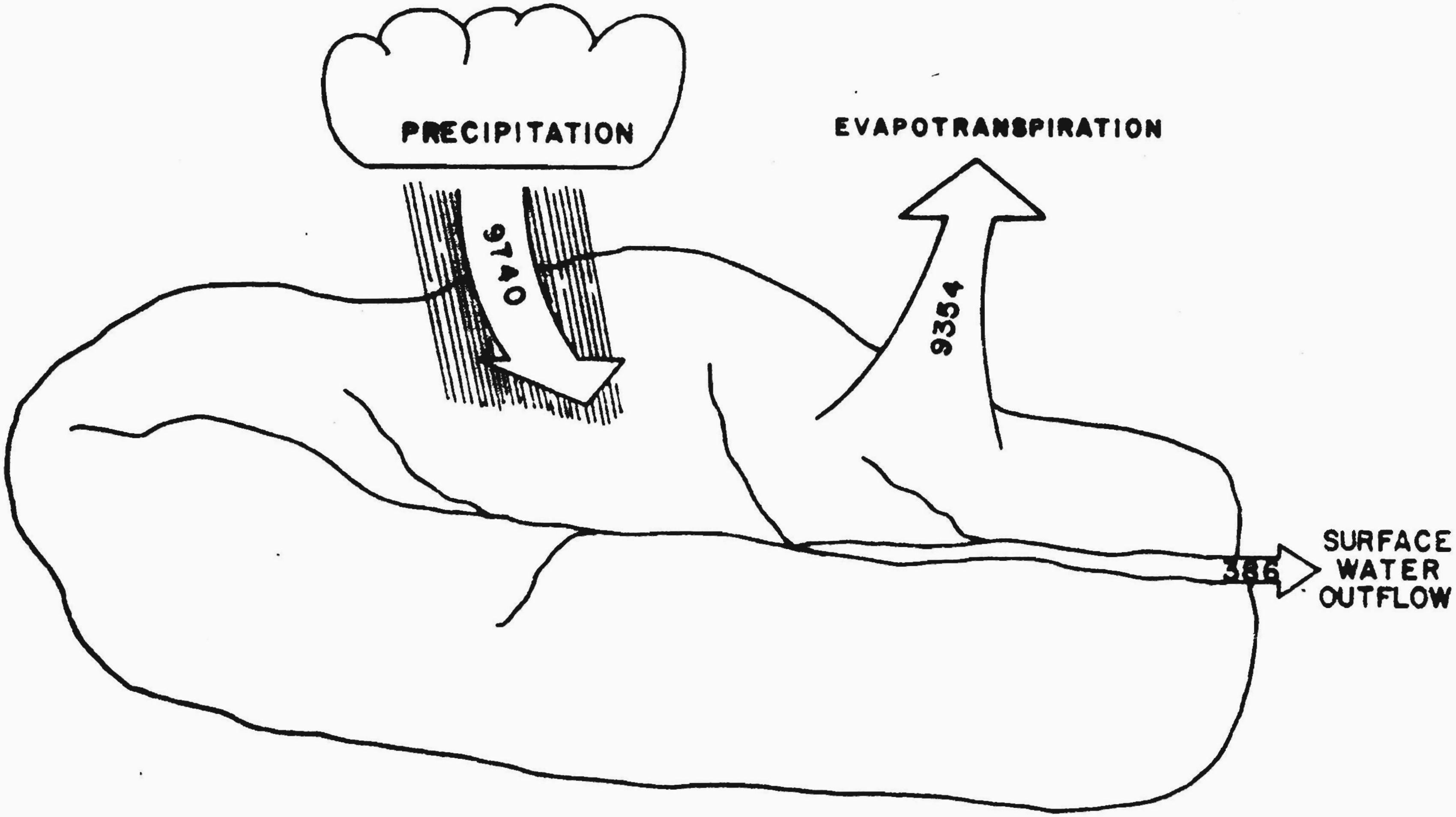
GRAND RIVER BASIN

SIMPLIFIED HYDROLOGIC BUDGET FOR BASINS

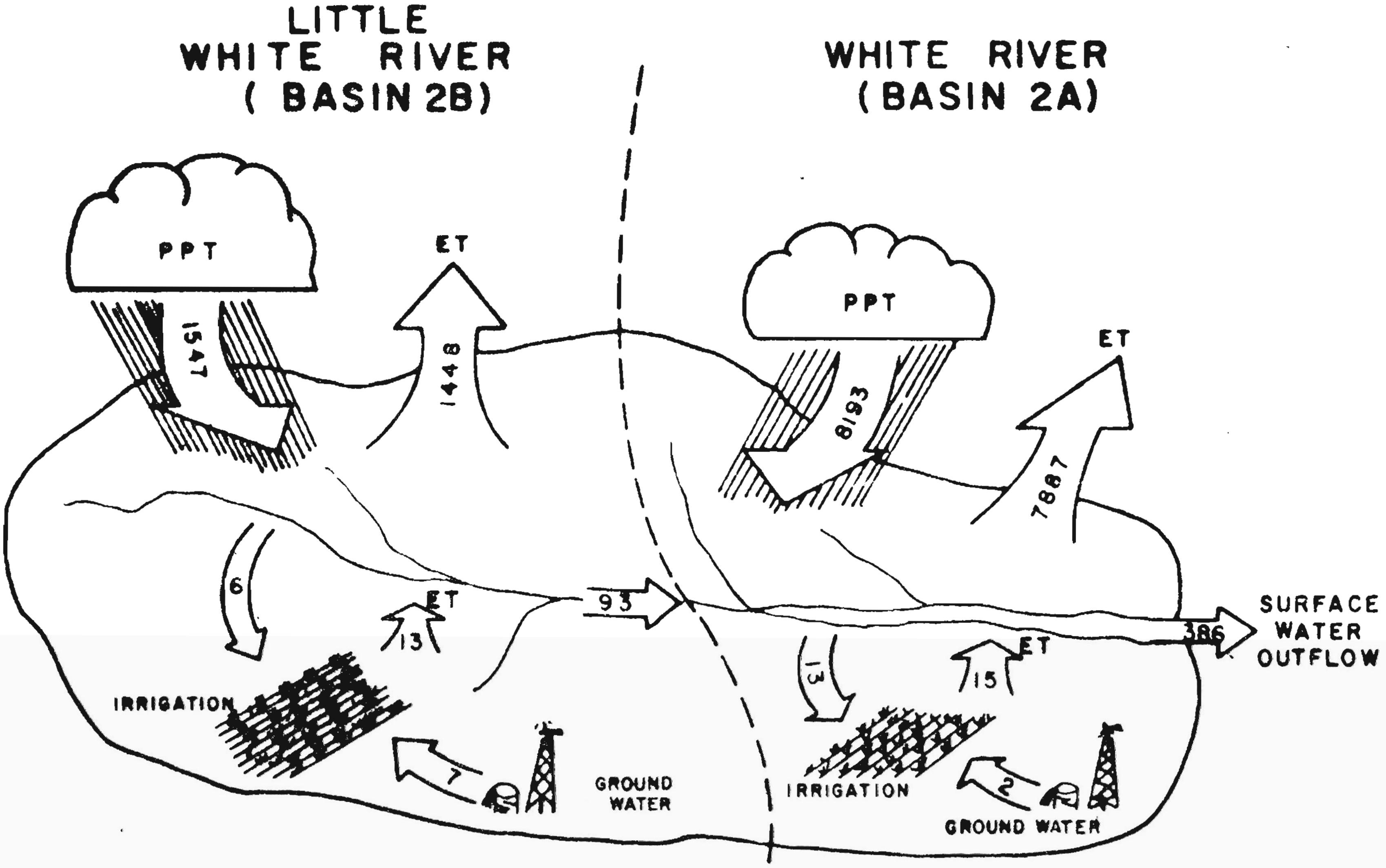
(IN 1000 ACRE-FT/YR)

GRAND RIVER BASIN

DESTINATIONS / SOURCES		TRANSPORT				USE SECTORS								EXITS				TOTALS
		Bowman - Haley Subbasin	Upper Grand Subbasin	Shadehill Reservoir	Lower Grand Subbasin	Irrigation, Upper Grand	Irrigation, Lower Grand	Buffalo	Isabel	Lemmon	Towns <500	Restaurants	Reservations	Ground Water	Atmosphere	Out - Basin Discharge	Missouri River	
SUPPLIES	Avg. Atmosphere	414.53	2126.39		2007.54			.01	.01	.03	.02							4548.53
	Ground Water							.03		.19	.12	.02	.06					.41
TRANSPORT	Bowman - Haley Subbasin		20.29												394.24			414.53
	Upper Grand Subbasin			107.30											2039.38			2146.66
	Shadehill Reservoir				86.94	4.23	1.78								14.35			107.30
	Lower Grand Subbasin								.04						1915.34		179.10	2094.48
USE SECTORS	Irrigation, Upper Grand														4.23			4.23
	Irrigation, Lower Grand														1.78			1.78
	Buffalo													.01	.03			.04
	Isabel													.02	.03			.05
	Lemmon													.03	.08	.11		.22
	Towns <500													.02	.12			.14
	Restaurants													.01	.01			.02
	Reservations													.02	.03			.05
TOTALS		414.53	2146.68	107.30	2094.48	4.23	1.78	.04	.05	.22	.14	.02	.05	.11	4369.62	.11	179.10	9318.46



WHITE RIVER BASIN
SIMPLIFIED HYDROLOGIC BUDGET
(IN 1000 ACRE-FT/YR)



WHITE RIVER BASIN
SIMPLIFIED HYDROLOGIC BUDGET FOR BASINS
(IN 1000 ACRE-FT/YR)

WHITE RIVER BASIN

DESTINATIONS / SOURCES			TRANSPORT		USE SECTORS											EXITS		TOTALS
			White River Subbasin	Little White Subbasin	Irrigation, White River	Irrigation, Little White	Kyle	Murdo	Pine Ridge	Winner (& Indian Comm.)	Towns <500	Martin	St. Francis	White River	Towns <500	Atmosphere	Missouri River	
							White River					Little White						
SUPPLIES		Avg. Atmosphere	8192.75	1547.39														9740.14
		Ground Water			1.92	6.82	.03	.08	.26	.51	.20	.19	.15	.05	.04			10.25
TRANSPORT		White River Subbasin			13.20											7886.81	386.20	8286.21
		Little White Subbasin	93.46			6.24										1447.69		1547.39
USE SECTORS		Irrigation, White River														15.12		15.12
		Irrigation, Little White														13.06		13.06
	White River	Kyle														.03		.03
		Murdo														.08		.08
		Pine Ridge														.26		.26
		Winner (& Indian Comm.)														.51		.51
		Towns <500														.20		.20
	Little White	Martin														.19		.19
		St. Francis														.15		.15
		White River														.05		.05
		Towns <500														.04		.04
TOTALS			8286.21	1547.39	15.12	13.06	.03	.08	.26	.51	.20	.19	.15	.05	.04	9364.19	386.20	19613.68