EVALUATION OF GROUND-WATER RESOURCES
EASTERN SOUTH DAKOTA AND UPPER BIG SIOUX RIVER
SOUTH DAKOTA AND IOWA

TASK 7: GROUND WATER RECHARGE

FINAL REPORT
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INTRODUCTION

This report is part of a series of studies being conducted by the U.S. Army Corps of Engineers to evaluate water resources in South Dakota and the Upper Big Sioux River in South Dakota and Iowa. The output contained in this report (TASK 7) is restricted to portions of South Dakota east of the Missouri River and includes the Big Sioux Basin located within South Dakota. TASK 7 is designed to assess the natural recharge rates to all aquifer units in eastern South Dakota as defined in TASK 2. The following is a description of TASK 7.

TASK 7 - Make estimates of probable, maximum-minimum natural recharge rates to aquifers, where feasible.

A. Make a bibliographic search for all published and unpublished information available in the Department of Water and Natural Resources (DWNR) files, U.S. Geological Survey (USGS) files, and files from other public agencies.

B. Based on available information, estimate possible range of recharge rates using accepted geologic-hydrologic procedures.

C. Prepare maps and/or tables to show possible range of natural recharge rates.

GENERAL AQUIFER CLASSIFICATION FOR SURFICIAL DEPOSITS

For the purposes of this report and as defined in TASK 2, surficial deposits are defined as all unconsolidated glacial and non-glacial deposits of Pleistocene and Recent Age. TASK 2, (table 1), identified 97 surficial aquifer and/or management units in surficial deposits. This report, TASK 7, includes 3 additional aquifers and/or management units and identifies name changes to four units. These changes are identified and included on table 1. The names and/or abbreviations listed on this table are used throughout this report.

In TASK 2 aquifers or aquifer systems classified as surficial deposits were subdivided into four general groups for illustration and discussion.

1. Deep James and Fairmount systems.
2. Basal System
3. Intermediate System
4. Surface System

It was also mentioned in TASK 2 that systems may be interconnected, and they may be completely or in part water-table (unconfined) or artesian (confined).

TABLE 1

List of aquifers and management units in surficial deposits in eastern South Dakota.

Abbreviation	Aquifer : Management Unit Names
A	Altamont
AV	Antelope Valley
BC	Bad-Cheyenne
BS : A	Big Sioux : Aurora
BS : B	Big Sioux : Brookings
BS : MSC	Big Sioux : Middle Skunk Creek
BS : M	Big Sioux : Moody
BS : N	Big Sioux : North
BS : NDC	Big Sioux : North Deer Creek
BS : NSC	Big Sioux : Northern Skunk Creek
BS : SF	Big Sioux : Sioux Falls
BS : SMC	Big Sioux : Six Mile Creek
BS : S	Big Sioux : South
BS : SSC	Big Sioux : Southern Skunk Creek
BS : UC	Big Sioux : Unnamed Creek
B : E	Bowdle : Edmunds
B : HN	Bowdle : Hoven North
B : HS	Bowdle : Hoven South
B : L	Bowdle : Lebanon
BRC	Brule Creek
CHP	Chapelle Creek
CH : E	Choteau : East
CH : M	Choteau : Middle
CH : T	Choteau : Tyndall
CH : W	Choteau : West
CO	Corsica
COL	Coteau Lakes
COW	Cow Creek
CC	Crow Creek
CL	Crow Lake
DJ	Deep James
D	Delmont
EC	Elm Creek
E : I	Elm : Ipswich
E : NB	Elm : Northern Brown
E : SB	Elm : Southern Brown
ET	Ethan
FMT	Fairmount
F : A	Floyd : Alexandria

TABLE 1 -- continued.

	Abbreviation	Aquifer : Management Unit Names
	F : EJ	Floyd : East James
	F : PC	Floyd : Pearl Creek
	GE	Geddes
	G	Grand
	GG	Gray Goose
	HA	Harrisburg
	HB	Highmore-Blunt
	HV	Hillsview
	HO	Howard
	HU	Hubonmix
	I	Intermediate
	J	Java
	L	Lennox
	LT	Lesterville
(1)	LJM : J	Lower-James-Missouri : Jamesville
	LJM : S	Lower-James-Missouri : Scotland
	LVM	Lower-Vermillion-Missouri
	MJ : A	Middle James : Aberdeen
	MJ : C	Middle James : Columbia
(1)	M : EP	Missouri : Elk Point
	M : G	Missouri : Greenwood
	M : PE	Missouri : Peoria
	M : P	Missouri : Pierre
	M : T	Missouri : Tower
	NH	Newton Hills
	OK	Okobojo Creek
	O	Onaka
	PAC	Parker-Centerville
(2)	PS	Pleistocene Series
	PC	Plum Creek
	PCO	Prairie Coteau
	S	Selby
	SH	Shindler
(3)	SF	Sioux Falls
	SC : A	Spring Creek : Artas
	SC : H	Spring Creek : Herreid
	SC : M	Spring Creek : McPherson

TABLE 1 -- continued.

	Abbreviation	Aquifer : Management Unit Names
(1)	T : S	Tulare : Sully
	T : EJ	Tulare : East James
	T : HA	Tulare : Hand
	T : H	Tulare : Hitchcock
	T : HY	Tulare : Hyde
	T : M	Tulare : Miller
	T : RH	Tulare : Ree Heights
	T : WS	Tulare : Western Spink
	TL	Twin Lakes
	UVM	Upper-Vermillion-Missouri
	VEB	Veblen
(1)	VEF : M	Vermillion-East-Fork : Montrose
	VEF : AL	Vermillion-East-Fork : Antelope Lake
	VEF : RL	Vermillion-East-Fork : Reid Lake
	VEF : SL	Vermillion-East-Fork : Spirit Lake
	VEF : WL	Vermillion-East-Fork : Willow Lake
	VWF	Vermillion-West-Fork
	WK	Wakonda
	WAL	Wall Lake
	W : MC	Warren : Morris Creek
	W : WJ	Warren : West James
	W : W	Warren : Wolsey
	WL	White Lake
	WIL	Wilmot

NOTES

(1) In order to maintain consistency in aquifer naming convention, the following names have been changed from TASK 2.

TASK 2	TASK 7 (this report)
Lower James Missouri (LJM)	Lower-James-Missouri : Jamesville (LJM : J)
Missouri (M)	Missouri : Elk Point (M : EP)
Tulare (T)	Tulare : Sully (T : S)
Vermillion East Fork (VEF)	Vermillion-East-Fork : Montrose (VEF : M)

(2) All unnamed units from surficial deposits and miscellaneous management units have been grouped under Pleistocene Series.

(3) The Sioux Falls aquifer is included in order to make the list as complete as possible at this time.

For purposes of assessing the natural recharge capabilities of aquifers in the surficial deposits the most important criteria are whether they are confined or unconfined, and if unconfined, whether they are buried or exposed at the surface (or directly underlying the soil). In general, an unconfined aquifer is considered "buried" if 10 feet or more of relatively impermeable material overlies the aquifer material. The aquifers are generally considered non-buried if they occur at less than 10 feet from the surface. It should be emphasized that "buried" does not necessarirly mean "confined" because several "buried" aquifers <u>are not confined</u>. The following discussion of natural recharge makes this distinction. Tables 2 and 3 show the general aquifer classification categories used for this report and are cross-referenced to the classification by Aquifer System used in TASK 2.

METHODS OF CALCULATING RECHARGE

<u>Recharge Using Base Flow Recession Analysis</u>

Data Availability

Interpretation of streamflow records often aid in assesment of ground-water recharge. The two major drainage basins in eastern South Dakota, the James River Basin and the Big Sioux River Basin, cover about 70 percent of the land area. Water-discharge records are available for the James River near Scotland, South Dakota, and the Big Sioux River near Akron, Iowa, for a period of 55 years. Consequently long records of streamflow data exists and is available for analysis.

Methodology

In relatively undeveloped areas, ground water is in dynamic equilibrium with the regional hydrologic system. That is, if a volume of water is recharged to an aquifer an equal volume will be discharged. The water level in aquifers will remain steady and the volume of ground water in storage will remain constant. The aquifer transmits the ground water from recharge areas to discharge areas (Fetter, 1980). The discharged ground water enters the regional surface drainage system and provides a base flow which when combined with direct runoff from precipitation accounts for the total volume of streamflow. If within a particular drainage basin the following assumptions are made:

1. the surface water and ground water divides coincide,

2. all the aquifers within the basin are hydraulically connected, and

3. all the discharged ground water enters the streams within the basin,

the base flow component of streamflow will represent the volume

TABLE 2.

List of unconfined aquifers.

Aquifer : Management Unit	Aquifer system as designated in TASK 2
NON-BURIED AQUIFERS	
Antelope Valley	Surface System
Big Sioux : Aurora	Surface System
Big Sioux : Brookings	Surface System
Big Sioux : Middle Skunk Creek	Surface System
Big Sioux : Moody	Surface System
Big Sioux : North	Surface System
Big Sioux : North Deer Creek	Surface System
Big Sioux : Northern Skunk Creek	Surface System
Big Sioux : Sioux Falls	Surface System
Big Sioux : Six Mile Creek	Surface System
Big Sioux : South	Surface System
Big Sioux : Southern Skunk Creek	Surface System
Big Sioux : Unnamed Creek	Surface System
Bowdle : Edmunds	Surface System
Bowdle : Hoven North	Surface System
Bowdle : Hoven South	Surface System
Bowdle : Lebanon	Surface System
Chapelle Creek	Surface System
Coteau Lakes	Surface System
Cow Creek	Surface System
Crow Creek	Surface System
Delmont	Surface System
Elm Creek	Surface System
Highmore-Blunt	Surface System
Missouri : Elk Point	Basal System
Missouri : Greenwood	Basal System
Missouri : Peoria	Basal System
Missouri : Pierre	Basal System
Missouri : Tower	Basal System
Okobojo Creek	Surface System

TABLE 2 -- continued.

Aquifer : Management	Aquifer system as designated in TASK 2
NON-BURIED AQUIFERS	
Parker-Centerville	Surface System
Selby	Surface System
Spring Creek : Artas	Surface System
Spring Creek : Herreid	Surface System
Spring Creek : McPherson	Surface System
Vermillion-East-Fork : Antelope Lake	Surface System
Vermillion-East-Fork : Montrose	Surface System
Vermillion-East-Fork : Reid Lake	Surface System
Vermillion-East-Fork : Spirit Lake	Surface System
Vermillion-East-Fork : Willow Lake	Surface System
Vermillion-West-Fork	Surface System
BURIED AQUIFERS	
Choteau : East	Basal System
Floyd : Pearl Creek	Basal System
Gray Goose	Basal System
Tulare : East James	Basal System
Tulare : Hitchcock	Basal System

TABLE 3

List of confined aquifers.

Aquifer : Management Unit	Aquifer system as designated in TASK 2
Altamont	Basal System
Bad-Cheyenne	Basal System
Brule Creek	Intermediate System
Choteau : Middle	Basal System
Choteau : Tyndall	Basal System
Choteau : West	Basal System
Corsica	Basal System
Crow Lake	Intermediate System
Deep James	Deep System
Elm : Ipswich	Intermediate System
Elm : Northern Brown	Intermediate System
Elm : Southern Brown	Intermediate System
Ethan	Basal System
Fairmount	Deep System
Floyd : Alexandria	Basal System
Floyd : East James	Basal System
Geddes	Basal System
Grand	Basal System
Harrisburg	Intermediate System
Hillsview	Intermediate System
Howard	Basal System
Hubonmix	Intermediate System
Intermediate	Intermediate System
Java	Intermediate System
Lennox	Basal System
Lesterville	Intermediate System
Lower-James-Missouri : Jamesville	Basal System
Lower-James-Missouri : Scotland	Basal System
Lower-Vermillion-Missouri	Basal System
Middle James : Aberdeen	Basal System
Middle James : Columbia	Basal System
Newton Hills	Intermediate System

TABLE 3 -- continued.

Confined aquifers	Aquifer system as designated in TASK 2
Onaka	Intermediate System
Plum Creek	Basal System
Prairie Coteau	Intermediate System
Shindler	Intermediate System
Sioux Falls	Intermediate System
Tulare : Hand	Intermediate System
Tulare : Hyde	Intermediate System
Tulare : Miller	Intermediate System
Tulare : Ree Heights	Intermediate System
Tulare : Sully	Intermediate System
Tulare : Western Spink	Basal System
Twin Lakes	Intermediate System
Upper-Vermillion-Missouri	Basal System
Veblen	Basal System
Wakonda	Intermediate System
Wall Lake	Intermediate System
Warren : Morris Creek	Basal System
Warren : West James	Basal System
Warren : Wolsey	Basal System
Wilmont	Intermediate System
White Lake	Intermediate System

of ground-water recharge to the basin when it is at dynamic equilibrium.

Several techniques have been used to separate surface runoff and base flow components of a stream hydrograph. Most are based on an interpretation of recession or depletion curves. The method of base flow separation and estimation of ground-water recharge used in this report for the Big Sioux Basin and the James Basin was taken from Fetter (1980) and Meyboom (1961). The base flow recession curve can be expressed by the general regression equation:

where $[Qt = Qoe^{-ct}]$

$$\begin{bmatrix} Qt \\ Qo \\ c \\ t \end{bmatrix} \begin{matrix} = \text{flow at some time } [t] \\ = \text{flow at start of recession} \\ = \text{recession constant} \\ = \text{time since recession began} \end{matrix}$$

If the stream hydrograph is made by plotting the logarithm of discharge against time a linear relationship may be obtained. The best straight line connecting successive points of minimum stream discharge is considered to approach true baseline conditions.

A complete baseflow recession begins with the first minimum value on the recession curve and ends with the first spring flood. The amount of recharge that occurs between two consecutive ground-water recessions may then be calculated by the following:

Recharge (R) occurring between two consecutive base flow recessions 1 and 2	=	total potential ground water discharge of base flow recession 2	−	total remaining potential ground water discharge at the end of base flow recession 1

$$R = \frac{Qo_2 t_2}{2.3} - \frac{Qo_1 t_1}{2.3 \ 10^{\frac{t}{t_1}}}$$

where

Qo_1 = baseflow at start of recession 1
t_1 = time for base flow to go from Qo_1 to 0.1 Qo_1
t = length of recession 1
Qo_2 = base flow at start of recession 2
t_2 = time for base flow to go from Qo_2 to 0.1 Qo_2

Once the ground-water recharge is calculated by the above referenced method the total consumptive ground-water use in the basin must be added to derive an estimate of the total ground-water recharge. Consumptive ground water use can be estimated from TASK 6 and surface water use can be estimated from records from the Division of Water Rights. Because these records and estimates are incomplete, the total consumptive use estimate is probably a conservative value.

Monthly mean streamflow hydrographs were constructed from data for the period 1929-1980 for the Big Sioux River Basin above Akron, Iowa, and the James River Basin above Scotland, South Dakota. These data were obtained from the U.S. Geological Survey WATER RESOURCES DATA FOR SOUTH DAKOTA, WATER YEAR 1981: U.S. Geological Survey water data report SD-81-1, 365 p.

Basin Recharge Estimates

Calculations of recharge rates to aquifers in the Big Sioux and James River Basins are shown in table 4.

TABLE 4

Ground-water recharge to aquifers in the James and Big Sioux River Basins.

	Big Sioux River Basin	James River Basin
Area (above Akron, IA, and Scotland, SD	7060 sq. mi.	16,760 sq. mi.
Calculated annual ground-water recharge	0.55 in./yr. (207,093 ac-ft)	0.10 in./yr. (89,386 ac-ft)
Estimated annual consumptive water use from aquifer	0.13 in./yr. (48,949 ac-ft)	0.06 in./yr. (53,632 ac-ft)
Total annual ground-water recharge	0.68 in./yr. (256,042 ac-ft)	0.16 in./yr. (143,018 ac-ft)

Examination of total recharge values for the two basins shows that aquifers in the Big Sioux River Basin receive about 4 times as much recharge per unit area as aquifers in the James Basin. The significant difference in recharge rates is attributed mainly to three factors:

1. Average annual precipitation in the Big Sioux River Basin is 3 to 4 inches greater (15 to 20 percent) than that in the James River Basin;

2. The proportion of highly permeable material at the land surface in the Big Sioux River Basin is much greater than in the James River Basin, thus providing an easily rechargeable reservoir for available water;

3. The Big Sioux River is in contact with highly permeable sand and gravel throughout much of its course. The sand and gravel provides a ready conduit for transmitting water from the aquifer to the river. Relatively impermeable alluvium along the course of the James River acts as an effective barrier to the

transmittal of appreciable groundwater to streamflow.

If it is assumed that the entire base flow of the Big Sioux River is derived from the Big Sioux aquifer then the acre feet of recharge (258,000 ac-ft) divided by acres of aquifer (475,000 acres) equals average feet (0.54 ft = 6.5 inches) of recharge over the entire aquifer. The value of 6.5 inches compares favorably with estimated recharge calculated by computer model analysis and by observation well record analysis discussed later in this report.

In the James Basin it is assumed that base flow is also derived from aquifers. The calculated acre feet of recharge (143,000 ac-ft) divided by acres of aquifer (2,341,600 acres) equals average (0.06 feet = 0.72 inches) recharge for aquifers in the James Basin. It should be pointed out that the 0.72 inches average annual recharge to aquifers in the James Basin is a <u>maximum value</u> because of the probability of additional unknown aquifers in the basin contributing to the base flow.

<u>Recharge Using Computer Models</u>

Data Availability and Methodology

Computer modeling of ground-water flow systems has been used as a common analytical tool since about 1970. Because of the tedious complexities of theories and applications no attempt will be made to summarize the methods used. Instead the details for each model area can be obtained from the references listed.

To date there has been three computer models in eastern South Dakota which attempt to quantify annual average recharge for portions of an aquifer system. Two of these are for areas within the Big Sioux Aquifer (non-buried, unconfined) and one for part of the Tulare aquifer which contains a buried, unconfined portion and a confined portion. These studies are identified below.

Koch, Neil C., 1980, <u>Appraisal of the Water Resources of the Big Sioux Aquifer, Brookings, Deuel, and Hamlin Counties, South Dakota</u>: U.S. Geol. Survey Water-Resources Investigations 80-100, 46 p.

Koch, Neil C., 1982, <u>A Digital-Computer Model of the Big Sioux Aquifer in Minnehaha County, South Dakota</u>: U.S. Geol. Survey Water-Resources Investigations, 82-4064, 49 p.

Kuiper, Logan K., 1982, <u>Appraisal of the Water Resources of the Eastern Part of the Tulare Aquifer, Beadle, Hand and Spink Counties, South Dakota</u>: U.S. Geol. Survey, preliminary draft, 44 p. plus figures and Appendix.

Recharge Calculations

Computer models have been used to determine recharge in portions of the Tulare and Big Sioux Aquifers. Recharge models have been completed in the Sioux Falls management unit and also in the area comprised of most of the Brookings, Aurora, Six-Mile Creek, Unnamed Creek, and Deer Creek management units of the Big Sioux Aquifer.

Portions of the Tulare aquifer modeled are comprised essentially of the East James, Hitchcock, and Western Spink management units. The East James and Hitchcock management units are primarily buried, unconfined while the Western Spink management unit is primarily confined. It should be noted that the model analysis did not differentiate between confined and unconfined areas in portions of the model representing the Hitchcock and Western Spink management units. The model incorporated an average recharge rate throughout. Thus, recharge rates shown in table 5 reflect the "best fit" recharge rates used for various simulation runs.

TABLE 5

Recharge rates determined by computer model analysis

Aquifer : Management unit		Inches per year Best fit	 Estimated Range
Big Sioux Aquifer :			
Sioux Falls		6.9	-------
Brookings	}		
Aurora	}		
Six-Mile Creek	}--COMBINED	3.6	-------
Unnamed Creek	}		
North Deer Creek	}		
Tulare Aquifer :			
East James		0.76	0.38-1.52
Hitchcock	}		
Western Spink	}--COMBINED	0.83	0.41-1.66

Recharge Using Observation Well Data

Data Availability

The Department Water and Natural Resources, Division of Water Rights, has maintained an observation well network throughout the State for over 25 years. To date there are approximately 1,300 observations wells in aquifers of the Surficial Deposits in eastern South Dakota. Water level measurements are normally taken at least three times a year. During the past 10 years selected wells may have monthly or even weekly readings for portions of the year.

As part of TASK 4 a computerized data base management system (ADABAS) was developed for the purpose of storage, retrieval, and manipulation of observation well data. From this data base selected observation wells were chosen to analyze water level fluctuations. To accomplish this, water level information was transferred from the data base to a separate SAS (Statistical Analysis System) file where the data was manipulated by pre-programmed statistical methods.

Methodology

The analysis of water level readings from observation wells was restricted to unconfined aquifers or unconfined portions of confined aquifers. The method used to calculate recharge in those wells was:

1. Identify all wells exhibiting unconfined conditions from each aquifer or management unit.

2. Totalling water level rises for each well for the total length of records (in years).

3. Combining the total increase in water levels for all wells from a specific aquifer or management unit.

4. Obtaining the total number of record years for the observed aquifer or management unit.

5. Dividing the total rise in water levels of all wells by the total number of record years. The resulting value is the average annual water level rise for the aquifer, management unit or series of wells.

6. Finally, the average annual increase in water levels were converted to inches and multiplied by the specific yield (0.15) to obtain the average annual recharge, in inches, to each aquifer, management unit, or series of wells.

Recharge to Unconfined Aquifers

Non-Buried

A list of aquifers for which adequate data are available to calculate recharge to non-buried, unconfined aquifers is shown on table 6. Calculated natural recharge rates for non-buried, unconfined aquifers are shown in table 7. Of the 46 aquifers and/ or management units listed in this category, 26 have adequate data to make reliable estimates of the recharge rates. The calculated recharge rates vary from 2.0 to 5.6 inches per year. This range is estimated to be the minimum-maximum range in this group of aquifers. Those 20 aquifers which do not have adequate data but are similar geologically and hydrologically, are assumed to have the same minimum-maximum rates.

Buried

The buried, unconfined aquifers are listed on table 6. Calculated recharge rates to buried, unconfined aquifers (table 7) are generally less than recharge rates to non-buried, unconfined aquifers. The range in calculated recharge rates of buried unconfined aquifers is 0.9 to 3.2 inches with an average of 2.0 inches, compared to a range of 2.0 to 5.6 inches with an average of 3.8 inches for non-buried, unconfined aquifers. Thus, the non-buried, unconfined aquifers receive about twice the average annual recharge as do the buried, unconfined aquifers as determined by the observation well analysis method of calculation.

Recharge to Confined Aquifers

Confined aquifers intermittently become unconfined. These points or areas are identified by the presence of observation wells which exhibit water-table conditions (pl. 1A and 1B). Table 8 presents available data for calculating recharge to unconfined portions of confined aquifers.

Table 9 demonstrates the average annual recharge in observation wells completed in these areas. The average annual recharge ranges from 2.2 to 5.2 inches and averages 3.7 inches. The range and average values shown are very close to those computed for recharge to non-buried, unconfined aquifers: 2 to 5.6 inches, and 3.8 inches respectively.

Generally, where wells in the confined aquifers encounter unconfined conditions they are found to be directly connected to non-buried aquifers, or surface water sources. Thus, the similarity of their water level responses to wells in unconfined aquifers is not surprising. However, to properly evaluate the significance of these areas in terms of total recharge and ground-water budget, much additional data would be required.

TABLE 6

Data availability for calculating recharge to unconfined aquifers.

Aquifer : Management Unit	Number of Observation wells	Total Number of Readings	Total Number of Record Years
NON-BURIED AQUIFERS			
Antelope Valley	3	117	13
Big Sioux : Aurora	13	686	102
Big Sioux : Brookings	58	3,443	478
Big Sioux : Middle Skunk Creek	7	509	72
Big Sioux : Moody	18	1,363	224
Big Sioux : North	25	1,901	290
Big Sioux : North Deer Creek	3	198	30
Big Sioux : Northern Skunk Creek	8	341	55
Big Sioux : Sioux Falls	15	418	65
Big Sioux : Six Mile Creek	5	263	53
Big Sioux : South	17	848	181
Big Sioux : Southern Skunk Creek	5	190	36
Bowdle : Edmunds	9	422	71
Bowdle : Hoven North	6	438	53
Bowdle : Hoven South	14	1,099	95
Bowdle : Lebanon	6	459	48
Coteau Lakes	7	308	28
Crow Creek	9	364	42
Delmont	11	1,415	129
Missouri : Elk Point	20	1,454	195
Parker-Centerville	18	1,311	175
Selby	11	736	99
Vermillion-East-Fork : Antelope Lake	5	164	16
Vermillion-East-Fork : Montrose	8	550	93
Vermillion-East-Fork : Spirit Lake	5	360	45
Vermillion-East-Fork : Willow Lake	4	221	25
BURIED AQUIFERS			
Choteau : East	3	171	16
Floyd : Pearl Creek	3	192	16
Gray Goose	7	120	16
Tulare : East James	18	1,506	137
Tulare : Hitchcock	17	1,440	135

TABLE 7

Recharge to unconfined aquifers.

Aquifer : Management Unit	Recharge by observation well analysis (inches/year)
NON-BURIED AQUIFERS	
Antelope Valley	2.3
Big Sioux : Aurora	5.0
Big Sioux : Brookings	4.0
Big Sioux : Middle Skunk Creek	3.2
Big Sioux : Moody	4.9
Big Sioux : North	3.2
Big Sioux : North Deer Creek	4.9
Big Sioux : Northern Skunk Creek	3.1
Big Sioux : Sioux Falls	5.6
Big Sioux : Six Mile Creek	5.0
Big Sioux : South	4.1
Big Sioux : Southern Skunk Creek	2.7
Bowdle : Edmunds	2.7
Bowdle : Hoven North	2.2
Bowdle : Hoven South	2.5
Bowdle : Lebanon	2.0
Coteau Lakes	4.5
Crow Creek	3.8
Delmont	5.6
Missouri : Elk Point	3.8
Parker-Centerville	4.9
Selby	2.0
Vermillion-East-Fork : Antelope Lake	3.0
Vermillion-East-Fork : Montrose	3.4
Vermillion-East-Fork : Spirit Lake	4.0
Vermillion-East-Fork : Willow Lake	5.6
BURIED AQUIFERS	
Choteau : East	1.4
Floyd : Pearl Creek	0.9
Gray Goose	3.2
Tulare : East James	2.5
Tulare : Hitchcock	2.0

TABLE 8

Data availability for calculating recharge to unconfined portions of confined aquifers.

Aquifer : Management Unit	Number of Observation wells	Total Number of Readings	Total Number of Record Years
Altamont	8	324	36
Choteau : Tyndall	3	171	16
Choteau : West	2	110	11
Floyd : East James	5	613	62
Grand	3	90	17
Lower-James-Missouri : Jamesville	21	662	108
Lower-Vermillion-Missouri	9	632	95
Prairie Coteau	3	127	15
Tulare : Hand	17	649	110
Veblen	11	454	46
Warren : West James	6	378	63

TABLE 9

Recharge rates to unconfined portions of confined aquifers.

Aquifer : Management Unit	Average Annual Recharge (inches/yr.)
Altamont	2.2
Choteau : Tyndall	3.2
Choteau : West	4.1
Floyd : East James	3.4
Grand	4.0
Lower-James-Missouri : Jamesville	3.9
Lower-Vermillion-Missouri	3.8
Prairie Coteau	4.9
Tulare : Hand	3.4
Veblen	5.2
Warren : West James	3.0

Recharge Using Regional Flow-Net Analysis

Data Availability

Interpretation of flow-net systems can provide insight into the recharge potential of a ground-water system. TASK 2 provided water level maps for aquifers where adequate data was available. Flow-net analysis of selected aquifers are included to help assist in evaluation of natural recharge rates determined by other methods.

Methodology

The amount of water flowing through an aquifer at any time can be calculated according to the equation:

$$Q = TIL$$

where:

Q = quantity in gallons per day
T = transmissivity in gallons per day per foot
I = hydraulic gradient in feet per mile
L = cross sectional length in miles

then:

Q -- 325,850 (converts gallons to acre feet) x 365 (days) = acre feet per year

then:

Q (in acre feet per year) -- acres X 12 (coverts feet to inches) = Recharge (in inches).

In using this method of calculation to estimate annual average recharge (in inches per year) the following assumptions are made:

1. That the aquifer is at equilibrium, that is, there has been no abnormal recharge or discharge event(s) which would significantly alter the normal piezometric surface.

2. Transmissivity is calculated by finding the average aquifer thickness in feet and multiplying by 1,000 gallons per day per foot thickness of that aquifer.

It should be noted that recharge rates calculated using flow-net analysis are suspect and conclusions based on this method are questionable.

Recharge Rates

Recharge rates calculated from regional flow net analysis are shown for the various aquifer groups on table 10. Two general conclusions from the results of these calculations are:

1. Confined aquifers as a group receive less recharge than does the buried, unconfined group which in turn receives less recharge than does the non-buried, unconfined.

2. The progressive decline in calculated recharge corresponds to a decreasing degree of contact with surface water and/or permeable material at the land surface.

TABLE 10

Recharge rates calculated from reigonal flow-net analysis.

Aquifer : Management Unit		Recharge (inches per year)
Non-Buried Unconfined		
Parker-Centerville		0.91
Bowdle : Hoven South		0.53
Bowdle : Lebanon		0.96
Big Sioux (minimum estimate)		1.00
		0.85 = average
Buried Unconfined		
Tulare : Hitchcock		0.24
Tulare : East James		0.72
Pearl Creek		0.22
Northern Spink County (estimated)		0.31
Lower-James-Missouri : Jamesville	Combined	
Lower-James-Missouri : Scotland	Combined	1.50
		0.60 = average
Average without including management units of Lower-James-Missouri		0.37
Buried Confined		
Veblen		0.24
Upper-Vermillion-Missouri		0.25
Floyd : East James		0.30
Warren : West James	Combined	
Warren : Morris Creek	Combined	0.35
Elm : Northern Brown		0.06
Elm : Southern Brown		0.42
		0.36 = average

Recharge rates calculated by flow-net analysis are in better agreement with other methods for the confined group of aquifers. A comparison of results will be made later in this report.

Water Use Statistics

Used alone, water use statistics are of little value in determining natural recharge rates to aquifers. However, when used in conjunction with other data and other methods of recharge calculations the statistics become useful. For this reason tables 11 and 12 have been compiled showing water use in inches and acre-feet for unconfined and confined groups of aquifers. The tables have been arranged from highest rate of water use (in inches), to lowest rate of water use (in inches).

To date the Division of Water Rights, DWNR, has determined that there are no aquifers in the surficial deposits where pumping exceeds the average annual recharge. Thus, the current average annual use for each aquifer could be interpreted as the minimum average annual recharge rate. In reality, there are several aquifers that are probably approaching or exceeding the actual average annual natural recharge rate. Where these aquifers have been identified they have been or are presently under consideration for withdrawal restrictions. These aquifers will be identified and discussed later in this report.

The average annual use calculations will be referred to throughout the remainder of this report where comparing and evaluating recharge rates for the aquifer groups and individual aquifers.

RECHARGE RATES TO UNCONFINED AQUIFERS

Non-Buried Aquifers

Big Sioux Aquifer

Recharge rates calculated for the various management units of the Big Sioux Aquifer are summarized in table 13. The calculated recharge rates range from 2.7 to 6.9 inches per year if flow-net analysis is ignored. This range is also likely to be the actual minimum-maximum range for management units within the Big Sioux Aquifer.

Recharge rates calculated using observation well data and computer models are generally in accord. Consequently, management programs using these values (table 13) should be acceptable.

TABLE 11

Average annual use for unconfined aquifers.

Aquifer : Management Unit	Average Annual Use (ac-ft)	Average Annual Use (inches)
NON-BURIED AQUIFERS		
Vermillion-East-Fork : Montrose	3,467	NA
Big Sioux : Sioux Falls	17,370	9.11
Cow Creek	2,146	7.15
Missouri : Pierre	2,920	6.15
Parker-Centerville	8,033	2.18
Big Sioux : South	7,222	1.76
Missouri : Elk Point	24,274	1.33
Big Sioux : Six Mile Creek	449	1.28
Big Sioux : Northern Skunk Creek	2,636	1.25
Okobojo Creek	1,419	1.23
Big Sioux : Unnamed Creek	561	1.16
Big Sioux : Southern Skunk Creek	890	1.10
Big Sioux : Aurora	3,483	1.06
Big Sioux : Moody	3,062	1.03
Big Sioux : North	7,130	1.02
Bowdle : Hoven South	867	0.87
Big Sioux : Brookings	13,339	0.84
Delmont	1,911	0.82
Big Sioux : North Deer Creek	376	0.79
Big Sioux : Middle Skunk Creek	1,192	0.78
Vermillion-East-Fork : Willow Lake	755	0.69
Missouri : Peoria	78	0.59
Vermillion-East-Fork : Spirit Lake	638	0.55
Bowdle : Lebanon	438	0.52
Elm Creek	534	0.40
Bowdle : Hoven North	352	0.39
Selby	4,029	0.28
Vermillion-West-Fork	149	0.26

Table 11 -- continued.

Aquifer : Management Unit	Average Annual Use (ac-ft)	Average Annual Use (inches)
Crow Creek	3,156	0.25
Antelope Valley	511	0.21
Bowdle : Edmunds	830	0.21
Vermillion-East-Fork : Antelope Lake	504	0.18
Chapelle Creek	104	0.16
Spring Creek : McPherson	831	0.10
Spring Creek : Artas	73	0.09
Spring Creek : Herreid	377	0.08
Coteau Lakes	493	0.07
Highmore-Blunt	442	0.07
Missouri : Greenwood	42	0.07
Wilmont	896	0.07
Missouri : Tower	5	0.02
Vermillion-East-Fork : Reid Lake	6	0.01
BURIED AQUIFERS		
Floyd : Pearl Creek	638	0.70
Tulare : East James	6,408	0.62
Tulare : Hitchcock	5,437	0.43
Gray Goose	1,005	0.36
Choteau : East	593	0.18

TABLE 12

Average annual use for confined aquifers.

Aquifer : Management Unit	Average Annual Use (ac-ft)	Average Annual Use (inches)
Sioux Falls	NA	NA
Choteau : Tyndall	1,867	0.72
Upper-Vermillion-Missouri	5,924	0.53
Warren : Wolsey	890	0.47
Lower-Vermillion-Missouri	3,948	0.38
Tulare : Western Spink	3,767	0.33
Lower-James-Missouri : Jamesville	4,694	0.29
Choteau : West	5,014	0.28
Choteau : Middle	638	0.24
Warren : West James	5,475	0.24
Geddes	443	0.22
Tulare : Hand	3,761	0.22
Ethan	547	0.21
Lennox	363	0.21
Wall Lake	1,207	0.20
Brule Creek	1,265	0.19
Elm : Ipswich	749	0.19
Floyd : East James	6,758	0.19
Plum Creek	385	0.16
Grand	4,362	0.13
Bad-Cheyenne	1,604	0.12
Hillsview	510	0.12
Hubonmix	283	0.12
Middle James : Aberdeen	1,148	0.12
White Lake	239	0.12
Lower-James-Missouri : Scotland	680	0.11
Crow Lake	246	0.10
Middle James : Columbia	2,233	0.08
Newton Hills	134	0.08
Tulare : Hyde	497	0.08

TABLE 12 -- continued.

Aquifer : Management Unit	Average Annual Use (ac-ft)	Average Annual Use (inches)
Veblen	3,367	0.08
Floyd : Alexandria	101	0.06
Elm : Southern Brown	444	0.06
Howard	589	0.06
Tulare : Miller	134	0.06
Tulare : Sully	30	0.06
Twin Lakes	88	0.06
Corsica	412	0.05
Harrisburg	177	0.05
Intermediate	557	0.05
Java	249	0.05
Onaka	109	0.05
Prairie Coteau	8,248	0.05
Shindler	128	0.05
Tulare : Ree Heights	45	0.05
Warren : Morris Creek	148	0.05
Altamont	5,932	0.04
Fairmount	315	0.04
Wakonda	50	0.04
Deep James	469	0.03
Lesterville	13	0.03
Elm : Northern Brown	3,197	0.02

TABLE 13

Summary of recharge rates in Big Sioux Aquifer.

Method of Analysis	Comments	Inches/year
Base flow recession analysis	Average of all management units in Basin	6.5
Computer model analysis	Model analysis for Brookings and Sioux Falls areas, respectively	3.6 - 6.9
Observation well analysis	Range of all management units	2.7 - 5.6
Flow net analysis	Average of all management units	1.0

Aquifer Evaluation

In the Sioux Falls management unit of the Big Sioux Aquifer the average annual use is 9.11 inches (table 11) compared to a calculated average annual recharge rate of 6.9 inches (table 13). Average annual use in all other management units in the Big Sioux Aquifer are less than average annual recharge. In spite of the calculated overdraft for the Sioux Falls management unit, the results of the computer model study (Koch, 1982) indicate that even more water could be pumped on an average annual basis using proper management techniques. This conclusion is based on the projection that decreased evapotranspiration and additional water induced into the aquifer from the Big Sioux River by pumping will offset the water deficit.

For water budget calculations and management scenarios the recharge calculated by the base flow recession analysis (258,000 acre-feet, table 4) is an important figure. That is because this is the maximum amount of ground water that can be consumed without exceeding the regional annual average recharge to the Big Sioux aquifer. Average annual use from the Big Sioux Aquifer currently is estimated to be 57,700 acre-feet.

Other Aquifers

Other non-buried, unconfined aquifers in eastern South Dakota have average annual recharge rates ranging from 2 to 5.6 inches (table 7) as calculated by the observation well analysis method. The calculated recharge using observation well data (2 to 5.6 inches, table 7) is considered to be the actual range of recharge for this group of aquifers. These values could be used for management and development programs until more refined interpretations become available. Those aquifers not shown on table 7 (because of a lack of data) are shown on table 14 with a relative range indicated. It should be noted that these values are subjective estimates based on all known data plus general knowledge of the local geohydrologic conditions.

Possible exceptions to the 2-inch minimum recharge rates are in the confined portions of the Coteau Lakes, Highmore-Blunt, and Selby aquifers. Additional data are needed before documented estimates can be made of average annual recharge for these aquifers.

TABLE 14

Range of estimated recharge rates for other unconfined aquifers.

Aquifer : Management Unit	Estimated recharge range (1)
Big Sioux : Unnamed Creek	H
Chapelle Creek	L-M
Cow Creek	L-M
Elm Creek	L-M
Highmore-Blunt	L
Missouri : Greenwood	H
Missouri : Peoria	H
Missouri : Pierre	H
Missouri : Tower	H
Okobojo Creek	L
Spring Creek : Artas	L
Spring Creek : Herreid	M
Spring Creek : McPherson	M
Vermillion-East-Fork : Reid Lake	M-H
Vermillion-West-Fork	M

(1) Based on a recharge range of 2 to 5.6 inches per year:
L = Low M = Medium H = High

Aquifer Evaluations

The Parker-Centerville Aquifer has an estimated 2.18 inches (table 11) of average annual use. Even though the estimated average annual use exceeds the minumum estimated average annual recharge of 2.0 inches, observation well records and known geohydrologic factors present for this aquifer support the conclusion that the recharge rate of 4.9 inches per year (table 7) calculated using observation well data more closely approximates actual recharge.

The Cow Creek Aquifer has a average annual estimated use of 7.15 inches per year (table 11). This rate of use significantly exceeds its maximum estimated recharge rate. Therefore, further hydrologic evaluation should be completed before additional development takes place.

Management units of the Missouri Aquifer (Elk Point, Greenwood, Peoria, Pierre, and Tower) exhibit good hydraulic connection to the Missouri River. With proper well spacing and aquifer management practices these aquifers could produce virtually unlimited supplies of waters.

Estimated average annual use for the Bowdle: Hoven South (0.87 inches), Delmont (0.82 inches), Vermillion-East-Fork: Willow Lake (0.69), and Vermillion-East-Fork: Spirit Lake (0.55) are all below the estimated 2-inch minimum recharge for aquifers in this group. Difficulties experienced in these aquifers in the past may be due to aquifer and/or well management practices, or there is inadequate data available to properly evaluate aquifer budget factors. These aquifers therefore may require additional hydrologic evaluation before additional development.

Buried Aquifers

Estimated Recharge Rates

A summary of the recharge rates to buried, unconfined aquifers from the various methods of calculation is shown as table 15. Although there is relatively good agreement among the different values, those calculated by observation well analysis appear to be somewhat higher than the other values.

It is believed that the 2 inch average annual recharge figure, which was determined by observation well analysis, is realistic in some areas and should not be discounted. However, it does represent a paradox because both the computer model and observation well analysis methods of calculating recharge appear to produce generally acceptable values. The paradox is solved by looking at the water budget. Kuiper (1982) noted that there is no major stream-flow gain in the James River as it passes by the Tulare aquifer. Because of his model input (about 0.8 inches of annual recharge), he concludes that ground water was not being contributed as base flow. Conceptually the water therefore must be leaving the aquifer system as evapotranspiration.

Slightly lower values for average annual recharge were obtained from the base flow recession and flownet analysis. This is to be expected because both methods include proportionately larger areas of confined aquifers which collectively have the lowest recharge rates. In summary, it is estimated average annual recharge to buried, unconfined aquifers ranges from about 0.25 to 1.25 inches per year.

TABLE 15

Summary of recharge rates in buried, unconfined aquifers.

Method of Analysis	Comments	Range (inches/year)
Base flow recession analysis	Includes both unconfined and confined buried aquifers	0.72
Computer model analysis	Tulare : East James	0.38-1.52 (Best fit = 0.76)
	Tulare : Hitchcock and Western Spink	0.41-1.66 (Best fit = 0.83)
Observation well analysis		0.9 -3.2 (Ave. = 2.0)
Flow net analysis	One of seven calculations (1.50) is slightly more than twice the next lower value. Thus, the lower range and average is probably more representative.	0.22-0.72 (Ave. = 0.36)
		0.22-1.50 (Ave. = 0.50)
		Ave. 0.36-0.50

Aquifer Evaluations

The average annual use from the five buried, unconfined aquifers ranges from 0.18 to 0.70 inches per year (table 11). Use in two of these, the Floyd : Pearl Creek, and the Tulare : East James has been restricted by the Board of Water Management. The Tulare : Hitchcock should be able to provide at least twice the amount of water now withdrawn (0.43 inches) according to the recharge rate of 0.83 in/year determined by the computer model study. The Gray Goose aquifer which has an average annual use of 0.36 inches should be further evaluated before additional water is appropriated. Finally, the Choteau : East with an average annual use of 0.18 inches and its relatively small size, should also be subject to a more detailed hydrologic study before additional amounts of water are appropriated.

RECHARGE RATES TO CONFINED AQUIFERS

Estimated Recharge Rates

A summary of the calculated recharge rates to confined aquifers is shown in table 16. The range from different methods of calculation is 0.24 to 0.83 inches per year. The actual range is probably smaller because both the computer model analysis and flownet analysis included unconfined portions of aquifer essentially equivalent in size to the confined portion. It must therefore be assumed that the 0.83 inches represents a compromise value between recharge rates for the confined and unconfined portions. Thus both the minimum and maximum calculated rates are probably higher than the actual recharge rates.

Calculated recharge rates and the above discussion leads to the conclusion that for management and development programs the minimum recharge rate to confined aquifers is estimated to be 0.15 inches per year and the maximum rate is 0.60 inches per year. Locally, where the confined aquifers encounter unconfined conditions, the recharge rates may be within the range calculated for non-buried surficial aquifers. Each confined aquifer should therefore be evaluated separately to determine the magnitude of the surface connection. Then maximum recharge range for each aquifer can be adjusted accordingly.

TABLE 16

Summary of recharge rates in confined aquifers.

Method of Analysis	Comments	Range (inches/year)
Base flow recession analysis	Includes both unconfined and confined buried aquifers	0.72
Computer digital model analysis	Tulare : Hitchcock and Western Spink (unconfined and confined, respectively)	0.83 (0.41-1.66)
Observation well analysis		Not Applicable
Flow net analysis	Confined aquifers only	0.24-0.35

Aquifer Evaluations

Close examination of table 12 demonstrates that 18 of 51 (35 percent) of the confined aquifers exceed the minimum estimated recharge of 0.15 inches per year and one (2 percent) exceed the maximum of 0.60 inches per year. Those aquifers that exceed the minimum estimated recharge should be subjected to additional hydrologic evaluation before allowing significant increases in appropriations.

The Choteau : Tyndall has an estimated average annual use of 0.72 inches per year which is 0.12 inches over the maximum. To date there has been no noticeable permanent decline in artesian head. However, a more detailed hydrologic analysis of this aquifer should be made before significant additional water is appropriated.

FACTORS AFFECTING RECHARGE RATES

Precipitation

Average annual precipitation within eastern South Dakota ranges from about 17 inches in the northwest sector to about 25 inches in the southeast sector. While the calculated recharge rates to aquifers in the southeast are generally higher, there apparently is no definite and consistent relationship between amount of average annual precipitation and recharge rate. Other factors such as precipitation intensity, local topographic and geologic conditions, type and thickness of overburden, and hydraulic connnections to surface water bodies are apparently more important factors.

Bedrock Aquifers

The Map of Eastern South Dakota Showing Distribution of Bedrock Units Underlying Surficial Deposits. (Pl. 2, Task 2) shows those areas where the bedrock aquifer units directly underly surficial deposits. The Composite Aquifer Map of Eastern South Dakota, (pl.4, Task 2) shows the distribution of the aquifers from surficial deposits. Comparison of the two maps delineate areas where significant portions of the aquifers in surficial deposits overly bedrock aquifer units, particularly in the southern two to three tiers of counties and throughout the James Basin. These bedrock aquifers are ubiquitously confined, and generally have the piezometric surfaces at or above the piezometric surface of aquifers in the surficial deposits. Thus, there is substantial potential for upward migration (recharge) of water from bedrock aquifers to the surficial deposits. As development of water resources continues and head pressures in the aquifers from surficial deposits decline, this recharge potential will probably increase. Some aquifers in surficial deposits are or may be receiving significant recharge from this source. An example is the Choteau : West aquifer which is directly underlain by Niobrara Formation and/or Codell Sandstone throughout much of its areal extent. Much more detail is needed on head relationships between the aquifers before making definite conclusions about recharge potential in these situations.

Bedrock Wells

During the past 100 years many thousands of wells have been drilled through aquifers in surficial deposits into the underlying bedrock aquifers. A high percentage of these wells were drilled across the southern two to three tiers of counties and northward in the James Basin. Deterioration of these wells allows water from the bedrock aquifers to flow around or through the casing and into the overlying surficial deposits. In some areas this process could contribute significant amounts of water (recharge) to aquifers in the surficial deposits.

The combination of upward or lateral migration of water from the bedrock, coupled with intrusion of water from deteriorated artesian bedrock wells may be contributing factors to recharge of aquifers in surficial deposits. In nearly all cases water from Bedrock aquifers is of a inferior quality to that stored in surficial aquifers. Thus, degradation of water quality in surficial aquifers should be considered as an ongoing phenomenon.

FINAL COMMENTS REGARDING RECHARGE AND MANAGEMENT

South Dakota law (statute SDCL 1983 vol. 13 Title 46-6-3.1.) states, that ground water use cannot exceed the annual average recharge. As already mentioned, average annual water use from the Big Sioux : Sioux Falls aquifer exceeds the calculated average annual recharge under normal or undeveloped conditions. Furthermore, the computer model analysis indicates that a future increase in water use on an average annual basis would not deplete the aquifer. An examination of the water budget as projected by the computer model analysis provides the answer to this dilemma.

The pre-pumping water budget for the Big Sioux : Sioux Falls aquifer is shown in table 17. This shows a total budget of 13,000 acre feet where maximum recharge (inflow) is 13,000 acre feet. Table 18 shows the same area under developed (pumped) conditions. The water budget is now 22,000 acre feet but notice that discharge from pumpage alone is 13,700 acre feet (or 700 acre feet more than recharge under pre-pumping conditions). Examination of the two tables quickly demonstrates that additional water enters the budget. The additional 9,000 acre feet of water is induced recharge from the Big Sioux River. Theoretically this type of development could proceed, with proper well spacing and pumping management procedures. The water budget would finally be restricted by the transmissivity of the aquifer and/or the availability of adequate flow in the Big Sioux River.

The foregoing example points out that the rate of "average annual recharge" is subject to change with time if non-depletion of the aquifer is the only criteria. However, other areas of the total hydrologic budget will suffer losses or gains depending on specific circumstances. One of the major conclusions is that average annual recharge as it relates to depletion or non-depletion of water levels in an aquifer over time, must ultimately be defined by management policy decisions and/or laws and/or regulations as water resource development progresses.

Another major conclusion apparent from the data presented in this report is that the average annual rate of recharge to confined aquifers is generally quite low as compared to rates of recharge in unconfined aquifers. Because of this, more restrictive management criteria may be necessary until or unless detailed analysis indicate otherwise.

TABLE 17

Pre-pumping water budget (from Koch, 1982)

A hydrologic budget of computer-simulated flow rates at predevelopment (no pumpage) under equilibrium conditions is shown below. Note that compared to the previous budget which included ground-water pumpage, evapotranspiration was larger because the water levels were higher and recharge to the aquifer from streams was much smaller.

Budget component	Flow rates, acre-feet per year	Percent
INFLOW		
Recharge to the aquifer from precipitation ----------------------	11,600	89
Recharge to the aquifer from the streams ------------------------	1,400	11
Total inflow	13,000	100
OUTFLOW		
Discharge from the aquifer to the stream ------------------------	11,700	90
Evapotranspiration from the aquifer -----------------------------	1,300	10
Total outflow	13,000	100

TABLE 18

Water budget after pumping
(from Koch, 1982)

A hydrologic budget of computer-simulated flow rates at equilibrium associated with the various components of the Big Sioux aquifer for a model area of about 36 square miles are shown below:

Budget component	Flow rates, acre-feet per year	Percent
INFLOW		
Recharge to the aquifer from precipitation	11,600	53
Recharge to the aquifer from the streams	10,400	47
Total inflow	22,000	100
OUTFLOW		
Discharge from the aquifer to the stream	7,800	35
Evapotranspiration from the aquifer	600	3
Pumpage:		
Sioux Falls	13,500	61
Irrigation	200	1
Total outflow	22,100	100

RECHARGE TO BEDROCK AQUIFERS

Information is very limited with regard to recharge rates to bedrock aquifers. However, gross general estimates exist for the Dakota formation.

Water use, (table 19) from the Dakota Formation is within the range of estimates for potential recharge (Schoon, 1971). However, unused water dispensed from flowing wells probably exceeds 100,000 acre-feet per year. This water loss plus natural discharge has doubtlessly caused the large head loss observed in the aquifer since the first well was drilled (Schoon, 1971).

The Niobrara Formation, Codell Sandstone, Inyan Kara Group, and Madison Group have such high storage and low use (table 19) that it is unlikely that use is approaching or exceeding recharge. Furthermore, there is no evidence of significant head loss in any of these aquifers over the years that would suggest that use is exceeding recharge.

Hydrologic information on the Split Rock Creek, Sioux Quartzite Wash, and Sioux Quartzite is practically nonexistent.

TABLE 19

Storage and annual water use for bedrock aquifers

Aquifer	Storage (ac-ft)	Average Annual Use (ac-ft)
Split Rock Creek	99,400	1,939
Niobrara Formation	NA	6,124
Codell Sandstone	9,985,700	3,710
Dakota Formation	381,104,000	19,100
Inyan Kara Group	65,483,800	1,765
Madison Group	51,512,300	890
Sioux Quartzite Wash	?	156
Sioux Quartzite	?	4,438

REFERENCES CITED

Fetter, C. W., Jr., 1980, Applied Hydrogeology: Charles E. Merrill Publishing Company, Columbus, Ohio.

Koch, Neil C., 1980, Appraisal of the Water Resources of the Big Sioux Aquifer, Brookings, Deuel, and Hamlin Counties, South Dakota: U.S. Geol. Survey Water-Resources Investigations 80-100, 46 p.

------ 1982, A Digital-Computer Model of the Big Sioux Aquifer in Minnehaha County, South Dakota: U.S. Geol. Survey Water-Resources Investigations, 82-4064, 49 p.

Kuiper, Logan K., 1982, Appraisal of the Water Resources of the Eastern Part of the Tulare Aquifer, Beadle, Hand and Spink Counties, South Dakota: U.S. Geol. Survey, preliminary draft, 44 p. plus figures and Appendix.

Meyboom, P., 1961, Estimating Groundwater Recharge from Stream Hydrographs: Journal of Geophysical Research, V. 66, p. 1203-14.

Schoon, R. A., 1971, Geology and Hydrology of the Dakota Formation in South Dakota: S. D. Geological Survey, Report of Investigation, No. 104, 55 p.