PRELIMINARY ASSESSMENT OF POTENTIAL WELL YIELDS AND THE POTENTIAL FOR ARTIFICIAL RECHARGE OF THE ELM AND MIDDLE JAMES AQUIFERS IN THE ABERDEEN AREA, SOUTH DAKOTA

By Patrick J. Emmons

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CONVERSION FACTORS

For readers who may prefer to use metric units rather than inch-pound units used in this report, conversion factors are listed below:

Multiply inch-pound unit	By	To obtain metric unit
acre	4,047	square meter
cubic foot	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
gallon per minute (gal/min)	0.06308	liter per second
inch	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square foot	0.09294	square meter
square foot per day (ft^2/d)	0.09294	square meter per day
square mile (mi^2)	2.590	square kilometer

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Seal Level of 1929."

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ABSTRACT

A complex hydrologic system exists in the glacial drift overlying the bedrock in the Aberdeen, South Dakota, area. The hydrologic system has been subdivided into three aquifers: the Elm, Middle James, and Deep James. These sand-and-gravel outwash aquifers generally are separated from each other by till or other fine-grained sediments. The Elm aquifer is the uppermost and largest of the aquifers and underlies about 204 square miles of the study area. The maximum altitude of the top of the Elm aquifer is 1,400 feet and the minimum altitude of the bottom is 1,225 feet. The Middle James aquifer underlies about 172 square miles of the study area. The maximum altitude of the top of the Middle James aquifer is 1,250 feet and the minimum altitude of the bottom is 1,150 feet. The lowermost Deep James aquifer was not evaluated.

The quality of the water from the Elm and Middle James aquifers varies considerably throughout the study area. The predominant chemical constituents in the water from the aquifers are sodium and sulfate ions; however, calcium, magnesium, bicarbonate, or chloride may dominate locally.

The calculated theoretical total well yield from the Elm and Middle James aquifers ranges from a minimum of 64 cubic feet per second, which may be conservative, to a maximum of 640 cubic feet per second. Based on available data, yields of 100 to 150 cubic feet per second probably can be obtained from properly sited and constructed wells.

The feasibility of artificially recharging an aquifer, using the technique of water spreading, depends on the geologic and hydraulic characteristics of the aquifer and of the sediments overlying the aquifer through which the recharge water must percolate. The sites suitable for artificial recharge in the study area were defined as those areas where the average aquifer thickness was more than 20 feet and the average thickness of the fine-grained sediments overlying the aquifer was less than 10 feet. Using these criteria, about 14 square miles of the study area are suitable for artificial recharge. Infiltration rates in the study area are estimated to range from 1.3 to 4.3 feet per day. Using an infiltration rate of 2 feet per day, a spreading pond with an area of 0.16 square mile would be required to artificially recharge at a rate of 100 cubic feet per second.

INTRODUCTION

The U.S. Bureau of Reclamation and the State of South Dakota are jointly investigating the potential of supplying additional water to the James River by diverting water from the Missouri River through Garrison Diversion Unit facilities. The additional water supplies in South Dakota would be used along the entire length of the James River for municipal, industrial, recreational, and fish and wildlife purposes.

Investigations were begun by the establishment of a Garrison Study Management Board in May 1981 by the Governor of South Dakota. At the request of the State and through the guidance of this Management Board, the U.S. Bureau of Reclamation (1982) completed a special report describing the potential for providing water service along the James River in South Dakota from the Garrison Diversion Unit in North Dakota. It became apparent from this report that further appraisal investigations were needed and a joint study titled "South Dakota Water Deliveries Study" by the Bureau and the State was begun. As part of this ongoing investigation, the Bureau requested that the U.S. Geological Survey determine potential well yields and the potential for artificial recharge of the Elm and Middle James aquifers in the Aberdeen area of Brown County (fig. 1).

Purpose and Scope

This report presents the results of the study by the U.S. Geological Survey to determine the potential well yields and the potential for artificial recharge of the Elm and Middle James aquifers. The study was conducted in cooperation with the U.S. Bureau of Reclamation.

The scope of this study included the collation and evaluation of existing well and test-hole logs, water-level measurements, pumpage, water quality, and other miscellaneous geohydrologic data. Unpublished well and test-hole data were obtained from the South Dakota Geological Survey, U.S. Geological Survey, U.S. Bureau of Reclamation, private drillers, and other miscellaneous sources. The well and test-hole data provided information on the extent, thickness, and composition of the aquifers and confining beds. Water levels measured in observation wells by the South Dakota Department of Water and Natural Resources and by the U.S. Geological Survey were used to evaluate and determine water-level changes in the Elm and Middle James aquifers. The observation-well sites are numbered according to the Federal land-survey system of eastern South Dakota. The site-numbering system is explained in figure 2. The South Dakota Department of Water and Natural Resources provided the pumpage data. These data were used to determine the potential well yields of the Elm and Middle James aquifers. Water-quality data were obtained from unpublished U.S. Geological Survey computer files. The water-quality data were used to assess the general quality of the water in the Elm and Middle James aquifers.

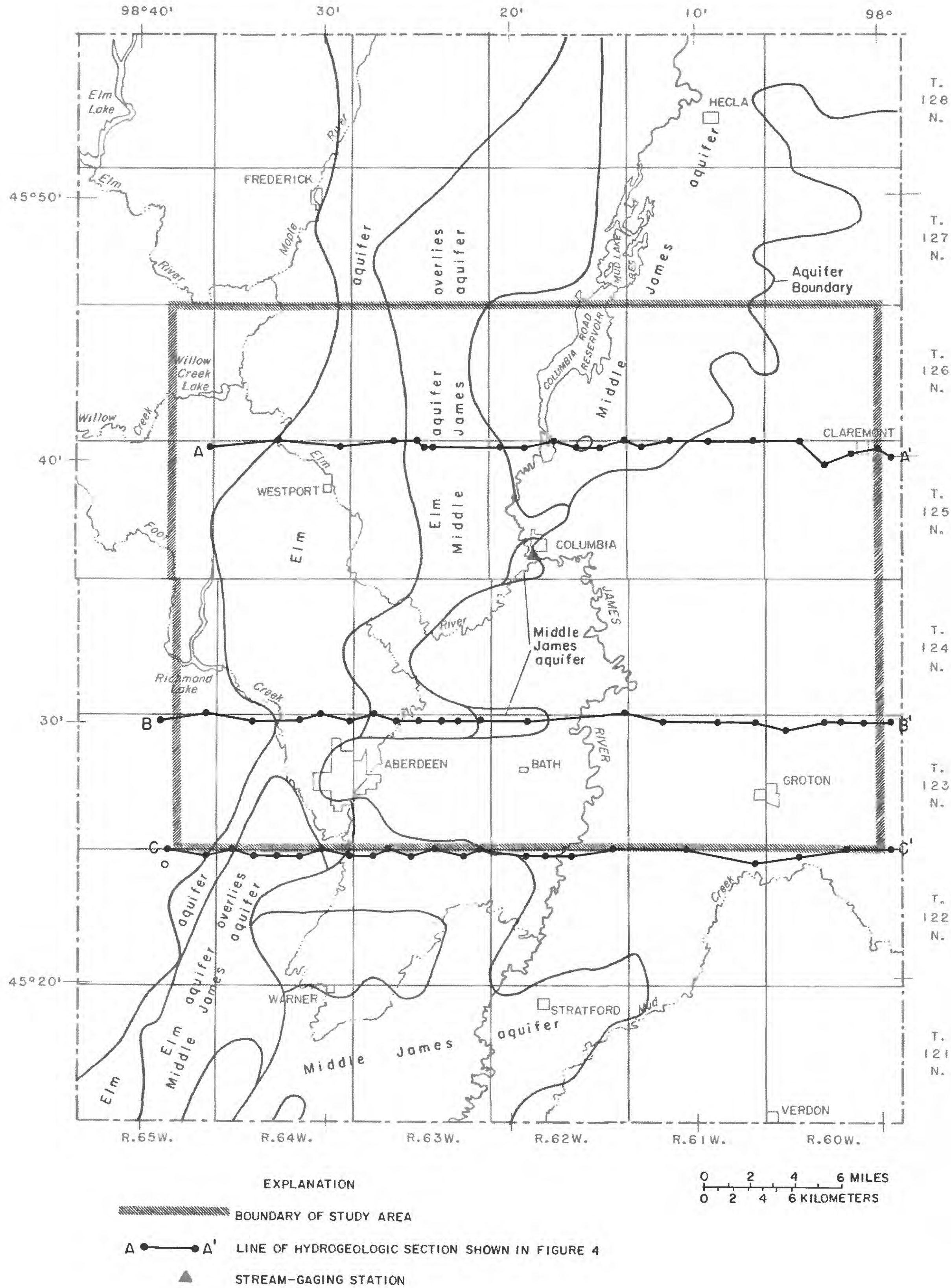

Figure 1.--Location of study area and the Elm and Middle James aquifers.

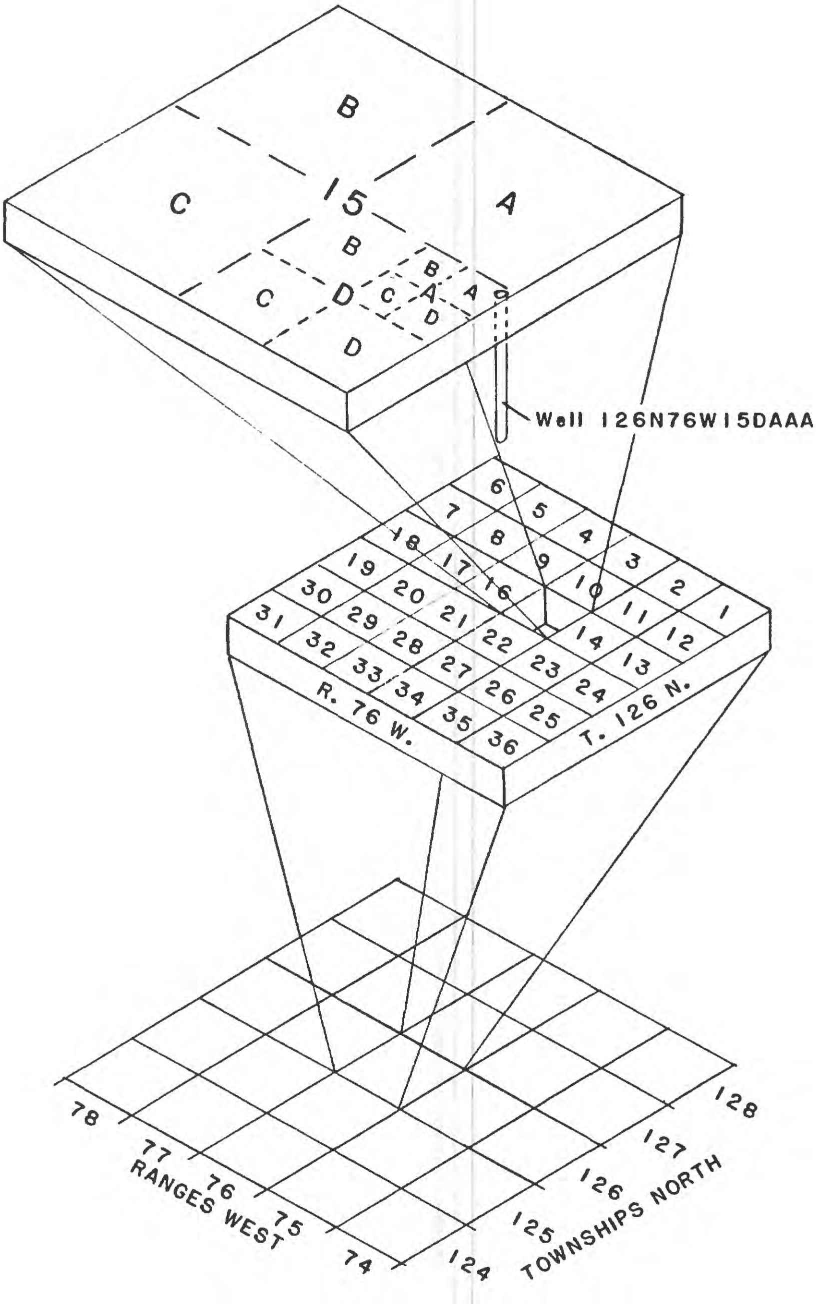

Figure 2.--Site-numbering diagram. The well number consists of township followed by "N," range followed by "W," and section number, followed by a maximum of four uppercase letters that indicate, respectively, the 160-, 40-, 10-, and $2\frac{1}{2}$-acre tract in which the well is located. These letters are assigned in a counterclockwise direction beginning with "A" in the northeast quarter. A serial number following the last letter is used to distinguish between wells in the same tract. Thus, well 126N62W15DAAA is the well recorded in the $NE\frac{1}{4}$ of the $NE\frac{1}{4}$ of the $NE\frac{1}{4}$ of the $SE\frac{1}{4}$ of section 15 in township 126 north and range 62 west of the 5th meridian and baseline system.

Geologic Setting

During the Pleistocene Epoch, continental glaciers from the north and east covered eastern South Dakota, depositing a blanket of glacial drift over the eroded preglacial bedrock surface. The glaciers radically altered the topography by partially filling major valleys, entirely obliterating many small valleys, scouring new valleys, and forming massive end moraines. The overall effect of glaciation has been to lower the local topographic relief. However, one of the greatest changes caused by the glaciers was the rearrangement of the surface drainage. Before glaciation, the main streams flowed toward the east. As a result of glaciation, the drainage in eastern South Dakota is now predominately southward (Flint, 1955).

The James basin is a lowland of low to moderate relief trending northward between the Coteau du Missouri and the Coteau des Prairies which are of glacial origin (fig. 3). The basin is 50 to 75 mi wide and about 250 mi long in South Dakota. The James River, which occupies the central axis of the basin, drains the basin to the south.

Most of the surficial deposits in the study area are the result of glaciation and are collectively called drift, which is any material deposited by or from a glacier. Drift can be subdivided into two major types--till and outwash--that differ greatly in physical and hydraulic characteristics. Till, which was deposited directly from or by glacial ice, is a heterogeneous mixture of silt, sand, gravel, and boulders in a clay matrix. Outwash, which was deposited from or by meltwater streams on top of the ice or beyond the margin of the active glacial ice, consists primarily of layers of clayey or silty sand and sandy gravel, interbedded with layers of sandy or gravelly silt or clay. Beds of well-sorted sand and gravel are contained in the outwash but are generally small and discontinuous (Howells and Stephens, 1968). When the last glacial ice sheet of Wisconsin age melted back into North Dakota, meltwater flowing from it accumulated in a shallow depression, glacial Lake Dakota. The area is a distinct physiographic unit known as the Lake Dakota plain (fig. 3).

The drift may be covered by deposits of alluvium along streams and rivers and locally may be covered by windblown sand and silt. The alluvium consists of poorly sorted, poorly stratified, thin, discontinuous layers of material that ranges in size from clay to boulders, but usually has a large silt content and does not contain significant sand and gravel.

The bedrock directly underlying the drift in the study area, in descending order, consists of the Cretaceous Pierre Shale and Niobrara Formation. The Pierre Shale is predominantly a dark-gray, fissile, bentonitic-clay shale with some thin beds of limestone, shaly chalk, and sandstone. The Niobrara Formation is predominantly a light- to dark-gray speckled marl or calcareous clay with some "chalk" and shaly beds. The marl contains shells of foraminifera that impart a distinctive, white-speckled appearance.

Figure 3.--Major physiographic divisions of eastern South Dakota.

Hydrologic Setting

Ground water is a major source of water for irrigation, municipal, farm, and domestic use in the James River basin. In the unconsolidated surficial deposits, only the more sandy and gravelly glacial-outwash deposits yield substantial quantities of water to wells. The remaining unconsolidated surficial deposits generally are either too clayey and silty or are too thin to serve as major sources of water except in very localized situations.

The natural recharge, movement, and discharge of water in the outwash aquifers are controlled by the lithology and stratigraphy of the surficial deposits and the underlying bedrock units. The till and the layers of silt and clay within the outwash deposits confine the outwash aquifers. In the study area, the Pierre Shale and Niobrara Formation generally yield little or no water to wells and are considered to be confining beds.

The units that comprise the complex hydrologic system in the glacial outwash have been subdivided into three aquifers in the study area by Koch and Bradford (1976): the Elm, Middle James, and Deep James aquifers. The topographic and stratigraphic relations of these aquifers are shown in the geohydrologic sections in figure 4. Koch and Bradford (1976) defined the Elm, Middle James, and Deep James aquifers based on altitude. The maximum altitude of the top of the Elm aquifer is 1,400 ft and the minimum altitude of the bottom is 1,225 ft. The maximum altitude of the top of the Middle James aquifer is 1,250 ft and the minimum altitude of the bottom is 1,150 ft. The maximum altitude of the top of the Deep James aquifer is 1,175 ft and the minimum altitude of the bottom is 950 ft.

The three glacial-outwash aquifers generally are separated from each other by till, as indicated in figure 4, and may be internally separated by till and thin clay and silt outwash layers. The till and thin clay and silt outwash layers allow some flow to occur between and within the aquifers.

The glacial-aquifer complex is comprised of a series of connected and disconnected lenses, fingers, stringers, and channels of sand and gravel separated by layers of clay and silt outwash and till. The thickness of the sand and gravel layers in the aquifer complex as well as other hydrologic characteristics differ greatly within short distances as indicated by the geohydrologic sections (fig. 4) and the map showing thickness of aquifers penetrated by test holes (fig. 5). As a result of the variations in thickness and composition, individual aquifer units usually can be traced for only short distances or not at all.

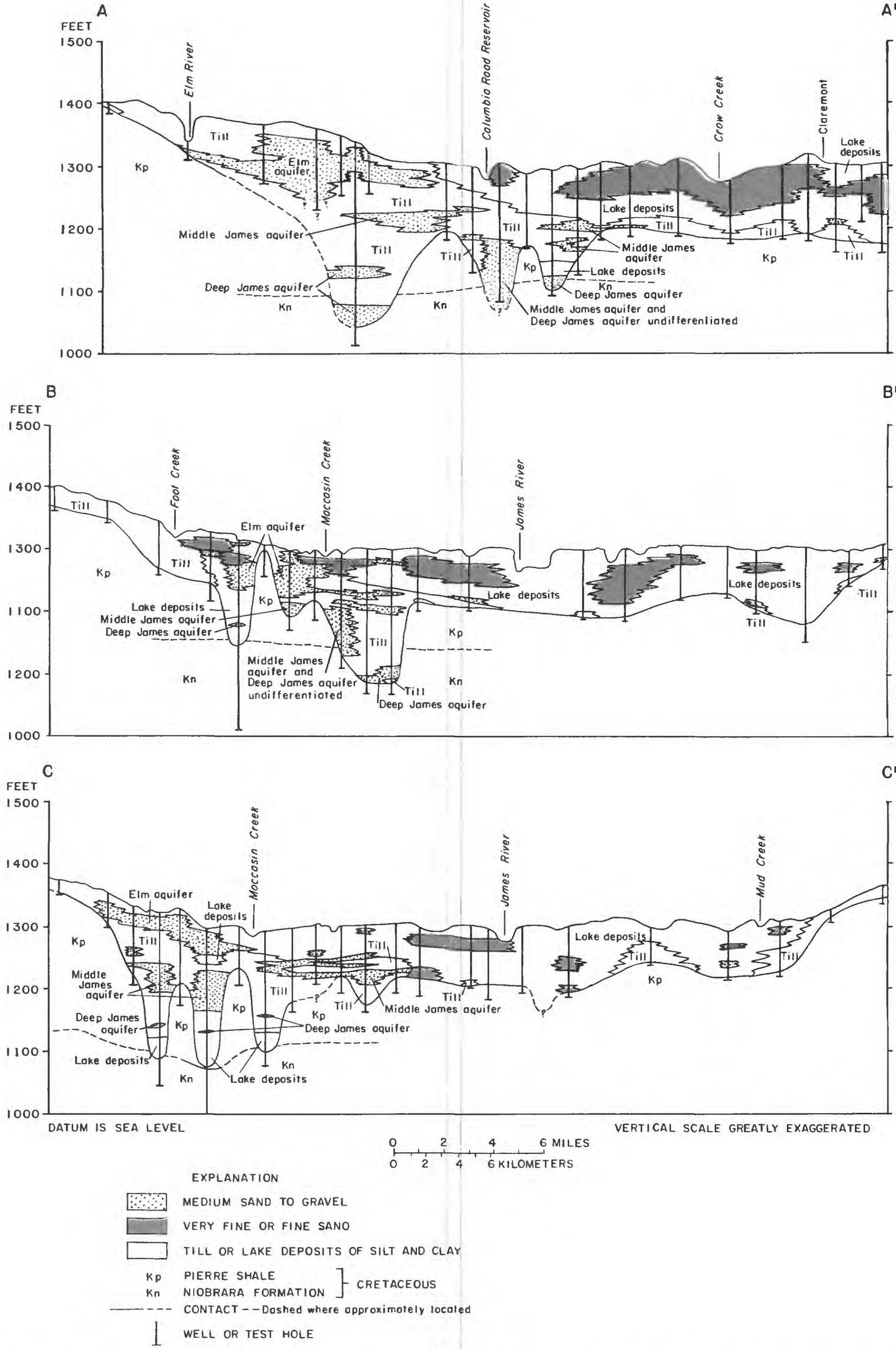

Figure 4.--Geohydrologic sections showing location of glacial aquifers.

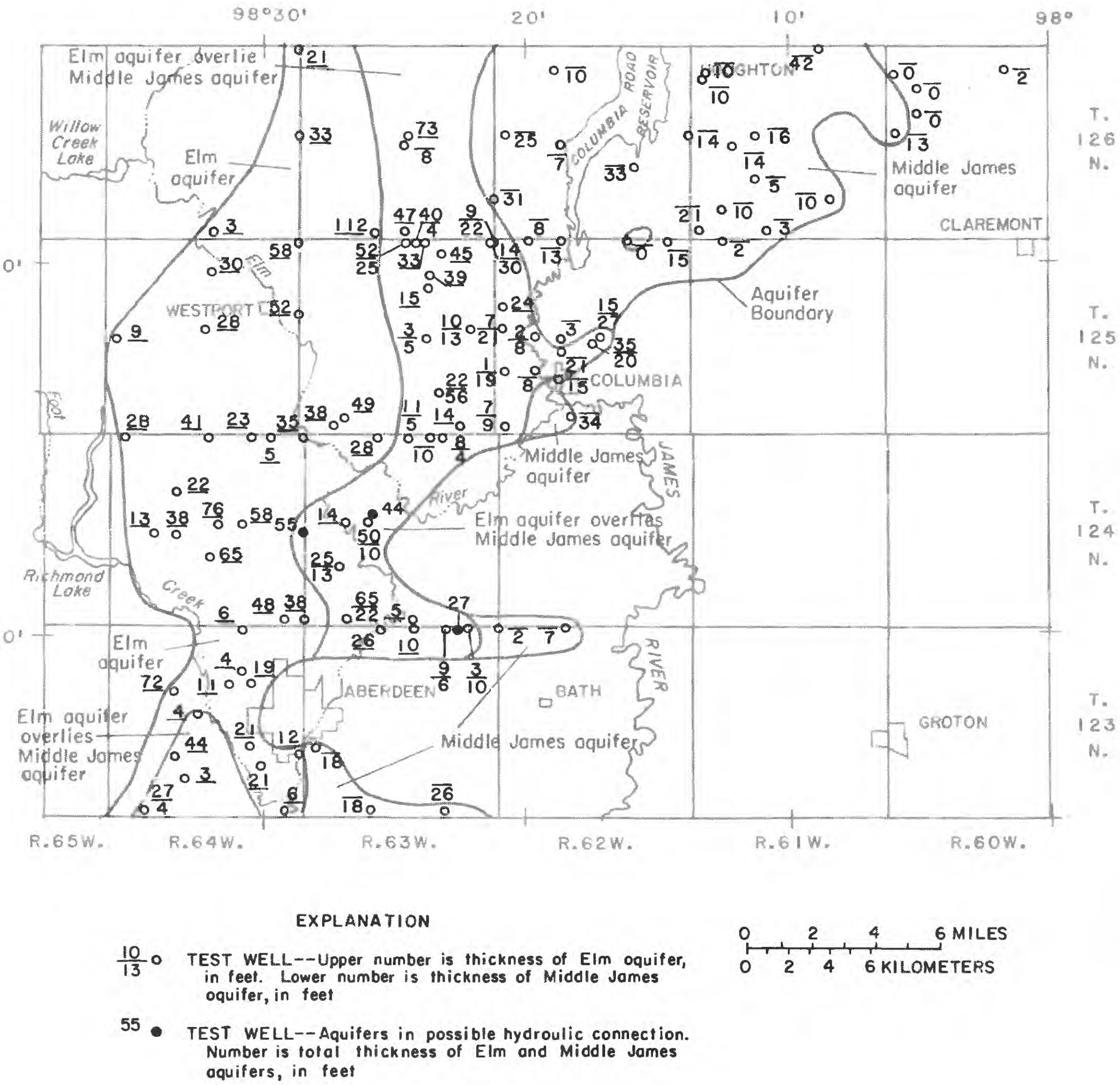

Figure 5.--Extent of the Elm and Middle James aquifers and thickness of aquifers at test holes.

DESCRIPTION OF THE ELM AND MIDDLE JAMES AQUIFERS

Geohydrology of the Elm Aquifer

The Elm aquifer is the uppermost and largest sand-and-gravel outwash aquifer in the glacial-aquifer complex (figs. 1 and 4) in the study area. The aquifer underlies about 204 mi^2 of the study area. The extent of the Elm aquifer and the thickness of the aquifer penetrated by test holes are shown in figure 5. The thickness ranges from zero at the boundaries to a maximum of 112 ft, about 4 mi northeast of Westport. The aquifer slopes to the east at about the same gradient as the topographic surface, about 15 ft/mi.

The water in the aquifer is under water-table (unconfined) conditions in some places and under artesian (confined) conditions where confining bed material overlying the aquifer is sufficiently thick. Emmons (in press), in developing a ground-water-flow model of the glacial-aquifer complex in the Sanborn-Beadle County area (fig. 3), estimated that a confining-bed thickness of 10 ft or greater overlying the aquifer probably is sufficient to confine the aquifer, causing artesian conditions. Even in areas where the aquifer is under water-table conditions, silt and clay layers within the aquifer may confine its lower parts. The thickness of the fine-grained, nonaquifer material (lake deposits and till) overlying the aquifer is shown in figure 6. The figure indicates that the thickness of confining-bed material overlying the Elm aquifer generally is greater than 20 ft.

Recharge to the Elm aquifer is by infiltration of precipitation, snowmelt, and surface water directly into the aquifer or by percolation through the overlying lake sediments and till. Recharge occurs more rapidly in level areas where the aquifer is at or near land surface or where more permeable sandy lake deposits overlie the aquifer. Recharge occurs more slowly where the aquifer is overlain by less permeable clayey or silty lake deposits or till.

Hydrographs of water levels from two observation wells completed in the Elm aquifer are shown in figure 7. Examination of the hydrographs indicates that no long-term water-level declines have occurred in the aquifer, although seasonal changes have occurred because of variations in available recharge. Koch and Bradford (1976) determined that the water level in the Elm aquifer varied in direct response to snowmelt, rainfall, or drought with only a short time lag. They also compared long-term water-level data and cumulative departure of precipitation from normal. Although precipitation was more than 25 inches less than normal from 1950 to 1972, water levels in the Elm aquifer remained about the same.

Natural discharge occurs as seepage into the Elm River and Foot Creek, by evapotranspiration, by recharge into the Middle James aquifer, and by eastward flow into the lacustrine deposits underlying the Lake Dakota plain. According to Koch and Bradford (1976), the general direction of water movement in the aquifer is to the southeast at a gradient of about 10 ft/mi. Discharge from the aquifer also occurs by pumpage from wells and as seepage into gravel pits that penetrate the aquifer. Most of the wells completed in the Elm aquifer are small-yield domestic, stock, and farm wells. In addition, currently (1986) about 52 ft^3/s of irrigation and municipal pumpage is permitted from

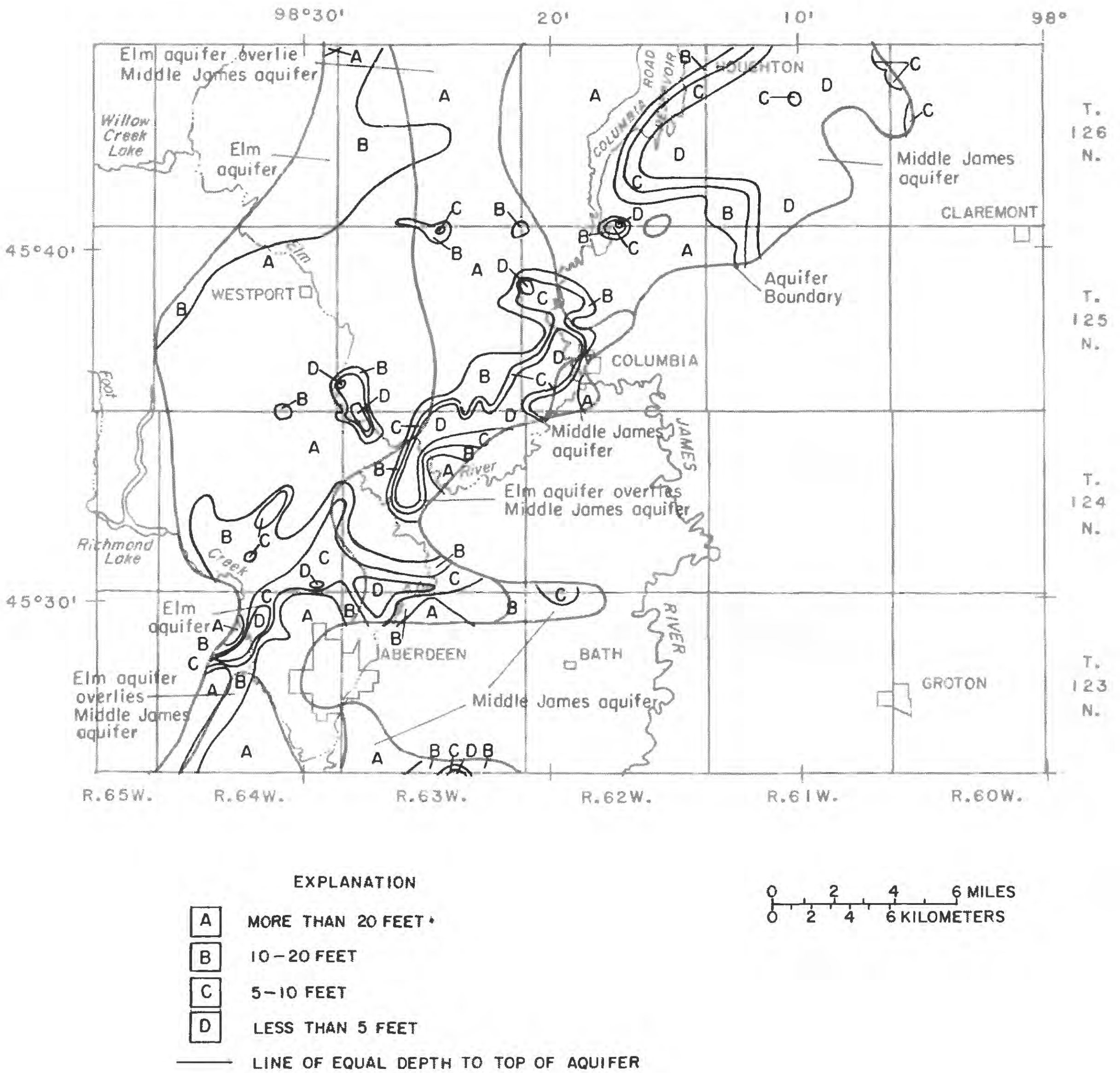

Figure 6.--Depth below land surface to top of the Elm or Middle James aquifers.

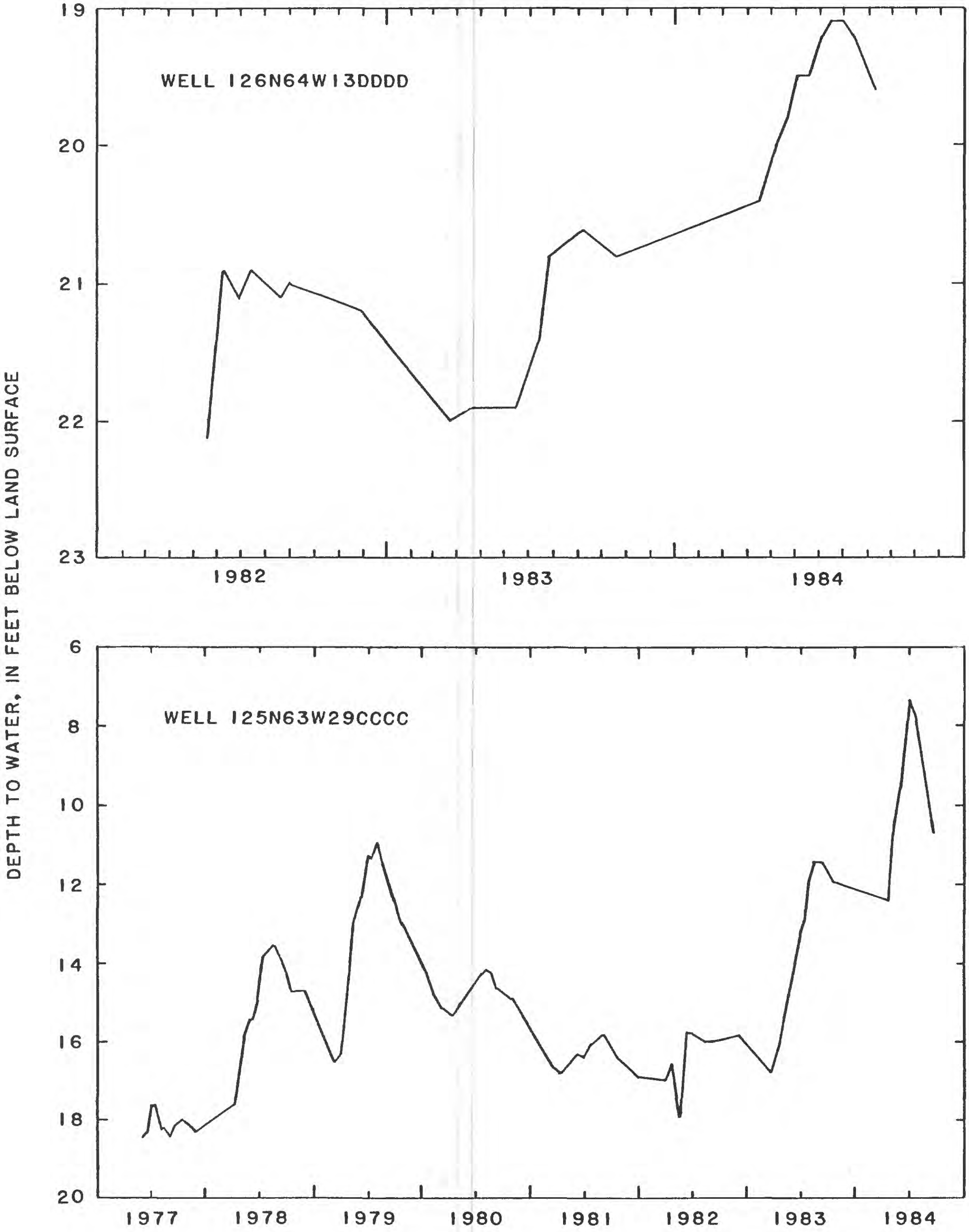

Figure 7.--Water-level changes in wells completed in the Elm aquifer.

the Elm aquifer from 22 different locations in the study area according to unpublished data provided by the South Dakota Department of Water and Natural Resources. The 22 locations are either single wells, multiple wells on a single permit, or gravel pits. There also are 14 sites in the area where the Elm aquifer overlies the Middle James aquifer with a combined permitted pumpage rate of about 33 ft^3/s. These wells may yield water from the Elm aquifer, the Middle James aquifer, or both. According to Koch and Bradford (1976), wells can be constructed to yield 500 gal/min or more where at least 40 ft of medium-grained sand is present. For coarser material, a lesser thickness is needed.

Geohydrology of the Middle James Aquifer

The location of the Middle James sand-and-gravel outwash aquifer is shown in figure 1, and its stratigraphic relation to the Elm aquifer is shown in figure 4. The aquifer underlies about 172 mi^2 of the study area. The extent of the Middle James aquifer and the thickness of the aquifer penetrated by test holes are shown in figure 5. The thickness ranges from zero at the boundaries to a maximum of 56 ft, about 4 mi west of Columbia. The aquifer commonly is lenticular in shape and contains many clay and silt layers.

Water in the Middle James aquifer generally is under artesian conditions except where the overlying confining bed is less than about 10 ft thick (fig. 6). Even in areas where the upper part of the aquifer is under water-table conditions, the intervening clay and silt layers commonly confine the lower parts of the aquifer.

Recharge to the Middle James aquifer is from the Elm aquifer and from percolation of snowmelt and precipitation through the overlying lake deposits and till. Probably the largest source of recharge water is from the overlying Elm aquifer where it is in contact with the Middle James aquifer (Koch and Bradford, 1976).

Hydrographs of the water levels measured in two observation wells completed in the Middle James aquifer are shown in figure 8. Examination of these hydrographs indicates no long-term water-level declines have developed. Seasonal and annual fluctuations occur because of variations in recharge, evapotranspiration, and ground-water withdrawal due to pumping. Koch and Bradford (1976) determined that water levels in the Deep and Middle James aquifers have remained about the same from 1950 to 1972 even though precipitation totaled 25 inches less than normal for that period.

Natural discharge from the aquifer occurs as percolation into the Deep James aquifer, which underlies parts of the Middle James, and as eastward flow into the lake deposits and till. According to Koch and Bradford (1976), the general direction of water movement in the aquifer is to the east. Discharge from the aquifer also occurs by pumpage from wells. Like the Elm aquifer, most of the wells that penetrate the Middle James are small-yield domestic, farm, and stock wells. Only two large-capacity irrigation wells, having a total permitted yield of approximately 2.7 ft^3/s, are reported to have been completed in only the Middle James aquifer, according to unpublished data provided by the South Dakota Department of Water and Natural Resources. There also are 14 sites in the area where the Middle James underlies the Elm

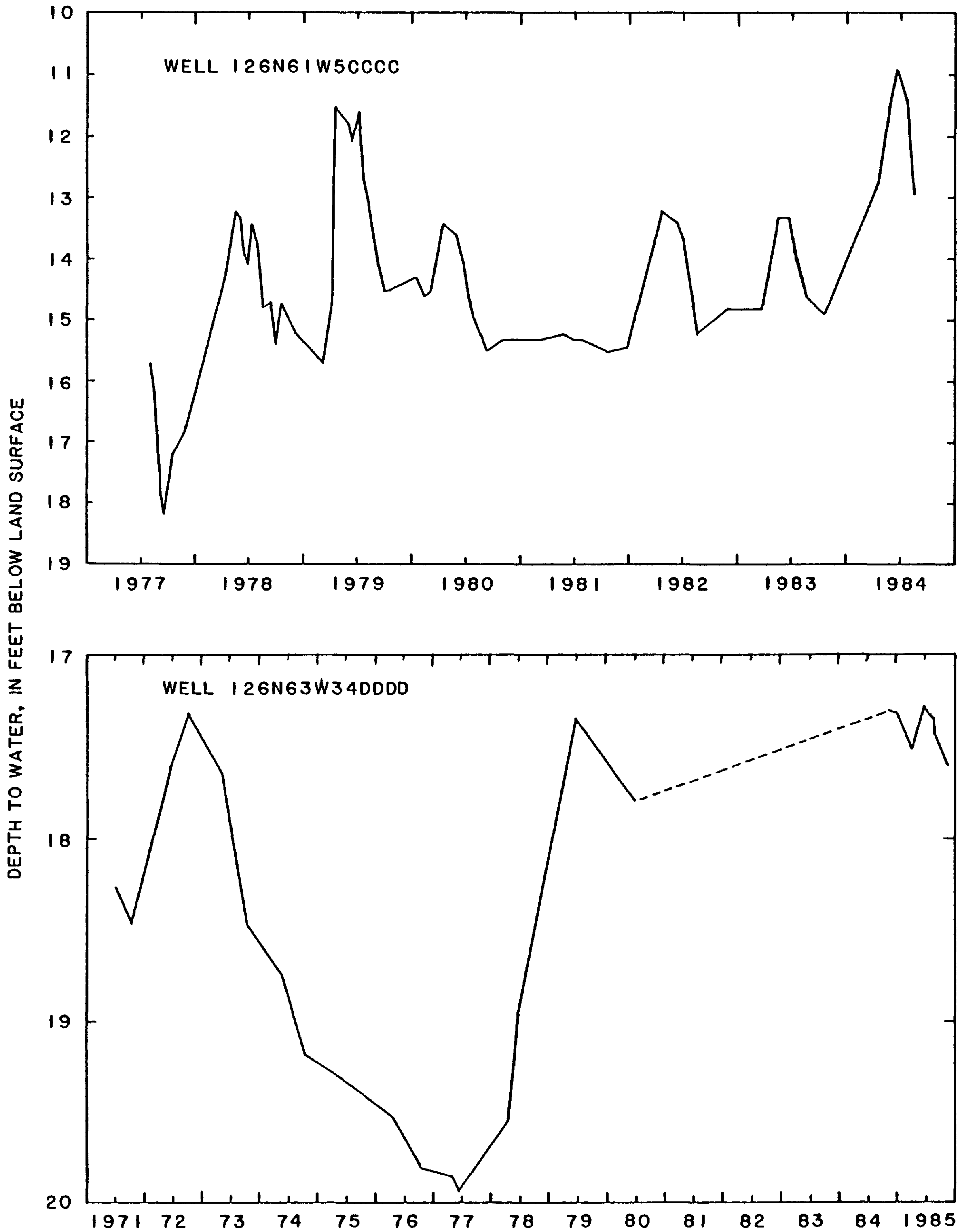

Figure 8.--Water-level changes in wells completed in the Middle James aquifer.

aquifer. These sites consist of permits for single wells or for multiple wells on a single permit that have a reported combined permitted pumpage of about 33 ft^3/s. These wells may yield water from the Elm aquifer, the Middle James aquifer, or both. According to Koch and Bradford (1976), well yields of 500 gal/min or more can be expected from properly constructed wells where medium-grained sand to gravel is 40 ft or more thick.

Relation to Other Aquifers in Glacial Deposits

The Deep James aquifer, which underlies the Elm and Middle James aquifers, is a buried interconnected system of ancient river channels containing outwash and alluvium. Although the Deep James aquifer receives recharge water through the overlying lake deposits, outwash, and till, most of the recharge comes from the overlying aquifers where they are hydraulically connected (fig. 4). Where hydraulically connected, the Deep James can significantly effect the potential well yields and the potential for artificial recharge of the overlying aquifers. Water in the Deep James is under artesian conditions. The direction of ground-water movement generally is northward.

The Lake Dakota plain covers much of the study area (fig. 3). Glacial meltwaters deposited an average of about 75 ft of fine sand, silt, and clay on the bed of ancient Lake Dakota. Wells completed in these deposits may yield 1 to 5 gal/min, but well failure is common because of clogging of the well screens by fine-grained sediments. These sediments commonly pass through the well screen and enter the water system, not only clogging the well but abrading and seriously damaging pumps and other equipment (Koch and Bradford, 1976). The lake deposits are not an important aquifer in the study area; however, they commonly control recharge to and discharge from the Elm and Middle James aquifers, as well as control interaquifer flow.

Water Quality

The quality of water from the Elm and Middle James aquifers varies considerably throughout the study area as indicated by the range of values listed in table 1. The predominant chemical constituents in the water from the aquifers are sodium and sulfate ions, however, calcium, magnesium, bicarbonate, or chloride may be dominant locally. The considerable differences in the major ions from one location to another make it difficult to predict water quality, or even the predominant ions in the water, in areas for which no data are available.

Table 1.--Summary of chemical analyses of water from the Elm and Middle James aquifers

[Results in milligrams per liter except as indicated; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25° Celsius]

Constituent or property	Number of analyses	Mean	Median	Range
Calcium (Ca)	63	160	120	40-800
Magnesium (Mg)	63	56	38	7-340
Sodium (Na)	62	230	100	12-2,000
Potassium (K)	43	12	12	3-26
Bicarbonate (HCO_3)	124	460	440	210-1,160
Sulfate (SO_4)	139	670	300	4-4,400
Chloride (Cl)	113	270	140	33-2,800
Fluoride (F)	27	0.6	0.4	0.1-4.7
Iron (Fe) (µg/L)	12	6,400	1,900	0-39,000
Manganese (Mn) (µg/L)	7	1,000	300	0-4,700
Hardness as $CaCO_3$	145	940	610	87-8,000
Specific conductance (µS/cm)	125	2,730	2,030	630-20,500
Percent sodium	54	35	31	6-94
Sodium-adsorption ratio (SAR)	70	4	2	0.3-59
pH (units)	127	7.4	7.4	7.0-8.2

The median values for the specific conductance and the sodium-adsorption ratio of the water from the Elm and Middle James aquifers (table 1) can be used to determine its salinity and sodium hazards. Using the classification of ground water for irrigation use developed by the U.S. Salinity Laboratory Staff (1954), the ground water in the Elm and Middle James aquifers has a high salinity hazard and a low sodium hazard. High-salinity water (C3) cannot be used for irrigation on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance need to be selected. Low-sodium water (S1) can be used for irrigation on almost all soils with little danger of development of harmful levels of exchangeable sodium. The range of values for the specific conductance and sodium-adsorption ratio of the ground water indicates that the salinity hazard ranges from medium to very high and the sodium hazard from low to very high.

The considerable variation in the chemical composition of the water within short distances in the Elm and Middle James aquifers may be the result of one or more of the following factors (Koch and Bradford, 1976):

1. The slow drainage of surface water results in evaporation, which increases the salinity of the water that percolates downward to the aquifers.

2. Saline water from flowing wells completed in the underlying bedrock aquifers percolates to the Elm and Middle James aquifers. These flowing wells have discharged billions of gallons of saline water onto the land surface in Brown County during the past 80 years.

3. Effects of water moving between the Elm and Middle James aquifers.

4. The lenticular and discontinuous nature of the aquifers, especially the Middle James aquifer.

The James River is the source of artificial recharge water in the study area. The river water could be used to recharge the Elm and Middle James aquifers during the spring months when flows in the river are high. A summary of the chemical analyses of water from the James River at Columbia (fig. 1) for March and May 1983-85 is presented in table 2. The analyses indicate that the chemical concentrations in the river water have been fairly constant with the exception of manganese. The concentration of manganese varied from 63 µg/L (micrograms per liter) on May 23, 1985, to 34,000 µg/L on May 18, 1983. The reason for this large fluctuation is not known.

Comparing the six analyses of water from the James River with the median values of water samples from the Elm and Middle James aquifers indicates that the water from the James River generally is less mineralized than water from the Elm and Middle James aquifers for the constituents or properties compared, except for manganese.

Artificially recharged water usually forms a plume in the existing ground water. Within several months, only a partial mixing of the recharged and aquifer waters would occur along their interface. The chemical effects of the artificially recharged water on the aquifer material and the existing ground water cannot be assessed without additional work. However, because the river water tends to be less mineralized than the ground water, it is assumed that no chemical-compatability problems would occur for those constituents listed in table 1.

POTENTIAL WELL YIELDS FROM THE ELM AND MIDDLE JAMES AQUIFERS

Because no aquifer-test data are known to be available for the Elm and Middle James aquifers in or around the area of study, potential well yields can only be estimated. The hydraulic conductivity calculated from aquifer-test data from the Sanborn-Beadle County area (fig. 3) ranges from 20 to 1,430 ft/d with an average of about 300 ft/d (Emmons, in press). Because the composition of the glacial drift in Brown, Sanborn, and Beadle Counties are similar, it is assumed that the aquifer characteristics also are similar.

Water in the Elm and Middle James aquifers can occur under water-table and artesian conditions. As a result of the complexity of the aquifers, conditions can change within a short distance. The aquifers, especially their upper parts where the overlying till or lake deposits are less than 10 ft thick, generally are under water-table conditions. In the lower parts of the aquifers and in the upper parts where the overlying confining bed is greater than 10 ft, the aquifers may be confined. The value of the storage coefficient is an indication of whether the aquifer is confined or unconfined. The

Table 2.--Summary of chemical analyses of water from the James River at Columbia and median values of water samples from the Elm and Middle James aquifers

[Results in milligrams per liter except as indicated; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25° Celsius; ft^3/s, cubic feet per second; a dash indicates no data or not applicable]

Constituent or property	James River at Columbia						Elm and Middle James aquifers (median)
	1983		1984		1985		
	March 29	May 18	March 22	May 21	March 28	May 23	
Calcium (Ca)	45	49	100	50	61	45	120
Magnesium (Mg)	23	26	55	23	36	35	38
Sodium (Na)	49	52	94	44	76	77	100
Potassium (K)	11	15	23	11	17	16	12
Bicarbonate (HCO_3)	--	--	--	--	--	--	440
Sulfate (SO_4)	110	97	210	92	160	140	300
Chloride (Cl)	23	17	38	19	27	32	140
Fluoride (F)	0.1	0.2	0.3	0.2	0.2	0.2	0.4
Iron (Fe) (µg/L)	52	15	30	18	25	38	1,900
Manganese (Mn) (µg/L)	26,000	34,000	1,100	100	3,300	63	300
Hardness as $CaCO_3$	210	230	480	220	300	260	610
Specific conductance (µS/cm)	660	630	1,240	620	837	780	2,030
Percent sodium	33	31	29	29	34	38	31
Sodium-adsorption ratio (SAR)	2	2	2	1	2	2	2
pH (units)	7.8	7.5	8.0	8.0	8.1	8.8	7.4
Temperature (degrees Celsius)	3.0	15.0	.0	17.0	2.0	18.0	--
Streamflow (ft^3/s)	701	445	90	491	117	13	--

storage coefficient of most confined aquifers ranges from about 0.00001 to 0.001. The storage coefficient in an unconfined aquifer, referred to as specific yield, generally ranges from 0.1 to 0.3. Wells penetrating the Elm and Middle James aquifers could be open to aquifer zones ranging from unconfined to confined. Estimated storage coefficients, therefore, could range within several orders of magnitude for the aquifer or aquifers.

A series of idealized theoretical drawdowns calculated for the Elm and Middle James aquifers is listed in table 3. The calculations assume the aquifers are infinite in extent, isotropic and homogeneous, and no well losses occur--that is, the drawdown cone produced by the pumping is not effected by boundaries, the hydraulic conductivity is independent of the direction of measurement and is independent of the position in the aquifer, and the well construction does not effect drawdown in the pumped well. The Elm and Middle James aquifers, however, consist of sand and gravel outwash with layers of silt, clay, and till. The aquifers may be hydraulically connected or separated by variable thicknesses of till and lake deposits and are not infinite in extent. Transmissivity of the aquifers is a function of the hydraulic conductivity and the saturated thickness of the aquifer. As drawdown in the aquifer occurs, the transmissivity decreases. As a result, the actual drawdowns may be greater than those presented in table 3.

If maximum drawdown in the pumped well is limited to 50 percent of the aquifer thickness, figure 5 and table 3 then can be used to estimate potential well yield of the aquifer. About 200 gal/min probably could be obtained where the aquifer thickness is 20 ft, 400 gal/min where the aquifer thickness is 30 ft, and 750 gal/min where the aquifer thickness is 40 ft.

In the study area, about 40 mi^2 are underlain by 20 to 30 ft of aquifer material, about 49 mi^2 are underlain by 30 to 40 ft of aquifer material, and about 65 mi^2 are underlain by more than 40 ft of aquifer material. Assuming a well spacing of 0.5 mi (fig. 5), the maximum total well yield was calculated to be about 288,000 gal/min or about 640 ft^3/s during a 90-day pumping period. Because wells cannot be placed at the aquifer boundaries, the calculation assumes that 123 wells could be located in the area underlain by 20 to 30 ft of aquifer material, 172 wells in the area underlain by 30 to 40 ft of aquifer material, and 260 wells in the area which is underlain by more than 40 ft of aquifer material. With a 1-mi well spacing, the maximum total well yield from the area was calculated to be about 67,000 gal/min or about 150 ft^3/s. This maximum yield was calculated with 15 wells in the area underlain by 20 to 30 ft of aquifer material, 46 wells in the area underlain by 30 to 40 ft of aquifer material, and 61 wells in the area underlain by more than 40 ft of aquifer material.

The potential well yields are based on an assumed aquifer hydraulic conductivity of 300 ft/d. Because of the variability of the aquifer composition and thickness, well yields could differ substantially from those that would be anticipated using figure 5 and table 3. Examination of unpublished South Dakota Department of Water and Natural Resources permitted ground-water withdrawal rates from the Elm and Middle James aquifers indicates that these potential well yields are reasonable but probably high estimates of the aquifers' potential. The maximum permitted ground-water withdrawal rate is about 1,000 gal/min.

Table 3.--Idealized theoretical drawdowns in the Elm and Middle James aquifers

Aquifer thickness (feet)	Transmissivity[1] (square feet per day)	Storage coefficient (dimensionless)	Pumping rate[2] (gallons per minute)	Calculated drawdown in the aquifer at various distances from pumped well after 90 days of pumping[3] (feet)			
				0.75	100	2,640	3,960
20	6,000	0.0004	200	11.4	6.4	3.1	2.7
		.004		10.3	5.3	1.9	1.5
		.04		9.1	4.1	.8	.5
		.15		8.4	3.4	.3	.1
30	9,000	.0004	400	15.5	8.9	4.4	3.9
		.004		14.0	7.3	2.8	2.3
		.04		12.4	5.7	1.3	.8
		.15		11.5	5.2	.1	.0
40	12,000	.0004	750	22.1	12.8	6.5	5.7
		.004		19.9	10.5	4.3	3.5
		.04		17.7	8.3	2.1	1.4
		.15		16.4	7.1	.0	.0

[1]Transmissivity was calculated by multiplying the hydraulic-conductivity value of 300 feet per day by the aquifer thicknesses of 20, 30, and 40 feet, respectively. For example, the transmissivity of 6,000 square feet per day was obtained by multiplying the hydraulic conductivity of 300 feet per day by the aquifer thickness of 20 feet.

[2]The pumping rate was limited so that calculated drawdowns at a distance of 0.75 foot, the assumed radius of the pumped well, was about 50 percent of the aquifer thickness. Effects on drawdown of pumping from neighboring wells are not considered.

[3]Drawdowns were calculated using the Theis method for nonsteady radial flow without vertical movement as described by Lohman (1972, p. 15-16).

The data in table 3 indicate that where the aquifer is confined, the theoretical drawdown cones extend greater than 0.5 mi. If a well spacing of 0.5 mi was implemented, interference between drawdown cones could result in a decrease in the saturated thickness at each individual well because of the effects of superposition of drawdown. However, because of the anisotropy and heterogeneity of the aquifers, optimum well spacing can be determined only by detailed drilling and aquifer testing.

The data in table 4 indicate a more conservative estimate of drawdowns in the Elm and Middle James aquifers. The transmissivity was decreased by 50 percent to account for the anisotropy and heterogeneity of the aquifer and decreases in the saturated thickness caused by pumping. The maximum drawdown was limited to 40 percent of the aquifer thickness and the effect of pumping of neighboring wells was considered. The pumping rate was varied for different values of transmissivity and storage coefficient so that the summation of the drawdown in the pumped well and the drawdown at 0.5 mi (2,640 ft) did not exceed about 40 percent of the aquifer thickness.

Because the aquifers commonly are under water-table conditions near their tops and can be under artesian conditions at depth, a storage coefficient of 0.04 probably is a reasonable estimate of the overall storage coefficient. Using the pumping rates listed in table 4 corresponding to a storage coefficient of 0.04 and a 1-mi well spacing (fig. 5) to minimize drawdown effects from neighboring pumped wells, the maximum total well yield would be about 28,800 gal/min or about 64 ft^3/s.

The effects of various theoretical pumping alternatives on the Elm and Middle James aquifers are summarized in table 5. With a maximum total pumping rate of 640 ft^3/s from 555 wells, the average water-level decline in the aquifer after 90 days of pumping would be 29.0 ft with a storage coefficient of 0.04, and 7.7 ft with a storage coefficient of 0.15. The total pumping rate of 640 ft^3/s is a theoretical maximum and probably could not be achieved. A pumping rate of 150 ft^3/s from 122 wells for 90 days theoretically would cause an average water-level decline of 6.8 ft with a storage coefficient of 0.04, and 1.8 ft with a storage coefficient of 0.15. The 100-ft^3/s rate from 46 wells for 90 days theoretically would cause an average decline of 4.5 and 1.2 ft for storage coefficients of 0.04 and 0.15, respectively. The 100- and 150-ft^3/s rates probably are achievable using properly sited and constructed wells. The pumping rates of 64 and 75 ft^3/s are based on the conservative theoretical estimates of drawdown presented in table 4.

Assuming that the aquifers can be recharged uniformly throughout the entire areal extent of about 150 mi^2, the average annual recharge required to replace water pumped at a rate of 150 ft^3/s for 90 days would be 3.3 inches. For a rate of 100 ft^3/s, the recharge required would be 2.2 inches.

Although no natural recharge rates to the aquifers have been calculated in the study area, Hedges and others (1983) calculated that the average annual ground-water recharge for an area south of the study area in the James River basin is 0.6 inch for unconfined aquifers overlain by till and 0.36 inch for confined aquifers, using regional flow-net analysis. Recharge to the unconfined aquifers where not overlain by till is about 3.0 in/yr.

Table 4.--Theoretical drawdowns in the Elm and Middle James aquifers with variable pumping rates and with drawdown in the pumping well limited to about 40 percent of the aquifer thickness

Aquifer thickness (feet)	Transmissivity[1] (square feet per day)	Storage coefficient (dimensionless)	Pumping rate[2] (gallons per minute)	Calculated drawdown in the aquifer at various distances from pumped well after 90 days of pumping[3] (feet)			
				0.75	100	2,640	3,960
20	3,000	0.0004	60	6.6	3.7	1.7	1.4
		.004	70	6.9	3.4	1.1	.8
		.04	85	7.4	3.2	.4	.2
		.15	95	7.7	2.9	.1	.0
30	4,500	.0004	115	8.7	4.8	2.3	1.9
		.004	150	10.1	5.1	1.9	1.4
		.04	185	11.0	4.9	.8	.5
		.15	210	11.6	4.6	.3	.1
40	6,000	.0004	220	12.6	7.1	3.4	3.0
		.004	265	13.6	7.0	2.6	2.0
		.04	325	14.8	6.7	1.3	.8
		.15	375	15.8	6.4	.4	.2

[1]Transmissivity was calculated as 50 percent of the product by multiplying the hydraulic-conductivity value of 300 feet per day by the aquifer thicknesses of 20, 30, and 40 feet, respectively. For example, the transmissivity of 3,000 square feet per day was obtained by multiplying the hydraulic conductivity of 300 feet per day by the aquifer thickness of 20 feet and reducing the transmissivity by 50 percent.
[2]The pumping rate was limited so that calculated drawdowns at a distance of 0.75 foot, the assumed radius of the pumped well, was limited to about 40 percent of the aquifer thickness. The effects of pumping from neighboring wells were considered.
[3]Drawdowns were calculated using the Theis method for nonsteady radial flow without vertical movement as described by Lohman (1972, p. 15-16).

Table 5.--Theoretical average water-level declines and required recharge for various pumping rates and storage values in the Elm and Middle James aquifers

Well spacing (miles)	Total number of wells	Storage coefficient (dimensionless)	Maximum total pumping rate (cubic feet per second for 90 days)	Average water-level decline[1] (feet)	Average annual recharge required to replace total pumpage[2] (inches)
0.5	555	0.04	640	29.0	13.9
1.0	122	.04	150	6.8	3.3
1.0	[3]46	.04	100	4.5	2.2
1.0	122	.04	64	2.9	1.4
.5	555	.15	640	7.7	13.9
1.0	122	.15	150	1.8	3.3
1.0	[3]46	.15	100	1.2	2.2
1.0	122	.15	76	.9	1.7

[1]Assumes no flow across aquifer boundaries.
[2]Assumes an aquifer area of 154 square miles.
[3]All wells located where aquifer thickness is greater than 40 feet.

Natural recharge is limited by the thickness of the till and other fine-grained sediments overlying the aquifer (fig. 6). As a result, many parts of the aquifer receive little or no direct recharge. Recharge to these areas occurs as underflow from areas where the overlying material is thinner and, hence, transmits greater recharge. Lowering the water levels in an aquifer may induce additional natural recharge.

POTENTIAL FOR ARTIFICIAL RECHARGE OF THE ELM AND MIDDLE JAMES AQUIFERS

The feasibility of artificially recharging an aquifer, using the technique of water spreading, depends on both the geologic and hydraulic characteristics of the aquifer and of the sediments overlying the aquifer through which the recharge water must percolate. Water spreading consists of allowing water to cover a large area at a relatively shallow depth in order to provide a large surface area through which the water can infiltrate. In determining the artifical-recharge potential of an aquifer, consideration needs to be given to (Emmons, 1977):

1. The availability and quality of the water to be artificially recharged.

The recharge water will need to be conveyed to the artificial-recharge sites. The lack of an economical method of conveyance may make some locations unsuitable. Recharge water should be as free as possible of sediment and biological organisms, and of a chemical quality compatible with the ground water. Sediment transported into the spreading ponds with the recharge water, along with sediment resulting from bank and wind erosion, may clog the recharge-pond bottom and decrease infiltration. Organisms in the recharge ponds may cause clogging by bacterial growth in the sediments beneath the pond and by algal growth on the pond bottom. The recharge water may react chemically with the aquifer material causing a decrease in the rate of infiltration. The recharge water also may react with the water in the aquifer causing chemical-quality changes in the ground water. The use of recharge water that is more mineralized than water in the aquifer for extended periods may result in the degradation of the water in the aquifer.

2. <u>The capability of the overlying deposits to transmit water and the capability of the aquifer to accept the artificially recharged water.</u>

The glacial deposits overlying the aquifer need to be sufficiently permeable to allow reasonably rapid infiltration rates from the spreading ponds. The presence of confining clay and silt layers in the till and lake deposits or in the sand-and-gravel outwash deposits comprising the aquifer may make a site unsuitable for artificial recharge.

3. <u>The availability of adequate storage space in the aquifer for the recharge water.</u>

The volume of artificially recharged water that may be temporarily stored in the unsaturated sand and gravel overlying the saturated aquifer can be calculated from the equation:

$$V = SAh,$$

where V = the volume of additional water to be stored, in cubic feet;
S = the specific yield of the aquifer (dimensionless);
A = the area of the aquifer in which the storage occurs, in square feet; and
h = the average rise in the water table, in feet.

The volume of water computed from the above equation is a theoretical maximum and assumes that the water table can be raised an average height, h, throughout the entire area, A. Ground-water movement and gains and losses from the aquifer affect the computed storage volume.

4. <u>Assurance that the recharge water will not be lost to evapotranspiration or flow out of the area before the water can be used.</u>

To minimize losses by evapotranspriation, the water table needs to be maintained at a depth of more than 5 ft and possibly as much as 10 ft below land surface. The rate and direction of ground-water movement need to be considered in the location of the artificial-recharge sites to ensure that recharge water can be withdrawn before the water moves out of the area of need. Artificial recharge and the subsequent water-table rise may alter the rate and direction of ground-water movement.

The selection of artificial-recharge sites in the study area was limited to consideration 2, "The capability of the overlying deposits to transmit water and the capability of the aquifer to accept the artificially recharged water." For an area to be suitable for artificial recharge, the coarsegrained outwash deposits that comprise the aquifer need to be at or near the land surface. Where the fine-grained till and lake deposits overlying the aquifers are sufficiently thick, they can impede the rate of artificial recharge. Areas where the top of the aquifer averages 10 ft or less below land surface are shown in figure 6. These areas, in general, would be the best suited for artificial recharge using spreading ponds.

In addition to the proximity of the aquifer to land surface, the aquifer has to have sufficient thickness to accept useful volumes of water. The thickness of the Elm and Middle James aquifers at test holes is shown in figure 5. It is assumed that the aquifer needs to be at least 20 ft thick to warrant consideration for artificial recharge. It also is assumed that the aquifer has sufficient hydraulic conductivity and is mostly isotropic, that is, the hydraulic conductivity is relatively independent of the direction of movement, so that the aquifer can accept and transmit the water from the spreading ponds.

Areas where artificial recharge using spreading ponds most likely would be suitable are shown in figure 9, which is a composite of figures 5 and 6. The suitable areas where the aquifer is at least 20 ft thick and the aquifer is less than 10 ft below land surface underlie about 14 mi^2 of the study area.

The rate at which an aquifer can be artificially recharged is, in part, a function of the permeability of the soil underlying the spreading pond and the quality of the recharge water. The following table shows the range of infiltration rates that can be anticipated for different soil textures (Blair, 1970):

Soil texture	Infiltration rate (feet per day)
Coarse	2.0-13.1
Medium	2.0-4.3
Fine	Less than 1.3

The soils in Brown County generally are fine to medium textured. Using the data in the preceeding table, it is anticipated that the infiltration rates in the study area probably will range from less than 1.3 to 4.3 ft/d. Recharge water containing large quantities of sediment can decrease rapidly the infiltration rate or completely seal a pond bottom unless the site is properly designed. A typical decrease in infiltration rate with time is shown in figure 10. Longer-term decreases in infiltration rate commonly are caused by the clogging action of microogranisms (bacteria and algae) on the pond bottom and in the soil. One of the techniques to enhance infiltration in spreading ponds is to construct more than one pond to allow for periodic drying and cleaning of the ponds to restore infiltration rates. According to Blair (1970), a cleaning frequency of 1 to 2 times per year would be required with soil types similar to those in the study area. A typical basin-type, artificial-recharge site is shown in figure 11.

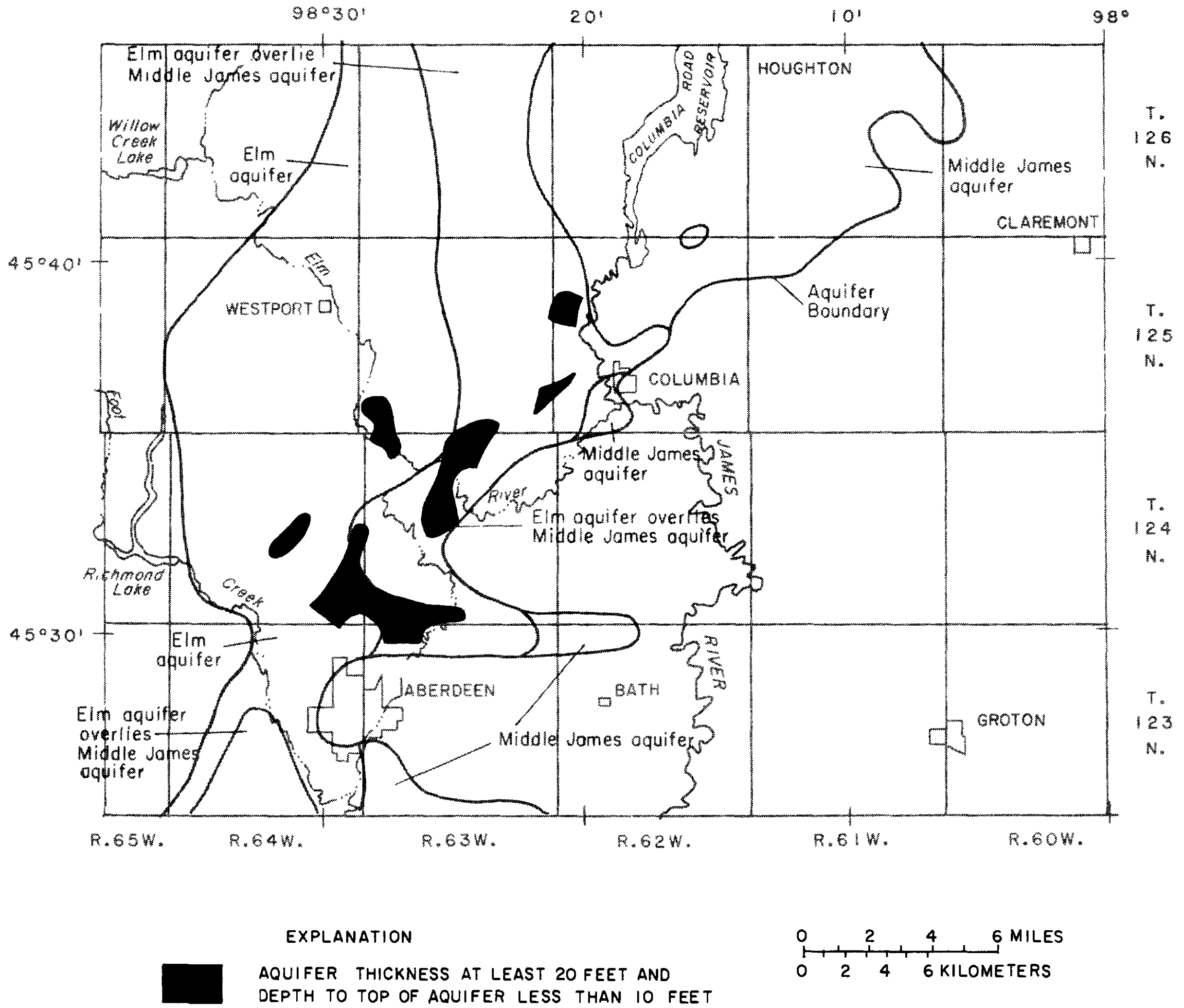

Figure 9.--Locations most suitable for artificial recharge using spreading ponds.

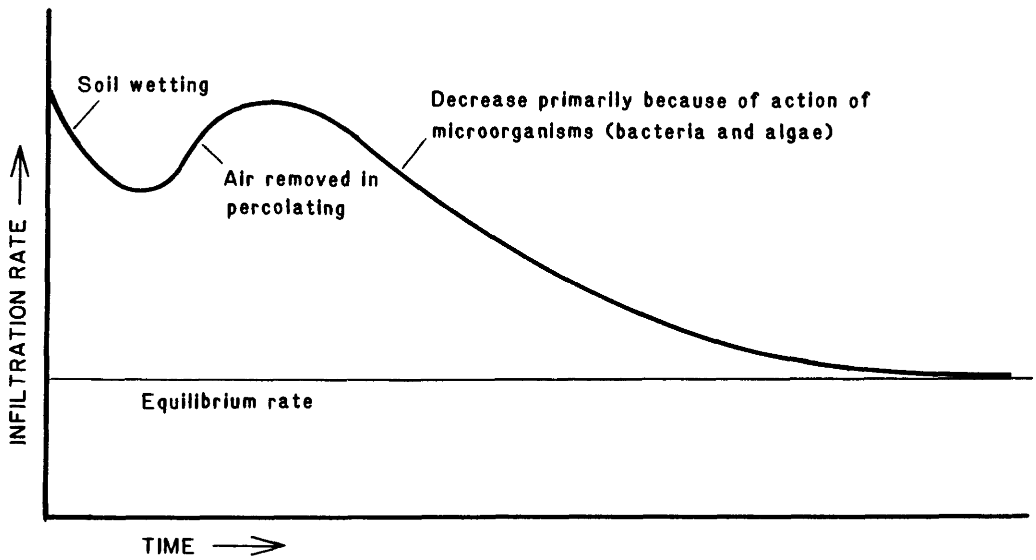

Figure 10.--Typical decrease in spreading-pond infiltration rate (modified from McGauhey, 1968).

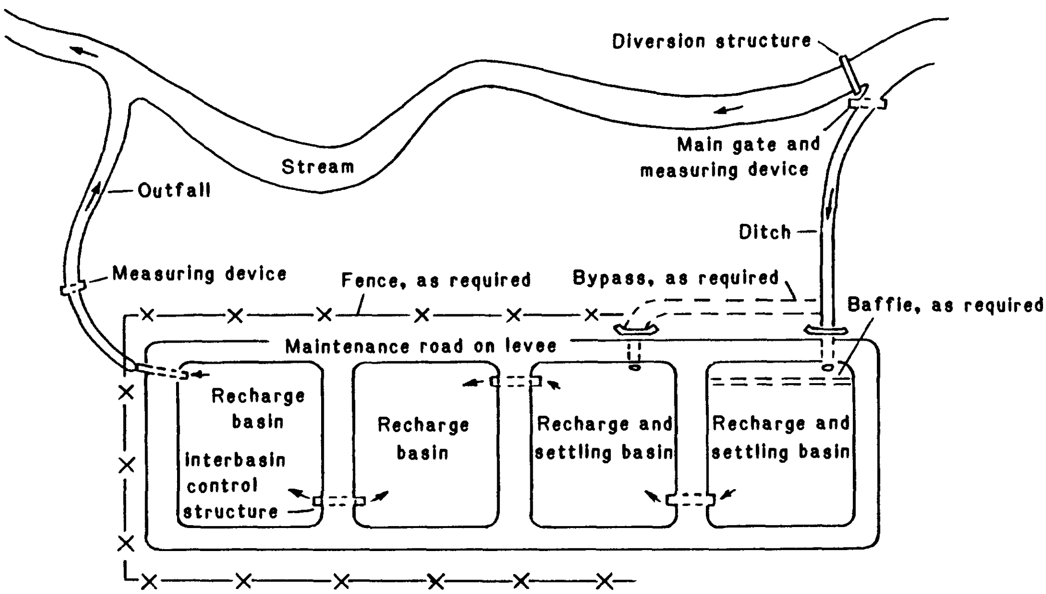

Figure 11.--Typical basins used for artificial recharge of stream water (after Bianchi and Muckel, 1970).

thickness ranges from 0 to 112 feet. The Middle James aquifer underlies about 172 square miles of the study area. The maximum altitude of the top of the Middle James aquifer is 1,250 feet and the minimum altitude of the bottom is 1,150 feet. The thickness ranges from 0 to 56 feet. The Deep James aquifer was not evaluated in this study.

The quality of the water from the Elm and Middle James aquifers differs considerably throughout the study area. The predominant chemical constituents in the water from the aquifers are sodium and sulfate ions; however, calcium, magnesium, bicarbonate, or chloride may dominate locally.

The calculated total yield of hypothetical wells completed in the Elm and Middle James aquifers ranges from a minimum 64 cubic feet per second, which is conservative, to a maximum 640 cubic feet per second. The conservative estimate was based on a 50-percent reduction in calculated transmissivity values and a storage coefficient of 0.04. The drawdown in the pumped wells was limited to about 40 percent of the aquifer thickness and the well spacing was 1 mile. The maximum composite yield was based on an aquifer hydraulic conductivity of 300 feet per day and the drawdown in the pumped well was limited to about 50 percent of the aquifer thickness. It was estimated that about 200 gallons per minute could be obtained where the aquifer is 20 feet thick, 400 gallons per minute where the aquifer is 30 feet thick, and 750 gallons per minute where the aquifer is 40 feet thick. Using these pumping rates and a well spacing of 0.5 mile, the maximum total well yield for this study area was calculated to be about 640 cubic feet per second. With a 1-mile well spacing, the maximum total well yield was calculated to be about 150 cubic feet per second. Based on the available data, the rates of 100 to 150 cubic feet per second from the study area probably are achievable using properly sited and constructed wells.

Because no aquifer-test data are available in the study area, the potential well yields can only be estimated based on a range of assumed aquifer values. To improve definition of the range of aquifer values that can be anticipated, it would be desirable to conduct several aquifer tests in the study area.

The feasibility of artificially recharging an aquifer, using the technique of water spreading, depends on both the geologic and hydraulic characteristics of the aquifer and of the sediments overlying the aquifer through which the recharge water must percolate.

In determining the artificial-recharge potential of an aquifer, consideration needs to be given to: (1) The availability and quality of the water to be artificially recharged; (2) the capability of the overlying deposits to transmit water and the capability of the aquifer to accept the artificially recharged water; (3) the availability of adequate storage space in the aquifer for the recharge water; and (4) assurance that the recharge water will not be lost to evapotranspiration or flow out of the area before the water can be used. The selection of artificial-recharge sites in the study area was limited to consideration of the capability of the overlying deposits to transmit water and the capability of the aquifer to accept the artificially recharged water. The areas suitable for artificial recharge were defined as those areas where the average aquifer thickness was greater than 20 feet and

The theoretical pond area required to recharge the aquifers with varying infiltration rates is presented in table 6. For example, 0.16 mi^2 of pond area is required to recharge 100 ft^3/s at an infiltration rate of 2 ft/d.

Table 6.--Theoretical spreading-pond sizes required to artificially recharge the aquifer

Infiltration rates (feet per day)	Area of spreading pond, in square miles, required for artificial recharge[1]			
	64 cubic feet per second	100 cubic feet per second	150 cubic feet per second	640 cubic feet per second
1	0.20	0.30	0.46	1.98
2	.10	.16	.23	.99
3	.07	.10	.16	.66

[1]Assumming that boundaries do not allow flow and natural recharge is not increased or decreased to replace water pumped from aquifers.

The best locations for artificial recharge are in the same areas as the proposed ground-water withdrawal. In the study area, the aquifer underlies about 154 mi^2 (fig. 5), whereas the area most suitable for artificial recharge is only 14 mi^2 (fig. 9). Because of the direction of ground-water movement and the distance between artificial recharge sites and ground-water withdrawal points, artificial recharge in some areas where pumpage occurs may not be feasible using spreading ponds.

SUMMARY

During the Pleistocene Epoch, continental glaciation from the north and east covered eastern South Dakota, depositing a blanket of glacial drift over the preglacial bedrock surface. The drift can be subdivided into two major types, till and outwash, that differ greatly in both physical and hydrologic characteristics. Only the more sandy and gravelly glacial-outwash deposits yield significant quantities of water to wells. The natural recharge, movement, and discharge of water in the outwash aquifers are controlled by the lithology and stratigraphy of the surficial deposits and the underlying bedrock units.

The units that comprise the complex hydrologic system in the glacial outwash have been subdivided into three aquifers in the study area: the Elm, Middle James, and Deep James aquifers. These aquifers generally are separated from each other by till or other fine-grained sediments. The Elm aquifer is the uppermost and largest of the aquifers and underlies about 204 square miles of the study area. The maximum altitude of the top of the Elm aquifer is 1,400 feet and the minimum altitude of the bottom is 1,225 feet. The

the average thickness of the fine-grained material overlying the aquifer was 10 feet or less. Using these criteria, about 14 square miles of the study area are suitable for artificial recharge.

Infiltration rates in the study area are estimated to range from 1.3 to 4.3 feet per day. Using an infiltration rate of 2 feet per day, 0.16 square mile of spreading pond would be required to artificially recharge at a rate of 100 cubic feet per second. To test the validity of the estimated range of infiltration rates, it would be desirable to conduct several small-scale artificial recharge tests using spreading ponds. These tests would provide data on actual infiltration rates, and on the clogging effects of sediment in the recharge water and of growth of microorganisms on the pond bottoms and in the underlying soil profile. The tests also would provide information on any water-quality changes that might occur in the aquifer as a result of artificial recharge.

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