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Hydrogeology and recharge of the Split Rock Creek Aquifer, southeastern South Dakota

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HYDROGEOLOGY AND RECHARGE OF THE SPLIT ROCK CREEK AQUIFER, SOUTHEASTERN SOUTH DAKOTA

by

Stan F. Pence
Bachelor of Science, University of South Dakota, 1989

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota
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1996

This thesis, submitted by Stan F. Pence in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Harvey Knull
Dean of the Graduate School

9-13-96
Date

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Department: Geology

Degree: Master of Science

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ABSTRACT

The rapid growth of the city of Sioux Falls, South Dakota, has created a great demand for additional sources of ground water. Due to limited information on the buried, confined Split Rock Creek aquifer near Sioux Falls, a detailed hydrogeologic assessment of the aquifer was conducted to determine the mechanism of recharge to the aquifer.

A four-fold plan was carried out to gather the necessary data. This plan involved determining the general hydrostratigraphy of the study area by reviewing available data and by drilling test holes where data were limited, collecting water-level data over an extended period, collecting water samples for major inorganic, radionuclide, and stable isotope analyses, and determining the hydraulic characteristics of the aquifer and confining layers through aquifer and baildown tests.

Results indicate that the Split Rock Creek aquifer exists in paleo-valleys in the highly fractured Precambrian Sioux Quartzite. Aquifer materials are comprised of weathered and eroded Sioux Quartzite. The main portion of the aquifer lies to the east of Sioux Falls, between Brandon and Valley Springs, with aquifer thickness in this area exceeding 200 feet. Total dissolved solids in aquifer water collected from this area are less than 500 parts per million (ppm).

Water levels in the aquifer increase during years of above normal precipitation, indicating recharge of the aquifer. Recharge has been great enough to sustain the

approximately 292 million gallons of annual municipal pumping by Sioux Falls and Brandon. Water-chemistry data indicate post-depositional water present in the aquifer. Radiocarbon data indicate the age of the aquifer water ranges from approximately 3,000 to 10,000 years, and stable isotope data indicate the waters are meteoric in origin.

Low permeability, unfractured till overlies the majority of the aquifer, eliminating the possibility of significant recharge in those areas. Ground-water flow directions indicate the main source of recharge is the Sioux Quartzite aquifer. Induced recharge from surficial outwash and alluvium is possible in localized areas of river valleys.

I. INTRODUCTION

Until recently, very little was known about the hydrogeology of the Split Rock Creek aquifer. The sediments that comprise this buried, confined aquifer are the basal sands and sandstones (Iles, 1983) of the Upper Cretaceous Split Rock Creek Formation (Kairo, 1987). Because of the proximity of this aquifer to Sioux Falls, the largest city in the state of South Dakota, the potential for use of this aquifer as a supplemental source of water is great. Because of limited hydrogeologic information, the city requested that the South Dakota Geological Survey (SDGS) conduct a detailed hydrogeologic assessment of the aquifer. Most of the information presented in this thesis is derived from data gathered during the SDGS's study.

Objective

The objective of this study was to define the mechanism or mechanisms of recharge to the Split Rock Creek aquifer. Several possibilities arise:

- Indirect recharge to the aquifer occurs by fracture flow from the Sioux Quartzite either along the lateral margins of the aquifer or by direct upward movement into the aquifer.

- Infiltration of precipitation through the overlying tills provides recharge.

- Water from overlying alluvium and outwash, where present, infiltrates and recharges the aquifer.

- Indirect recharge occurs by inflow from channels of the aquifer that extend beyond the study area.

- Some combination of the above provides recharge.

- There is little or no recharge to the aquifer.

General Description of the Study Area

The study area includes Townships 101 to 103 North and Ranges 47 to 50 West in Minnehaha County in southeastern South Dakota (figures 1 and 2). The Big Sioux River and Split Rock Creek flow in broad, flat valleys surrounded by deeply eroded loess uplands (Tomhave, 1994). The maximum relief of the study area is approximately 360 feet, ranging from an elevation of less than 1,270 feet above mean sea level (msl), where the Big Sioux River exits the southeastern part of the county, to an elevation of greater than 1,630 feet above msl in the northwestern part of the study area.

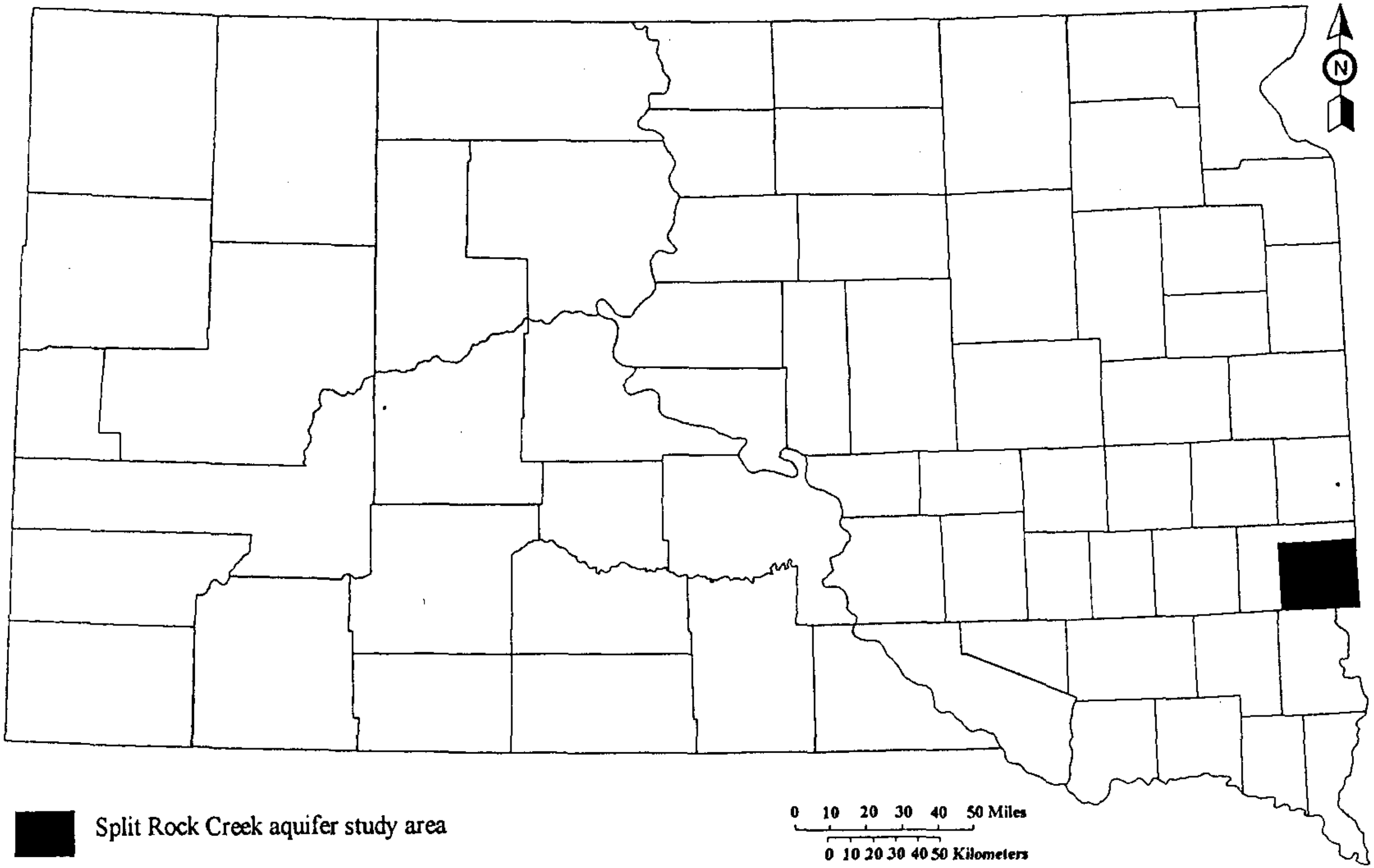


Figure 1. Location of the study area

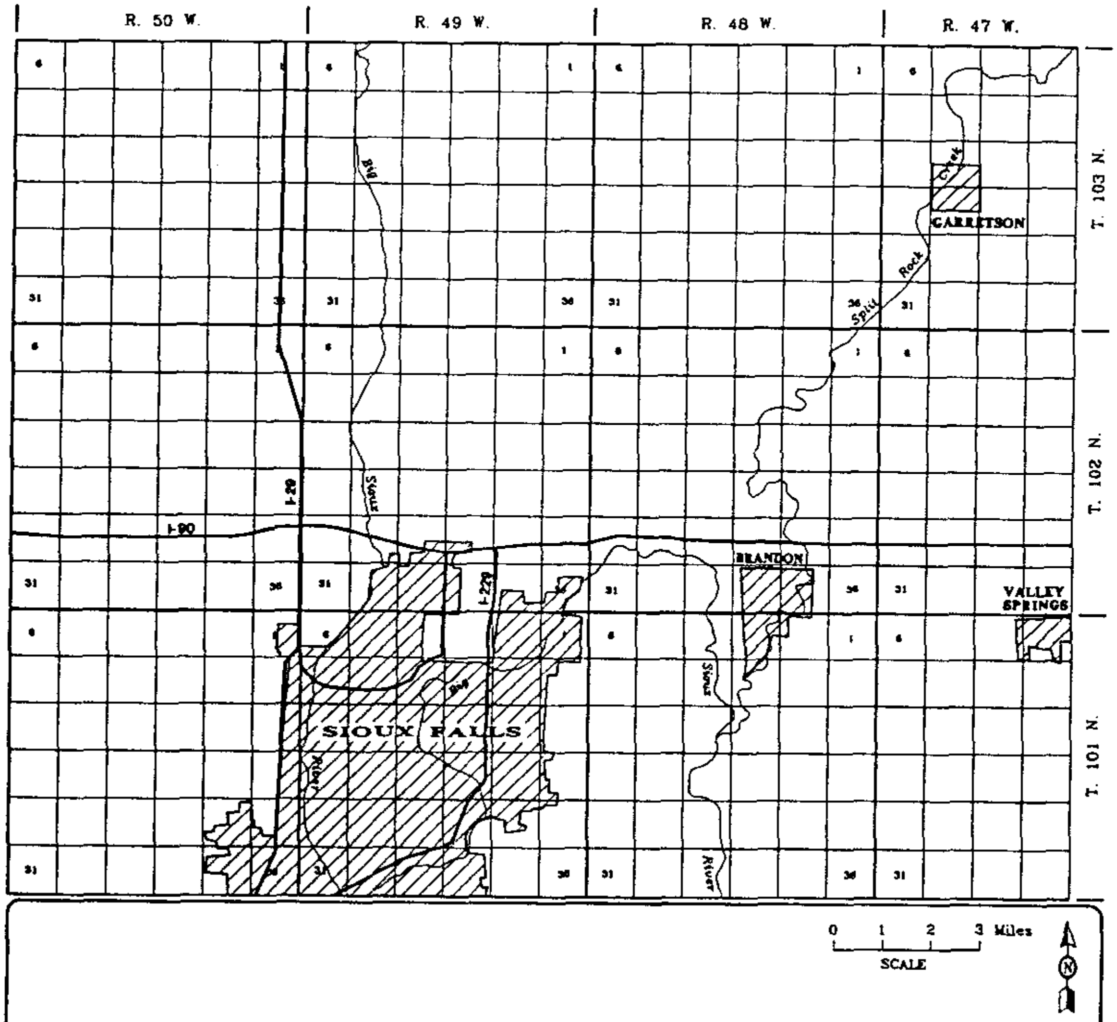


Figure 2. Split Rock Creek aquifer study area

Previous studies have identified three major units of rocks and sediments in the area. The oldest and stratigraphically lowest unit is the Precambrian Sioux Quartzite that underlies the entire study area. The second unit unconformably overlies the Sioux Quartzite and consists of the Cretaceous valley-fill sediments of the Split Rock Creek Formation. These units are present only in topographic lows formed on the surface of the Sioux Quartzite in some regions of the study area. The third unit consists of glacial sediments that rest unconformably on the Split Rock Creek Formation, and overlie the Sioux Quartzite in topographically high areas where the Split Rock Creek Formation is absent. This unit consists of clay till and gravel outwash (Kairo, 1987 and Tomhave, 1994). The gravel outwash deposits comprise the Big Sioux aquifer, which supplies most of the water used by the City of Sioux Falls, averaging slightly over 20 million gallons per day (Lyle Johnson, personal communication). Figure 3 illustrates the relationship of these units.

Previous Investigations

A description of these three geologic units follows. A brief description of the Sioux Quartzite and glacial sediments is provided with most of the following information concentrating on previous geologic and hydrogeologic investigations of the Split Rock Creek Formation.

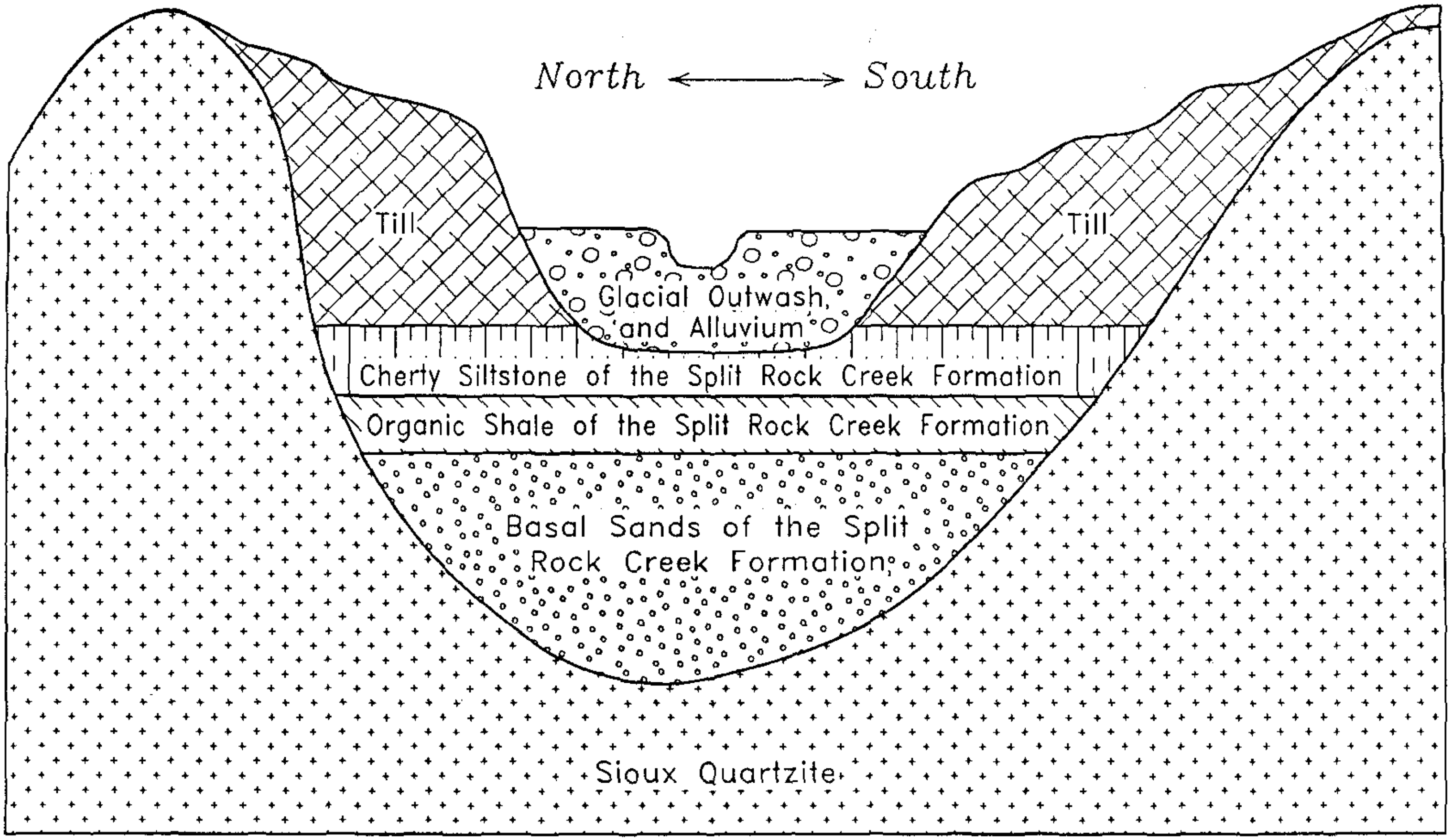


Figure 3. Generalized geologic cross-section of the Split Rock Creek aquifer study area

The Sioux Quartzite

The Sioux Quartzite, named by White (1870), has been described in many geologic reports. Upham (1885) was one of the first to publish detailed geologic information on the Sioux Quartzite describing it as very hard and reddish gray; he also mentioned the occurrence of "numerous vertical or nearly vertical joints" in the quartzite. Other early workers to report on the Sioux Quartzite include Irving (1885), Bain (1893), and Todd (1894).

The joints, or fracture system, in the quartzite was first described in detail by Beyer (1896). He reported "the presence of two systems of vertical cracks which are nearly at right angles to each other" which cause the quartzite to break into large blocks. Darton (1909) was the first to mention that in some places wells in the quartzite produced a small amount of water from the fractures.

Rothrock and Newcomb (1926) described the fractures in more detail than previous workers. They stated that there were two major sets of vertical fractures and a third set of nearly horizontal fractures. Rothrock and Otton (1947) noted that some small towns and many farms had wells completed in the formation. They concluded the water was able to move into these wells through fractures or poorly-cemented layers within the quartzite.

Baldwin (1949) integrated the previous investigations with his own work to provide a detailed report on the Sioux Quartzite. He described the quartzite as predominantly orthoquartzite with minor conglomerate and mudstone layers. He noted three major trends of vertical joints in the quartzite in Minnehaha County which were intersected by a nearly horizontal set of joints. Later study by Baldwin (1951) indicated that the average joint density was two to six per linear foot.

Rothrock (1958) described the quartzite as composed primarily of beach sands, "which have been so firmly cemented with silica that the rock breaks through the grains instead of around them." The silica cement has decreased the porosity of the formation to about two percent. Under certain conditions, Rothrock (1958) stated that the cement in the quartzite is subject to dissolution, leaving behind either a poorly cemented sandstone or a loose sand. Such sand is commonly encountered in thin layers in the quartzite, and in layers up to 40 feet thick on top of the quartzite.

Dienhart (1958) noted that joints may permit the flow of water through the quartzite. Rothrock (1958) also noted that the intersecting cracks in the quartzite were capable of storing large volumes of water. He also stated the recharge to the quartzite likely occurred where streams crossed the quartzite at higher elevations where the quartzite is exposed or thinly covered by glacial sediments.

Anderson and others (1976) have determined that ground water in the Sioux Quartzite in Minnesota flows away from structural highs (outcrop areas). In the southwestern part of Minnesota, immediately adjacent to the study area, ground water in the Sioux Quartzite flows towards the southeast.

In these adjacent areas of Minnesota, wells completed in the quartzite yield one to 450 gallons of water per minute. Seven municipalities in the area have municipal wells in the quartzite, with an average yield of 100 gal/min. Transmissivity calculated from aquifer tests conducted at the seven municipalities ranges from 20 to 940 ft^2/day and horizontal hydraulic conductivity ranges from 0.2 to 3.3 ft/day (Anderson, 1986).

Bergstrom and Morey (1985) have inferred the quartzite to be Early Proterozoic in age, or 1,630 to 1,760 million years old. Lindgren and Niehus (1992) and Niehus and Lindgren (1994) have briefly summarized the hydrogeology of the Sioux Quartzite mostly using data supplied by the SDGS. They also concluded that recharge occurs by infiltration where the quartzite is shallow or exposed. They suggest that water discharged by the Sioux Quartzite aquifer recharges the Split Rock Creek aquifer. The predominant movement of water through the quartzite was observed to be south and southwest in South Dakota, although insufficient water-level data were available to construct an accurate potentiometric surface map of the area (Lindgren and Niehus, 1992).

The Split Rock Creek Formation

Upham (1885) was the first to document the occurrence of outcrops now considered part of the Split Rock Creek Formation. He noted two occurrences of what he called "chalk rock" outcrops. One outcrop was located along Split Rock Creek just north of Brandon, South Dakota (Township 102 North, Range 48 West, Section 25), and the other outcrop was further north near Split Rock Creek in an area known as the Palisades (Township 103 North, Range 47 West, Sections 30 and 31). This "chalk rock" was also noted by Bain (1895), Beyer (1896), Todd (1900), and Darton (1909). These early studies incorrectly described this "chalk rock" as part of the Niobrara Formation, thus dating the Split Rock Creek Formation as Cretaceous.

In a study for the Pathfinder Steam Plant (Township 102 North, Range 48 West, Sections 30 and 31), Dienhart (1958) noted the occurrence of the Split Rock Creek Formation in the subsurface, although he was unaware that this was part of the same geologic unit exposed approximately three miles to the east near Brandon.

Dienhart (1958) was the first to mention the basal sands and sandstones of the Split Rock Creek Formation. He described beach sands up to 60 feet thick in the Pathfinder area. He was also the first to note that these sands were water-bearing and under artesian pressure. Dienhart (1958) was unsure if there was a connection between this artesian aquifer and the overlying Big Sioux aquifer (figure 3), but based on topographic relationships, he stated that ground-water flow (recharge) would be "into the artesian aquifer in the Pathfinder vicinity." Dienhart (1958) determined that many of the farm wells adjacent to the site were drilled into the upper shales of the formation. These wells supplied adequate water for domestic purposes, but to obtain water for a power-plant (such as the Pathfinder Steam Plant) it would be necessary to draw water from the basal sands and sandstones.

Additional study was conducted by Rothrock (1958) at the Pathfinder location. He was unable to accurately correlate the strata currently referred to as the Split Rock Creek Formation with known formations in South Dakota or nearby states; for convenience he designated these strata as the Pathfinder Formation. Rothrock (1958) described three distinct members of the formation: an upper clay member, a middle black rock member, and a lower clay member. He did not consider the lower sands and sandstones as part of this formation; rather, he stated that these sands were a result of weathering of the underlying Sioux Quartzite prior to deposition of the Pathfinder Formation. Based on the fossils found in the formation and the knowledge that the last major advance of an interior seaway occurred during the Cretaceous, Rothrock (1958) suggested a Cretaceous age for the formation.

Rothrock (1958) stated that the sands and sandstones overlying the Sioux Quartzite were porous and permeable. During an aquifer tests of these sands, a test well at the Pathfinder site was pumped at a rate of 120,500 cubic feet per day (cfd) for eight days with an observed drawdown of 90 feet. The radius of influence extended approximately 6,900 feet. After nine days of recovery, water levels in six of seven wells monitored during the test had not fully recovered. Rothrock (1958) attributed this incomplete recovery to inadequate recharge to the aquifer.

Rothrock (1958) disagreed with Dienhart's (1948) conclusion that recharge to the aquifer was from the overlying Big Sioux aquifer because the lower sand aquifer was under "an artesian pressure sufficient to make it flow from wells drilled in the bottom of the Big Sioux Valley" (Rothrock, 1958). He concluded that the main recharge to the aquifer was probably "coming from below, through fractures in the underlying quartzite." The artesian pressure in the aquifer was interpreted as a result of the quartzite outcrop areas being at a much higher elevation than the top of the underground "reservoir" at the Pathfinder Plant.

This caused considerable pressure to develop against the "confining clay roof" of the aquifer.

Vaughan and Ackroyd (1968) reported a "recently discovered aquifer" approximately six miles west/southwest of the Pathfinder site (Township 101 North, Range 49 West, Sections 5 and 8). They did not realize that this aquifer was the same as the basal sands and sandstones at the Pathfinder site. They reported a sand and gravel unit directly overlying the Sioux Quartzite. This aquifer was overlain by a confining clay and under artesian conditions.

A three-day aquifer test at this location (Vaughan and Ackroyd, 1968) yielded 63,140 cfd with 16 feet of drawdown in the production well. The aquifer thickness at the production well was 29 feet. Analysis of the drawdown data indicated a transmissivity value of 1,924 square feet per day (ft^2/day), with a storage coefficient of 2.8×10^{-4}. After three days of recovery, water levels had returned to pre-pumping levels. Vaughan and Ackroyd (1968) stated that the source of recharge to this aquifer was unknown.

Based on regional relationships, Ludvigson and others (1981), reported that the formation was a shallow water facies probably equivalent to the Upper Cretaceous Niobrara Formation. They officially proposed the name Split Rock Creek Formation after compilation of the pre-existing data and determination that the rock exposed along Split Rock Creek and at the Pathfinder Plant were part of the same formation.

The hydrogeological study of the Split Rock Creek Formation was conducted by Iles (1983). He concluded that the basal quartz sand and sandstones lying directly on the

Sioux Quartzite probably resulted from two processes: 1) in-situ weathering of the Sioux Quartzite and 2) erosion, transportation, and re-deposition of weathered sand grains that originated from the Sioux Quartzite.

Iles (1983) also noted that many of the overlying claystones and siltstones of the formation were highly fractured and permeable. He based this on loss of circulation during mud rotary drilling. Iles' (1983) work indicated that there were areas near the Pathfinder plant where the sands and gravels of the Big Sioux aquifer appeared to be in direct contact with the basal sands of the Split Rock Creek Formation. In such locations, the basal sands would discharge directly to the Big Sioux aquifer.

Iles (1983) concluded that there was no significant recharge to the aquifer via overlying glacial aquifers. He based this on water level, water quality, and stratigraphic data, and suggested that the most likely source of recharge was meteoric water that entered fractures in the quartzite and then flowed into the basal sands of the Split Rock Creek aquifer. He also suggested that there was no significant source of modern recharge, most of the water in the formation was emplaced at some time in the past.

Additional studies of the Split Rock Creek Formation have been conducted by Mckay and Ludvigson (1981), Hammond and Ludvigson (1985), Hammond (1987), Holzheimer (1987), Setterholm and Morey (1987), and Kairo (1987). All of these studies focused on the stratigraphy, depositional environment, and paleontology of the formation. Additional studies in the area were all regional (county-wide or larger) and only briefly mentioned the Split Rock Creek Formation. They include Bretz (1981), Lindgren and

Niehus (1992), Tomhave (1994), and Niehus and Lindgren (1994). All of these later studies have used data collected and maintained by the SDGS.

Kairo (1987) gives one of the best and most detailed descriptions of the Split Rock Creek Formation. A summary of her general description states that the formation is bounded by unconformities and varies from a few feet to about 300 feet in thickness. The formation sediments, in ascending stratigraphic order, consist of sands, silts, muds, clays, organic-rich opaline sediments, and chert. The formation seems to represent an overall transgressive sequence of sediment deposited in embayments into the Precambrian Sioux Quartzite highland as Cretaceous seas encroached upon South Dakota, Minnesota, and Iowa. Her work on the nanofossils found in the Split Rock Creek Formation has indicated Cenomanian age for the upper part of the formation.

The two reports by Lindgren and Niehus provide brief overviews of the known surface water and ground water resources in the area. Lindgren and Niehus (1994) suggest that recharge to the basal sand of the Split Rock Creek Formation is likely meteoric water entering fractures in the quartzite and moving into the Split Rock Creek aquifer. They suggest, as did Iles (1983), that the Split Rock Creek aquifer is discharging into the Big Sioux aquifer.

Chandler's (1994) study in southwestern Minnesota, immediately adjacent to this study area, indicated the presence of deep channels in the Sioux Quartzite that are filled with Cretaceous sediments. It is likely that these sediments are equivalent to the Split Rock Creek Formation. Anderson and others (1976) also indicated Cretaceous rocks in this area.

Although mapped at large scale, they noted a southerly ground-water flow direction in these Cretaceous rocks.

Glacial Sediments

The Pleistocene glacial sediments in the study area consist mainly of clay till and gravel outwash, with isolated kame and terrace deposits. These sediments have been mentioned in many reports over the last 150 years, but only those containing relevant information on the water resources or geology will be discussed.

Rothrock and Newcomb (1926) were the first to conduct and publish a detailed study of the glacial sediments in Minnehaha County, with emphasis on the sand and gravel resources. They indicated that most of the county was mantled by clayey till, with sand and gravel outwash found in the larger river valleys, such as the Big Sioux. Their work also indicated the presence of kames and terraces on some of the hillsides.

The first report on the ground-water resources in the Sioux Falls area was published by Rothrock and Otten (1947). Their work indicated that water-supply wells in the area were completed in the Sioux Quartzite, the Split Rock Creek Formation, "boulder clay" (till), and in sand and gravel outwash found in the Big Sioux River valley. Most wells, and all of the high capacity wells, were completed in the outwash sands and gravels of the Big Sioux aquifer.

Rothrock and Newcomb (1926) and Rothrock and Otten (1947) described the till as "the typical, unsorted mixture of heavy clay, sand grains, pebbles, cobbles and boulders deposited by glacial ice where meltwater has been insufficient to sort out the material of different sizes." They described the upper, weathered part of this clay to be "not entirely impervious" and to be able to furnish enough water for small wells. They suggested that the source of recharge to the weathered clay occurs by slow seepage of rainwater into the subsurface.

Both groups also described the Big Sioux valley as a spillway for glacial torrents that were responsible, not only for making the valley, but also for depositing the sand and gravel which converted it into a ground-water reservoir. It is these gravels and sands which constitute the Big Sioux aquifer. The gravels consist mainly of pink and gray granite, white dolomite, gneiss, and quartzite, and the sands are composed predominately of clear, angular pieces of quartz with minor amounts of feldspar and dolomite (Rothrock and Otten, 1947).

Recharge to the Big Sioux aquifer is through rapid infiltration of meteoric water and water from the Big Sioux River during periods of high flow (Rothrock and Otten, 1947). Five aquifer-pumping tests in the immediate area of Sioux Falls were conducted and analyzed for Rothrock and Otten's (1947) study. These tests indicated the average transmissivity of the aquifer is approximately 20,050 ft^2/day and the hydraulic conductivity ranges from 321 to 1,069 feet per day (ft/day). These tests revealed that the aquifer can supply large quantities of water to pumping wells (over 192,500 cubic feet per day for an individual well).

Other workers, most mentioned in the preceding section, who described these glacial sediments and water resources included Flint (1955), Dienhart (1958), Rothrock

(1958), Steece (1958), Jorgensen and Ackroyd (1973), Bretz (1981), Lindgren and Niehus (1992), Niehus and Lindgren (1994), and Tomhave (1994).

Lindgren and Niehus' (1992) work is one of the most complete references on the Big Sioux aquifer, with much of their data supplied by the SDGS. They state that the aquifer underlies about 68 square miles near the Big Sioux River in Minnehaha County. They report the maximum thickness of the aquifer to be 71 feet, with an average thickness of about 22 feet.

Lindgren and Niehus (1992) indicate that the major sources of recharge to the aquifer are infiltration of precipitation and Big Sioux River water when river stage is higher than the water table in the aquifer. They point out that in certain areas the aquifer may also be receiving water from the Split Rock Creek aquifer. Main sources of discharge are evapotranspiration and baseflow to the Big Sioux River. Ground water flow normally parallels the flow of the Big Sioux River.

Other Sources of Information

Extensive data have been collected during geologic and hydrogeologic investigations in this area, especially county and city studies conducted by the SDGS. These data consist of lithologic logs, geophysical logs, inorganic water quality analyses, and water-level measurements that are stored in databases maintained by the SDGS in Vermillion, South Dakota. These unpublished data are available on request from the SDGS by requesting individual data sets (i.e., water-level data, lithologic logs, etc.) for specific townships, ranges, and sections.

II. METHODOLOGY

Approach

To gather the data needed to determine the mechanism of recharge to the Split Rock Creek aquifer, the following four-fold research plan was carried out: (1) The general geology of the Split Rock Creek and adjacent formations was determined by using existing SDGS data, by reviewing available literature, and by drilling and geophysically logging test holes in areas where geologic data were not available or were inadequate.

(2) Water-level data were collected over an extended period. Past water-level data were compiled from the SDGS's water-level database and from published water-level data from adjacent areas in Minnesota. Most of the water-level data used in this study were collected regularly from existing monitoring wells and from monitoring wells installed for this study. Water-level data were used to determine flow directions and rates, which were needed to determine recharge and discharge areas. These water-level data were also used to determine the aquifer's response to meteorological events and to aquifer pumping.

(3) Water samples were collected for major ion, radionuclide, and stable isotope analyses. Additionally, the SDGS's inorganic water-quality database was searched for existing analyses. These analytical data were used to determine possible sources of

recharge, the approximate age of the water, and the pathline of the water from recharge to discharge areas.

(4) Hydraulic conductivity, transmissivity, and storativity of the Split Rock Creek aquifer and, where possible, of the adjacent geologic formations, were determined. Most were estimated from baildown and aquifer tests. Some published information on the transmissivity of the underlying Precambrian Sioux Quartzite was available for adjacent areas in Minnesota.

An advantage of this hydrogeologic study compared to many others was the opportunity to collect data for eight years. When Sioux Falls originally requested a study of the Split Rock Creek aquifer by the SDGS, a minimum study time of five years was proposed. This was considered a minimum amount of time needed to collect data. To more fully delineate the aquifer and its hydraulic properties, the study was extended to eight years.

Field Methods

Test-Hole Drilling

Fifty test holes were completed between the summer of 1989 and the fall of 1993. Drilling was performed using the mud rotary drilling method with a Failing 1500 drilling rig. In most cases, a 5 1/2 inch diameter wing-bit was used. In some instances where hard geologic materials were encountered, such as drilling some of the siltstones, boulders, and

Precambrian Sioux Quartzite, it was necessary to use a 5 3/4 inch diameter roller cone rock bit.

Lithologic samples were collected from the drill cuttings at ten-foot intervals. A Century brand geophysical logger was used to log many of the test holes for gamma radiation, spontaneous potential, and electrical resistivity. Lithologic samples and geophysical logs were then used jointly to determine the composition of the material encountered while drilling so that detailed lithlogic logs could be obtained. Detailed geophysical logs and lithologic logs of the test holes drilled for this study and lithologic logs of previously drilled test holes are available through the SDGS.

Monitoring-Well Installation

Monitoring wells were completed in 23 of the test holes and were constructed using threaded, 2-inch diameter, schedule 80 polyvinyl chloride (PVC) casing. Most well screens were 0.010 inch, mill-slot PVC ten feet long. Filter pack consisting of washed, coarse sand was placed around the outside of the screen to a depth of no less than three feet above the top of the screen. A tremie pipe was used to ensure proper positioning of the filter pack. Bentonite grout was then pumped through the tremie pipe into the remaining annular space from the top of the filter pack to a depth of 20 feet below ground surface. A cement grout was placed from the top of the bentonite grout to the ground surface. At this point, a locking steel well protector was installed (figure 4). Well construction logs for the monitoring wells used in this study may be acquired from the SDGS.

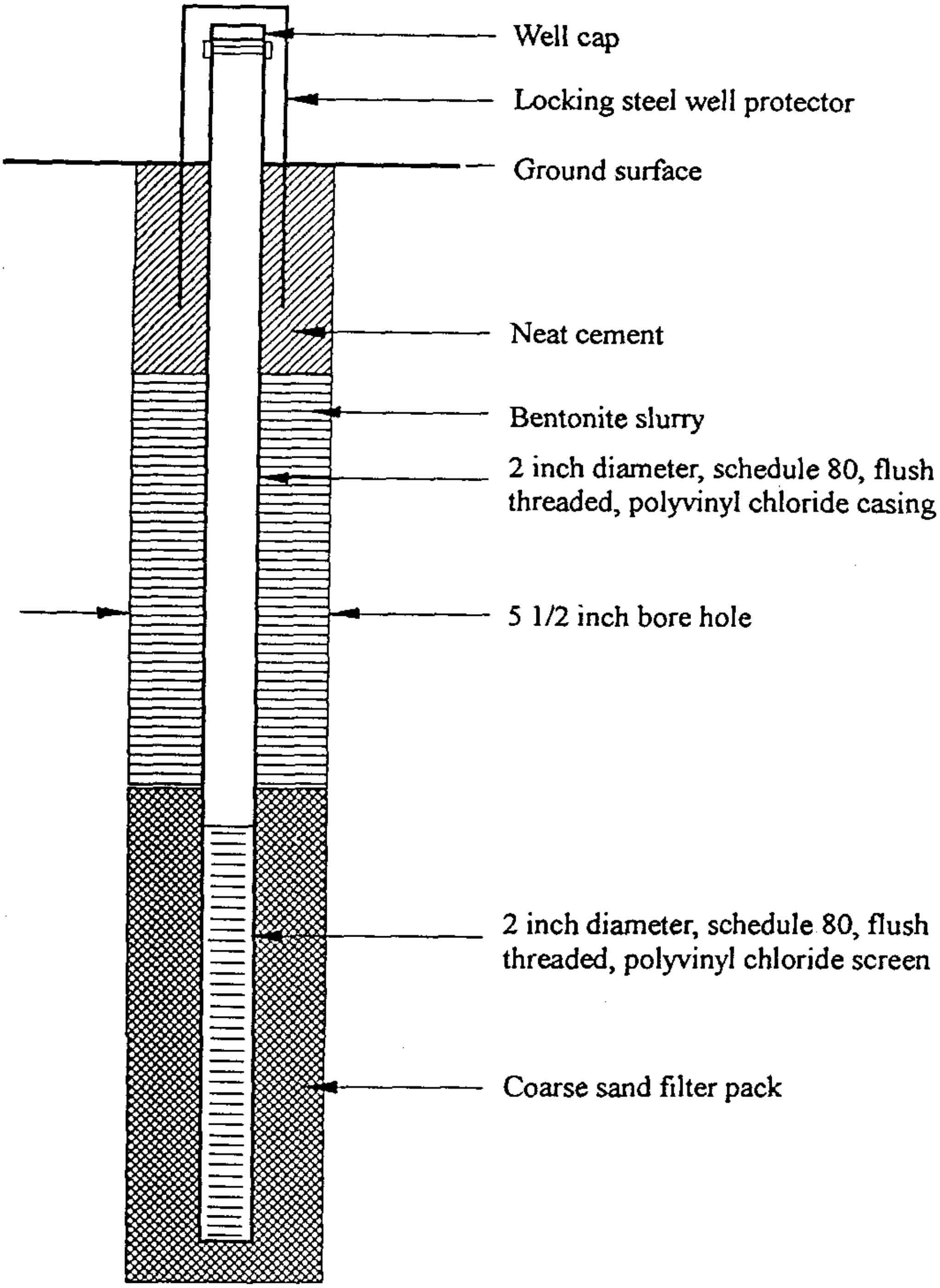


Figure 4. Generalized diagram showing monitoring well construction

Wells completed in the Split Rock Creek aquifer were monitored at 47 sites. When referred to in the text, these monitoring well numbers will be preceded by the prefix "SRC", which stands for Split Rock Creek. Many of these sites had nested monitoring wells, or wells completed in more than one geologic unit. If more than one well is present at a site, the individual well number is followed by an "A", "B", "C", or "D." The "A" designates the well is completed in the basal sands of the Split Rock Creek aquifer. The "B" designates that the well is completed in a geologic unit overlying the Split Rock Creek aquifer (normally an outwash unit in the till). The only exceptions to this lettering system are at site SRC-38 and SRC-39. At these locations the "B" well is completed in the middle to upper portion of the Split Rock Creek Formation (often the transition between siltstones and the lower sands), the "C" well is completed in unweathered till, and the "D" well is completed in weathered till.

Well Development

Most monitoring wells installed for this study were developed with compressed air (the air-lift method). Water was removed from all of the wells until temperature and conductivity had stabilized and the well water was clear. This involved removing a minimum of three to five well volumes in the bailed wells to as many as 1,000 well volumes in wells developed with air.

The air-lift method of developing the wells used a 3/4 inch diameter hollow steel pipe two feet long with 1/4 inch holes. This pipe was attached to 500 feet of 3/4 inch diameter air hose that was attached to a 100 gallon air storage tank connected to a high capacity air compressor. The ventilated, hollow steel pipe and air hose were lowered down to the bottom of the screened zone of the monitoring well and approximately 150 pounds per square inch (psi) of air applied. The rising air/water mixture evacuated water from the monitoring well. The wells were surged several times at different intervals throughout the screened zone until the well was fully developed.

If water could not be removed from the monitoring well using the air-lift method, the wells were then developed using a bailer. A 1.5 inch PVC bailer with a capacity of one liter was used. This bailer was attached with nylon cord to a reel which was used to manually lower and raise the bailer. The bailer was lowered to the screened zone and then raised out of the well and emptied. This was repeated until the well was fully developed.

Surveying of Monitoring Wells

The elevations of the casing tops of the monitoring wells were surveyed to the nearest 0.01 foot above mean sea level using a Lietz B1C automatic level and Lietz stadia rod. Closure error was kept to less than 0.01 feet. United States Department of Transportation or United States Geological Survey (USGS) benchmarks were used as reference points to survey the monitoring wells.

Water-Level Collection

The depths to water in the monitoring wells were measured to the nearest 0.01 foot using three different methods. The first method utilized a steel measuring tape with a concave-shaped device on the end, otherwise known as a "plopper." When the concave-shaped device contacted the water in the monitoring well, a sound or "plop" was heard, the depth to water from casing top was then directly read off the tape. These measuring tapes were used during the first four years of the study.

Solinst electronic water-level tapes replaced the "plopper" tapes in 1993. The depth to water from casing top was read directly off the tape that was marked in 0.01-foot intervals.

Water levels by the first two methods of collection were measured in all of the monitoring wells on a regular basis, approximately every four to six weeks. More frequent water levels were collected in monitoring wells used during aquifer tests. The surveyed casing-top elevations of individual monitoring wells, the depth to water, water-level elevations, and the date of measurement were all stored in spreadsheets.

The third method of water-level measurement used ORS DL-150, 2-channel data loggers coupled with Instrumentation Northwest pressure transducers. The pressure transducers had a range of 0-5 or 0-15 psi, depending on how much water level fluctuation was anticipated in the individual monitoring well. The 0-5 psi transducers measured water level fluctuations of up to approximately 11 feet, and the 0-15 psi transducers were capable of measuring water level fluctuations of up to approximately 32 feet. During the study, at least three monitoring wells were instrumented with data loggers and pressure transducers.

At the time of installation, a portable laptop computer was used to program the data loggers, and the following information was recorded: the elevation of the casing top, the depth to water from casing top, and the measured height of the water column above the pressure transducer. The data loggers were then programmed to record water levels twice daily (more frequently during aquifer tests) in these wells. This water-level information, along with the date, time, and data logger identification, were then stored in the memory of the data loggers. Date were retrieved from the data loggers every four to eight weeks.

At the time the logger data were downloaded, the depth to water from casing top and water column height were both recorded again. This information was used to determine if the data logger and pressure transducer were operating properly or if electronic drift had occurred. On three occasions, electronic drift of greater than 0.10 feet had occurred; therefore, the pressure transducers were recalibrated to compensate for this electronic drift. Retrieved data which had greater than 0.10 feet of electronic drift were corrected. Data was corrected by assuming drift had occurred linearly throughout the downloaded time interval; from zero at the beginning of the time interval to the maximum drift at the end of the time interval.

The downloaded data, along with data recorded at the time of the data logger and pressure transducer installation, were then transferred to a spreadsheet and used to prepare hydrographs for the instrumented monitoring wells. Water-level data used in this study may be acquired from the SDGS.

Water-Sample Collection

At least three well volumes of water were pumped or bailed from the monitoring wells before a sample was collected. Temperature, pH, and conductivity were all monitored to ensure that these parameters had stabilized before a sample was collected. In most cases, water was removed from the monitoring wells using the air-lift method. When this method was used, care was taken to ensure that the bottom of the air hose remained a minimum of 15 feet above the top of the well screen to prevent aeration of the sample. In those monitoring wells that could not be pumped using the air-lift method, a bailer was used to remove the necessary well volumes prior to sampling. In all cases, water samples were collected from the screened intervals of the monitoring wells using a clean PVC bailer. When water samples were collected from private or municipal wells, water was allowed to run from a spigot or tap for at least 15 minutes to ensure collection of a representative sample. Temperature, pH, and conductivity were also monitored to ensure that these parameters had stabilized before a sample was collected.

Inorganic Ion Samples

Fifty-seven water samples (46 samples from the Split Rock Creek aquifer and 11 samples from the Sioux Quartzite) were collected for this study and analyzed for major inorganic ions. The following parameters were measured and recorded immediately prior to sample collection using Orion brand meters and probes and a Hach digital titrator: temperature, conductivity, pH, Eh, and alkalinity. After the measurement of these parameters, the samples were filtered using a three micron fiberglass pre-filter and a 0.45 micron final filter. The field parameters were again measured and recorded immediately following filtering. Water samples were then collected and placed in sample bottles.

All water samples collected for major ion analysis were placed into three clean polyethylene bottles. The first bottle had a capacity of 500 milliliters (mL) and had no preservative added. The second bottle also had a capacity of 500 mL; after the water sample had been added to this bottle, 2 mL of nitric acid preservative was added. The third bottle had a capacity of 250 mL; after the water sample had been added to this bottle, 1 mL of sulfuric acid preservative was added to the water sample.

Stable Isotope and Radionuclide Samples

Water samples collected and analyzed for stable isotopes (15 D/H and $^{18}O/^{16}O$ samples) and radionuclides (24 gross alpha samples, 4 radiocarbon samples, and 5 tritium samples) were all collected using the water-sample collection methods previously described. The gross alpha samples were filtered to remove any clay particles to which alpha particles may have adsorbed. To minimize any potential for contamination of the other water samples, they were not filtered and no preservatives were used.

The gross alpha samples were placed in one-liter, translucent, plastic containers supplied by the laboratory. The first sample collected for radiocarbon analysis was obtained by filling a 100-liter stainless-steel funnel with water collected from the well. Aeration was kept to a minimum during this process. A sodium hydroxide solution was added to the sample to raise the pH and de-protonate the bicarbonate. A barium chloride solution was added to effectively precipitate barium carbonate from the sample. The precipitate was then collected and sealed in a two-liter polyethylene bottle.

The remaining water samples collected for deuterium/hydrogen, oxygen-18/oxygen-16, radiocarbon, and tritium analyses were placed into 1-liter, amber glass jars with Teflon-lined lids.

Baildown Tests

Baildown tests to estimate hydraulic conductivity of confining sediments were conducted in three locations. Water was removed, or bailed-down, from the monitoring wells by using a 1-liter PVC bailer. Wells were bailed until water levels had dropped at least 4 feet; water levels were not bailed below the screen or filter pack. Water levels were then measured until they had recovered a minimum of 70%. Data collected from these baildown tests were analyzed using methods outlined by Hvorslev (1951) and Bouwer (1989). Data collected during these baildown tests may be acquired from the SDGS.

Aquifer-Pumping Tests

Seven aquifer-pumping tests were used to stress the Split Rock Creek aquifer by removing large volumes of water for periods ranging from two to 14 days. Pumping rates varied from 9,800 cfd to 290,000 cfd. Pumping rates and time depended on estimated water yields from the aquifer (based on saturated thickness, aquifer material, and possible nearby hydrogeologic boundaries), and economic constraints.

An instantaneous rate flow meter and totalizer were used to maintain a constant rate of pumping. To prevent any recharge to the aquifer or overlying layers, water was discharged into a nearby surface drainage course where water could quickly flow downslope. The pumping well was either a 12- or a 14-inch diameter steel-cased well. A turbine-type submersible pump was installed in the pumping well. Power was supplied by a gasoline or diesel motor that was connected to the pump via a drive shaft. Following pumping, water levels were measured for several hours and in some cases, to a time equal to the pumping phase.

Water levels in the pumping well, nearby monitoring wells completed in the Split Rock Creek aquifer, and monitoring wells completed in adjacent geologic formations were typically monitored during both phases of the test. Water levels were monitored using a combination of the three methods described previously. A minimum of two and a maximum of 20 wells were monitored during each aquifer test. The number of monitoring wells used depended on their proximities to the pumping well.

Data collected from the aquifer test were used to estimate the transmissivity and storativity of the Split Rock Creek aquifer through methods developed by Cooper and Jacob (1946). In addition to determining transmissivity and storativity of the Split Rock Creek aquifer, data from the aquifer tests were used to determine the occurrence of boundaries. Locations of these boundaries were analyzed using a method outlined in the U.S. Department of Interior's Ground Water Manual (1995). This method uses the change in slope of drawdown data to calculate approximate locations of boundaries. Complete data sets for these aquifer tests may be acquired from the SDGS.

Determination of the hydraulic characteristics and aquifer boundaries was necessary to estimate maximum rates at which the aquifer could be pumped. The maximum pumping rates greatly depend upon the amount and distribution of recharge to the aquifer. To maintain a long-term, reliable water supply for Sioux Falls, overdraft (amount of water pumped exceeds net recharge) of the Split Rock Creek aquifer should be avoided.

Laboratory Techniques

Table 1 summarizes the laboratories conducting chemical and isotopes analyses, laboratory methodology, and supervisory chemists.

Table 1. Laboratory Summary.

Parameter Analyzed	Method	Laboratory	Supervisory Chemist
Major Inorganic Ions	Standard Methods for the Examination of Water and Wastewater, 18th ed., 1992. Analytical precision, is stated in Standard Methods and is based on repeated laboratory analyses. Additional check on laboratory precision and accuracy is done by keeping ion balance to < 1.0 meq/L.	SDGS's Analytical Laboratory	Marjory Coker
Stable Isotopes (D/H and $^{18}O/^{16}O$)	VG 602 Mass Spectrometer analysis of original and equilibrated carbon dioxide gas, and VG 602 Mass Spectrometer analysis of hydrogen gas produced by reduction of water by hot zinc shot. In-house lab manual titled *Procedures in Oxygen and Hydrogen Stable Isotope Analysis of Water University of Arizona*, by Austin Long, August 1987, describes methodology. The 2σ analytical precision, based on repeated laboratory analyses is ±3.3 ‰ for D/H and is ±0.4 ‰ for $^{18}O/^{16}O$.	University of Arizona Laboratory of Isotope Geochemistry	Austin Long
Tritium	Period addition electrolysis using Mg reduction to yield protium gas. Described in *Rapid Electrolytic Enrichment and Hydrogen Gas Proportion Counting of Tritium*, by Ostlund and Dorsey, 1975. The 1σ analytical precision, based on repeated laboratory analyses is ±3 %.	University of Miami Tritium Laboratory	Charlene Grall

Table 1 continued.

Parameter Analyzed	Method	Laboratory	Supervisory Chemist
Carbon-14 and Carbon-13	Accelerator Mass Spectrometry (AMS). In-house lab manual titled Procedures for Collecting and Processing Ground Water Samples for Natural Carbon-14 and Stable Isotope Analysis, by Austin Long describes methodology. The 1σ analytical precision, based on repeated laboratory analyses is ±0.5 % for carbon-14 and is ±0.1 ‰ for carbon-13.	University of Arizona Laboratory of Isotope Geochemistry	Austin Long
Gross Alpha and Uranium	EPA Method 903.0 for Gross Alpha and EPA Method 908.1 (Fluorometric/DirectAddition) for Uranium. The 1σ analytical precision, based on methodology and repeated laboratory analyses, is ±15 % for gross alpha and ±7 % for uranium.	South Dakota State Health Laboratory	Mike Smith

III. RESULTS

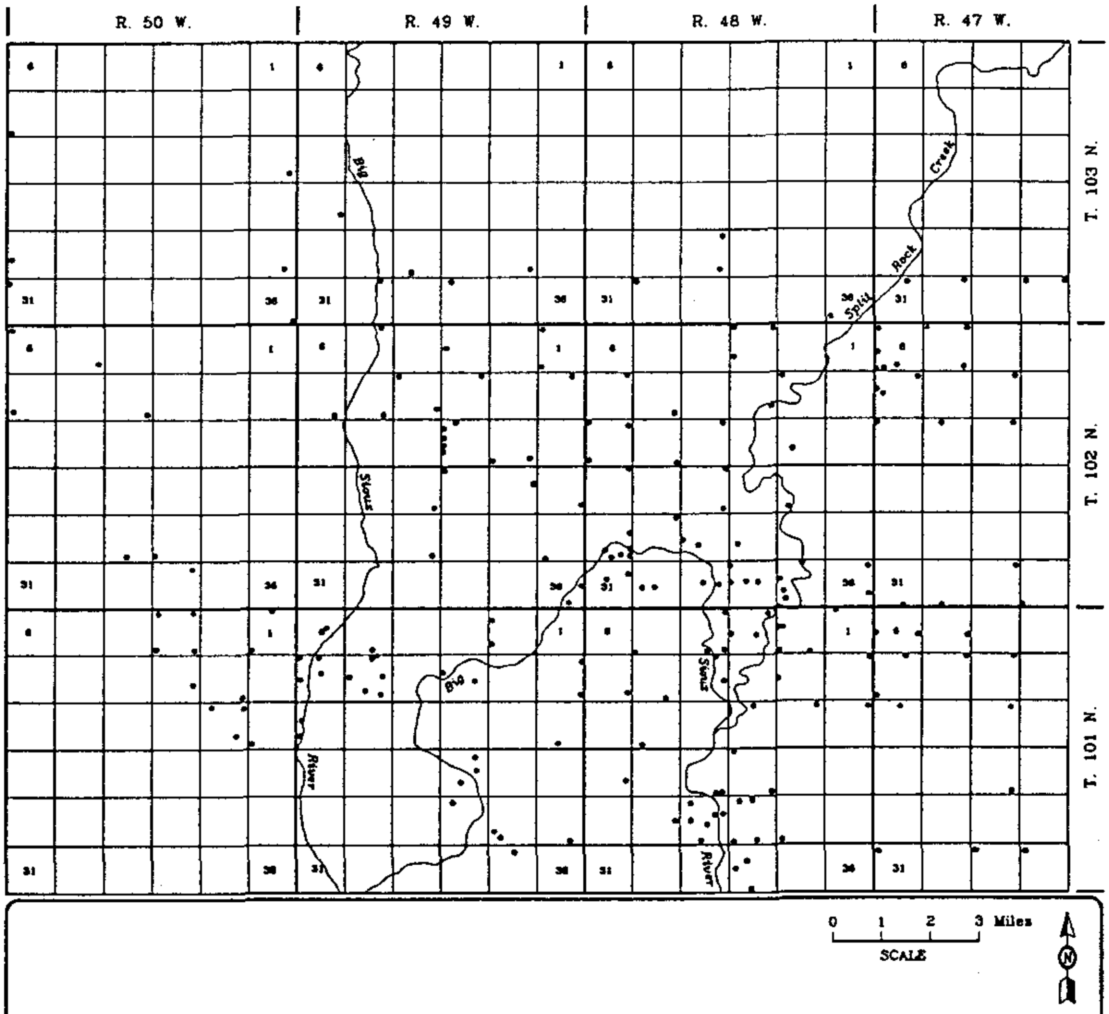
Location and Thickness of the Split Rock Creek Aquifer

Data collected from the test-holes drilled for this study, along with pre-existing data (figure 5), were used to construct a map showing the areal extent of the Split Rock Creek aquifer (figure 6). The main body of the aquifer was found to exist in a narrow valley, approximately three to four miles wide, that extends from the eastern edge of Sioux Falls, South Dakota, into Minnesota. Two western valleys in the quartzite contain basal sands of the Split Rock Creek Formation. These valleys or "arms" of the aquifer are not in direct hydraulic connection to the main body of the aquifer.

The test-hole data were also used to construct a map showing the thickness of the aquifer sands (figure 7). The greatest thickness was encountered in the eastern part of the main body of the aquifer. Over 200 feet of aquifer sands were encountered in the area immediately south of Brandon and extending eastward toward Valley Springs.

General Hydrostratigraphy of the Study Area

Results of test drilling in this area generally agree with previous work. The three lithologic units discussed in *Previous Investigations* were found to exist in the study area.



• Individual test hole location.

Figure 5. Locations of test holes used for this study

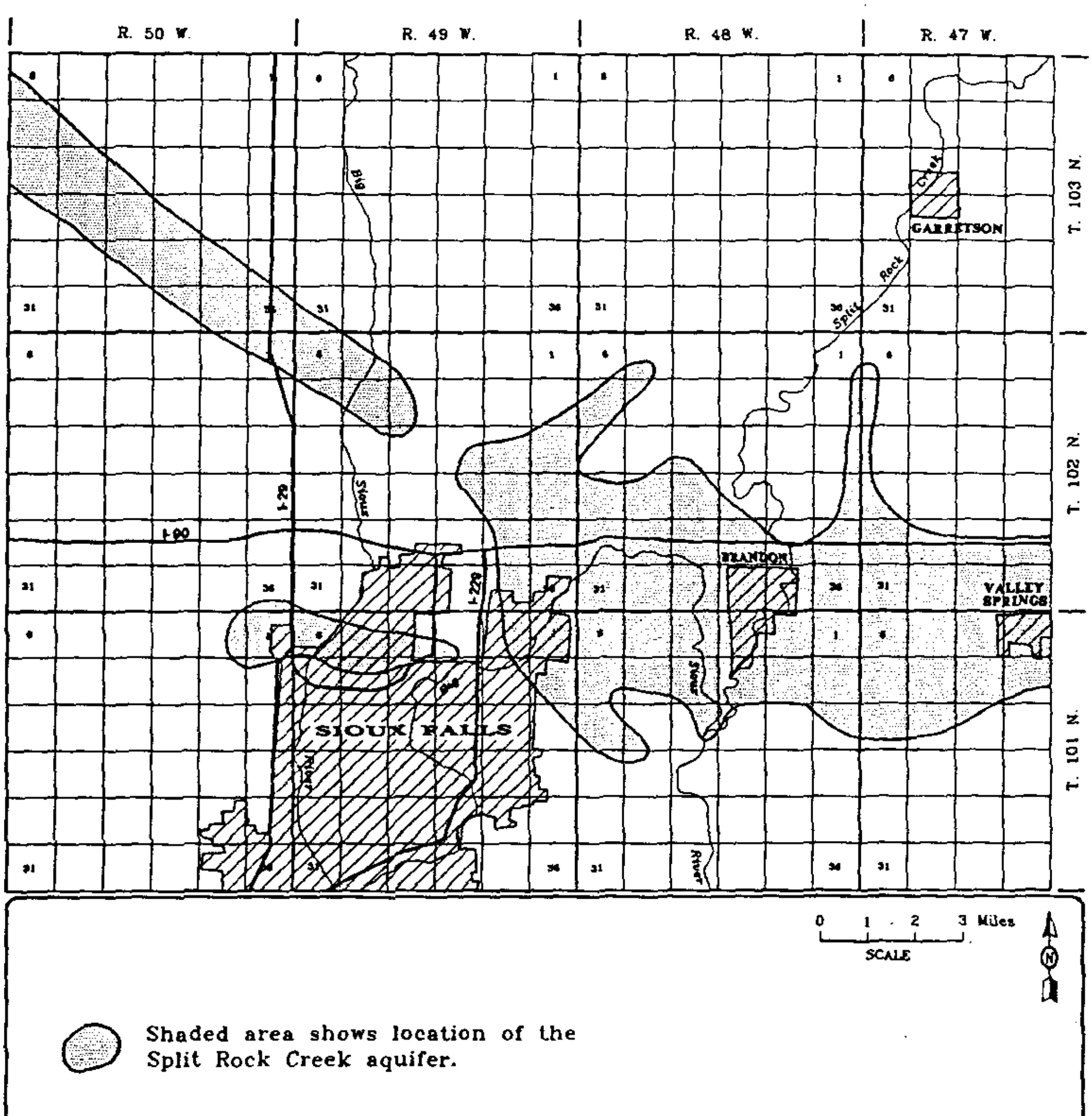
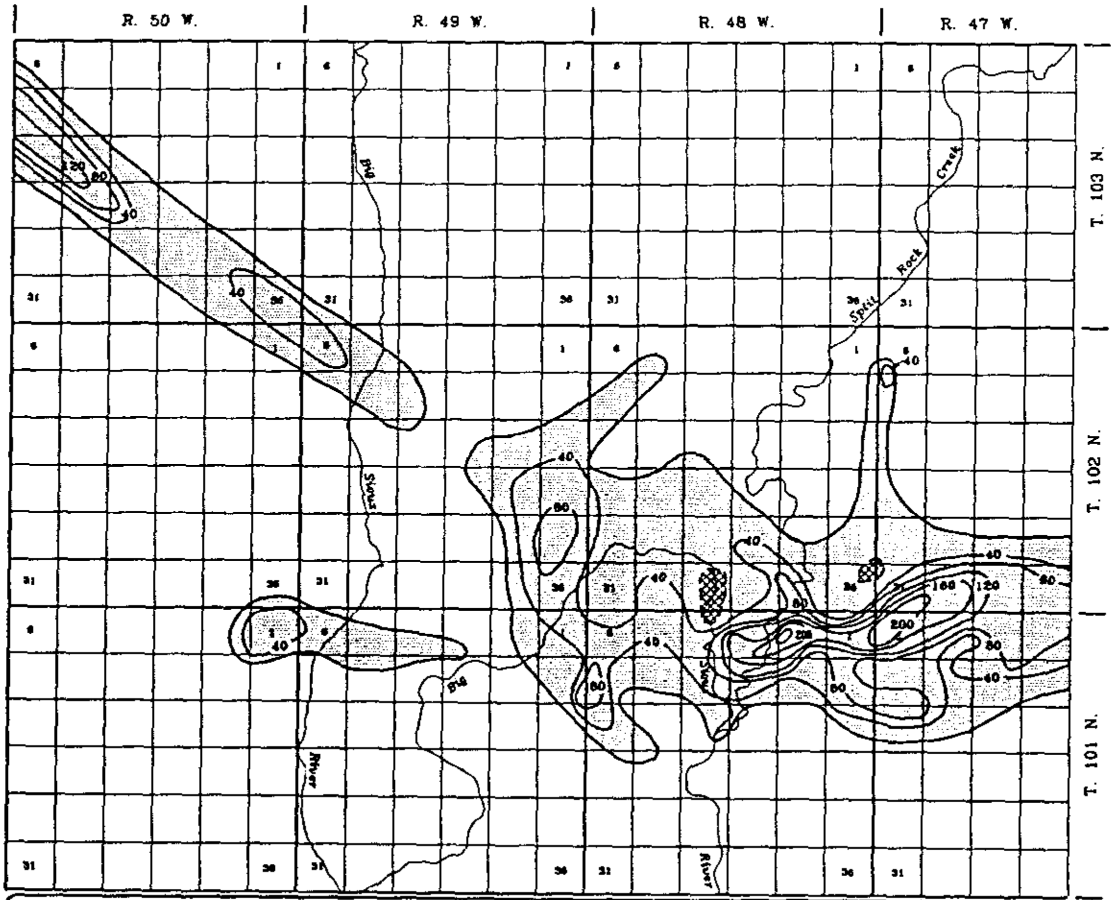


Figure 6. Areal extent of the Split Rock Creek aquifer



0 1 2 3 Miles
SCALE

120 — Line connecting points of equal saturated thickness. Number is total thickness (in feet) of all Split Rock Creek Formation sands encountered in subsurface. Contour interval = 40 feet.

▩ Approximate area where Split Rock Creek Formation sands are absent.

▨ Shaded area shows location of the Split Rock Creek aquifer.

Figure 7. Thickness of the Split Rock Creek aquifer

The Sioux Quartzite

The Sioux Quartzite is deeply buried in many areas and crops out in others. In several outcrops, very large fracture openings (>1 inch) were observed. In many of the outcrops, abandoned quartzite quarries exist where the extensive fracture system within the quartzite is visible on the side-walls. In some areas of these quarries, layers of sandstone approximately 1 foot thick were observed within the quartzite. In several areas of the quarries, water seeps from the fractures and sandstone layers.

The Split Rock Creek Formation

Where the Sioux Quartzite is deeply buried, the Split Rock Creek Formation was found to be present in paleo-valleys in the Sioux Quartzite. Kairo's (1987) general description of the formation is accurate, although in many locations not all of the individual units of the formation described are present. In several areas, the marine clays and shales which normally rest directly on the aquifer sands are absent. In these areas it was found that the Split Rock Creek aquifer sands are overlain by cherty, fractured siltstones that are overlain by Holocene outwash and alluvium associated with present-day river systems (figure 8).

Basal sands of the Split Rock Creek aquifer are buried throughout the study area. In some areas the upper shales and siltstones of the formation are exposed at the land surface. The aquifer is confined in the study area except for an area near well 26 where approximately 20 feet of unsaturated sands are present (figure 9).

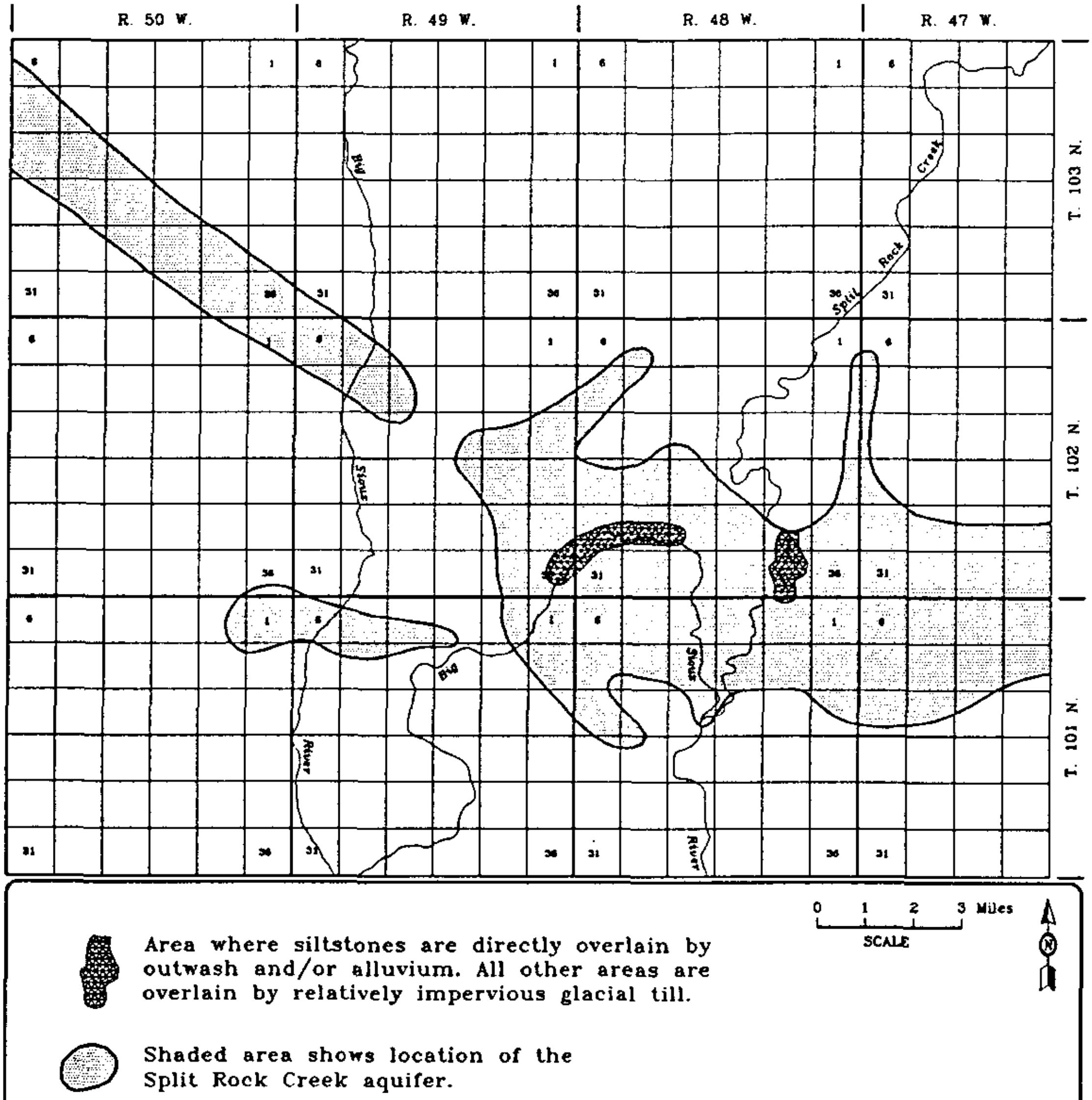


Figure 8. Approximate locations where Split Rock Creek Formation siltstones are directly overlain by outwash and alluvium

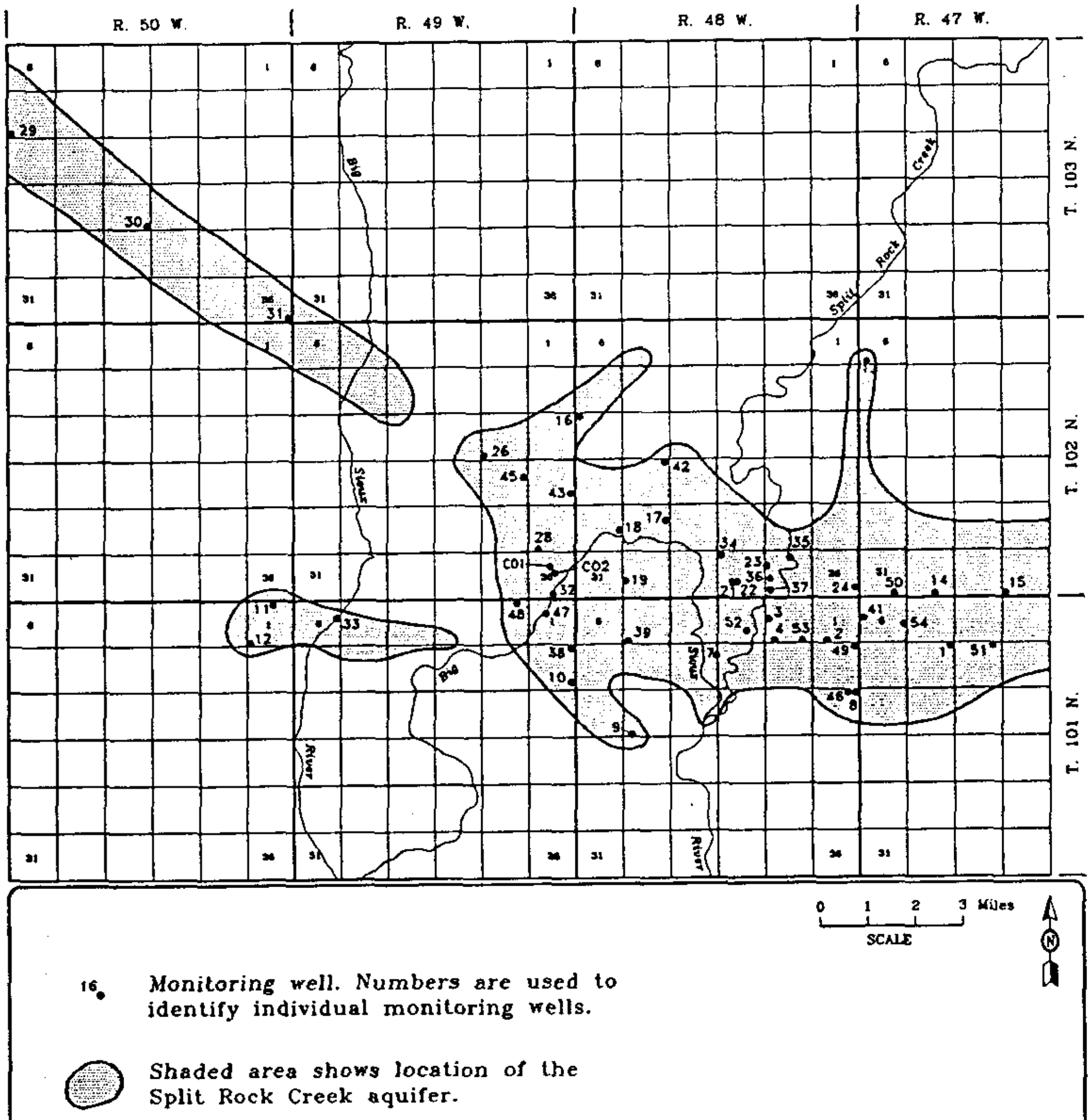


Figure 9. Locations of monitoring wells completed in the Split Rock Creek aquifer

In many of the test holes, laminated organic black shales are interbedded with the basal sands of the Split Rock Creek Formation. These layers are several feet thick and do not appear to be laterally continuous, apparently pinching out within several hundred feet. Circulation was commonly lost through the fractured opaline and cherty siltstones of the Split Rock Creek Formation during mud-rotary drilling.

Glacial Sediments

Overlying the Split Rock Creek Formation in most of the study area (except in the present-day river valleys) are approximately 100 feet or more of clayey tills. The tills have two zones. The upper weathered zone is normally around 20-30 feet thick and consists of silty, pebbly clay. This weathered till is yellowish-brown and exhibits many small fractures. The lower zone consists of unweathered grayish clay that is slightly silty and pebbly. Fractures are not evident in the lower zone.

In the Big Sioux and Split Rock Creek valleys, glacial outwash and Holocene alluvium are the surficial units. These sediments are normally 20-40 feet thick, but between wells 17 and 34 (figure 9) they are nearly 100 feet thick. These units, when saturated with water, comprise the Big Sioux aquifer. They are often referred to as the Brandon aquifer in the Split Rock Creek valley and where terrace deposits associated with the Big Sioux outwash near Brandon exist.

In one area it was found that the outwash associated with the Big Sioux River fills a valley incised through the upper sediments of the Split Rock Creek Formation and is in direct contact with the basal sands of the Split Rock Creek Formation, as Iles (1983) had noted. At this location approximately 98 feet of sand and gravel are present (NW ¼, SW ¼, NE ¼, SW ¼ Section 28, Township 102 North, Range 48 West, between Split Rock Creek aquifer wells 17 and 34 shown on figure 9). Underlying these sands and gravels are six feet of black shale (commonly observed in the Split Rock Creek basal sands) directly overlying the Sioux Quartzite.

Aquifer Tests

Results of the seven aquifer tests conducted in the Split Rock Creek aquifer (figure 10) are shown in table 2. Transmissivity and storativity were estimated using Cooper and Jacob (1946) straight-line approximation. Four representative examples of the data used in transmissivity and storativity analyses are indicated by the regression lines shown in figures 11, 12, 13, and 14. Raw data and brief well-construction summaries for these four data sets are given in Appendix A.

Table 2. Summary of Split Rock Creek Aquifer Tests

Test Site ID	Start Date	Number of Wells Monitored	Pumping Rate (cfd)	Pumping Duration (days)	Transmissivity (ft^2/day)	Storativity
NSP (Test #1)	4/27/88	4	76,000	2	2,900 to 3,300	1.3×10^{-4} to 5.2×10^{-4}

Table 2 continued.

Test Site ID	Start Date	Number of Wells Monitored	Pumping Rate (cfd)	Pumping Duration (days)	Transmissivity (ft^2/day)	Storativity
NSP (Test #2)	5/10/88	4	38,000	1	2,556 to 3,174	2.4×10^{-4} to 4.2×10^{-4}
Renner	2/13/89	3	9,800	1	610 to 990	9.5×10^{-5} to 1.1×10^{-4}
Brandon	6/26/89	5	50,000	3	1,600 to 1,700	1.1×10^{-4} to 6.7×10^{-4}
NSP (Test #3)	6/21/90	3	95,000	2	2,900 to 3,100	3.0×10^{-4} to 3.4×10^{-4}
Watrec	11/13/89	8	72,000	3	2,100 to 3,000	1.6×10^{-4} to 2.9×10^{-4}
'95 SRC	10/23/95	20	290,000	7	7,100 to 10,000	6.8×10^{-5} to 5.3×10^{-3}

Saturated thickness of the aquifer at the test sites is 69 feet at Brandon, 53 feet at NSP, 57 feet at Watrec, 10 feet at Renner, and 240 feet at '95 SRC site. These saturated thickness and transmissivity data yield hydraulic conductivity values from 23 ft/day to 61 ft/day, with an average of 48 ft/day.

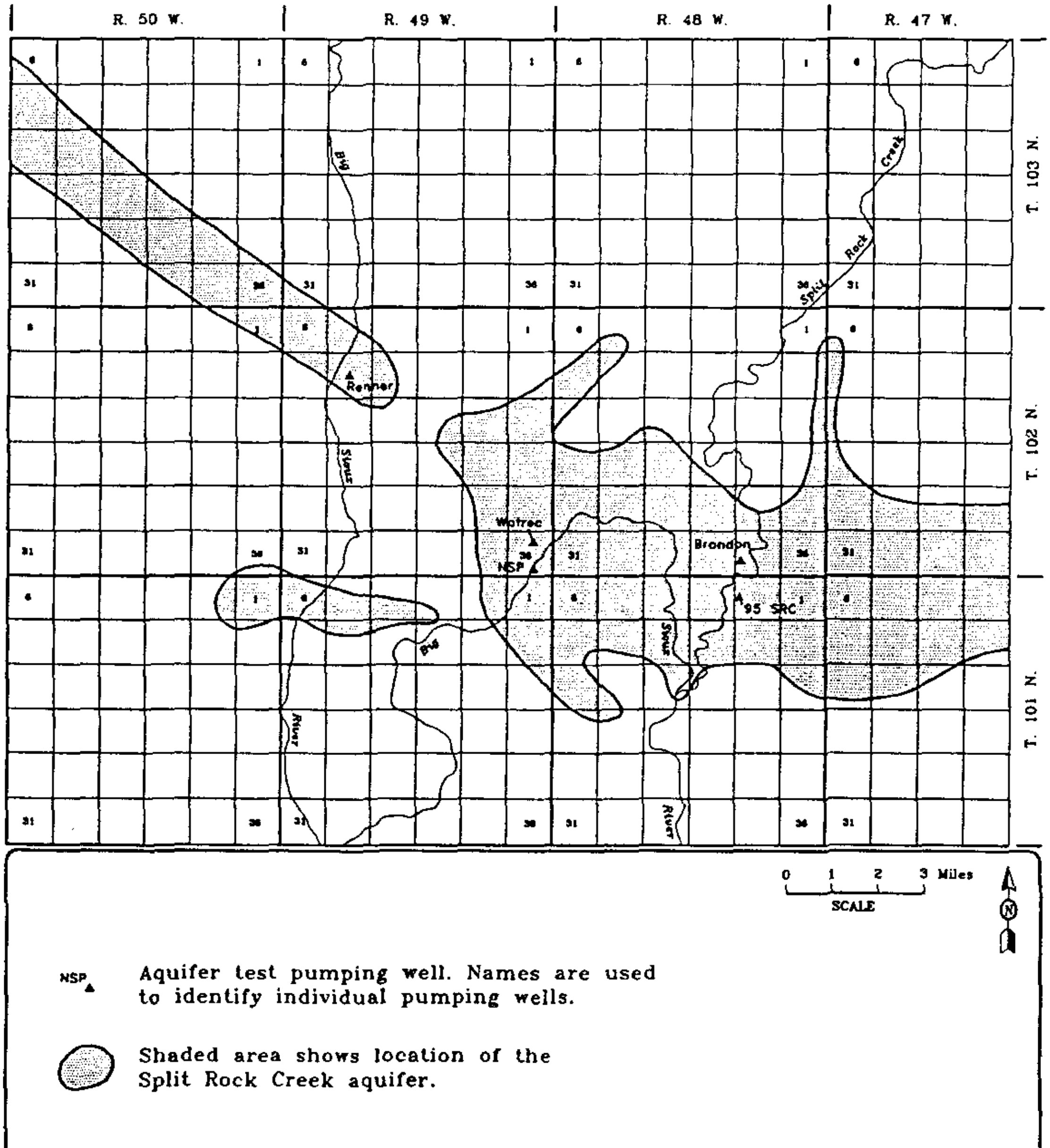


Figure 10. Locations of Split Rock Creek aquifer tests

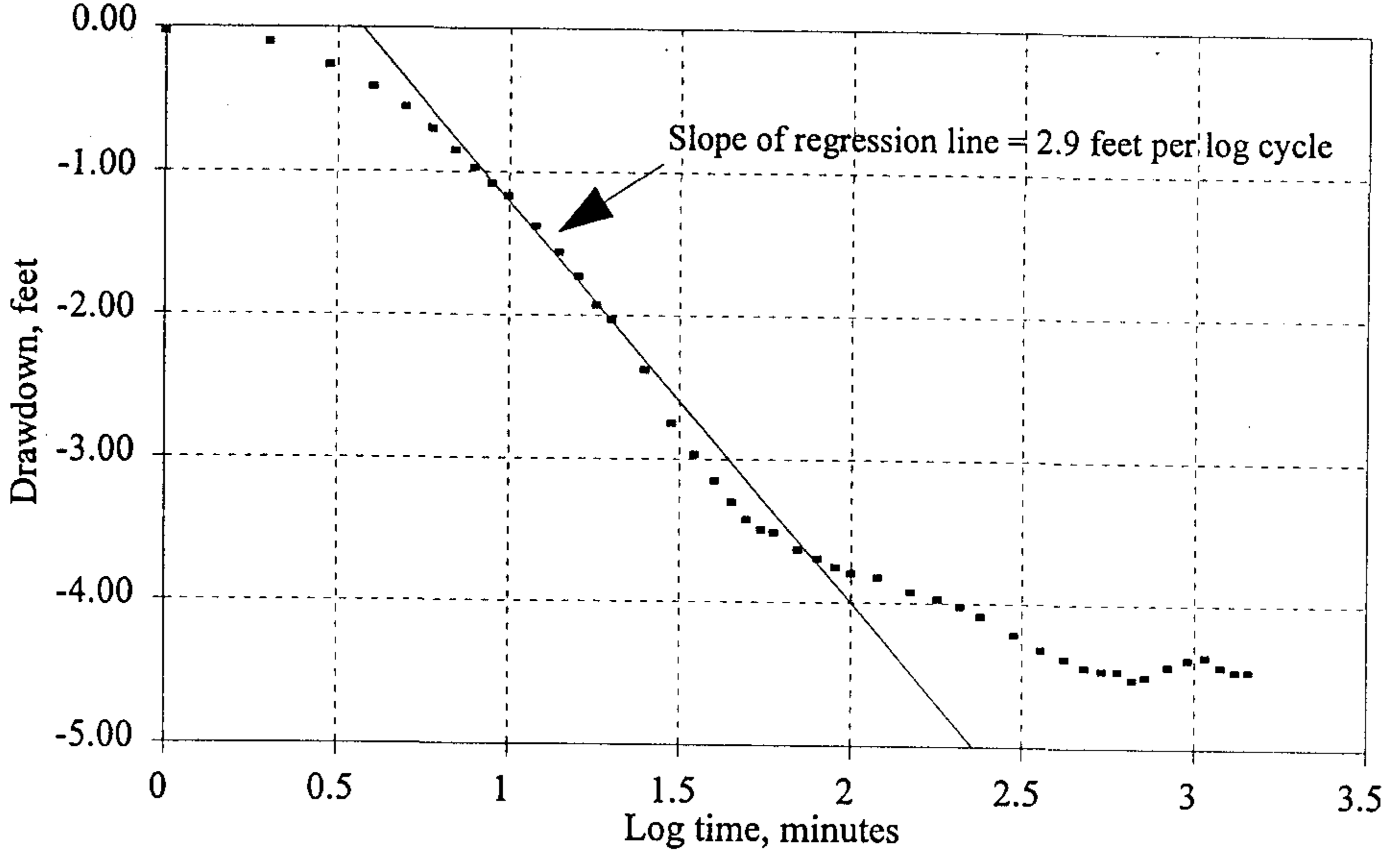


Figure 11. Renner Aquifer Test
"NW Well" Time-Drawdown Graph

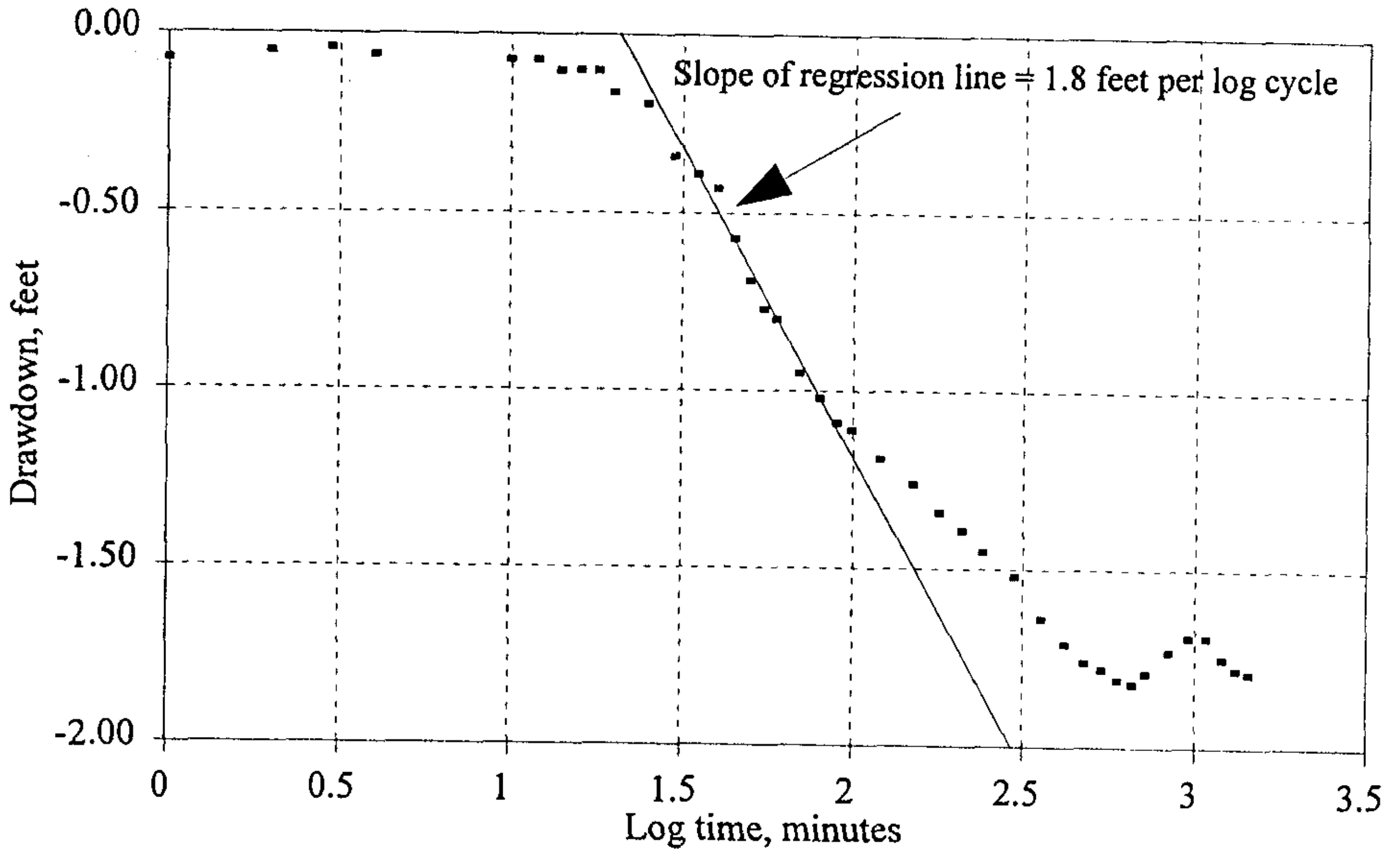


Figure 12. Renner Aquifer Test
"SE Well" Time-Drawdown Graph

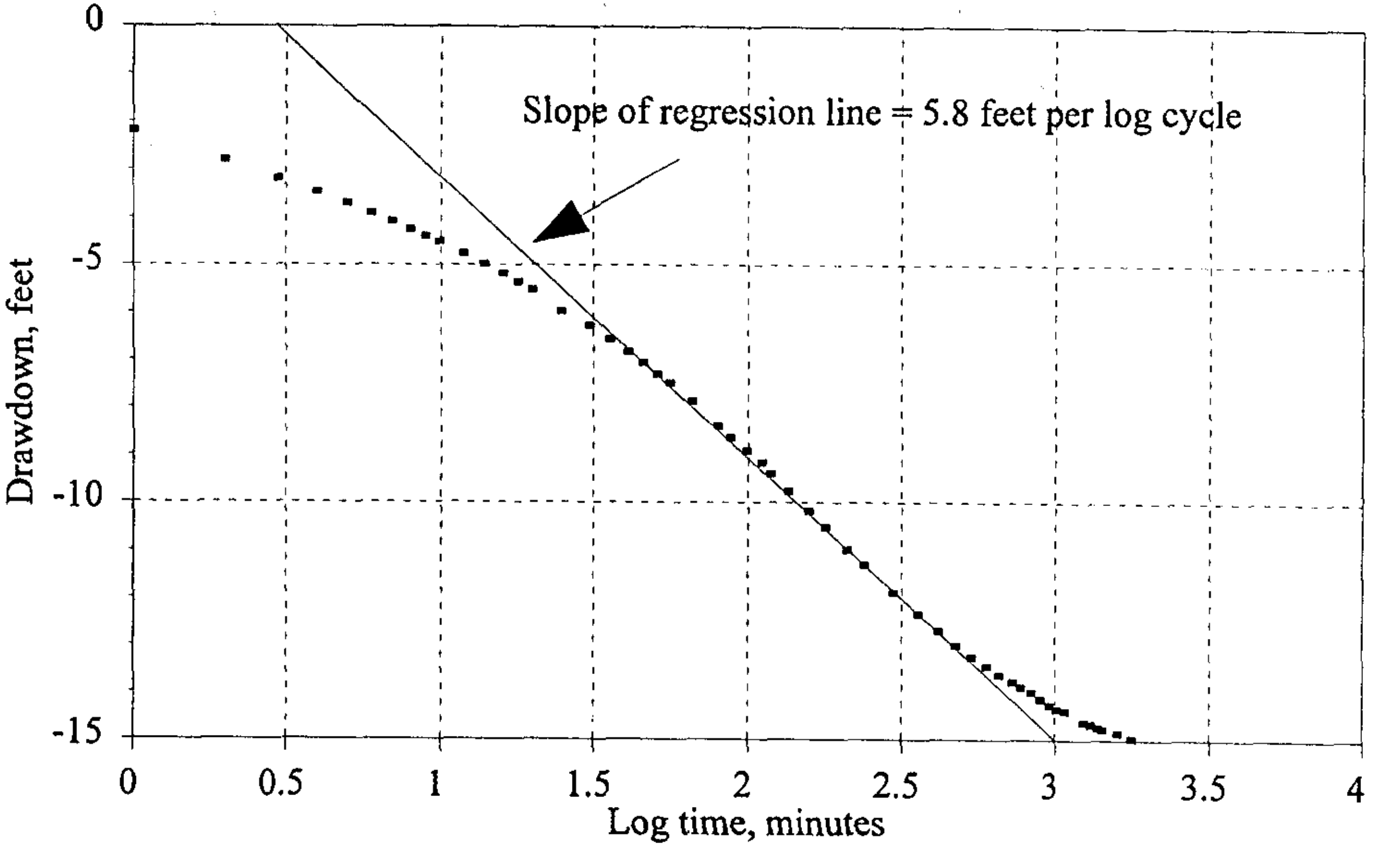
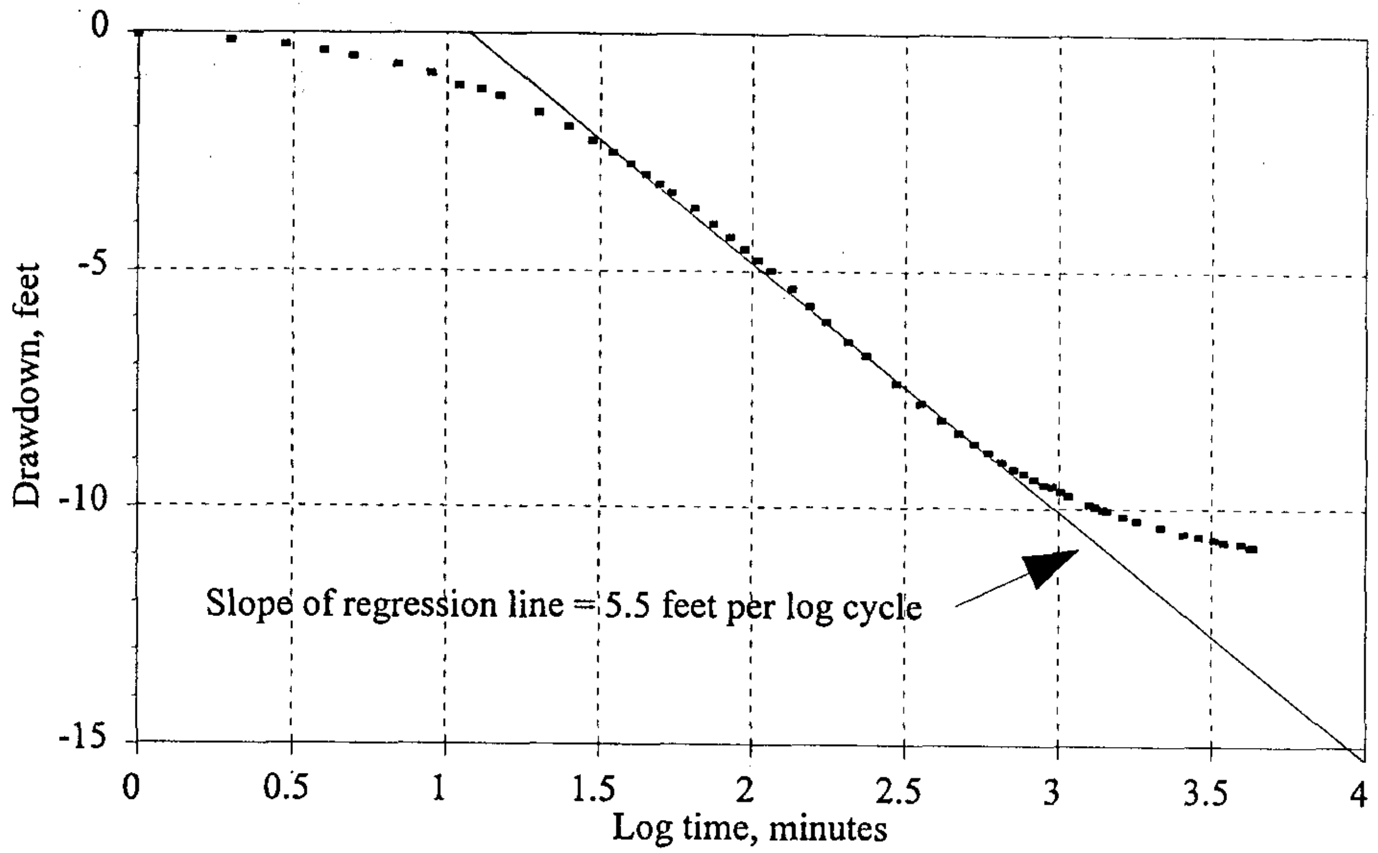


Figure 13. Brandon Aquifer Test
SRC-36 Time-Drawdown Graph



Slope of regression line = 5.5 feet per log cycle

Figure 14. Brandon Aquifer Test
SRC-37 Time-Drawdown Graph

Recovery measurements were normally not taken for the same period of time as the pumping phase of the test; therefore, it is not known if complete recovery had occurred, although in most cases one foot or less of recovery was left when measurements were stopped. Complete recovery measurements were taken only for the Watrec and '95 SRC tests. Transmissivity and storativity were calculated from recovery data when complete recovery data were available; results were in agreement with calculations using drawdown data.

Only during two aquifer tests were boundary conditions encountered -- the Renner aquifer test (figures 11, 12, and 15) and the Brandon aquifer test (figures 13, 14, and 16). During both aquifer tests, the boundaries encountered were positive, suggesting either recharge or areas of higher transmissivity.

Analysis of the boundaries at the Renner site was done to determine their location using the straight-line approximation method outlined in the Ground Water Manual (1995). This method uses the change in slope of drawdown data to calculate the distance to a recharging image well. Data from several observation wells is used to plot the radius to the image well from the pumping well. The intersection of these circles show the approximate location of the image well, with the recharge boundary, or area of higher transmissivity, located halfway between pumping well and the image well. Analysis of the Renner data did not yield intersecting circles; therefore, the analysis was inconclusive, possibly due to the occurrence of multiple boundaries.

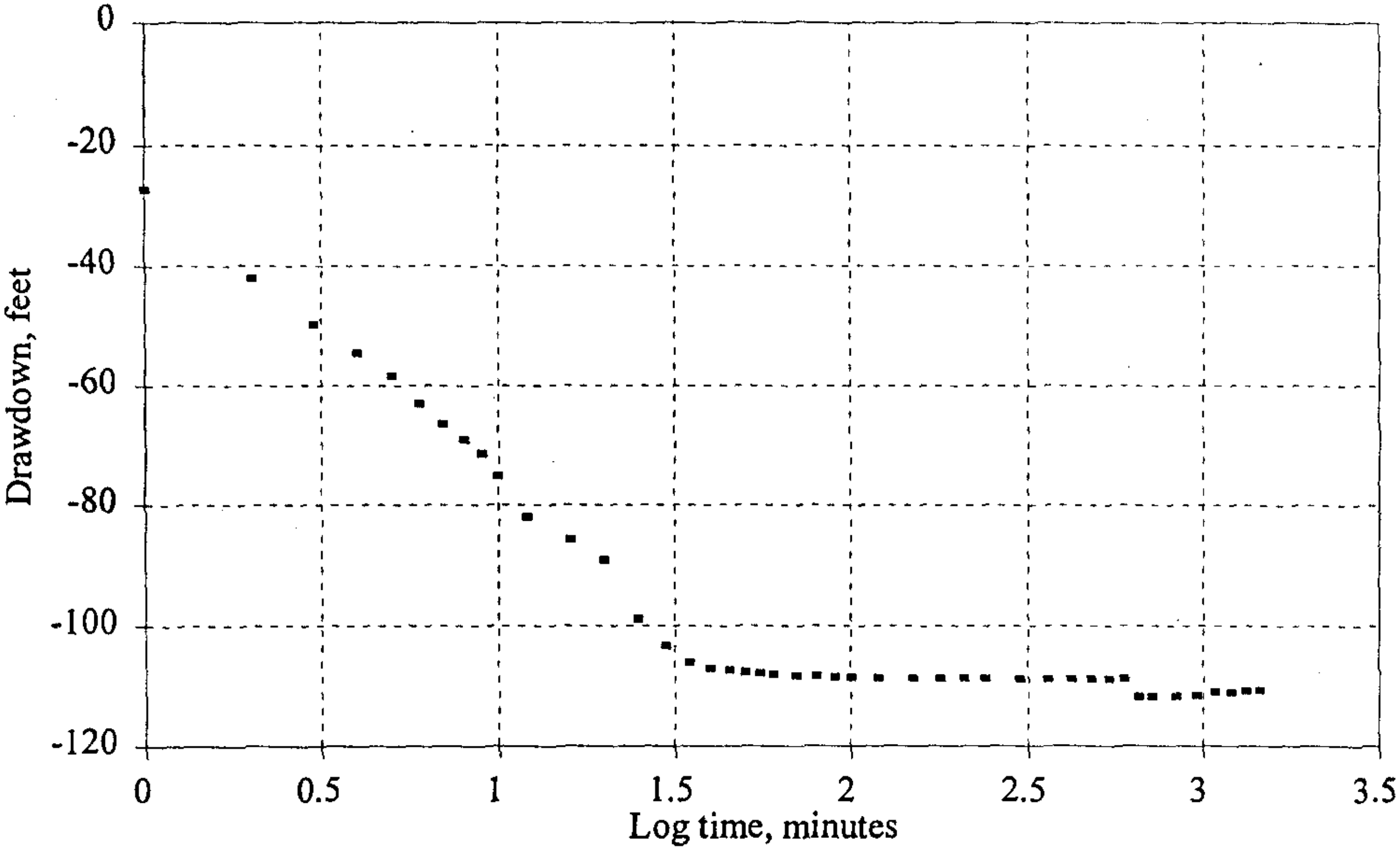


Figure 15. Renner Aquifer Test
Production Well Time-Drawdown Graph

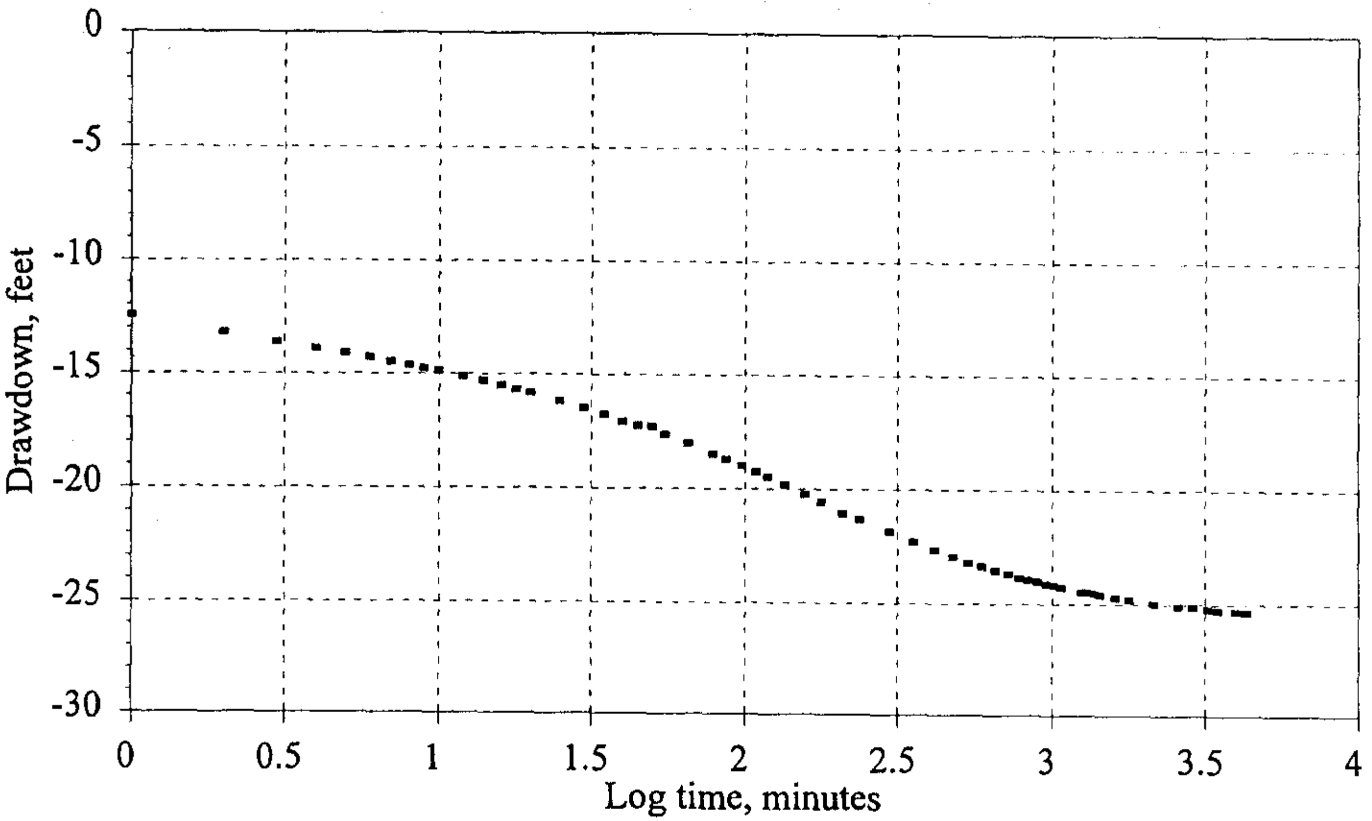


Figure 16. Brandon Aquifer Test
Production Well Time-Drawdown Graph

Boundaries encountered during the Brandon aquifer test were also analyzed using the straight-line approximation method (Ground Water Manual, 1995). Monitoring wells SRC-36 and SRC-37 were used in the analysis. The middle part of both data sets, which represents the aquifer characteristics (neglecting the initial wellbore storage effects), and the last part of the data set, which represents the boundary conditions, were used in the analysis (figures 13 and 14). The analysis indicated a positive boundary somewhere between approximately 1,000 and 2,700 feet from the production well.

During the '95 SRC test just south of Brandon, Cooper and Jacob (1946) analysis suggested no nearby hydrogeologic boundaries, as data did not deviate from the regression line. Hantush (1960) analysis of wells SRC-35A and SRC-37, both located near Brandon (figure 9), was done using the AQTESOLV® (1991) software package. The graphs produced from these analyses are shown in Appendix B. An "r/B" value greater than 0 indicates potential leakage; the larger this value, the greater the amount of leakage. This analysis indicated little or no leakage from overlying layers at well SRC-35A and indicated potential leakage had occurred near well SRC-37.

Baildown Tests

Estimation of the hydraulic conductivity of the layers which overlie and confine the Split Rock Creek aquifer was done by conducting baildown tests on five monitoring wells at three sites: 38C and 39C which are completed in unweathered till; 38D which is completed in fractured, weathered till; and CO1 and CO2 which are both completed in the upper fractured, cherty siltstone units of the Split Rock Creek Formation (figure 9).

The Hvorslev (1951) method was used to estimate the hydraulic conductivity (K):

$$K = (r^2 \ln (L / R)) / (2 L T_0)$$

where r = the radius of the well casing (one inch or 0.083 feet), L = length of the well intake (five feet in all cases), R = radius of the borehole around the well screen (2.75 inches or 0.229 feet in all cases), and T_0 = time lag, or the time it takes for the water level to rise to a point where 37 percent of the initial change remains (which is determined by graphically analyzing the data). The Hvorslev (1951) equation is valid only when $L / R > 8$, which is true in all of the above cases, as $L/R = 21.8$.

Data collected from these baildown tests are graphed with the elapsed time shown on the X axis and the ratio of H/H_0 on the Y axis, where H = the change in water level (from static) at a given time and H_0 = the maximum change in water level from static (Figures 17, 18, 19, 20, and 21). The line of best fit, along with the T_0 value is shown on each of the graphs. Raw data for the baildown tests and brief well-construction summaries are given in Appendix C.

Solving the Hvorslev (1951) equation using the previous data and the T_0 values shown on the graphs yields the hydraulic conductivity values shown in table 3.

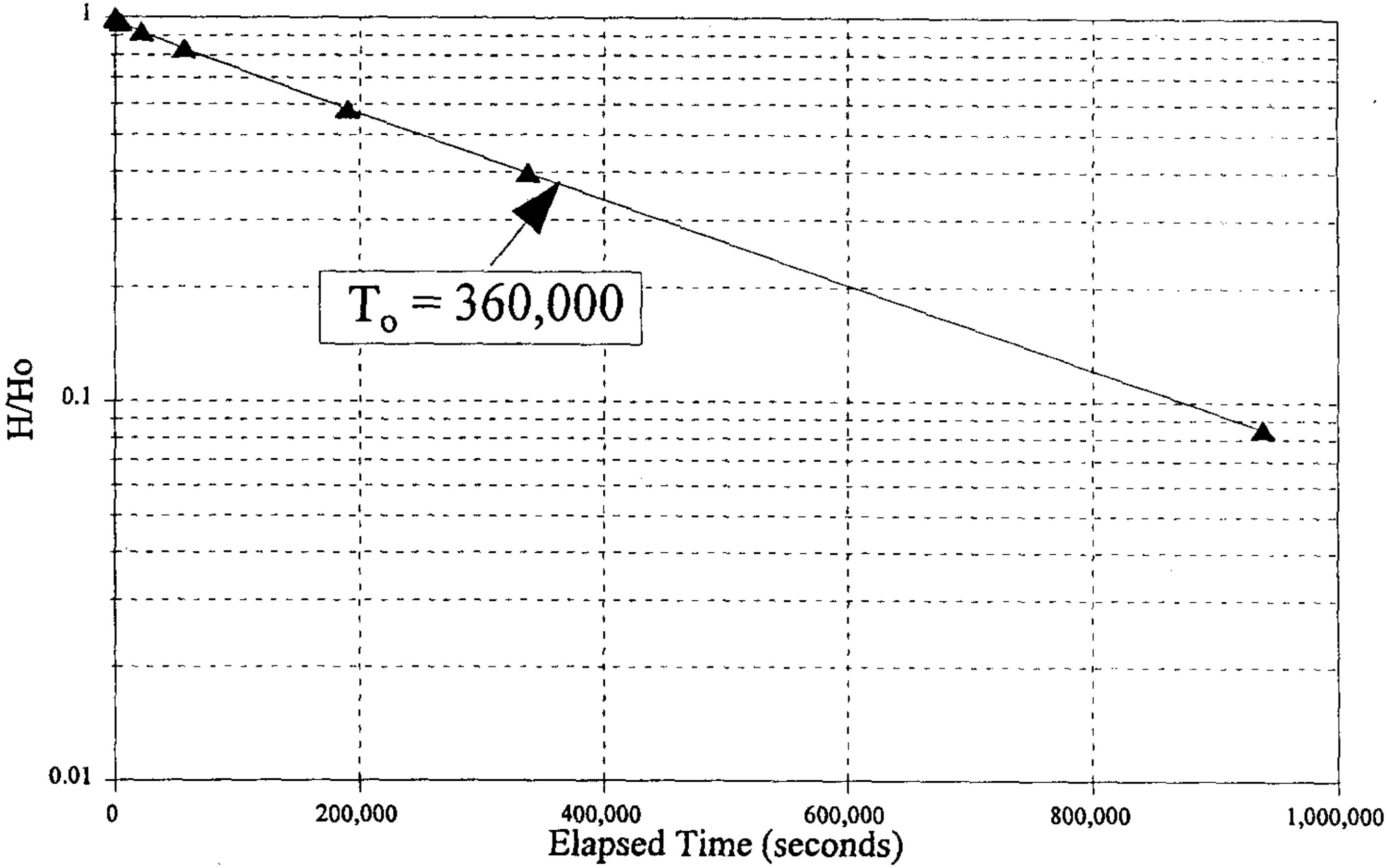


Figure 17. SRC-38C Slug Test
showing recovery of water levels

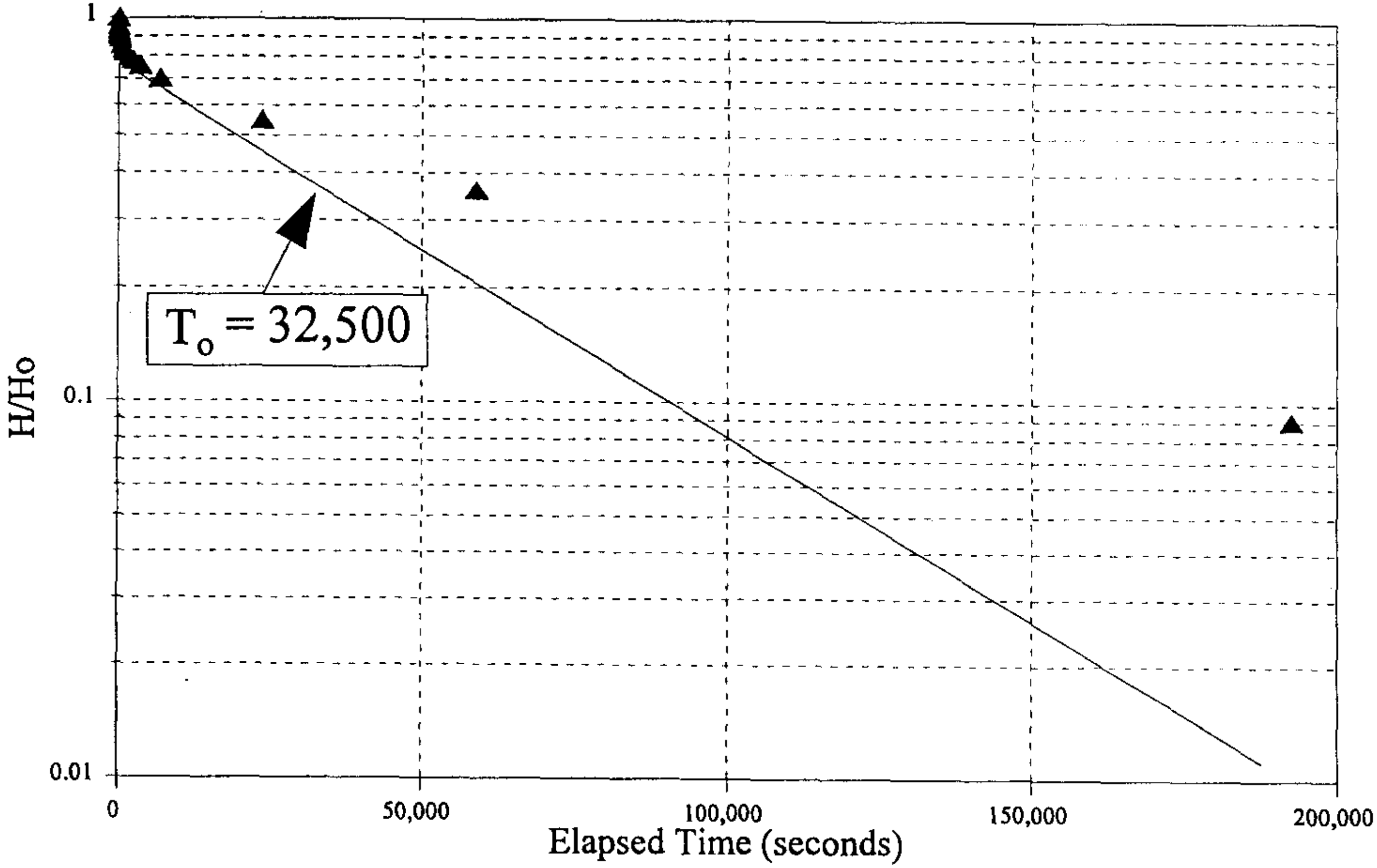


Figure 18. SRC-38D Slug Test
showing recovery of water levels

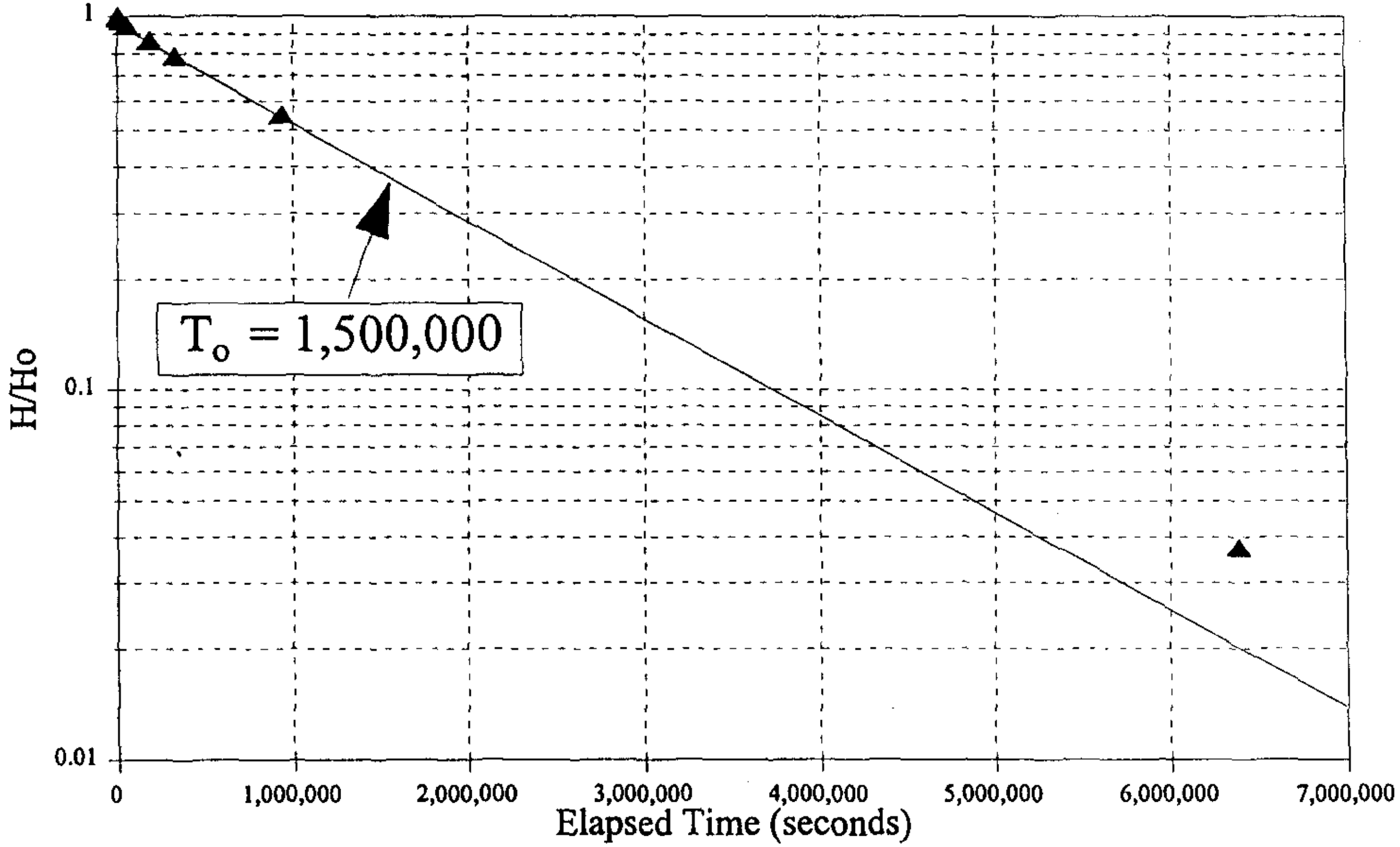


Figure 19. SRC-39C Slug Test
showing recovery of water levels

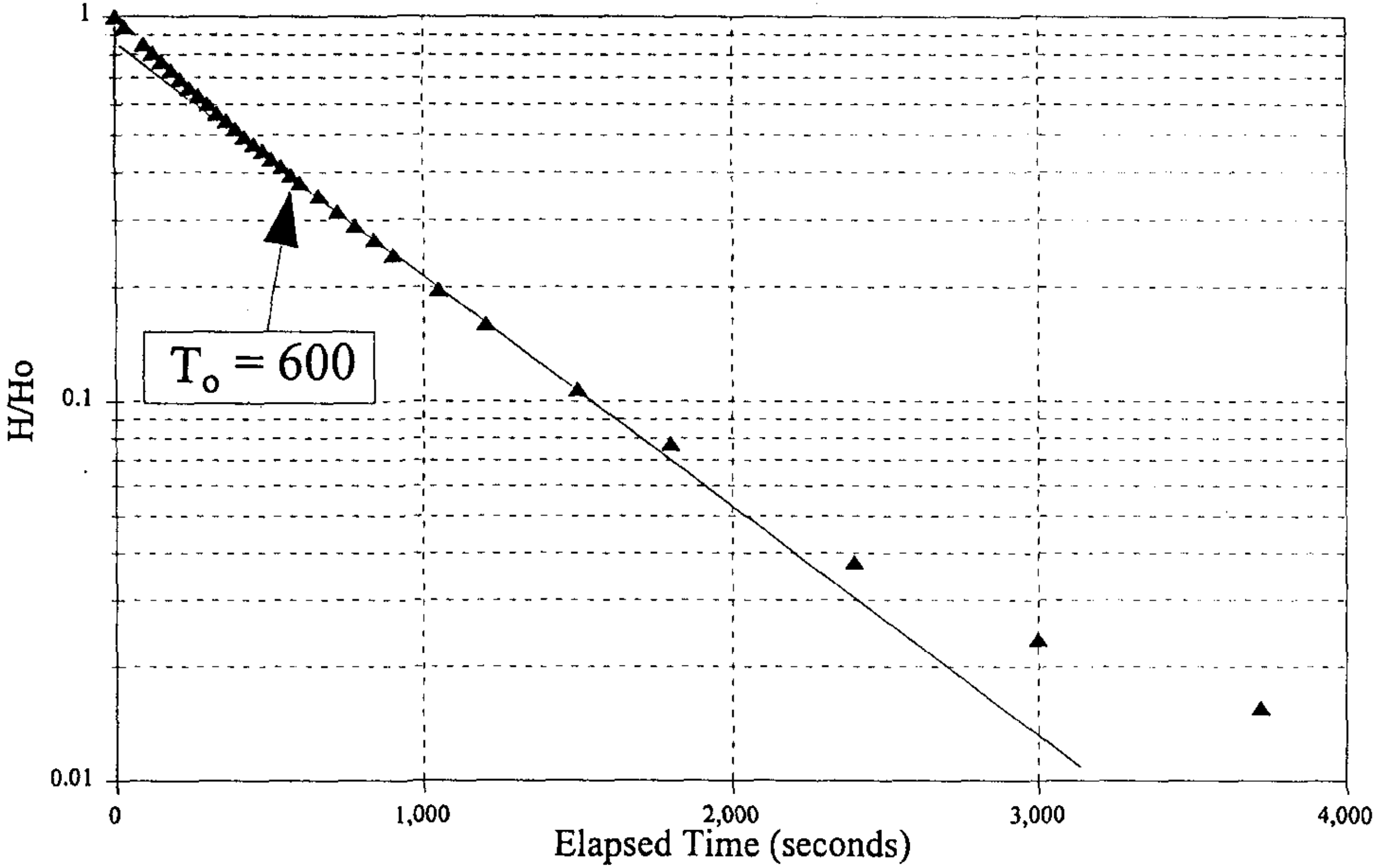


Figure 20. SRC-CO1 Slug Test
showing recovery of water levels

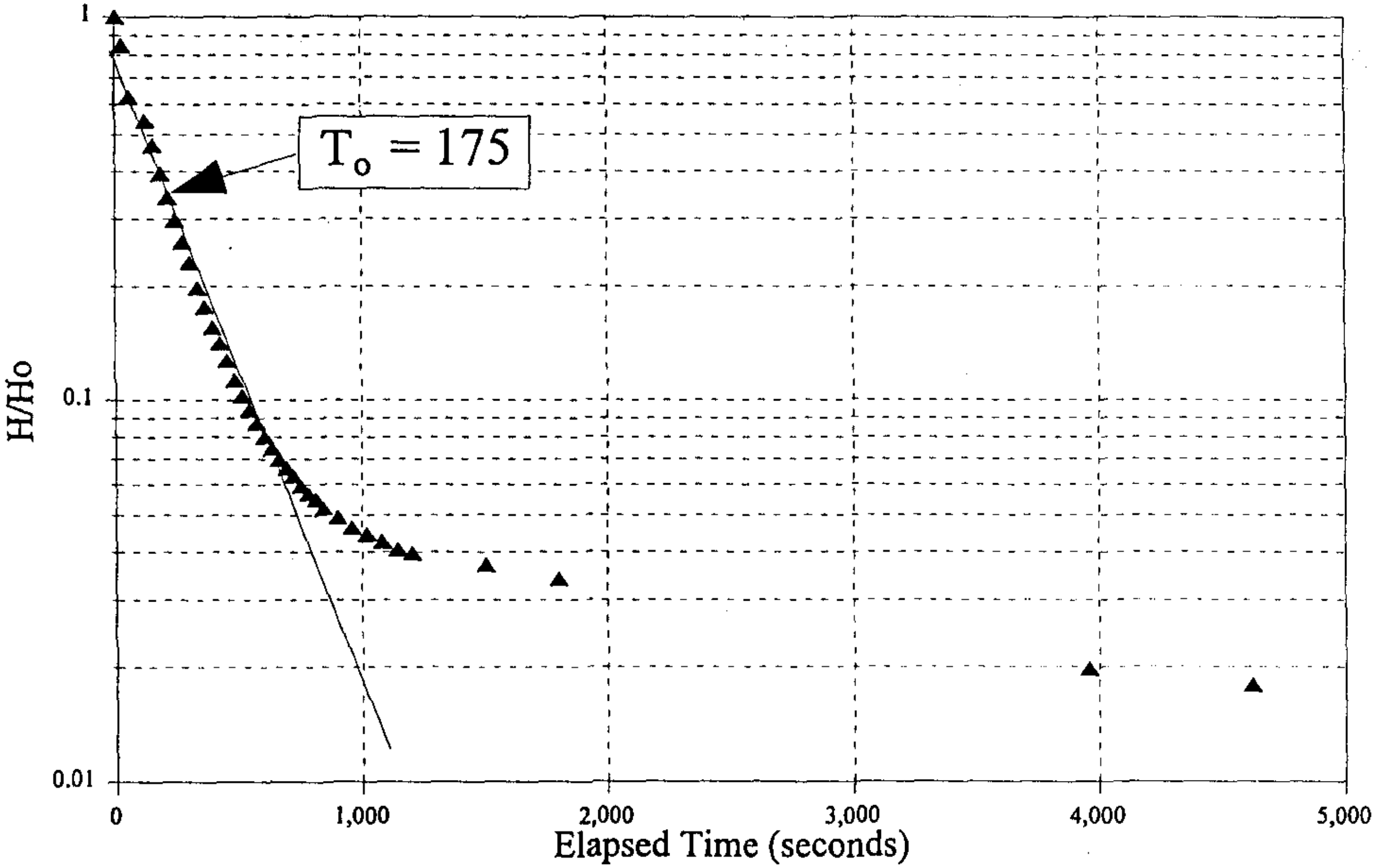


Figure 21. SRC-CO2 Slug Test
showing recovery of water levels

Table 3. Results of Hydraulic Conductivity Tests

WELL ID	Geologic Unit	Hydraulic Conductivity (ft/day)
SRC-38C	Unweathered till	5.1×10^{-4}
SRC-38D	Weathered till	3.4×10^{-3}
SRC-39C	Unweathered till	1.2×10^{-4}
SRC-CO1	Cherty siltstone	3.1×10^{-1}
SRC-CO2	Cherty siltstone	1.1×10^{0}

Hvorslev analysis of three of the five baildown tests was straightforward. The line of best-fit was not as easily determined in the remaining two baildown tests. In the analysis of SRC-38D, it is possible to draw three regression lines through the data using: 1) the first 300 seconds of data, 2) the data between 300 and 23,940 seconds, and 3) the last segment of data greater than 23,940 seconds (data beyond T_o). Based on the Hvorslev (1951) method, it was determined that the middle segment of data was likely representative of the sediments; therefore the analysis was conducted using these data. The first segment of data, which shows rapid recovery of water levels, was interpreted to result from dewatering of the filter pack, and the last segment of data was beyond T_o and probably not representative of the sediments; therefore, neither data segment was used in the analysis.

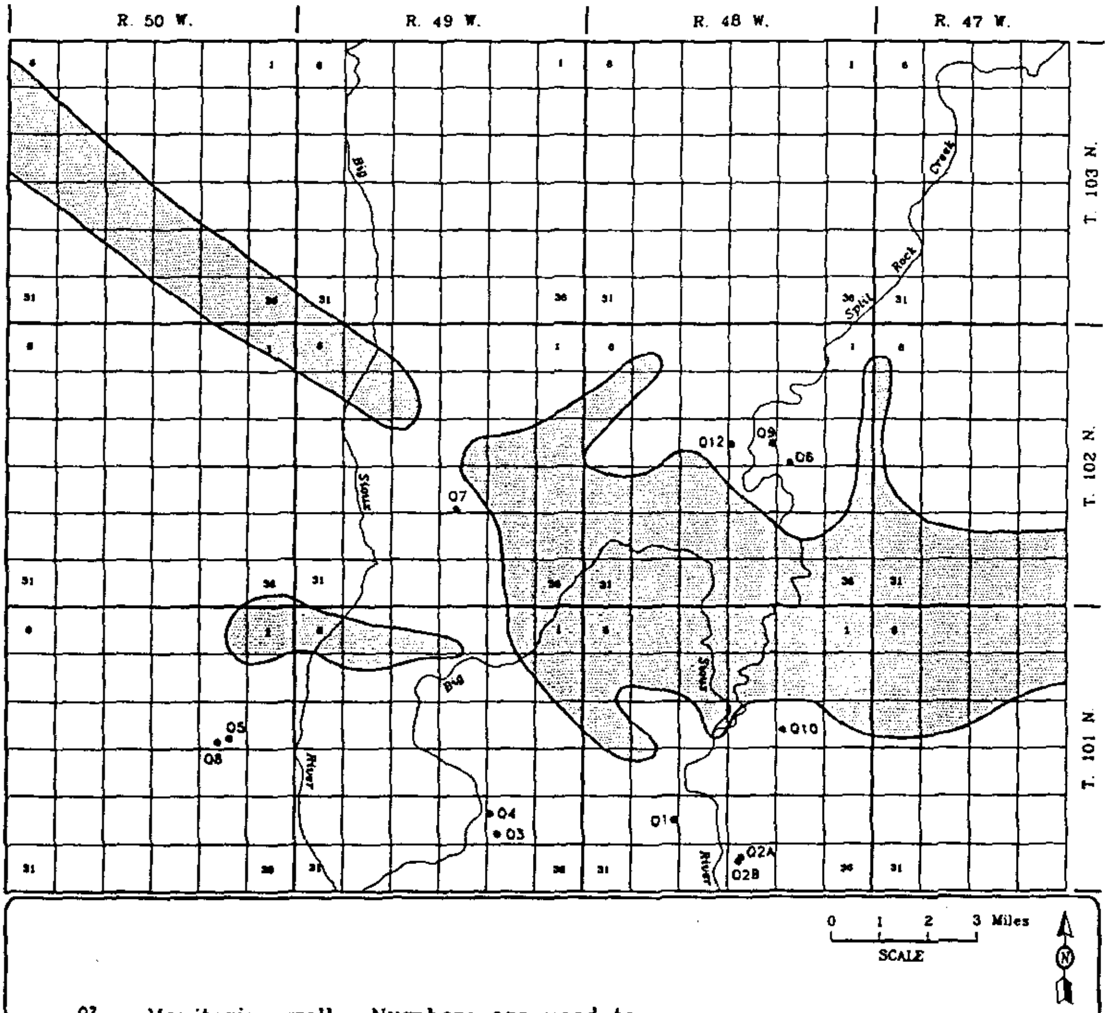
In the analysis of SRC-CO2, only the first 660 seconds of data were used in the analysis, as approximately 95% recovery had occurred during this time. The very last segment of data are probably not representative of the formation, as recharge to the sediments had nearly caused equilibrium to be reached.

As a check on the validity of the Hvorslev (1951) analysis for SRC-CO2, the data from this well were also analyzed using the Bouwer-Rice (1989) method available in the AQTESOLV® software package (the graph produced from this analysis is in Appendix D). This analysis resulted in a hydraulic conductivity value of 4.8×10^{-1} ft/day which closely agrees with the Hvorslev (1951) analysis. The values of hydraulic conductivity for the weathered and unweathered tills also agree with values obtained from the SDGS's till research conducted throughout the state of South Dakota (Assad Barari, verbal communication).

The estimated hydraulic conductivities indicate that the fractured siltstones have a permeability similar to a silty sand and the weathered tills have a slightly lower permeability, similar to the loess. The permeability associated with the weathered tills is likely secondary, created by small fractures. The unweathered tills have the lowest permeabilities, similar to those observed in unweathered marine clays (Freeze and Cherry, 1979, p. 29).

Water Level Trends and Flow Directions

Domestic wells completed in the Sioux Quartzite aquifer were monitored at 12 sites (figure 22). No nested domestic well sites were available for water level measurement. Based on well-construction logs, all domestic wells were cased and grouted from the



O7 ● Monitoring well. Numbers are used to identify individual monitoring wells.

▨ Shaded area shows location of the Split Rock Creek aquifer.

Figure 22. Locations of private wells completed in the Sioux Quartzite aquifer

surface down to the top of the quartzite. The remaining space in the quartzite was left as an open borehole to allow water flow from all available fractures into the well. Wells completed in the Big Sioux aquifer were monitored at four sites (figure 23).

Not all of these wells were continuously monitored throughout the study. As the study progressed, new monitoring wells were installed throughout the aquifer. Also, no domestic wells in the Sioux Quartzite aquifer were monitored until 1991. Due to seasonal events and activities (i.e., heavy snowfall or rain, road construction) access to all of the wells at all times was not always possible. Because of these reasons, only limited data are available for some of the monitoring wells.

Water-Level Trends

Hydrographs of wells from Split Rock Creek aquifer, Sioux Quartzite aquifer, and Big Sioux aquifer all show similar patterns (figures 24, 25, and 26). The water level trends observed in these three aquifers correlate closely with annual precipitation (figure 27) (National Oceanic and Atmospheric Administration, 1980-1995). This would indicate that recharge to all three aquifers results from precipitation.

Prior to the summer of 1989, only minor quantities of water were pumped from the Split Rock Creek aquifer, mainly from several domestic wells. Pumping records for the Split Rock Creek aquifer indicate that the city of Brandon pumped approximately 600 million gallons of water (an average continuous pumping rate of approximately 175 gpm) from the summer of 1989 to December 1995 (Dennis Olson, written communication).

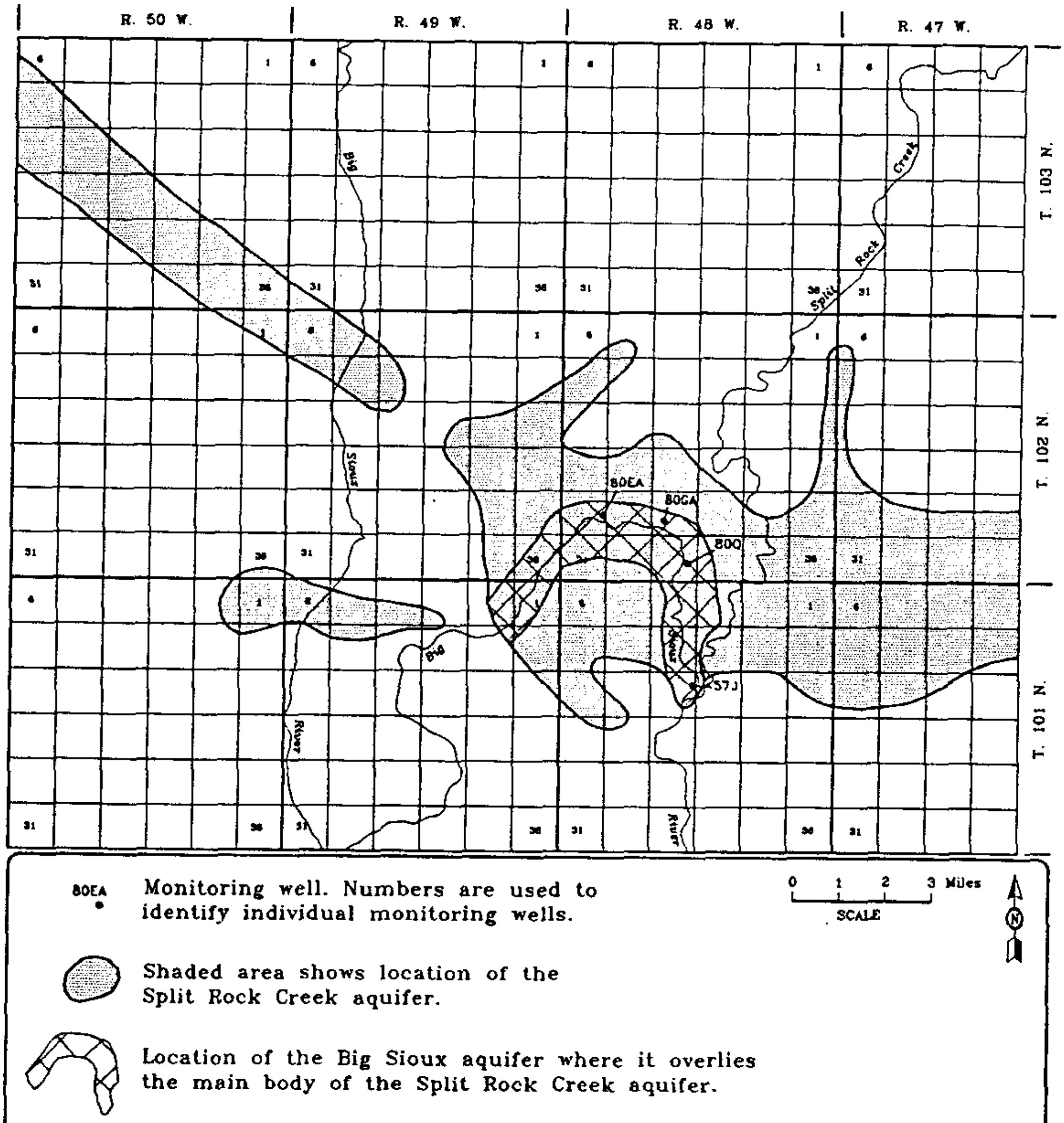


Figure 23. Locations of monitoring wells completed in the Big Sioux aquifer

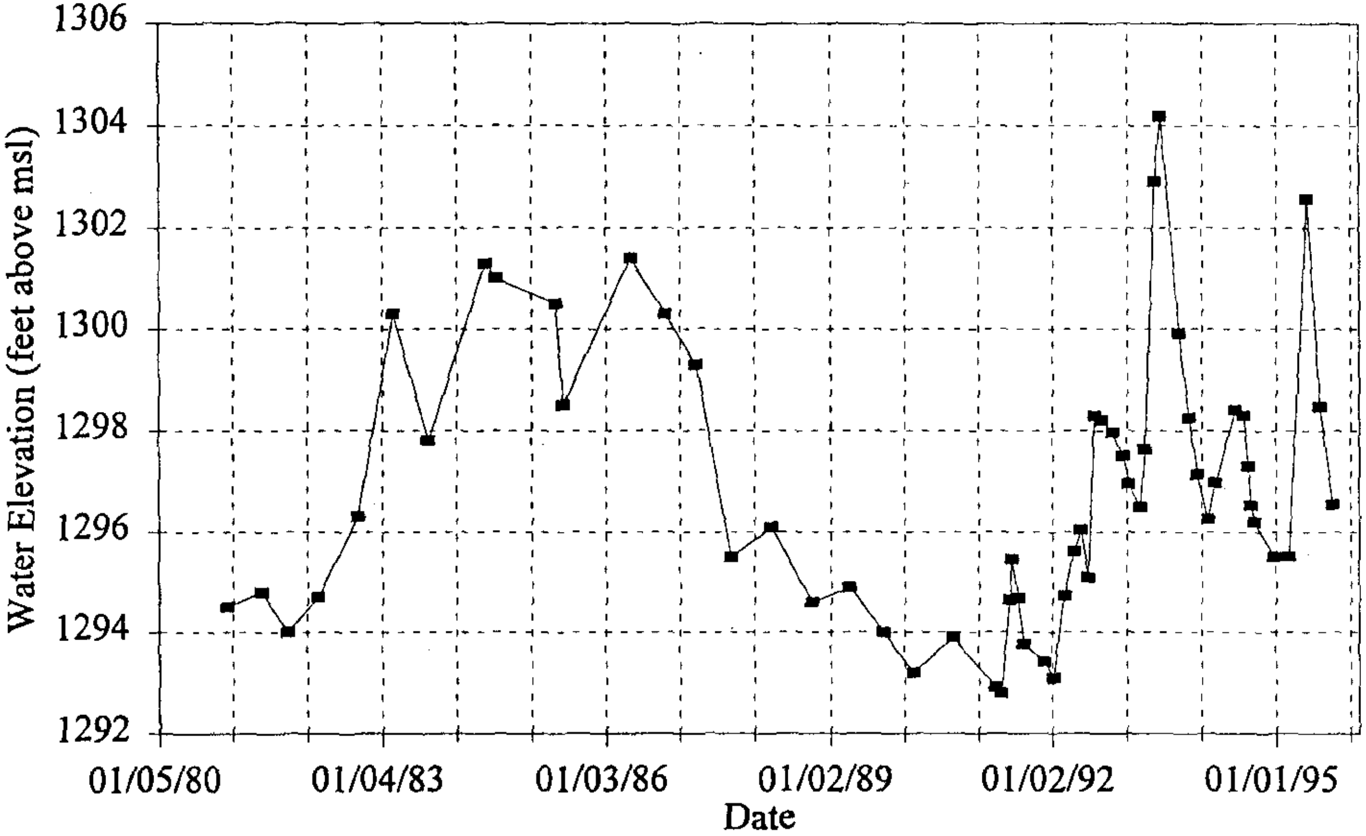


Figure 24. SRC-18B Hydrograph
Big Sioux Aquifer

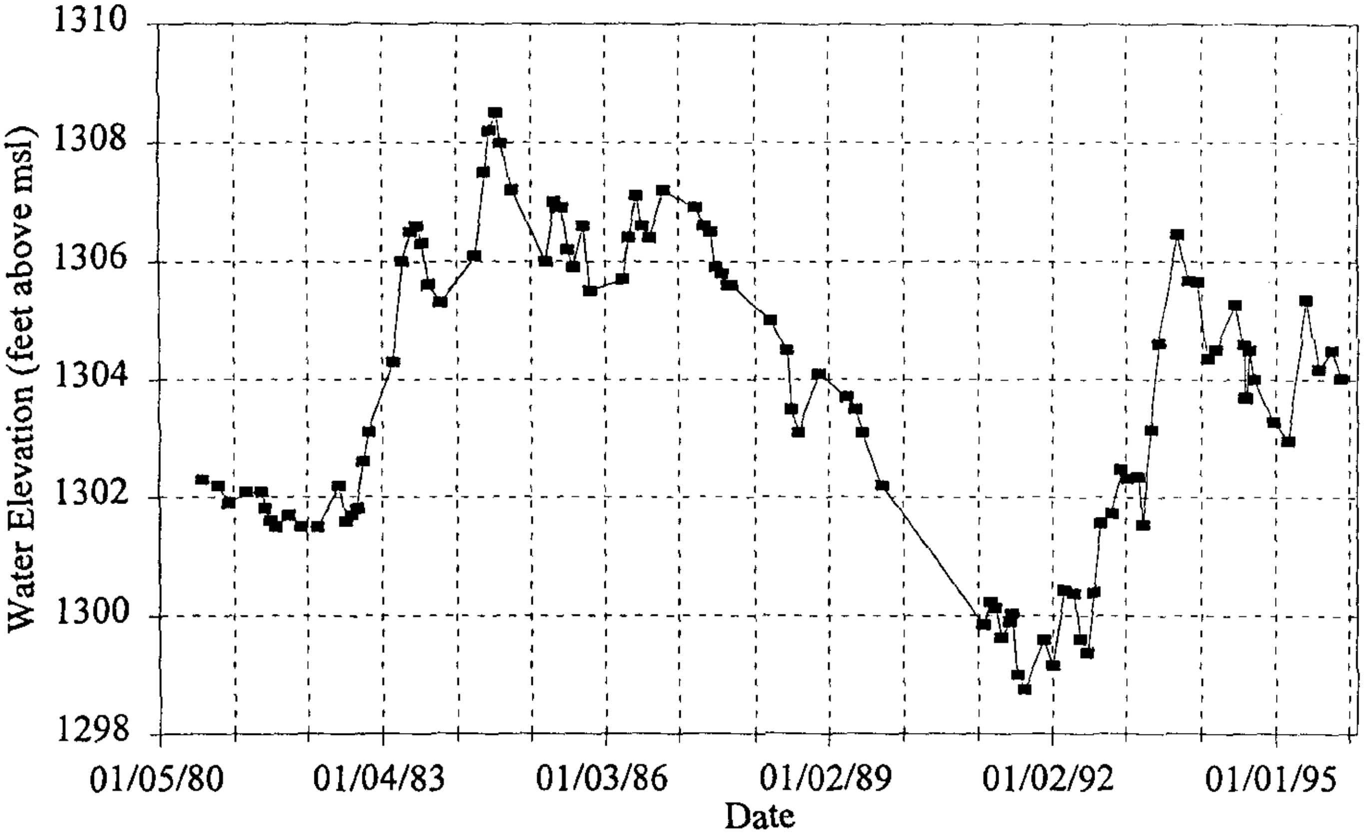


Figure 25. SRC-41 Hydrograph
Split Rock Creek Aquifer

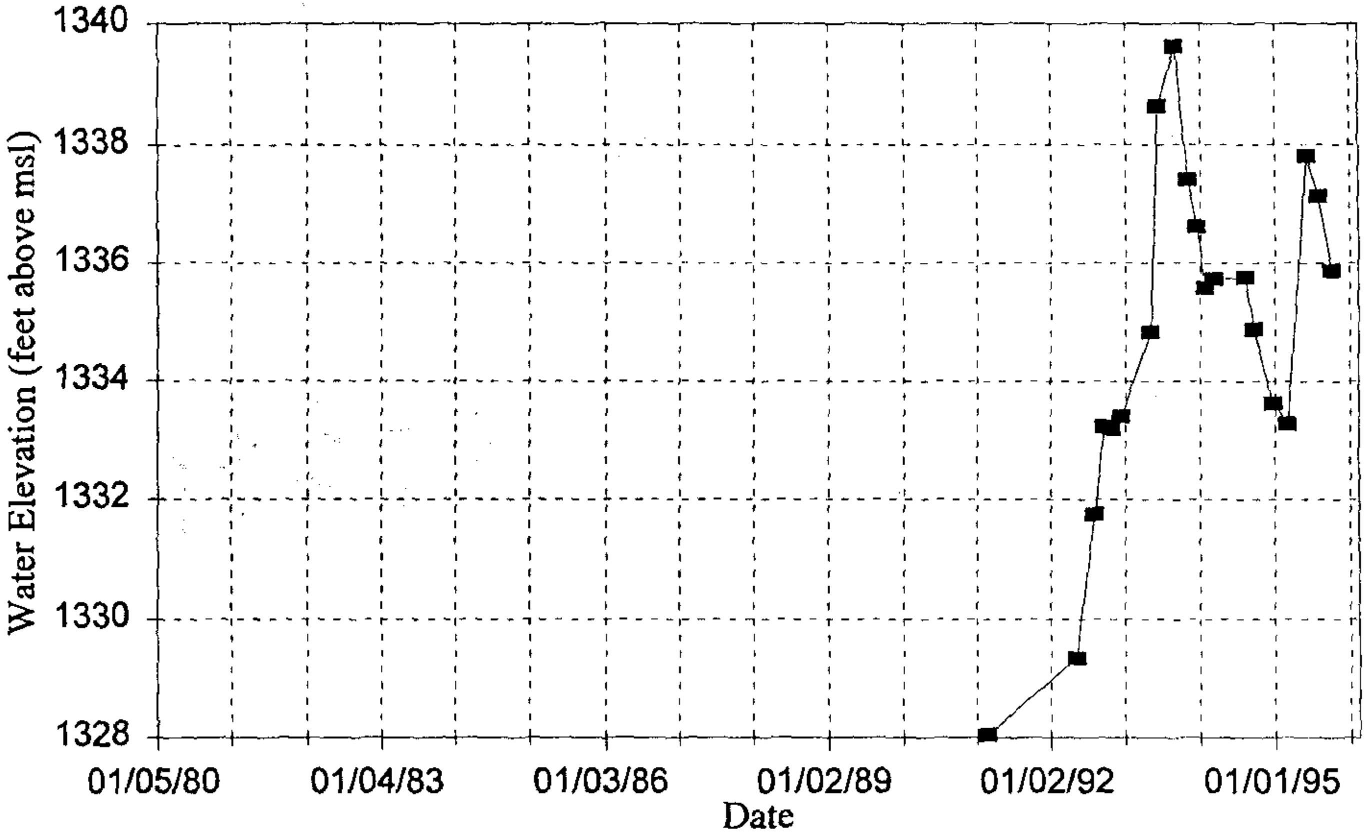


Figure 26. Q6 Hydrograph.
Sioux Quartzite Aquifer

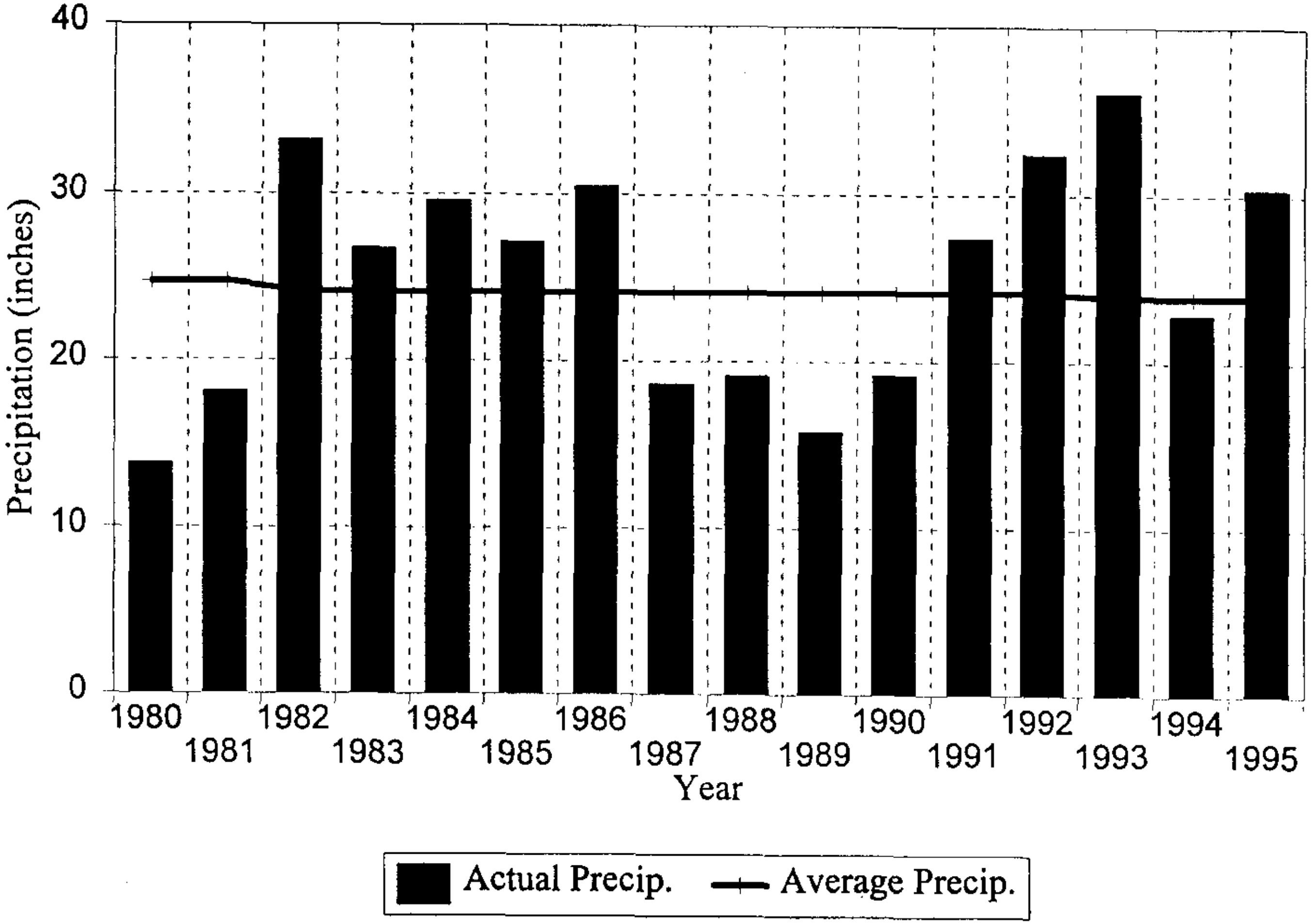


Figure 27. Annual Precipitation
at Sioux Falls, South Dakota
(from NOAA)

Sioux Falls has pumped slightly more than 1 billion gallons of water (an average continuous pumping rate of approximately 380 gpm) from September 1990 to December 1995 at the NSP and Watrec sites (Doug Holden, written communication). Locations of production wells are shown on figure 28.

A hydrograph of well SRC-32 (figure 29), within one mile of two Sioux Falls production wells, shows the immediate response of the aquifer to production pumping. After Sioux Falls began production pumping in 1989, water levels declined for approximately 5 months. After this time water levels stabilized and even began to rise. In 1993, when the production wells were shut off for extended periods during maintenance, water levels recovered to approximately two feet higher than pre-pumping levels.

A hydrograph of well SRC-37 (figure 30), approximately 500 feet from Brandon's production well, also shows the aquifer's immediate response to pumping (and periods of non-pumping). Despite nearly continuous pumping of the production well, water levels did not decline. When the production well is turned off for extended periods, water levels recover to levels approximately two feet higher than pre-pumping levels.

Because water levels recover at both locations to levels greater than pre-pumping levels, this indicates that recharge to the aquifer has occurred. If recharge were not occurring, water levels would continue to decline during pumping, and recovery would be incomplete after pumping ceased.

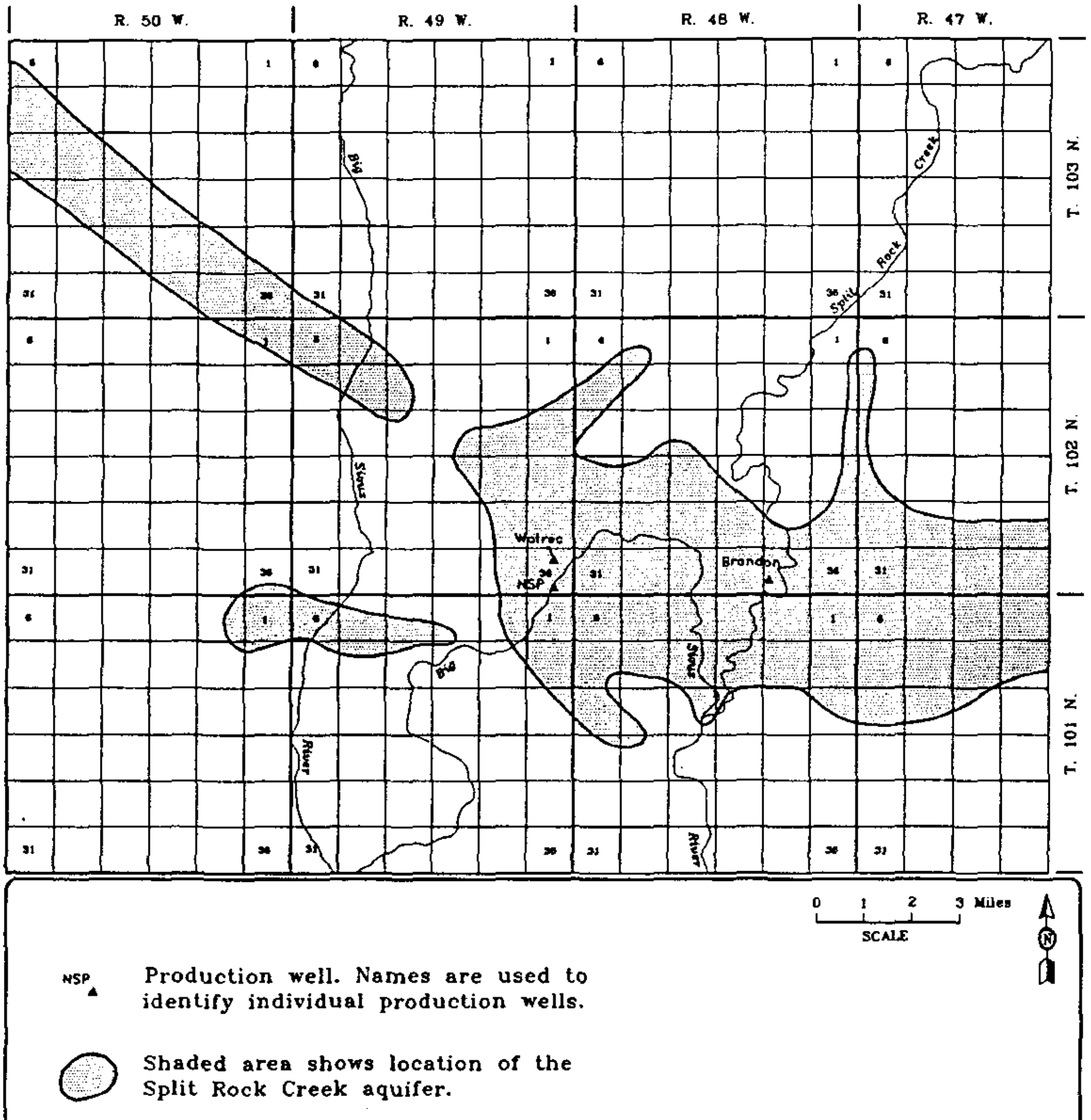


Figure 28. Locations of production wells completed in the Split Rock Creek aquifer

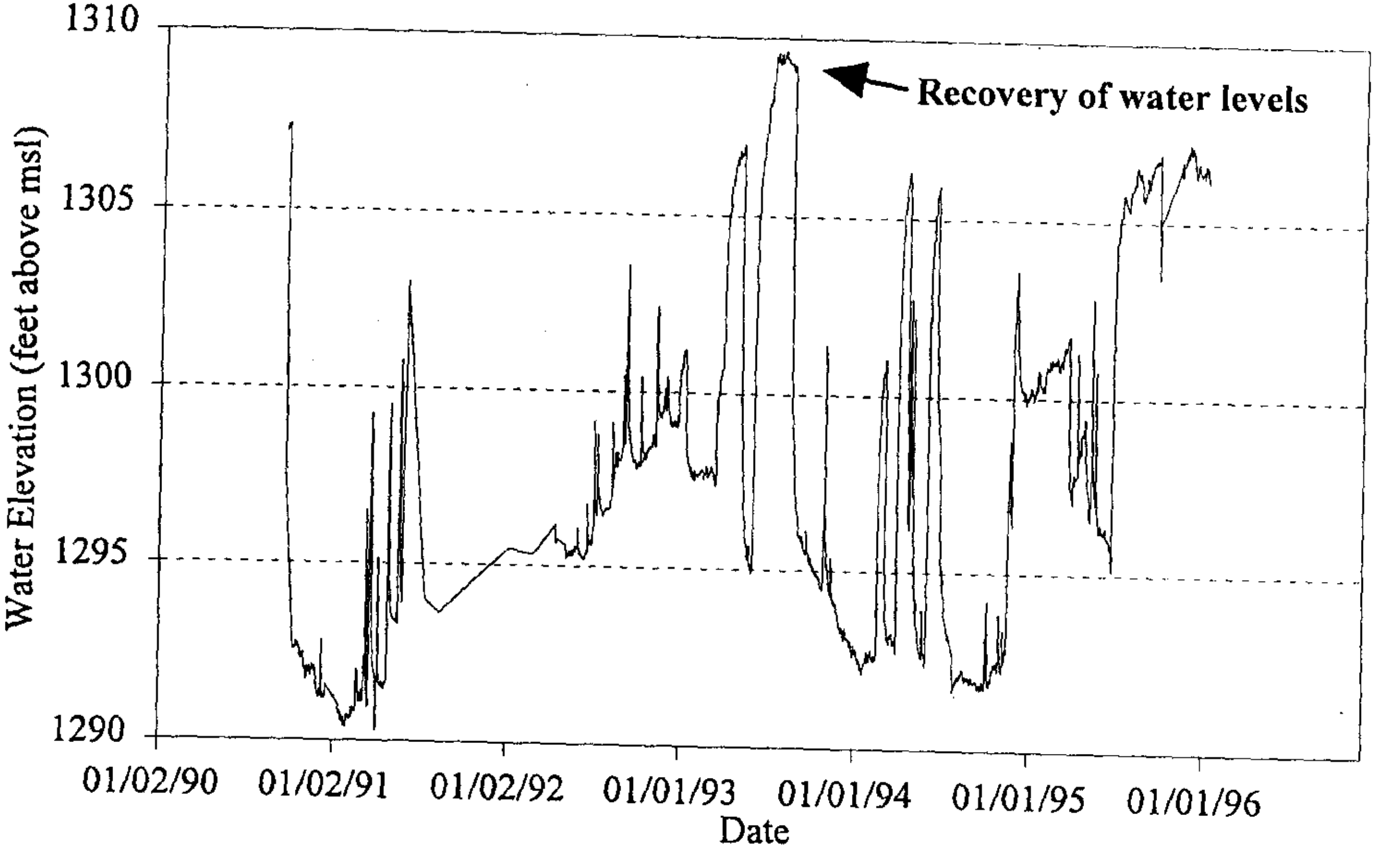


Figure 29. **SRC-32 Hydrograph**
Near Sioux Falls' Production Wells

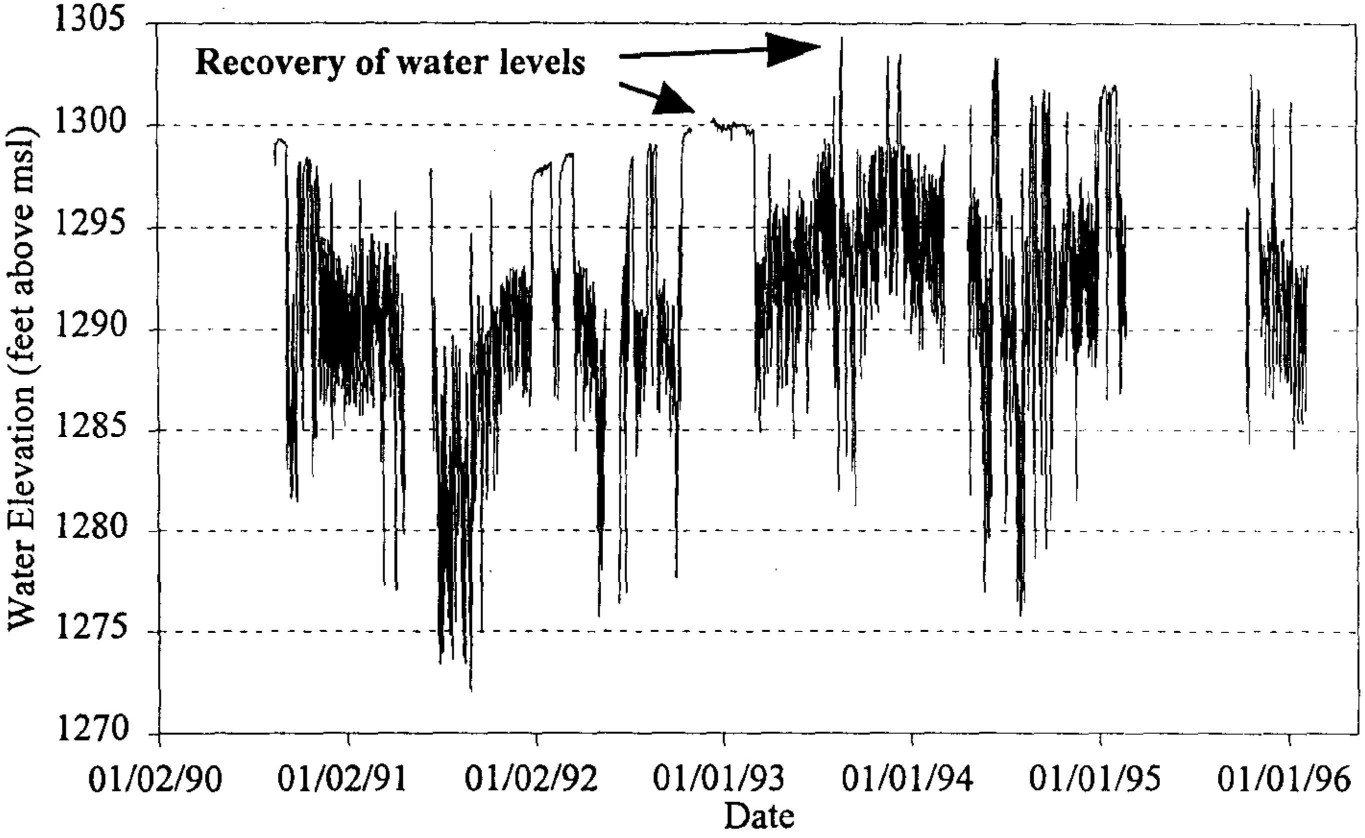


Figure 30. SRC-37 Hydrograph
Near Brandon's Production Well

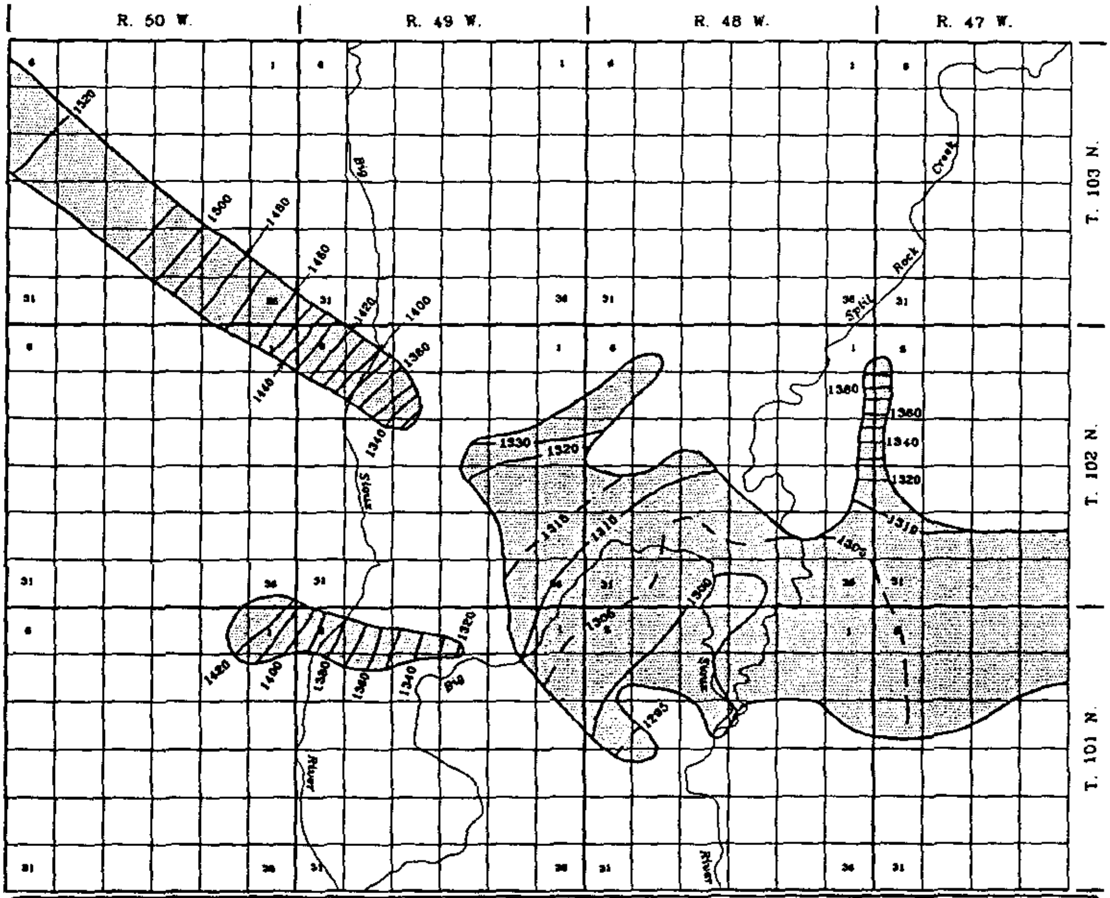
Horizontal Flow Directions and Rates

The Split Rock Creek Aquifer

Potentiometric maps of the Split Rock Creek aquifer were prepared for March 10, 1989; January 6, 1992; and July 31, 1995 (figures 31, 32, and 33). These dates were selected because enough data existed to construct accurate potentiometric maps on these dates, and they cover sufficient time to determine if ground-water flow directions had changed in the last several years, especially due to ground-water pumping. The potentiometric maps were prepared using water-level data from monitoring wells completed in the same hydrostratigraphic horizon of the aquifer.

Horizontal ground-water flow directions in the Split Rock Creek aquifer are similar on all three dates. Water levels were lower than static near Sioux Falls' production wells on January 6, 1992, due to pumping. On July 31, 1995, the production wells near Sioux Falls had been turned off for several weeks and water levels were nearly static, but water levels were lower than static near Brandon's production well due to pumping at this location. Overall, ground-water flow directions are from the northwest in the western part of the aquifer, and from the east-northeast in the eastern part of the aquifer. Ground-water flow converges near the Big Sioux River in the south-central portion of the main body of the aquifer.

The horizontal gradient in the main body of the aquifer ranges from approximately 1.5 to over 20 feet per mile, with an average gradient of approximately 5 feet per mile (0.001). Modifying the Darcy equation to obtain the true mean flow velocity results in the



1420 Line connecting points of equal potentiometric surface elevation. Number is elevation in feet above mean sea level. Contour interval = 10 feet.

1295 Supplemental contour, interval = 5 feet.

Shaded area shows location of the Split Rock Creek aquifer.

Figure 31. Potentiometric surface of the Split Rock Creek aquifer on March 10, 1989

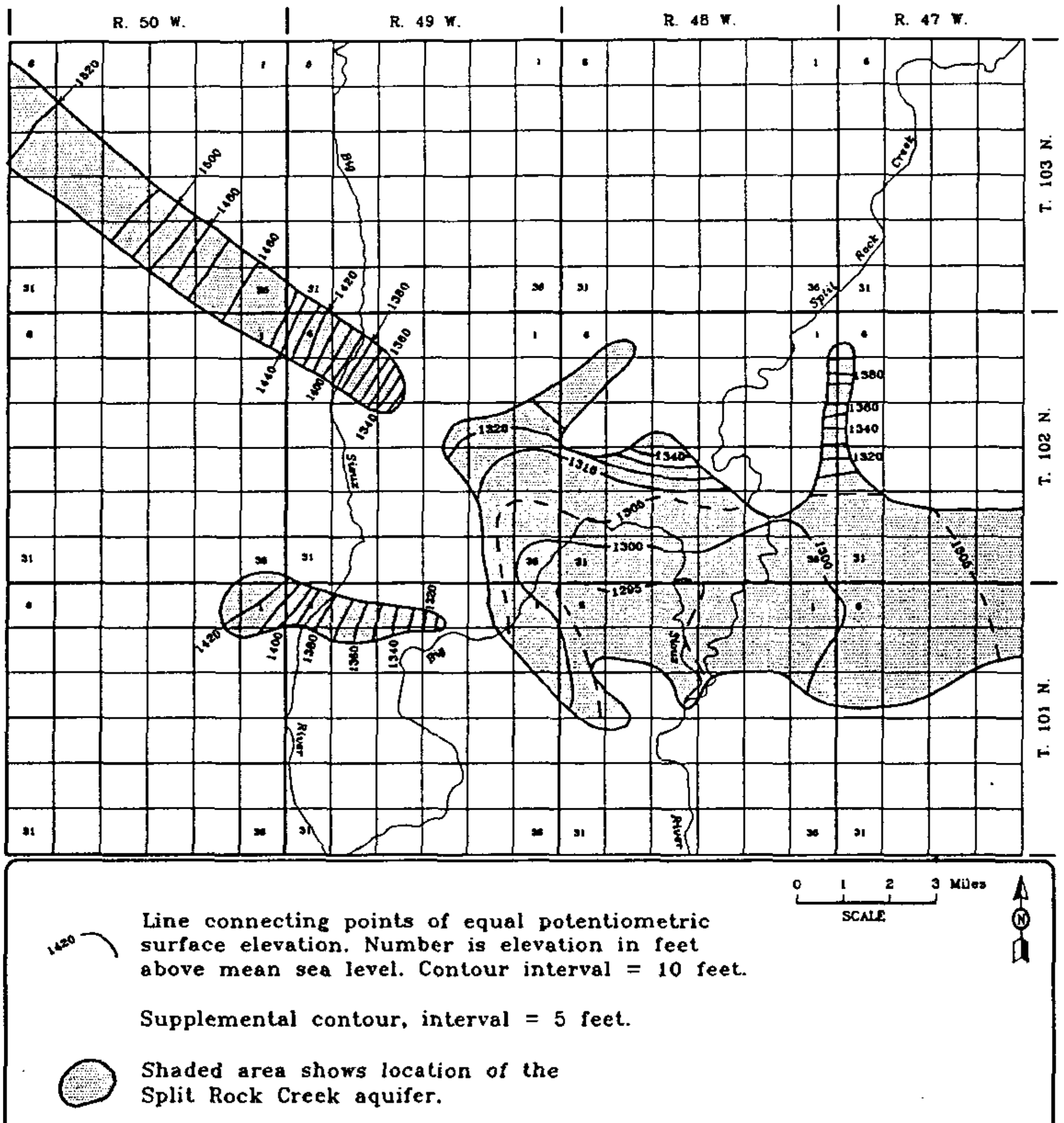
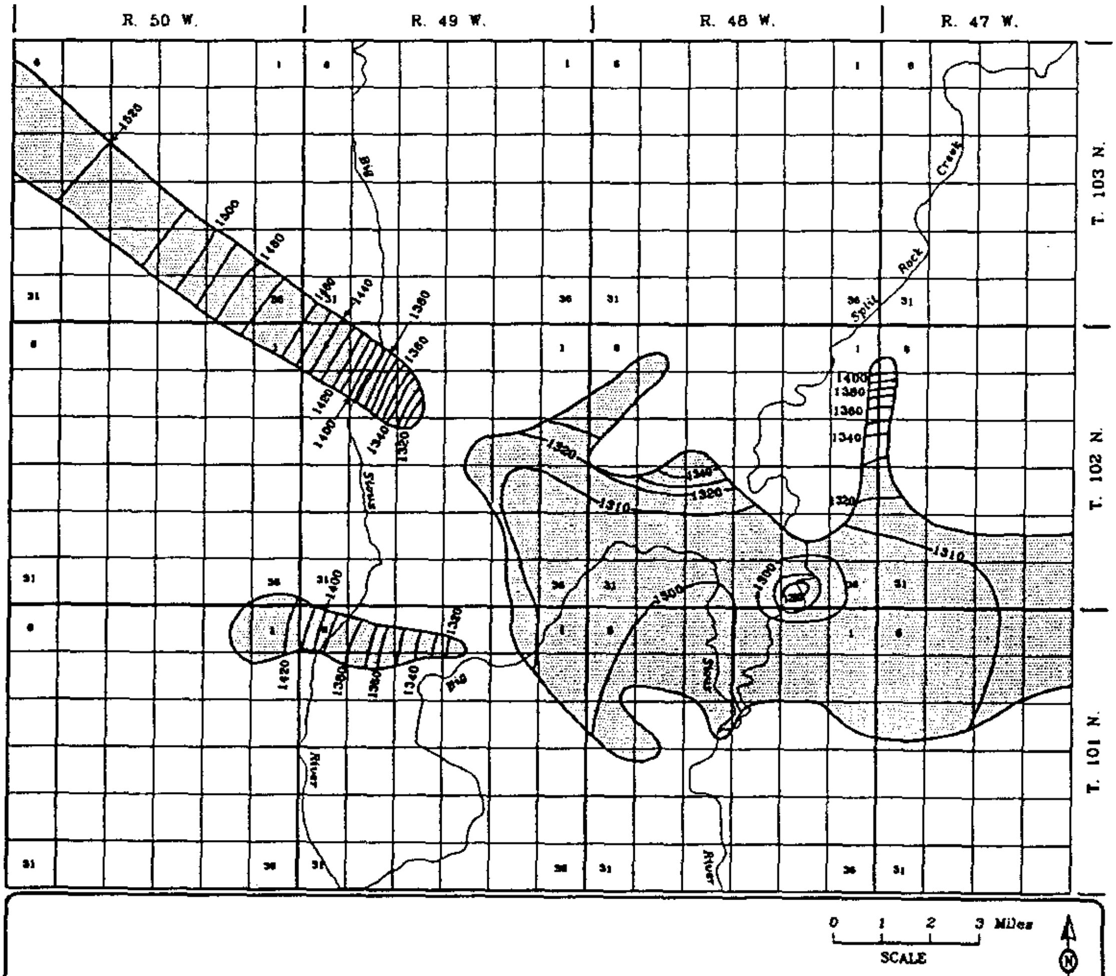


Figure 32. Potentiometric surface of the Split Rock Creek aquifer on January 6, 1992.



1420 Line connecting points of equal potentiometric surface. *Number is elevation in feet above mean sea level.* Contour interval = 10 feet.

Shaded area shows location of Split Rock Creek aquifer.

Figure 33. Potentiometric surface of the Split Rock Creek aquifer on July 31, 1995

equation $V = -(K / \phi)(dh / dl)$; where V is the flow velocity, K is the hydraulic conductivity, ϕ is the effective porosity, and dh/dl is the gradient. Using an average hydraulic conductivity of 48 ft/day, an average gradient of 0.001, and assuming an effective porosity of 0.25 for the aquifer sands results in an average flow velocity of 0.19 ft/day or 70 ft/year. Using the full range of aquifer gradients and hydraulic conductivities yields an approximate range of flow velocities from 0.03 ft/day to 0.9 ft/day.

The Sioux Quartzite and Big Sioux Aquifers

A contour map of water levels in the Sioux Quartzite aquifer (figure 34) shows water elevations and flow directions similar to those observed in adjacent areas of the Split Rock Creek aquifer. A water-table contour map of the Big Sioux aquifer (figure 35) shows that ground water flows parallel to the direction of flow in the river.

Vertical Flow Directions

Water elevations in the Big Sioux aquifer are approximately 10 to 20 feet lower than the water levels in the underlying Split Rock Creek aquifer. Therefore, there is an upward vertical gradient between these aquifers along the Big Sioux River between Sioux Falls and Brandon. A nested well site is at SRC-18, where the A well is completed in the Split Rock Creek aquifer and the B well is completed in the Big Sioux aquifer. On March 10, 1989, the approximate water elevations were 1,308 feet in the A well and 1,295 feet in the B well. With 80 feet separating the centers of the well screens, the estimated upward gradient

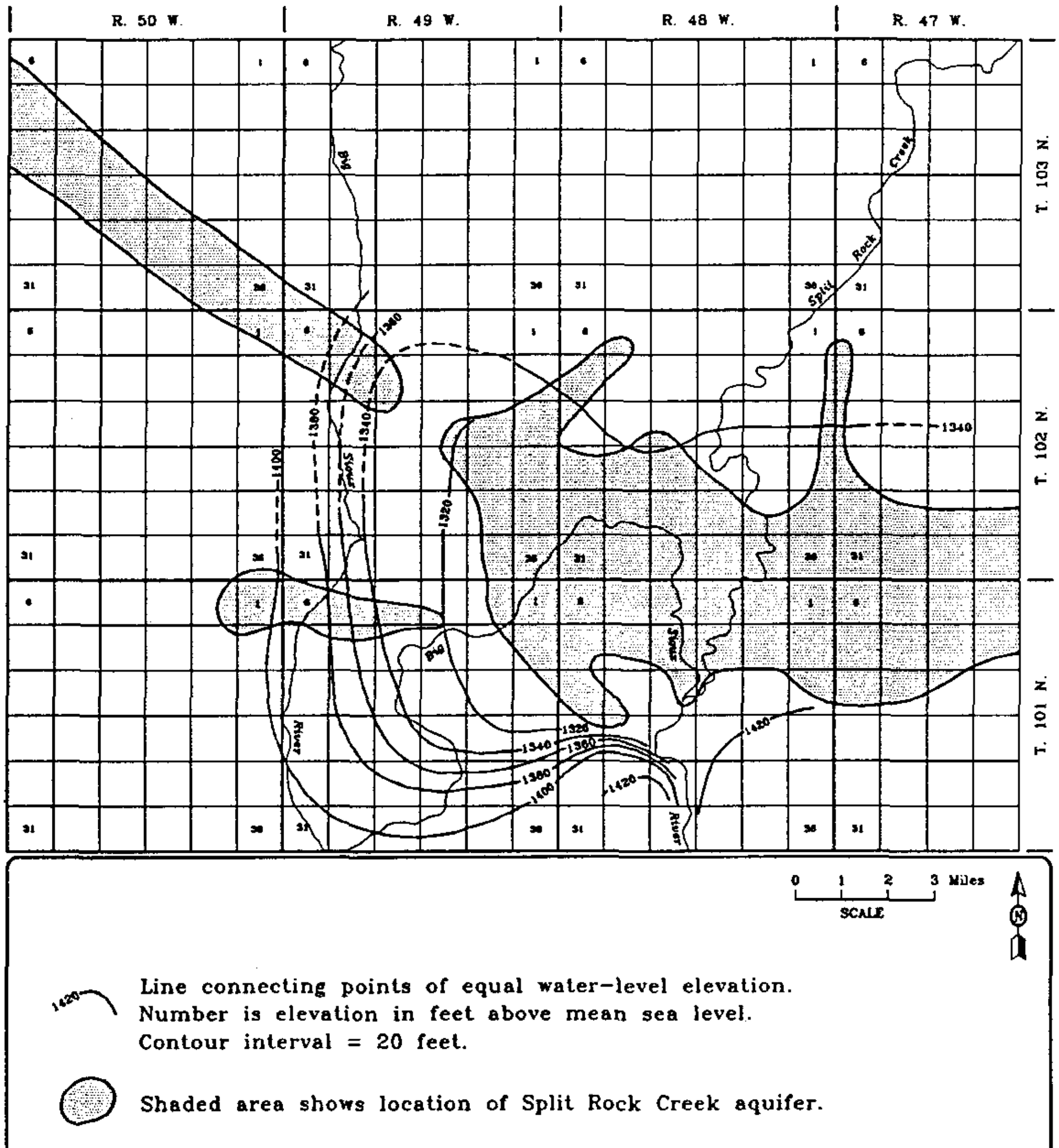


Figure 34. Water levels in the Sioux Quartzite on July 31, 1995

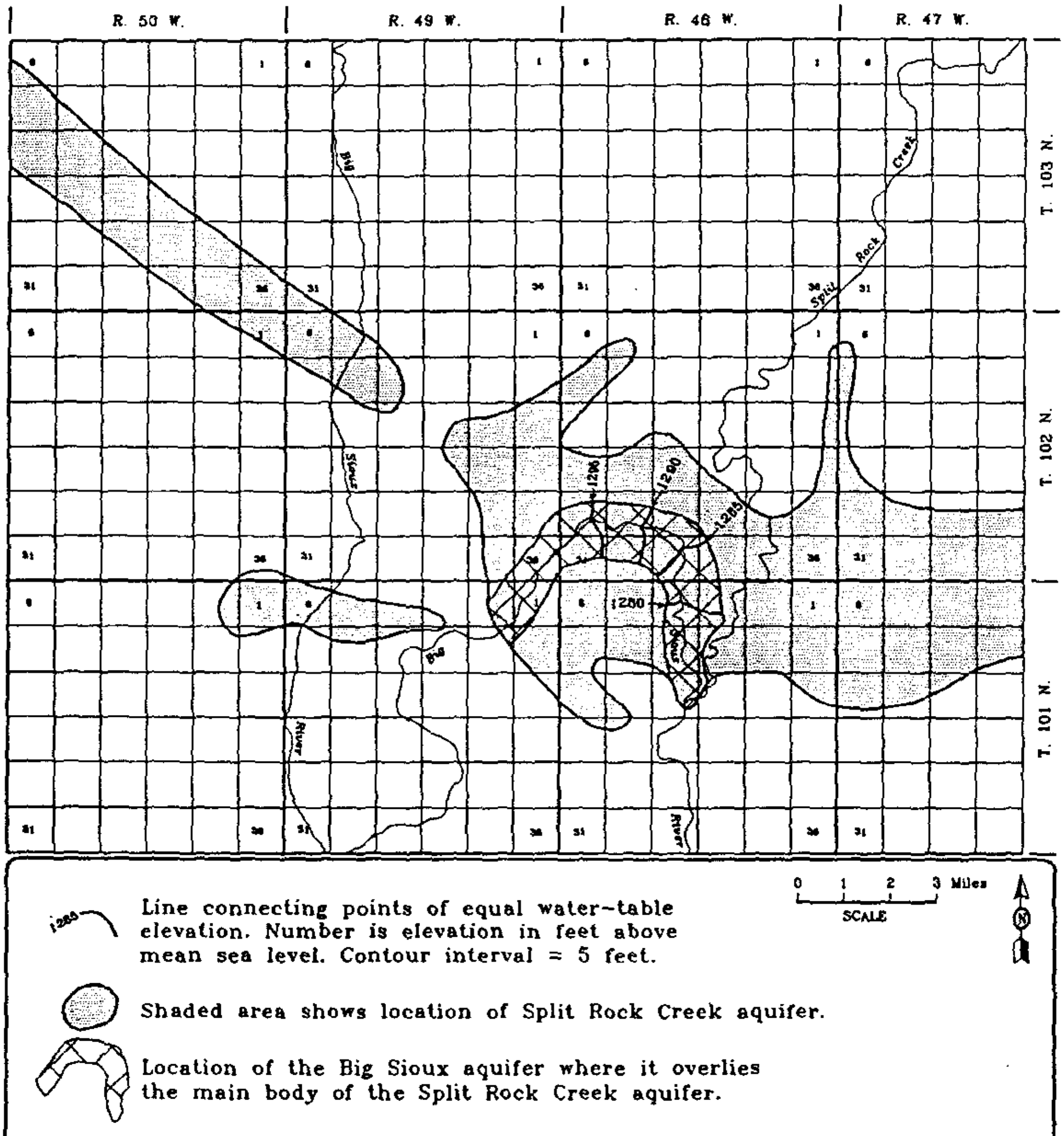


Figure 35. Water table elevation in the Big Sioux aquifer on March 10, 1989

(dh/dl) is 0.16. Because the difference in water levels between the two aquifers increases downstream, the vertical gradients also increase downstream. As a result of this upward gradient and the fact that the aquifers appear to be in direct hydraulic connection just downstream of SRC-18, it is likely that ground water is discharging from the Split Rock Creek aquifer into the Big Sioux aquifer.

All other regions in the study area show downward vertical gradients between the Split Rock Creek aquifer and the water-table, with the exception of the area discussed previously and an area near SRC-35 where there is a slight upward gradient (described in the *Discussion* section). Typical downward gradients range from approximately -0.09 at site SRC-15 to -0.75 at site SRC-38, as measured on October 4, 1995.

Water Chemistry

Major Inorganic Ions

In addition to the 57 water samples collected and analyzed for inorganic parameters (46 from the Split Rock Creek aquifer and 11 from the Sioux Quartzite aquifer), 29 water samples previously collected from the Big Sioux aquifer were used in this study. The large number of samples was used for several reasons: 1) to determine the general water quality of the different aquifers (especially in relation to potential recharge from one unit to another); 2) to identify any anomalous parameters which may indicate recharge from one unit to another; and 3) to identify potential recent recharge through the occurrence of anthropogenic nitrate.

The results of the inorganic analyses are shown in the following four tables. Table 4 summarizes the water quality of the samples collected from the entire Split Rock Creek aquifer (including the western valleys of the aquifer which are not in direct hydraulic connection to the main body of the aquifer), table 5 summarizes the water quality of the samples collected from the main body of the Split Rock Creek aquifer, table 6 summarizes the water quality of the samples collected from the Sioux Quartzite aquifer, and table 7 summarizes the water quality of the samples collected from the entire Big Sioux aquifer (Big Sioux aquifer data are from Barari and others, 1989).

Table 4. Inorganic Water Quality of the Entire Split Rock Creek Aquifer.

Mean Concentration in Milligrams per Liter													
N=46	HCO_3	Ca	Cl	K	Mg	Na	SO_4	Fe	Mn	F	NO_3 & NO_2	TDS	Hardness
Avg.	402	161	5.0	6.2	55	37	373	0.53	0.47	0.54	0.15	880	626
Std.	31	84	3.7	2.4	27	14	327	0.62	0.27	0.15	0.74	484	317
Max.	511	545	23.0	12.0	143	87	1730	2.00	1.40	1.17	5.00	2820	1950
Min.	327	79	1.3	1.9	26	15	31	0.03	0.03	0.34	0.02	366	317

Explanation: N = number of samples analyzed; Avg. = average; Std. = standard deviation; Max. = maximum; Min. = minimum.

Note: all water samples were collected from the basal sands at the base of the aquifer. Vertical variations in inorganic parameters were not checked.

Table 5. **Inorganic Water Quality of the Main Body of the Split Rock Creek Aquifer.**

Mean Concentration in Milligrams per Liter

N=40	HCO_3	Ca	Cl	K	Mg	Na	SO_4	Fe	Mn	F	NO_3 & NO_2	TDS	Hardness
Avg.	404	148	5.1	6.2	52	38	330	0.56	0.44	0.55	0.04	817	582
Std.	30	54	3.8	2.2	23	14	234	0.65	0.25	0.13	0.08	354	227
Max.	511	298	23.0	12.0	125	87	1080	2.00	1.40	1.17	0.52	1900	1259
Min.	368	84	2.0	1.9	26	16	57	0.03	0.03	0.34	0.02	400	325

Explanation: N = number of samples analyzed; Avg. = average; Std. = standard deviation; Max. = maximum; Min. = minimum.

Table 6. **Inorganic Water Quality of the Sioux Quartzite Aquifer.**

Mean Concentration in Milligrams per Liter

N=11	HCO_3	Ca	Cl	K	Mg	Na	SO_4	Fe	Mn	F	NO_3 & NO_2	TDS	Hardness
Avg.	353	110	12.6	3.4	38	23	170	0.22	0.36	0.45	3.01	595	431
Std.	49	33	11.7	1.1	12	18	136	0.47	0.78	0.20	4.40	186	130
Max.	428	163	40.0	5.8	57	78	437	1.67	2.74	0.77	14.60	887	642
Min.	289	57	2.1	1.8	19	9	11	0.03	0.03	0.18	0.02	316	221

Explanation: N = number of samples analyzed; Avg. = average; Std. = standard deviation; Max. = maximum; Min. = minimum.

Table 7. Inorganic Water Quality of the Big Sioux Aquifer.

Mean Concentration in Milligrams per Liter

N=29	HCO_3	Ca	Cl	K	Mg	Na	SO_4	Fe	Mn	F	NO_3 & NO_2	TDS	Hardness
Avg.	345	129	22.3	4.5	37	29	214	0.41	1.23	0.33	0.67	656	475
Std.	53	38	16.0	2.1	13	13	112	0.81	0.99	0.08	1.04	179	127
Max.	433	211	58.0	8.6	72	47	400	3.75	3.28	0.51	3.82	980	694
Min.	223	58	1.9	1.8	14	10	54	0.03	0.03	0.20	0.02	398	281

Explanation: N = number of samples analyzed; Avg. = average; Std. = standard deviation; Max. = maximum; Min. = minimum.

Results of inorganic ion analyses indicate no major differences in water quality between the three aquifers. The water quality in the main body of the Split Rock Creek aquifer, especially in relation to TDS (total dissolved solids), has lower concentrations than the water in the western valleys of the aquifer (figure 36). Based on these data, the Sioux Quartzite aquifer contained the water of the best quality; the Sioux Quartzite aquifer had the lowest concentrations of inorganic ions, with the exception of nitrate + nitrite.

Radionuclides

Occurrence of Tritium

Hydrogen has three isotopes in nature: 1) ^1H or protium, which is the most common and is stable, 2) ^2H or deuterium (D), which is rare and also is stable, and 3) ^3H or tritium, which is very rare and is radioactive with a half-life of 12.43 years (Fontes, 1985). Tritium is produced in one of three different ways: cosmic-ray neutron bombardment of nitrogen in

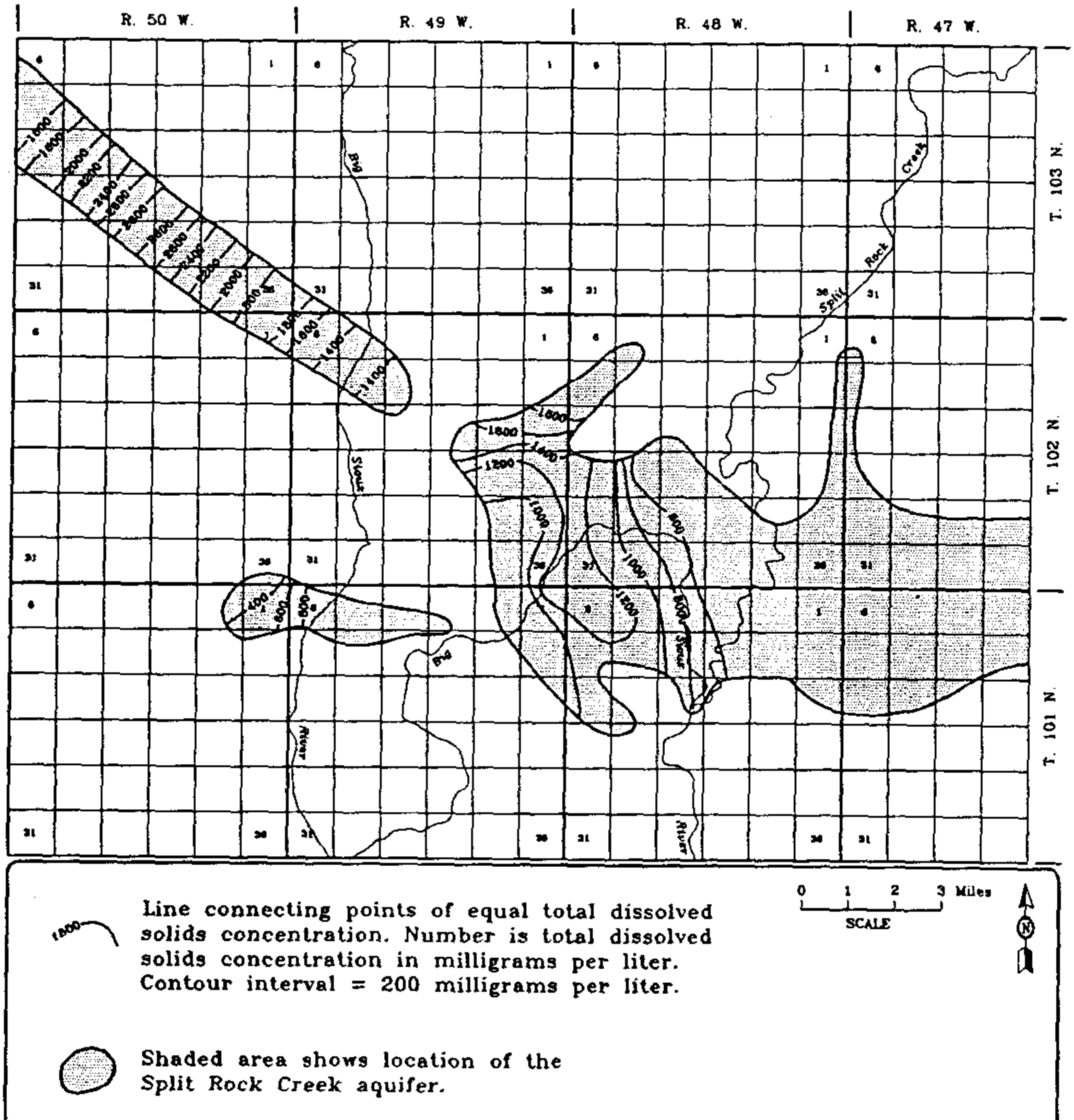


Figure 36. Total dissolved solids concentrations in the Split Rock Creek aquifer

the upper atmosphere, thermonuclear explosions, and production in nuclear power reactors. After tritium has been produced, it is oxidized into water and is removed from the atmosphere by precipitation (Fontes, 1985). Once the meteoric water enters the saturated zone, no new tritium is added, and the remaining tritium decays.

Tritium concentrations in the atmosphere have been elevated well above natural levels following the first thermonuclear detonation on October 31, 1952. Since the moratorium on atmospheric thermonuclear tests in 1963, the supply of bomb tritium entering the atmosphere has stopped almost completely (Fontes, 1985).

Because tritium is present in small amounts in natural waters, this has led to the definition of the "Tritium Unit," or TU as the reference. One TU corresponds to an atomic ratio of one atom of tritium to 10^{18} atoms of protium.

Because tritium has such a short half-life, it is useful in evaluating the residence time of ground water that originated as meteoric water. A ground-water sample containing tritium indicates that the ground water has been recently recharged; meaning that water from the "post-bomb era" has probably entered the ground-water system. A water sample with no tritium present would indicate that recharge probably occurred prior to the "bomb era." Fritz and Fontes (1980) and Fontes (1985) provide a more detailed explanation on the occurrence of tritium.

<u>Tritium Results.</u> Tritium analyses of the five water samples collected from the Split Rock Creek aquifer are listed in table 8. All samples were collected from production wells used during aquifer tests (figure 10).

Table 8. Laboratory Results of Tritium Analyses.

Well ID	Date Sampled	TU
NSP-3 PW	04/27/88	0 ± 0.10
Renner PW	02/13/89	0 ± 0.09
Renner PW	02/14/89	0 ± 0.09
Brandon PW	06/28/89	0 ± 0.09
Watrec PW	11/15/89	0 ± 0.09

Duplicate samples were not run by the laboratory.

These results show no tritium present in the ground-water samples collected from this aquifer.

Occurrence of Radiocarbon

Carbon has three isotopes in nature: 1) ^{12}C, which is the most common and is stable, 2) ^{13}C, which is rare and also stable, and 3) ^{14}C, or radiocarbon, which is rare and radioactive with a half-life of approximately 5,730 years (Fritz and Fontes, 1980).

^{14}C produced in the atmosphere is very quickly mixed with the carbon dioxide in the rest of the atmosphere, and a steady state occurs. Because plants absorb carbon dioxide and animals ingest these plants, a similar steady state occurs between these plants and animals and ^{14}C in the atmosphere. ^{14}C is introduced into ground water by the respiration processes of plants, by the decay of organic matter, and by dissolved carbon dioxide in meteoric water. Most of the carbon dioxide is added to meteoric water as it percolates through the soil layer, as soil air contains around 100 times more carbon dioxide than free air (Fritz and

Fontes, 1980). Once this meteoric water reaches the saturated zone, radiocarbon is no longer added to the water, and the remaining radiocarbon decays.

^{14}C concentration in a sample is generally expressed as a specific activity, i.e., as the radioactivity in ^{14}C disintegrations per minute per gram of carbon. The radioactivity of a sample is then compared to the specific activity of the international standard NBS oxalic acid, and the measured activity of the sample is reported as a percentage of the standard activity. This percentage is reported as the PMC (percentage modern carbon) of the sample (Fritz and Fontes, 1980). The long-half life of ^{14}C makes it a useful tool to date ground water as old as approximately 50,000 years (Fontes, 1985).

As ground water moves from one reservoir to another, i.e., from the recharge area to the aquifer materials, or from one type of aquifer material to another, isotopic fractionation can occur. The isotopic fractionation can cause the addition of very old carbon to the water (i.e., carbon with no ^{14}C activity), thus lowering the true PMC value. The ^{13}C abundance in the sample is commonly used to correct the true PMC value of the sample (Fritz and Fontes, 1980).

The abundance of ^{13}C is expressed in per mil deviation, or $\delta^{13}C‰$, of the $^{13}C/^{12}C$ ratio in the sample from that of the international standard known as PDB -- a belemnite carbonate from the Pee Dee Formation of South Carolina (Fritz and Fontes, 1980). Many marine carbonate rocks have a $\delta^{13}C‰$ near 0 (Shampine and others, 1979), whereas values for organic material and carbon dioxide in the soil range from approximately -28‰ to -12‰. Plants in temperate climates generally have a $\delta^{13}C = -23 \pm 3‰$, and plants in semi-arid climate have a $\delta^{13}C = -14 \pm 2‰$. These variations are attributed to different metabolic pathways among plants (Fritz and others, 1979).

In the radiocarbon model utilized for this study, it was assumed that the $\delta^{13}C$ value of the water entering the ground was approximately -23‰, the same as the assumed $\delta^{13}C$ value of the plants in the recharge area(s). This model also assumes that any deviation of the $\delta^{13}C$ value of aquifer water from that of the recharge water results from interaction (isotopic fractionation) with geologic materials in the subsurface that have $\delta^{13}C = 0‰$. Analysis of the ground-water samples collected for this study yielded $\delta^{13}C$ values that ranged from -9.90 to -11.35‰, indicating that the recharge waters had interacted with materials in the subsurface. This interaction has resulted in the addition of older carbon into the ground-water system.

To determine the ^{14}C date for a sample, the standard equation for radioactive decay is used:

$$t = -1/\lambda \ln (N/N_0).$$

where t is the age of the sample, λ is the decay constant (ln 2 / half-life), N is the measured radiocarbon activity, or PMC, N_0 is the initial radiocarbon activity, assumed to be 100 PMC (Fritz and Fontes, 1980). Because of the interaction of the recharge water with geologic materials in the subsurface, this equation is corrected to account for the introduction of extraneous carbon, which yields:

$$t = -1/\lambda (\ln (N/N_0) + \ln (\delta^{13}C_{\text{recharge area}} / \delta^{13}C_{\text{sample}}))$$

where $\delta^{13}C_{\text{recharge area}}$ is the $\delta^{13}C$ value of the plants in the recharge area, assumed to be -23‰ for this study (Fritz and Fontes, 1980 and Ferronsky and Polyakov, 1982).

Fritz (1979), Fritz and Fontes (1980), Fontes (1985), Ferronsky and Polyakov (1982), and Mazor (1991) provide detailed explanations of ^{14}C and the interpretation of ^{14}C in natural waters.

Radiocarbon Results. Radiocarbon analyses of the four water samples collected from the Split Rock Creek aquifer are listed in table 9. All samples were collected from production wells used during aquifer tests (figure 10).

Table 9. Laboratory Results of Radiocarbon Analyses and Calculated Ages.

Well ID	Date Sampled	PMC	$\delta^{13}C$	Calculated Age
NSP-3 PW	04/27/88	28.2 ± 0.4	-9.90 ± 0.1‰	3,400
Renner PW	02/14/89	12.0 ± 0.2	-10.31 ± 0.1‰	10,600
Brandon PW	06/28/89	20.2 ± 0.2	-10.97 ± 0.1‰	6,900
Watrec PW	11/15/89	15.7 ± 0.3	-11.35 ± 0.1‰	9,200

Duplicate samples were not run; and analyses of standards were not reported.

The results of radiocarbon dating show the aquifer water ranging from approximately 3,000 years to 10,000 years old.

Occurrence of Gross Alpha Radiation and Uranium

Gross alpha radiation, which consists of an emitted helium-4 nucleus ($^{4}He^{2+}$), is one of the most common forms of radioactivity in water. The uranium-238 decay series gives rise to most of the naturally occurring radioactivity in water, with alpha being the majority of the radiation associated with this decay series (Hem, 1989). Alpha radiation, as other types of radiation, is commonly measured in picocuries (pCi), where one pCi is equal to 10^{-12} Ci (one Ci is equal to 3.7 x 10^{10} disintegrations per second). More detailed explanations on gross alpha and uranium occurrence are provided by Hem (1989), Ferronsky and Polyakov (1982), Mason and Moore (1982), and Zapecza and Szabo (1986).

Gross Alpha and Uranium Results. Gross alpha radiation analyses of the 24 water samples collected for this study are listed in table 10. The samples were collected from 16 wells completed in the Split Rock Creek aquifer and six wells completed in the Sioux Quartzite aquifer (figures 9, 10, and 22). In those cases where the gross alpha value was greater than 15 pCi/liter, uranium analyses were also conducted.

Table 10. Laboratory Results of Gross Alpha Analyses.

Well ID	Date	Gross Alpha (pCi/L)	Uranium (pCi/L)
Q3*	06/23/92	8.4 ± 7.1	
Q3* (duplicate)	06/23/92	7.1 ± 6.7	
Q8*	06/23/92	1.1 ± 6.2	
Q2 (b)*	06/23/92	8.8 ± 4.6	
Q10*	06/23/92	32.9 ± 6.2	6.7 ± 0.5
Q1*	06/23/92	17.9 ± 6.1	6.7 ± 0.5
Q6*	06/22/92	20.6 ± 5.6	6.7 ± 0.5
SRC-41	06/22/92	6.0 ± 4.1	
Brandon PW**	06/28/89	3.4 ± 3.3	
Watrec PW**	11/13/89	27.5 ± 10.4	9.8 ± 0.7

Table 10 continued.

Well ID	Date Sampled	Gross Alpha (pCi/L)	Uranium (pCi/L)
Watrec PW**	11/16/89	30.9 ± 10.6	9.8 ± 0.7
Watrec E	08/08/89	29.2 ± 12.5	24.0 ± 1.7
Watrec D	04/27/89	19.1 ± 5.6	12.0 ± 0.8
SRC-32	07/06/89	17.3 ± 10.1	4.7 ± 0.3
SRC-28	07/06/89	40.0 ± 8.4	6.7 ± 0.5
SRC-1	01/17/91	6.1 ± 2.7	
SRC-2	01/17/91	10.6 ± 3.2	
SRC-7	01/17/91	10.6 ± 0.4	
SRC-9	01/17/91	4.8 ± 9.4	
SRC-13	01/18/91	12.7 ± 2.9	
SRC-15	01/17/91	26.9 ± 4.0	3.3 ± 0.2
SRC-16	01/18/91	40.4 ± 12.7	6.7 ± 0.5
SRC-17	01/18/91	2.7 ± 5.3	
SRC-26	01/18/91	17.9 ± 8.3	17.3 ± 1.2
SRC-35	01/17/91	18.1 ± 3.7	4.7 ± 0.3

* - *Indicates the water sample is from a Sioux Quartzite aquifer well.*

** - Indicates the water sample was collected from a pumping well used for an aquifer test.

Three of the six water samples collected from wells in the Sioux Quartzite aquifer were above 15 pCi/L (primary drinking water standard) and ten of the 18 water samples collected from the Split Rock Creek aquifer were also above 15 pCi/L. The only detectable geographic trend in the data appears to be a clustering of high values (above 15 pCi/L) in the area near the Watrec PW, near the western boundary of the main body of the aquifer. Currently, it is unclear why this trend occurs in this area.

Occurrence of Stable Hydrogen and Oxygen Isotopes

Hydrogen has three isotopes in nature, which were discussed in the section on tritium. Oxygen also has three naturally occurring isotopes, all of which are stable: 1) ^{16}O, the most common, 2) ^{17}O, which is rare, and 3) ^{18}O, which is less rare (Mazor, 1991).

Deuterium (D) and ^{18}O have greater atomic mass than ^{1}H and ^{16}O, respectively. Water, which is made of 2 atoms of hydrogen and 1 of oxygen, can be made of any combination of the isotopes of hydrogen and oxygen, with most of the water molecules formed of the most common isotopes.

During evaporation, isotopically lighter water molecules evaporate more efficiently as they have a higher vapor pressure, with residual water enriched in heavier water molecules. This isotopic separation is referred to as fractionation. Evaporated water eventually forms clouds with a lighter isotopic composition than the ocean which supplied the water. When cloud vapor condenses to form rain, fractionation occurs again. The heavier water molecules condense more efficiently, leaving behind cloud vapor even more depleted of the stable isotopes D and ^{18}O (Mazor, 1991).

The stable isotope composition is usually reported as a relative deviation from the ratio of the standard reference material SMOW -- standard mean ocean water (Craig, 1961) as follows:

$$\delta D = ((D/H_{sample} - D/H_{SMOW}) / (D/H_{SMOW})) \times 1000‰$$

and

$$\delta^{18}O = ((\,^{18}O/^{16}O_{sample} - \,^{18}O/^{16}O_{SMOW}) / (\,^{18}O/^{16}O_{SMOW})) \times 1000‰$$

Therefore, the more isotopically light (less D or less ^{18}O) the water is, the more negative the δ value, while water with more D or ^{18}O than SMOW would have a positive δ value (Fritz and Fontes, 1980).

Craig (1961) showed that global meteoric water analyzed for D and ^{18}O, if plotted with δD on the Y axis and $\delta^{18}O$ on the X axis, plot in a straight line referred to as the Meteoric Water Line (MWL). His equation describing this best fit line is:

$$\delta D = 8\,\delta^{18}O + 10$$

If a meteoric water sample does not plot on or near this best-fit line, it indicates that the water has undergone extensive fractionation, often due to intense evaporation or a much different climatic regime than that of the present (Mazor, 1991).

Dansgaard (1964) showed that the equation for the MWL of the Northern Hemisphere is $\delta D = (8.1 \pm 1)\,\delta^{18}O + (11 \pm 1)$. This Northern Hemisphere MWL is nearly identical to Craig's (1961) global MWL. Dansgaard (1964) also showed that temperature is the major parameter that determines this isotopic value of precipitation. He showed that there is a linear correlation between the mean annual isotopic composition and the local mean annual air temperature. The net effect of temperature on isotopic composition is expressed in the following relationships:

$$\delta^{18}O = 0.69\,T_a - 13.6\,‰\text{, and}$$

$$\delta\,D = 5.6T_a - 100.0\,‰\text{,}$$

where T_a is the mean annual air temperature in degrees Celsius.

The present-day mean annual air temperature in the Sioux Falls area is approximately 7.8 °C (Spuhler and others, 1971 and Bender, 1995, verbal communication). Solving the above equations for this annual air temperature results in $\delta^{18}O = -8.2$ and $\delta D = -56$. A composite sample of annual, present-day precipitation in the Sioux Falls area should plot on the MWL with approximately these values. Craig (1961), Dansgaard (1964), Fritz and Fontes (1980), and Mazor (1991) provide a more detailed explanation of ^{18}O and D.

Stable Isotope Results. δD and $\delta^{18}O$ analyses of the fifteen water samples collected for this study are listed in table 11. Samples were collected from six wells completed in the Split Rock Creek aquifer and from nine wells completed in the Sioux Quartzite aquifer (figures 9, 10, and 22).

Table 11. Laboratory Results of Oxygen-18 and Deuterium Analyses.

Well ID	Date Sampled	$\delta^{18}O$	δD
Q1*	08/15/91	-61	-8.8
Q2a*	08/15/91	-68	-10.8
Q4*	08/15/91	-61	-9.4
Q5*	08/15/91	-67	-9.8
Q6*	08/15/91	-62	-9.5
Q7*	08/15/91	-68	-10.1
Q8*	08/15/91	-66	-9.5
Q9*	08/15/91	-64	-9.8
Q10*	08/15/91	-57	-8.5
SRC-18A	08/15/91	-77	-11.8
SRC-41	08/15/91	-66	-10.1
SRC-43	08/15/91	-77	-11.2

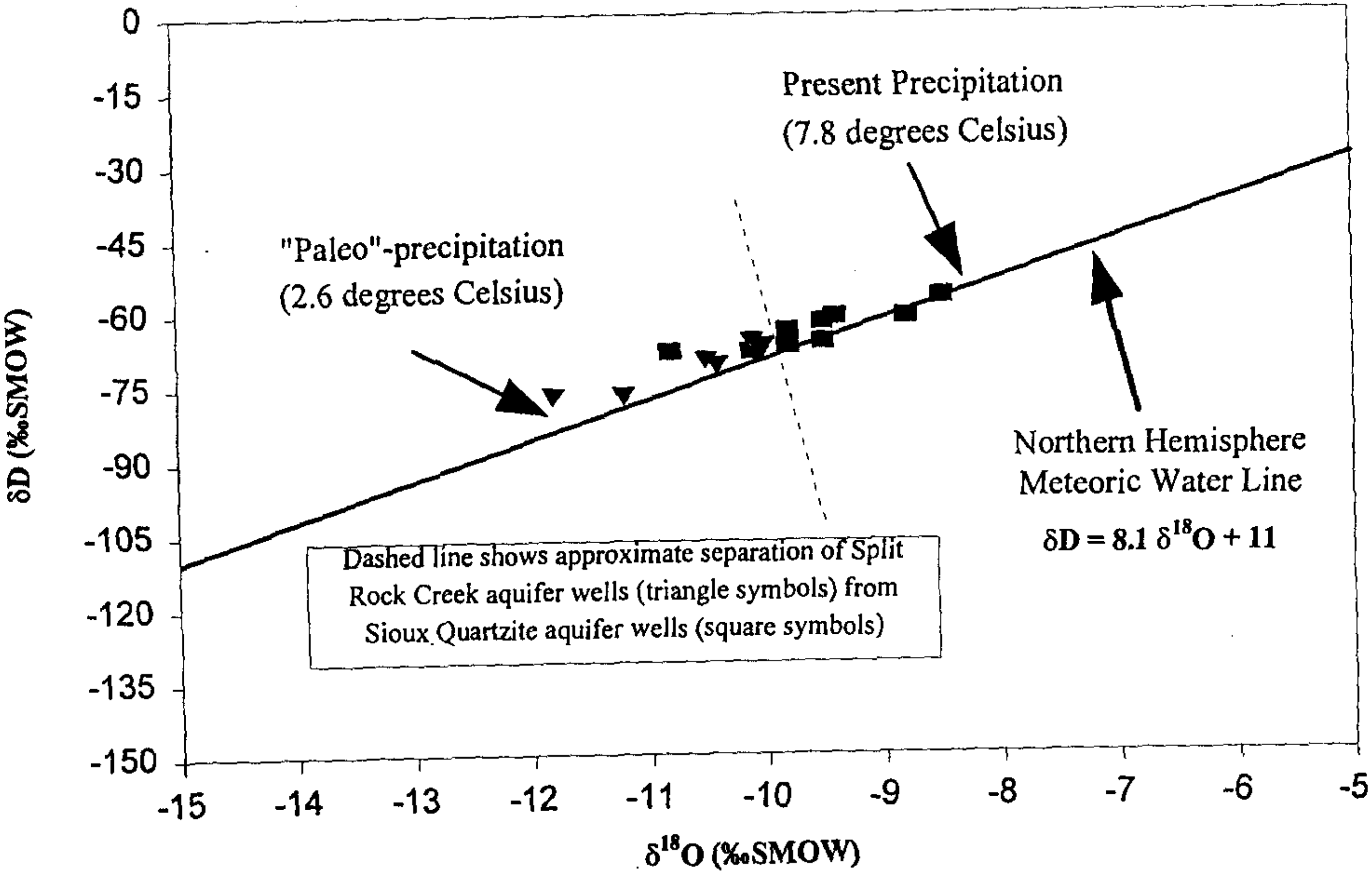
Table 11 continued.

Well ID	Date Sampled	$\delta^{18}O$	δD
NSP-3 PW**	08/15/91	-67	-10.0
Watrec PW**	08/15/91	-71	-10.4
Brandon PW**	08/15/91	-70	-10.5

Duplicate samples were not run and error limits were not reported by the laboratory.
* - Indicates the water sample is from a Sioux Quartzite aquifer well.
** - Indicates the water sample was collected from a pumping well used for an aquifer test.

The data plot on or very near the Northern Hemisphere MWL (figure 37). This indicates that the waters in the Split Rock Creek aquifer and in the Sioux Quartzite aquifer are meteoric in origin and have not been modified by intense evaporation (Mazor, 1991).

Application of Dansgaard's (1964) temperature relationships to these samples indicates that the average annual air temperatures, when these waters fell as meteoric water, ranged from 7.8 °C to 2.6 °C (figure 37). Note that most of the samples which plot on the lower left side of the MWL, closer to the lower temperatures, are from wells completed in the Split Rock Creek aquifer, whereas most samples from the Sioux Quartzite aquifer plot towards warmer temperatures, on the upper right side of the MWL.



Dashed line shows approximate separation of Split Rock Creek aquifer wells (triangle symbols) from Sioux Quartzite aquifer wells (square symbols)

Figure 37. Stable Isotope Results

IV. DISCUSSION

Evidence of Recharge

Evidence for recharge to the Split Rock Creek aquifer is indicated by aquifer test, water level, and water-chemistry data.

Aquifer-Tests

Measurements taken during the Watrec and '95 SRC aquifer tests indicated full recovery of water-levels had taken place. Also, positive boundaries were encountered during the Renner and Brandon aquifer tests, indicating possible recharge, or areas of higher transmissivity had been encountered.

Water Levels

Examination of the potentiometric surface of the Split Rock Creek aquifer (figures 31, 32, and 33) show converging flow of ground water in areas near the Big Sioux River. This appears to result from ground-water discharge from the Split Rock Creek aquifer into the Big Sioux aquifer. Discharge is likely to occur in those areas where only siltstones separate the two aquifers or where incision and deposition of glacial outwash has occurred in the Split Rock Creek Formation.

Discharge of water from the Split Rock Creek aquifer is confirmed by the general trend of water levels observed in the aquifer prior to production pumping. Examination of SRC-41 hydrograph (figure 25) indicates a downward trend in water levels from approximately 1987 to 1991. Because municipal aquifer pumping was not occurring during this time, the decrease in water levels can be associated only with natural discharge. During the years 1987 to 1991, below normal precipitation occurred in the area; therefore, recharge was less than discharge and water levels declined. The corresponding increase in water levels from approximately 1991 to 1994, years of above normal precipitation, indicates recharge exceeding discharge.

Water level data gathered near Brandon's production well and Sioux Falls' production wells (figure 28) show recovery of water to levels higher than pre-pumping levels, indicating recharge to the aquifer has occurred.

Water Chemistry

Inorganic Water Chemistry

The water quality of the Sioux Quartzite aquifer, especially in those wells close to outcrop areas, also suggests recent recharge to the Sioux Quartzite aquifer. This is based on low inorganic ion and TDS (especially wells Q1, Q2a, Q2b, Q6, Q9, and Q10; their TDS concentrations are all below 500 ppm) which may indicate meteoric water has not had sufficient residence time to elevate TDS and ion concentrations. Unfortunately, limited water-chemistry data are available for the Sioux Quartzite aquifer, and geochemical evolution of the water in this aquifer is unknown.

Another indicator of recent recharge in wells Q1, Q2a, and Q2b are elevated levels of nitrate + nitrite (8.28, 14.60, and 2.97 ppm, respectively). Nitrate values above 2 to 3 ppm are often associated with agricultural activities (fertilizers and feedlots) and septic systems (Madison and Brunett, 1984 and Hallberg, 1989). Based on visual observation at monitoring well Q7, the elevated nitrate + nitrite concentration (4.33 ppm) at this site may be due to surface contamination leaking around the casing.

Elevated nitrate + nitrite was also observed at SRC-11 (5.0 ppm), which is completed in the western part of the Split Rock Creek aquifer (figure 9). This concentration is likely due to surface contamination that had entered the well, as this well had been broken off and recently repaired.

No other anomalous parameters, other than nitrate + nitrite, were observed in any of the samples; therefore, no other inorganic ion tracers are available to indicate recent recharge or recharge of waters from one aquifer to another. Because water quality is similar in the three aquifers, water-level data must be used to infer possible flow directions from one aquifer to another.

Tritium

Tritium analyses do not conclusively prove that recharge occurs. These analyses indicate that essentially no tritium is present in the ground-water samples collected from the

Split Rock Creek aquifer. This suggests that very little post-bomb (after 1952) water has entered the aquifer, or if post-bomb water has entered the aquifer, it has entered in small quantities that have been diluted by water already in the aquifer.

Radiocarbon

Radiocarbon analyses also indicate that recharge to the Split Rock Creek aquifer has occurred. The formation that comprises the Split Rock Creek aquifer is Upper Cretaceous, approximately 100 million years old, based on Kairo's (1987) work. If no recharge has reached the aquifer since deposition (only connate water present), no measurable radiocarbon would be present in the formation. Radiocarbon results show that the ground water from this aquifer is only several thousand years old, indicating that post-depositional recharge has occurred. If more recent recharge (hundreds or tens of years ago) has entered the aquifer, it has been diluted by the water already in the aquifer.

Fritz and others (1979) and Fritz and Fontes (1980) found that plants in semi-arid regions have a $\delta^{13}C$ value near -14‰ and plants in temperate regions have a $\delta^{13}C$ value near -23‰. The present-day climate in the study area is temperate and it is likely that conditions have been similar since the last glacial advance. Therefore, it is likely that the plants in the recharge zone(s) of the study area have had a $\delta^{13}C$ value near -23‰, although analyses of the $\delta^{13}C$ values of the vegetation in the recharge areas have not been conducted.

Upon initially entering the ground-water system, recharge waters will have a $\delta^{13}C$ value similar to that of the plants in the recharge area. Analysis of water from the Split

Rock Creek aquifer indicates that the $\delta^{13}C$ values of the aquifer waters are more enriched in $\delta^{13}C$ (less negative values) than the assumed $\delta^{13}C$ values of the recharge water. This indicates isotopic fractionation has occurred as a result of interaction with geologic materials in the subsurface. These interactions have had the result of adding older carbonate to the water, which resulted in calculated ages older than the true age. Using $\delta^{13}C$ values to correct for these interactions yields younger calculated ages than using only the PMC values.

Stable Isotopes

Stable isotope analyses indicate the ground water within the Split Rock Creek and Sioux Quartzite aquifers are meteoric in origin, and have been recharged in a climate cooler than that of present day. The climatic signatures of these samples indicate possible post-glacial recharge with pathline migration of Sioux Quartzite waters into the Split Rock Creek aquifer.

Sources of Recharge

Data collected during this study indicate that recharge to the Split Rock Creek aquifer does occur. Identification of the source(s) of this recharge relies upon examination of the following data: boundaries encountered during aquifer pumping tests, water-levels and flow directions, permeability of overlying layers, and water chemistry.

Aquifer-Test Boundaries

Although analysis of the boundaries encountered at the Renner aquifer-test location site was inconclusive, it is likely that the boundaries encountered are the result of recharge. Because the aquifer thickness is consistent in this area, the boundary is likely not the result of the cone of depression expanding into higher transmissivity areas of the aquifer. The aquifer is in a narrow valley (approximately 1 mile wide) in this area and the Big Sioux River is located within 1,300 feet. Therefore, it is possible that recharge may be occurring from the river or the Sioux Quartzite aquifer, or a combination of both.

The boundary encountered during the Brandon aquifer test may be the result of the cone of depression encountering areas of higher transmissivity, such as those that occur less than one-half mile south of the production well (figures 7 and 10). These higher transmissivities south of the production well result from the sands exceeding 200 feet in thickness, compared to approximately 70 feet at the production well.

It is also possible that the boundary results from recharge through surficial outwash and alluvium associated with Split Rock Creek to the east and north of the production well. In this area the two aquifers are separated only by fractured siltstones (figure 8). Water elevations at nested well site SRC-35 on June 20, 1989, just one week after the termination of the pumping phase of the Brandon aquifer test, showed a small upward gradient of +0.01.

Unfortunately, water levels were not measured in either well during the Brandon aquifer test; but the calculated drawdown (based on distance-drawdown data) at the end of the pumping phase was 1.5 feet, creating a downward gradient in this general area. As a result of this downward gradient during pumping, and the permeable siltstones separating the two aquifers, it is possible that recharge may have been induced from the surficial aquifer in this general area.

During the '95 SRC test the drawdown observed at SRC-35, approximately 7,500 feet away, was 0.57 feet. The gradient at the start of test was +0.18 and was +0.15 at the end of pumping; therefore, drawdown was insufficient to reverse the gradient and induce recharge (leakage) into the aquifer at this location. Hantush (1960) analysis of the time-drawdown data from this well also shows no vertical leakage.

The storativity of the aquifer at the SRC-35 site was estimated at 5.3×10^{-3}, higher than expected. Because the upward gradient became less during pumping, reduced discharge may have occurred from the Split Rock Creek aquifer to overlying units. If less discharge were occurring in this area, more water would be available from storage, possibly resulting in the higher storativity value.

At well site SRC-37, 3,050 feet from the production well, Hantush analysis (Appendix B) also indicated a higher storativity value than expected, 1.6×10^{-3}, and potential leakage from overlying units. The storativity value may have resulted from the same reasons as the high storativity value at SRC-35; however, 1,200 feet east of this location, in the Split Rock Creek valley, drawdowns would have been sufficient to create a downward gradient, and cause leakage (induced recharge) from the overlying surficial aquifer.

Water Levels and Flow Directions

Direct meteoric recharge occurs to the shallow Big Sioux aquifer and the highly fractured Sioux Quartzite where it is exposed or covered by a thin veneer of sediment, and recharge to the Split Rock Creek aquifer likely occurs indirectly from both the Sioux Quartzite and Big Sioux aquifers.

The Split Rock Creek aquifer sands do not crop out in the study area and are normally overlain by many feet of till. In areas where till overlies the aquifer, gradients are downward; however, based on baildown tests, the unweathered tills have a very low permeability that effectively prevents direct infiltration of recharge water in these areas.

In the river valleys, where tills are absent, areas exist where relatively permeable siltstones separate the Split Rock Creek aquifer from overlying outwash and alluvium. In one area of the Big Sioux River valley, the Split Rock Creek aquifer appears to be in direct connection with the overlying Big Sioux aquifer. Due to the upward gradient in these river valleys, discharge from the Split Rock Creek aquifer is occurring. Aquifer pump-test data indicate the possibility of induced recharge in these areas if the Split Rock Creek aquifer is stressed sufficiently to cause a downward gradient.

Water elevations in the Sioux Quartzite aquifer (figure 34) are similar to water levels observed in adjacent areas of the Split Rock Creek aquifer (figure 33), suggesting a possible hydraulic connection between the two units. Flow generally occurs toward the main body of the Split Rock Creek aquifer, indicating recharge from the Sioux Quartzite aquifer.

In the main part of the Split Rock Creek aquifer, near the Minnesota border, ground-water flow is towards the west-southwest, indicating recharge to the aquifer from adjoining areas of Minnesota. Water-level data from the Sioux Quartzite aquifer in Minnesota (Anderson and others, 1976) agree with data collected for this study; therefore, the Split Rock Creek aquifer in Minnesota may also be receiving recharge from the Sioux Quartzite.

Water Chemistry

Stable Isotopes

Although the stable isotope analyses cannot directly indicate the age of the water in the Split Rock Creek aquifer, the data can be used to indicate the annual mean meteoric water temperature of the recharge water. Figure 37 shows where a composite annual sample of modern-day (present) precipitation would plot (7.8 °C), equivalent to modern-day infiltration and recharge. A sample with a climatic signature of 2.6 °C is also shown on figure 37. All of the samples collected for this study fall within this range of temperatures.

The stable isotope data also show that most of the samples that plot towards the colder temperatures on the MWL are from wells completed in the Split Rock Creek aquifer, and samples that plot on the warmer end of the MWL are mainly from wells completed in the Sioux Quartzite aquifer. This indicates that waters from the Split Rock Creek aquifer have a colder climatic signature. Meteoric water, shortly after the last ice age (approximately 10,000 years ago) would plot near the "Paleo"-precipitation (figure 37). As the climate has slowly warmed since the last ice age, meteoric water would begin to have a warmer climatic signature, and may provide the trend of less negative $\delta^{18}O$ and δD (figure 37).

Because the water from the Split Rock Creek aquifer has a colder climatic signature than water from the Sioux Quartzite aquifer, the stable isotope data may indicate more recent recharge has occurred to the Sioux Quartzite aquifer, while water in the Split Rock Creek aquifer is older (recharged slowly after the warming which followed the last Ice Age). The approximate ages associated with the climatic signature of waters from the Split Rock Creek aquifer compare well with ages obtained from radiocarbon analyses. These results show the ages of Split Rock Creek water range from approximately 3,000 to 10,000 years. Unfortunately, no radiocarbon analyses are available from water within the Sioux Quartzite aquifer to verify this pathline evolution of recharge water.

Although no radiocarbon data are available for water within the Sioux Quartzite aquifer, inorganic water quality data show nitrate present in several of the Sioux Quartzite aquifer wells. The presence of nitrate above 2-3 ppm potentially indicates recent recharge to the Sioux Quartzite aquifer in some areas.

Gross Alpha and Uranium

The Proterozoic Sioux Quartzite, which directly underlies the Split Rock Creek aquifer, and thought to be a potential source of recharge to the Split Rock Creek aquifer, has several layers of quartz-pebble conglomerates. Similar Proterozoic quartz-pebble conglomerates have been identified as potentially containing large deposits of uranium, the most common source of gross alpha radiation identified (Chadima, 1989; Brobst and Pratt, 1973; Klepper and Wyant, 1957). The Sioux Quartzite may potentially contain large deposits of uranium (Cheney, 1981; Southwick and others, 1982; Ansfield, 1981).

Because of the elevated levels of uranium within the quartzite, the ground water within the quartzite would also contain elevated levels of gross alpha radiation. Gross alpha and uranium measurements conducted by Southwick and Lively (1985), Michel and Jordana (1989), and for this study (table 10), have indicated that elevated levels of gross alpha radiation are present in the waters of the Sioux Quartzite aquifer.

The elevated levels of gross alpha radiation and uranium observed in many Split Rock Creek aquifer wells may be due to water that originated in the underlying Sioux Quartzite. As meteoric water enters the fractures in the quartzite in recharge areas and moves through the quartzite into the Split Rock Creek aquifer, the concentration of alpha radiation and uranium increase.

The gross alpha radiation and uranium may be coming directly from the Split Rock Creek Formation itself. Many layers of black, organic-rich shales are present within the lower sandy part of the formation. As stated in Mason and Moore (1982), these shales are deposited slowly in strongly reducing marine environments which allow uranium to precipitate. Measurements of uranium within Cretaceous shales in Minnesota, adjacent to this study area, indicate higher levels than those measured in the Sioux Quartzite (Southwick and Lively, 1985). Southwick and Lively's (1985) work indicates mean concentrations of uranium in the Cretaceous shales are approximately twice those in the

Sioux Quartzite, and the median concentrations of uranium in the Cretaceous shales are approximately 4.5 times greater than those in the Sioux Quartzite.

The Split Rock Creek aquifer sands may also supply the alpha radiation and uranium. Because these sands which comprise the Split Rock Creek aquifer are the result of weathering of the Sioux Quartzite, uranium from the Sioux Quartzite may have been directly deposited with these sands.

It is also possible that the alpha radiation and uranium may be a combination of recharge water moving through the quartzite, the black shale layers within the formation, and the uranium-bearing sands within the formation.

V. CONCLUSIONS

Results

The Split Rock Creek aquifer exists in paleo-valleys in the highly fractured Precambrian Sioux Quartzite. The aquifer sands of this Cretaceous formation are weathered and eroded Sioux Quartzite. Aquifer thickness in the main portion of the aquifer, between Brandon and Valley Springs, exceeds 200 feet. Inorganic water-quality analyses indicate the best quality water is also present in the main portion of the aquifer.

Recharge is indicated by water-level and water-chemistry data. Water levels in the aquifer increase during years of above normal precipitation, enough to offset the approximately 292 million gallons of annual municipal pumping by Sioux Falls and Brandon. Radiocarbon data indicate the age of the aquifer water is between 3,000 and 10,000 years, and stable isotope data indicate the aquifer waters are meteoric.

A downward gradient exists between the Split Rock Creek aquifer and the water table in most of the study area; however, the low permeability of the overlying tills in these areas precludes the possibility of significant recharge water percolating downward through these tills. An upward gradient exists in the Big Sioux River and Split Rock Creek valleys. In localized areas of these valleys fractured siltstones separate the Split Rock Creek aquifer from surficial aquifers. As a result of the upward gradient and the fractured siltstones, discharge occurs to the overlying units. During aquifer pumping it is possible to lower the potentiometric surface of the aquifer enough to create a downward gradient; thus, inducing recharge into the Split Rock Creek aquifer.

Ground-water flow directions in the Split Rock Creek aquifer and underlying Sioux Quartzite indicate the main source of recharge is the Sioux Quartzite aquifer. This recharge occurs at the lateral margins and base of the Split Rock Creek aquifer.

Application of Results

Because recharge to the aquifer does occur, the aquifer can be developed as a dependable source of water for the city of Sioux Falls. Information from this study will be used in assisting the city to locate and develop additional well fields in areas of the aquifer with the best water quality, production capability, and induced recharge capability.

Additional Investigation

Collection of additional data would be useful in more precise determination of the recharge mechanisms of the Split Rock Creek aquifer. These data include radiocarbon analyses of Sioux Quartzite aquifer waters, especially samples collected from those wells that were analyzed for D and ^{18}O. This radiocarbon information would be used to verify the pathline of flow from possible recharge areas into the Split Rock Creek aquifer. Additional sampling of the vegetation in the recharge areas to determine the $\delta^{13}C$ values would also aid in determination of the absolute age of the aquifer waters.

Gross alpha and uranium analysis of samples from the black shale layers within the basal sands of the Split Rock Creek aquifer would be useful in determining if the alpha radiation is a result of recharge from the Sioux Quartzite aquifer or from shale layers within the Split Rock Creek Formation.

Collection of additional water levels should also be used in the determination of mechanisms of recharge. Where data are limited within the Sioux Quartzite aquifer, additional private wells should be located or monitoring wells installed. The additional water-level data from the Sioux Quartzite would allow more accurate delineation of flow directions within the Sioux Quartzite, which would be useful in locating recharge and discharge areas within the Sioux Quartzite aquifer.

Collection of water levels within the Split Rock Creek aquifer, the Sioux Quartzite aquifer, and surficial outwash and alluvial aquifers during periods of extended, high-capacity pumping would be useful in determining the hydraulic connection between these units when the Split Rock Creek aquifer is stressed by pumping. These water-level data, along with pumping data, will allow possible quantification of induced recharge to the aquifer.

APPENDIX A: RAW DATA FOR TIME-DRAWDOWN GRAPHS SHOWN IN THE TEXT AND BRIEF WELL CONSTRUCTION SUMMARIES

WELL SRC-36

Well-Construction Summary

Depth (feet)	Lithology
0-2	topsoil
2-12	fine sand
12-25	tan silty clay
25-52	medium to coarse sand
52-86	gray pebbly clay (till)
86-92	medium sand
92-102	gray silty clay (till)
102-112	fine sand
112-135	black siltstone
135-150	black shale
150-219	fine sand
219-222	gray clay

Borehole Diameter:	5.5 inches
Casing Size:	2 inch
Casing Type:	PVC
Stickup:	2 feet
Screen Length:	15 feet
Slot Size:	0.010 inches
Depth of Screen:	202.5-217.5 feet

Coarse quartz sand filter pack around screen.

Bentonite grout from filter pack to land surface.

BRANDON AQUIFER TEST

SRC-36 DRAWDOWN DATA

Distance from pumping well = 101 feet

Pumping rate = 50,000 cubic feet per day

Date	Time	Water Level (feet from casing top)	Time (min)	Drawdown (ft)	Log of time
6/26/89	10:25	52.90			
6/26/89	11:40	52.91			
6/26/89	12:00	52.96	-5	0.00	
6/26/89	12:06	55.15	1	-2.19	0.00
6/26/89	12:07	55.76	2	-2.80	0.30
6/26/89	12:08	56.14	3	-3.18	0.48
6/26/89	12:09	56.42	4	-3.46	0.60
6/26/89	12:10	56.65	5	-3.69	0.70
6/26/89	12:11	56.87	6	-3.91	0.78
6/26/89	12:12	57.05	7	-4.09	0.85
6/26/89	12:13	57.22	8	-4.26	0.90
6/26/89	12:14	57.36	9	-4.40	0.95
6/26/89	12:15	57.48	10	-4.52	1.00
6/26/89	12:17	57.73	12	-4.77	1.08
6/26/89	12:19	57.94	14	-4.98	1.15
6/26/89	12:21	58.14	16	-5.18	1.20
6/26/89	12:23	58.32	18	-5.36	1.26
6/26/89	12:25	58.48	20	-5.52	1.30
6/26/89	12:31	58.93	25	-5.97	1.40
6/26/89	12:36	59.24	31	-6.28	1.49
6/26/89	12:41	59.53	36	-6.57	1.56
6/26/89	12:46	59.78	41	-6.82	1.61
6/26/89	12:51	60.01	46	-7.05	1.66

6/26/89	12:56	60.26	51	-7.30	1.71
6/26/89	13:01	60.45	56	-7.49	1.75
6/26/89	13:11	60.84	66	-7.88	1.82
6/26/89	13:25	61.35	80	-8.39	1.90
6/26/89	13:33	61.59	88	-8.63	1.94
6/26/89	13:44	61.87	99	-8.91	2.00
6/26/89	13:56	62.12	111	-9.16	2.05
6/26/89	14:04	62.36	119	-9.40	2.08
6/26/89	14:21	62.73	136	-9.77	2.13
6/26/89	14:43	63.14	158	-10.18	2.20
6/26/89	15:04	63.48	179	-10.52	2.25
6/26/89	15:36	63.96	211	-11.00	2.32
6/26/89	16:06	64.28	241	-11.32	2.38
6/26/89	17:03	64.85	298	-11.89	2.47
6/26/89	18:03	65.30	358	-12.34	2.55
6/26/89	19:03	65.66	418	-12.70	2.62
6/26/89	20:03	65.96	478	-13.00	2.68
6/26/89	21:03	66.21	538	-13.25	2.73
6/26/89	22:03	66.42	598	-13.46	2.78
6/26/89	23:03	66.61	658	-13.65	2.82
6/27/89	00:10	66.76	725	-13.80	2.86
6/27/89	01:00	66.86	775	-13.90	2.89
6/27/89	02:05	66.97	840	-14.01	2.92
6/27/89	03:05	67.11	900	-14.15	2.95
6/27/89	04:06	67.24	961	-14.28	2.98
6/27/89	05:05	67.32	1020	-14.36	3.01
6/27/89	06:05	67.36	1080	-14.40	3.03
6/27/89	09:03	67.60	1258	-14.64	3.10
6/27/89	10:03	67.65	1318	-14.69	3.12
6/27/89	11:17	67.71	1392	-14.75	3.14
6/27/89	12:03	67.75	1438	-14.79	3.16
6/27/89	15:11	67.83	1626	-14.87	3.21
6/27/89	18:06	67.91	1801	-14.95	3.26
6/28/89	00:05	68.08	2160	-15.12	3.33
6/28/89	07:06	68.29	2581	-15.33	3.41
6/28/89	12:04	68.30	2879	-15.34	3.46

6/28/89	18:04	68.42	3239	-15.46	3.51
6/28/89	22:05	68.48	3480	-15.52	3.54
6/29/89	06:05	68.55	3960	-15.59	3.60
6/29/89	11:02	68.58	4257	-15.62	3.63
6/29/89	12:00	68.58	4315	-15.62	3.63

WELL SRC-37

Well-Construction Summary

Depth (feet)	Lithology
0-2	topsoil
2-38	fine sand
38-48	gravel
48-82	gray pebbly clay (till)
82-119	fine to coarse sand
119-145	black siltstone
145-164	black shale
164-228	fine sand
228-235	black clay

Borehole Diameter:	5.5 inches
Casing Size:	2 inch
Casing Type:	PVC
Stickup:	2 feet
Screen Length:	20 feet
Slot Size:	0.010 inches
Depth of Screen:	203.5-223.5 feet

Coarse quartz sand filter pack around screen.

Bentonite grout from filter pack to land surface.

BRANDON AQUIFER TEST

SRC-37 DRAWDOWN DATA

Distance from pumping well = 589 feet

Pumping rate = 50,000 cubic feet per day

Date	Time	Water Level (feet from casing top)	Time (min)	Drawdown (ft)	Log of time
6/26/89	11:42	54.46			
6/26/89	12:00	54.46			
6/26/89	12:01	54.46			
6/26/89	12:02	54.47			
6/26/89	12:03	54.48			
6/26/89	12:04	54.48			
6/26/89	12:05	54.48	0	0.00	
6/26/89	12:06	54.53	1	-0.05	0.00
6/26/89	12:07	54.63	2	-0.15	0.30
6/26/89	12:08	54.73	3	-0.25	0.48
6/26/89	12:09	54.85	4	-0.37	0.60
6/26/89	12:10	54.96	5	-0.48	0.70
6/26/89	12:12	55.14	7	-0.66	0.85
6/26/89	12:14	55.32	9	-0.84	0.95
6/26/89	12:16	55.57	11	-1.09	1.04
6/26/89	12:18	55.65	13	-1.17	1.11
6/26/89	12:20	55.79	15	-1.31	1.18
6/26/89	12:25	56.14	20	-1.66	1.30
6/26/89	12:30	56.44	25	-1.96	1.40
6/26/89	12:35	56.73	30	-2.25	1.48
6/26/89	12:40	56.97	35	-2.49	1.54
6/26/89	12:45	57.21	40	-2.73	1.60
6/26/89	12:50	57.43	45	-2.95	1.65

6/26/89	12:55	57.64	50	-3.16	1.70
6/26/89	13:00	57.83	55	-3.35	1.74
6/26/89	13:10	58.16	65	-3.68	1.81
6/26/89	13:20	58.48	75	-4.00	1.88
6/26/89	13:30	58.76	85	-4.28	1.93
6/26/89	13:40	59.02	95	-4.54	1.98
6/26/89	13:50	59.25	105	-4.77	2.02
6/26/89	14:00	59.48	115	-5.00	2.06
6/26/89	14:20	59.87	135	-5.39	2.13
6/26/89	14:40	60.23	155	-5.75	2.19
6/26/89	15:00	60.56	175	-6.08	2.24
6/26/89	15:30	60.98	205	-6.50	2.31
6/26/89	16:00	61.27	235	-6.79	2.37
6/26/89	17:00	61.84	295	-7.36	2.47
6/26/89	18:00	62.27	355	-7.79	2.55
6/26/89	19:00	62.61	415	-8.13	2.62
6/26/89	20:00	62.88	475	-8.40	2.68
6/26/89	21:00	63.11	535	-8.63	2.73
6/26/89	22:00	63.31	595	-8.83	2.77
6/26/89	23:00	63.51	655	-9.03	2.82
6/27/89	00:00	63.68	715	-9.20	2.85
6/27/89	01:00	63.75	775	-9.27	2.89
6/27/89	02:00	63.87	835	-9.39	2.92
6/27/89	03:00	63.98	895	-9.50	2.95
6/27/89	04:00	64.02	955	-9.54	2.98
6/27/89	05:00	64.13	1015	-9.65	3.01
6/27/89	06:00	64.21	1075	-9.73	3.03
6/27/89	09:00	64.41	1255	-9.93	3.10
6/27/89	10:00	64.46	1315	-9.98	3.12
6/27/89	11:14	64.52	1389	-10.04	3.14
6/27/89	12:00	64.54	1435	-10.06	3.16
6/27/89	15:05	64.66	1620	-10.18	3.21
6/27/89	18:00	64.72	1795	-10.24	3.25
6/28/89	00:00	64.89	2155	-10.41	3.33
6/28/89	07:00	65.07	2575	-10.59	3.41
6/28/89	12:00	65.13	2875	-10.65	3.46

6/28/89	18:00	65.18	3235	-10.70	3.51
6/28/89	22:00	65.24	3475	-10.76	3.54
6/29/89	06:00	65.30	3955	-10.82	3.60
6/29/89	11:00	65.38	4255	-10.90	3.63
6/29/89	12:00	65.37	4315	-10.89	3.63

"SE WELL"

Well-Construction Summary

Depth (feet)	Lithology
0-8	black and brown alluvial clay
8-42	medium brown sand and gravel
42-56	gray silty clay; unoxidized (till)
56-68	yellow-brown silty clay; oxidized (till)
68-72	brown medium sand
72-92	yellow-brown silty clay; oxidized (till)
92-100	pinkish silty clay
100-111	black siltstone
111-118	gray shale
118-133	black siltstone
133-160	black shale
160-170	fine pink sand
170-171	quartzite

Borehole Diameter:	5.5 inches
Casing Size:	2 inch
Casing Type:	PVC
Stickup:	2 feet
Screen Length:	5 feet
Slot Size:	0.010 inches
Depth of Screen:	160-170 feet

Coarse quartz sand filter pack around screen.
Bentonite grout from filter pack to land surface.

RENNER AQUIFER TEST

"SE WELL" DRAWDOWN DATA

Distance from pumping well = 545.53 feet

Pumping rate = 9,800 cubic feet per day

Date	Time	Water Level (feet from casing top)	Time (min)	Drawdown (ft)	Log of time
2/13/89	12:00	8.21	0	0.00	
2/13/89	12:01	8.28	1	-0.07	0.00
2/13/89	12:02	8.26	2	-0.05	0.30
2/13/89	12:03	8.25	3	-0.04	0.48
2/13/89	12:04	8.27	4	-0.06	0.60
2/13/89	12:10	8.28	10	-0.07	1.00
2/13/89	12:12	8.28	12	-0.07	1.08
2/13/89	12:16	8.31	14	-0.10	1.15
2/13/89	12:20	8.31	16	-0.10	1.20
2/13/89	12:25	8.31	18	-0.10	1.26
2/13/89	12:30	8.37	20	-0.16	1.30
2/13/89	12:35	8.40	25	-0.19	1.40
2/13/89	12:40	8.55	30	-0.34	1.48
2/13/89	12:45	8.60	35	-0.39	1.54
2/13/89	12:50	8.64	40	-0.43	1.60
2/13/89	12:55	8.78	45	-0.57	1.65
2/13/89	13:00	8.90	50	-0.69	1.70
2/13/89	13:10	8.98	55	-0.77	1.74
2/13/89	13:20	9.01	60	-0.80	1.78
2/13/89	13:30	9.16	70	-0.95	1.85
2/13/89	13:40	9.23	80	-1.02	1.90
2/13/89	14:00	9.30	90	-1.09	1.95
2/13/89	14:30	9.32	100	-1.11	2.00

2/13/89	15:00	9.40	120	-1.19	2.08
2/13/89	15:30	9.47	150	-1.26	2.18
2/13/89	16:00	9.55	180	-1.34	2.26
2/13/89	17:00	9.60	210	-1.39	2.32
2/13/89	18:00	9.66	240	-1.45	2.38
2/13/89	19:00	9.73	300	-1.52	2.48
2/13/89	20:00	9.85	360	-1.64	2.56
2/13/89	21:00	9.92	420	-1.71	2.62
2/13/89	22:00	9.97	480	-1.76	2.68
2/13/89	23:00	9.99	540	-1.78	2.73
2/13/89	00:00	10.02	600	-1.81	2.78
2/13/89	02:00	10.03	660	-1.82	2.82
2/14/89	04:00	10.00	720	-1.79	2.86
2/14/89	06:00	9.94	840	-1.73	2.92
2/14/89	08:00	9.90	960	-1.69	2.98
2/14/89	10:00	9.90	1080	-1.69	3.03
2/14/89	12:00	9.96	1200	-1.75	3.08
2/14/89	10:00	9.99	1320	-1.78	3.12
2/14/89	12:00	10.00	1440	-1.79	3.16

"NW WELL"

Well-Construction Summary

Depth (feet)	*Lithology*
0-10	black and brown alluvial clay
10-40	medium brown sand and gravel
40-57	gray silty clay; unoxidized (till)
57-66	yellow-brown silty clay; oxidized (till)
66-74	brown medium sand
74-92	yellow-brown silty clay; oxidized (till)
92-102	pinkish silty clay
102-114	black siltstone
114-118	gray shale
118-134	black siltstone
134-163	black shale
163-173	fine pink sand
173-174	quartzite

Borehole Diameter:	5.5 inches
Casing Size:	2 inch
Casing Type:	PVC
Stickup:	2 feet
Screen Length:	5 feet
Slot Size:	0.010 inches
Depth of Screen:	163-173 feet

Coarse quartz sand filter pack around screen.
Bentonite grout from filter pack to land surface.

RENNER AQUIFER TEST

"NW WELL" DRAWDOWN DATA

Distance from pumping well = 190.93 feet

Pumping rate = 9,800 cubic feet per day

Date	Time	Water Level (feet from casing top)	Time (min)	Drawdown (ft)	Log of time
2/13/89	12:00	10.37	0	0.00	
2/13/89	12:01	10.40	1	-0.03	0.00
2/13/89	12:02	10.47	2	-0.10	0.30
2/13/89	12:03	10.63	3	-0.26	0.48
2/13/89	12:04	10.78	4	-0.41	0.60
2/13/89	12:05	10.92	5	-0.55	0.70
2/13/89	12:06	11.07	6	-0.70	0.78
2/13/89	12:07	11.22	7	-0.85	0.85
2/13/89	12:08	11.34	8	-0.97	0.90
2/13/89	12:09	11.45	9	-1.08	0.95
2/13/89	12:10	11.54	10	-1.17	1.00
2/13/89	12:12	11.75	12	-1.38	1.08
2/13/89	12:14	11.93	14	-1.56	1.15
2/13/89	12:16	12.10	16	-1.73	1.20
2/13/89	12:18	12.30	18	-1.93	1.26
2/13/89	12:20	12.40	20	-2.03	1.30
2/13/89	12:25	12.75	25	-2.38	1.40
2/13/89	12:30	13.12	30	-2.75	1.48
2/13/89	12:35	13.34	35	-2.97	1.54
2/13/89	12:40	13.52	40	-3.15	1.60
2/13/89	12:45	13.67	45	-3.30	1.65
2/13/89	12:50	13.79	50	-3.42	1.70
2/13/89	12:55	13.86	55	-3.49	1.74

2/13/89	13:00	13.88	60	-3.51	1.78
2/13/89	13:10	14.00	70	-3.63	1.85
2/13/89	13:20	14.06	80	-3.69	1.90
2/13/89	13:30	14.12	90	-3.75	1.95
2/13/89	13:40	14.16	100	-3.79	2.00
2/13/89	14:00	14.19	120	-3.82	2.08
2/13/89	14:30	14.29	150	-3.92	2.18
2/13/89	15:00	14.34	180	-3.97	2.26
2/13/89	15:30	14.39	210	-4.02	2.32
2/13/89	16:00	14.46	240	-4.09	2.38
2/13/89	17:00	14.59	300	-4.22	2.48
2/13/89	18:00	14.69	360	-4.32	2.56
2/13/89	19:00	14.75	420	-4.38	2.62
2/13/89	20:00	14.81	480	-4.44	2.68
2/13/89	21:00	14.83	540	-4.46	2.73
2/13/89	22:00	14.83	600	-4.46	2.78
2/13/89	23:00	14.89	660	-4.52	2.82
2/14/89	00:00	14.87	720	-4.50	2.86
2/14/89	02:00	14.80	840	-4.43	2.92
2/14/89	04:00	14.75	960	-4.38	2.98
2/14/89	06:00	14.73	1080	-4.36	3.03
2/14/89	08:00	14.80	1200	-4.43	3.08
2/14/89	10:00	14.83	1320	-4.46	3.12
2/14/89	12:00	14.83	1440	-4.46	3.16

APPENDIX B: HANTUSH (1960) ANALYSIS OF SRC-35 AND SRC-37 TIME-DRAWDOWN DATA USING AQTESOLV® ANALYSIS SOFTWARE

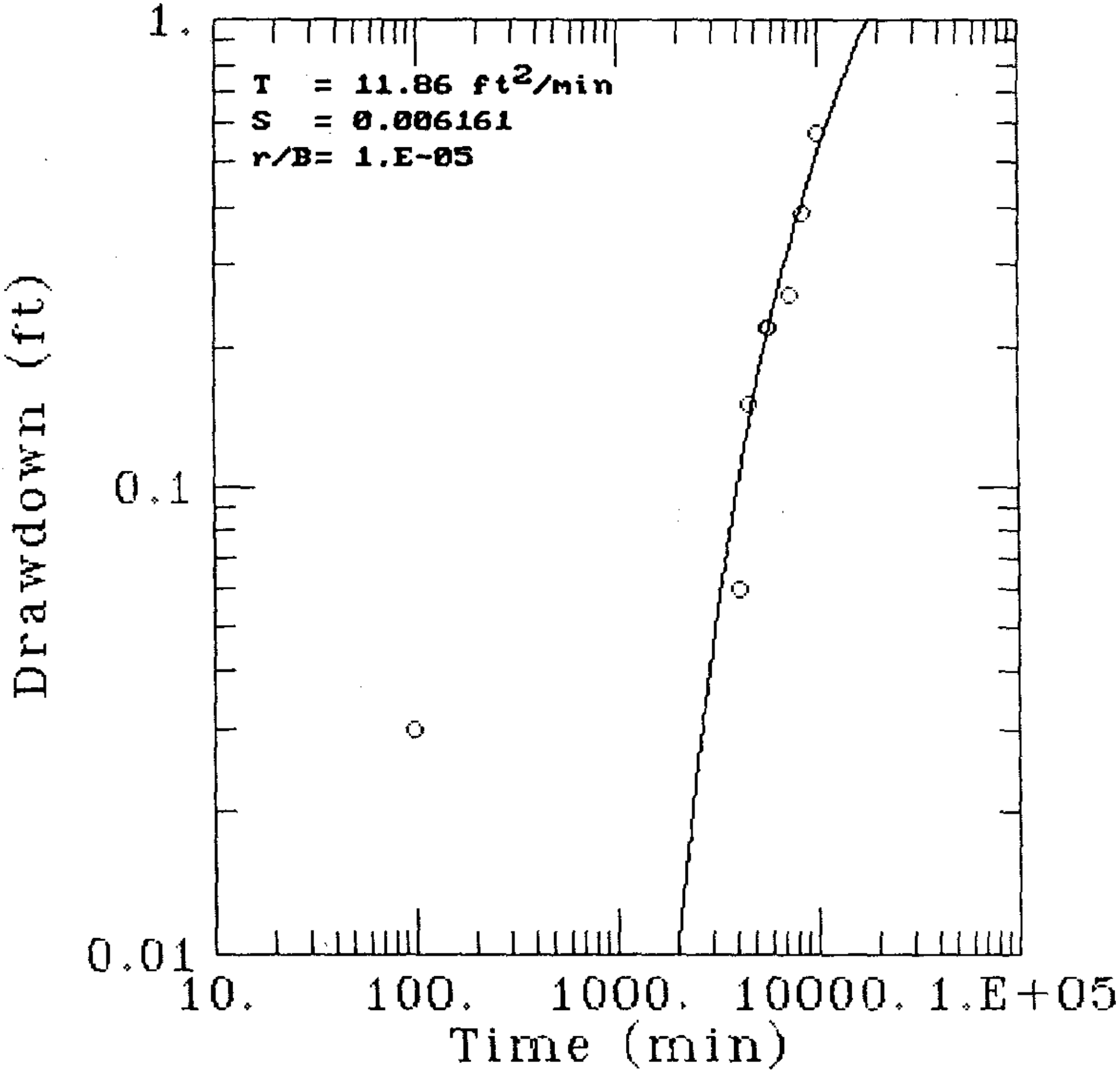


Figure 38. Hantush analysis of SRC-35

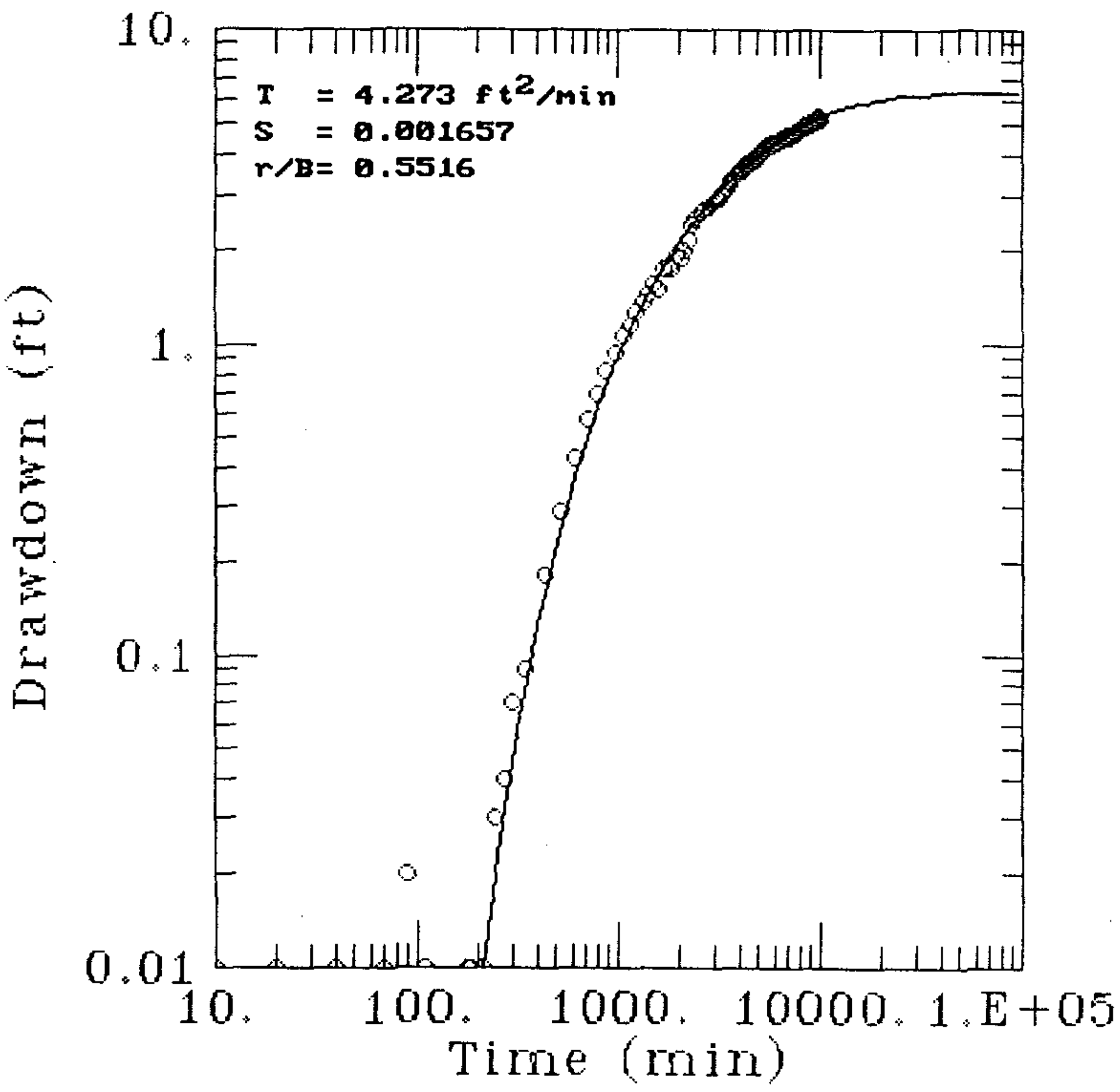


Figure 39. Hantush analysis of SRC-37

APPENDIX C: RAW DATA FOR THE BAILDOWN TESTS AND BRIEF WELL CONSTRUCTION SUMMARIES

WELL SRC-38C

Well-Construction Summary

Depth (feet)	***Lithology***
0-2	topsoil
2-74	brown pebbly clay; oxidized (till)
74-85	medium gravel
85-130	gray pebbly clay; unoxidized (till)

Borehole Diameter:	5.5 inches
Casing Size:	2 inch
Casing Type:	PVC
Stickup:	2 feet
Screen Length:	5 feet
Slot Size:	0.010 inches
Depth of Screen:	118-123 feet

Coarse quartz sand filter pack around screen.
Bentonite grout from filter pack to land surface.

WELL SRC-38C

Baildown data

Date	Time	Water Level (feet from casing top)	Elapsed Time (days)	Elapsed Time (seconds)	Change or h (feet)	h/ho
12/28/89	15:46	118.300	0.000	0	42.120	1.000
12/28/89	15:47	118.190	0.001	60	42.010	0.997
12/28/89	15:48	118.100	0.001	120	41.920	0.995
12/28/89	15:50	117.980	0.003	240	41.800	0.992
12/28/89	15:55	117.810	0.006	540	41.630	0.988
12/28/89	16:02	117.660	0.011	960	41.480	0.985
12/28/89	16:59	117.020	0.051	4,380	40.840	0.970
12/28/89	21:43	114.840	0.248	21,420	38.660	0.918
12/29/89	07:25	111.130	0.652	56,340	34.950	0.830
12/30/89	20:28	100.590	2.196	189,720	24.410	0.580
01/01/90	13:32	92.870	3.907	337,560	16.690	0.396
01/08/90	12:36	79.750	10.868	939,000	3.570	0.085

Static water level = 76.18 feet
Maximum Drawdown (ho) = 42.12 feet

WELL SRC-38D

Well-Construction Summary

Depth (feet)	Lithology
0-2	topsoil
2-22	brown pebbly clay; oxidized (till)

Borehole Diameter:	5.5 inches
Casing Size:	2 inch
Casing Type:	PVC
Stickup:	3.5 feet
Screen Length:	5 feet
Slot Size:	0.010 inches
Depth of Screen:	16.5-21.5 feet

Coarse quartz sand filter pack around screen.
Bentonite grout from filter pack to land surface.

WELL SRC-38D

Baildown data

Date	Time	Water Level (feet from casing top)	Elapsed Time (days)	Elapsed Time (seconds)	Change or h (feet)	h/ho
12/28/89	15:01	14.40	0.000	0	4.320	1.000
12/28/89	15:02	14.21	0.001	60	4.130	0.956
12/28/89	15:03	14.10	0.001	120	4.020	0.931
12/28/89	15:04	14.02	0.002	180	3.940	0.912
12/28/89	15:05	13.97	0.003	240	3.890	0.900
12/28/89	15:06	13.91	0.003	300	3.830	0.887
12/28/89	15:11	13.76	0.007	600	3.680	0.852
12/28/89	15:16	13.67	0.010	900	3.590	0.831
12/28/89	15:21	13.61	0.014	1,200	3.530	0.817
12/28/89	15:31	13.51	0.021	1,800	3.430	0.794
12/28/89	15:41	13.45	0.028	2,400	3.370	0.780
12/28/89	16:01	13.35	0.042	3,600	3.270	0.757
12/28/89	16:56	13.10	0.080	6,900	3.020	0.699
12/28/89	21:40	12.44	0.277	23,940	2.360	0.546
12/29/89	07:22	11.63	0.681	58,860	1.550	0.359
12/30/89	20:30	10.47	2.228	192,540	0.390	0.090

Static water level = 10.08 feet
Maximum Drawdown (ho) = 4.32 feet

WELL SRC-39C

Well-Construction Summary

Depth (feet)	Lithology
0-1	topsoil
1-21	yellow-brown silty clay; oxidized (till)
21-31	fine to medium gravel
31-38	yellow-brown silty clay; oxidized (till)
38-120	gray silty clay; unoxidized (till)

Borehole Diameter:	5.5 inches
Casing Size:	2 inch
Casing Type:	PVC
Stickup:	2 feet
Screen Length:	5 feet
Slot Size:	0.010 inches
Depth of Screen:	115-120 feet

Coarse quartz sand filter pack around screen.
Bentonite grout from filter pack to land surface.

WELL SRC-39C

Baildown data

Date	Time	Water Level (feet from casing top)	Elapsed Time (days)	Elapsed Time (seconds)	Change or h (feet)	h/ho
12/28/89	16:41	104.020	0.000	0	65.780	1.000
12/28/89	16:43	103.890	0.001	120	65.650	0.998
12/28/89	16:45	103.760	0.003	240	65.520	0.996
12/28/89	16:50	103.690	0.006	540	65.450	0.995
12/28/89	17:04	103.510	0.016	1,380	65.270	0.992
12/28/89	21:50	102.290	0.215	18,540	64.050	0.974
12/29/89	07:32	100.490	0.619	53,460	62.250	0.946
12/30/89	20:40	95.020	2.166	187,140	56.780	0.863
01/01/90	13:38	89.990	3.873	334,620	51.750	0.787
01/08/90	12:40	74.540	10.833	935,940	36.300	0.552
03/12/90	16:00	40.690	73.972	6,391,140	2.450	0.037

Static water level = 38.24 feet
Maximum Drawdown (ho) = 65.78 feet

WELL SRC-CO1

Well-Construction Summary

Depth (feet)	**Lithology**
0-26	sand
26-30	yellow-brown silty clay; oxidized (till)
30-56	siltstone; hard
56-67	siltstone; with clay stringers

Borehole Diameter:	5.5 inches
Casing Size:	2 inch
Casing Type:	PVC
Stickup:	2 feet
Screen Length:	5 feet
Slot Size:	0.010 inches
Depth of Screen:	56-61 feet

Coarse quartz sand filter pack around screen.
Bentonite grout from filter pack to land surface.

WELL SRC-CO1

Baildown data

Date	Time	Water Leve (feet from casing top)	Elapsed Time (days)	Elapsed Time (seconds	Change or h (feet)	h/ho
12/28/89	12:15:30	51.400	0.000	0	21.200	1.000
12/28/89	12:16:00	50.150	0.000	30	19.950	0.941
12/28/89	12:17:00	48.250	0.001	90	18.050	0.851
12/28/89	12:17:30	47.300	0.001	120	17.100	0.807
12/28/89	12:18:00	46.500	0.002	150	16.300	0.769
12/28/89	12:18:30	45.650	0.002	180	15.450	0.729
12/28/89	12:19:00	44.900	0.002	210	14.700	0.693
12/28/89	12:19:30	44.150	0.003	240	13.950	0.658
12/28/89	12:20:00	43.550	0.003	270	13.350	0.630
12/28/89	12:20:30	42.900	0.003	300	12.700	0.599
12/28/89	12:21:00	42.250	0.004	330	12.050	0.568
12/28/89	12:21:30	41.700	0.004	360	11.500	0.542
12/28/89	12:22:00	41.170	0.005	390	10.970	0.517
12/28/89	12:22:30	40.650	0.005	420	10.450	0.493
12/28/89	12:23:00	40.200	0.005	450	10.000	0.472
12/28/89	12:23:30	39.800	0.006	480	9.600	0.453
12/28/89	12:24:00	39.350	0.006	510	9.150	0.432
12/28/89	12:24:30	38.950	0.006	540	8.750	0.413
12/28/89	12:25:00	38.530	0.007	570	8.330	0.393
12/28/89	12:25:30	38.170	0.007	600	7.970	0.376
12/28/89	12:26:30	37.550	0.008	660	7.350	0.347
12/28/89	12:27:30	36.900	0.008	720	6.700	0.316
12/28/89	12:28:30	36.350	0.009	780	6.150	0.290
12/28/89	12:29:30	35.850	0.010	840	5.650	0.267
12/28/89	12:30:30	35.350	0.010	900	5.150	0.243
12/28/89	12:33:00	34.370	0.012	1,050	4.170	0.197
12/28/89	12:35:30	33.600	0.014	1,200	3.400	0.160
12/28/89	12:40:30	32.480	0.017	1,500	2.280	0.108

12/28/89 12:45:30	31.840	0.021	1,800	1.640	0.077
12/28/89 12:55:30	31.000	0.028	2,400	0.800	0.038
12/28/89 13:05:30	30.700	0.035	3,000	0.500	0.024
12/28/89 13:17:30	30.530	0.043	3,720	0.330	0.016

Static water level = 30.20 feet
Maximum Drawdown (ho) = 21.20 feet

WELL SRC-CO2

Well-Construction Summary

Depth (feet)	Lithology
0-1	topsoil
1-20	coarse gravel
20-40	siltstone; hard
40-57	siltstone; with clay stringers

Borehole Diameter:	5.5 inches
Casing Size:	2 inch
Casing Type:	PVC
Stickup:	2 feet
Screen Length:	5 feet
Slot Size:	0.010 inches
Depth of Screen:	49-54 feet

Coarse quartz sand filter pack around screen.

Bentonite grout from filter pack to land surface.

WELL SRC-CO2

Baildown data

Date	Time	Water Level (feet from casing top)	Elapsed Time (days)	Elapsed Time (seconds	Change or h (feet)	h/ho
12/28/89	11:30:30	35.050	0.000	0	10.600	1.000
12/28/89	11:31:00	33.430	0.000	30	8.980	0.847
12/28/89	11:31:30	31.070	0.001	60	6.620	0.625
12/28/89	11:32:30	30.200	0.001	120	5.750	0.542
12/28/89	11:33:00	29.400	0.002	150	4.950	0.467
12/28/89	11:33:30	28.620	0.002	180	4.170	0.393
12/28/89	11:34:00	28.070	0.002	210	3.620	0.342
12/28/89	11:34:30	27.600	0.003	240	3.150	0.297
12/28/89	11:35:00	27.220	0.003	270	2.770	0.261
12/28/89	11:35:30	26.900	0.003	300	2.450	0.231
12/28/89	11:36:00	26.550	0.004	330	2.100	0.198
12/28/89	11:36:30	26.320	0.004	360	1.870	0.176
12/28/89	11:37:00	26.100	0.005	390	1.650	0.156
12/28/89	11:37:30	25.950	0.005	420	1.500	0.142
12/28/89	11:38:00	25.800	0.005	450	1.350	0.127
12/28/89	11:38:30	25.650	0.006	480	1.200	0.113
12/28/89	11:39:00	25.540	0.006	510	1.090	0.103
12/28/89	11:39:30	25.450	0.006	540	1.000	0.094
12/28/89	11:40:00	25.370	0.007	570	0.920	0.087
12/28/89	11:40:30	25.300	0.007	600	0.850	0.080
12/28/89	11:41:00	25.240	0.007	630	0.790	0.075
12/28/89	11:41:30	25.190	0.008	660	0.740	0.070
12/28/89	11:42:00	25.150	0.008	690	0.700	0.066
12/28/89	11:42:30	25.120	0.008	720	0.670	0.063
12/28/89	11:43:00	25.080	0.009	750	0.630	0.059
12/28/89	11:43:30	25.050	0.009	780	0.600	0.057
12/28/89	11:44:00	25.030	0.009	810	0.580	0.055
12/28/89	11:44:30	25.000	0.010	840	0.550	0.052

12/28/89	11:45:30	24.970	0.010	900	0.520	0.049
12/28/89	11:46:30	24.940	0.011	960	0.490	0.046
12/28/89	11:47:30	24.920	0.012	1,020	0.470	0.044
12/28/89	11:48:30	24.900	0.012	1,080	0.450	0.042
12/28/89	11:49:30	24.880	0.013	1,140	0.430	0.041
12/28/89	11:50:30	24.870	0.014	1,200	0.420	0.040
12/28/89	11:55:30	24.840	0.017	1,500	0.390	0.037
12/28/89	12:00:30	24.810	0.021	1,800	0.360	0.034
12/28/89	12:36:30	24.660	0.046	3,960	0.210	0.020
12/28/89	12:47:30	24.640	0.053	4,620	0.190	0.018

Static water level = 24.45 feet
Maximum Drawdown (ho) = 10.60 feet

APPENDIX D: BOUWER (1989) ANALYSIS OF SRC-CO2 BAILDOWN DATA USING AQTESOLV® ANALYSIS SOFTWARE

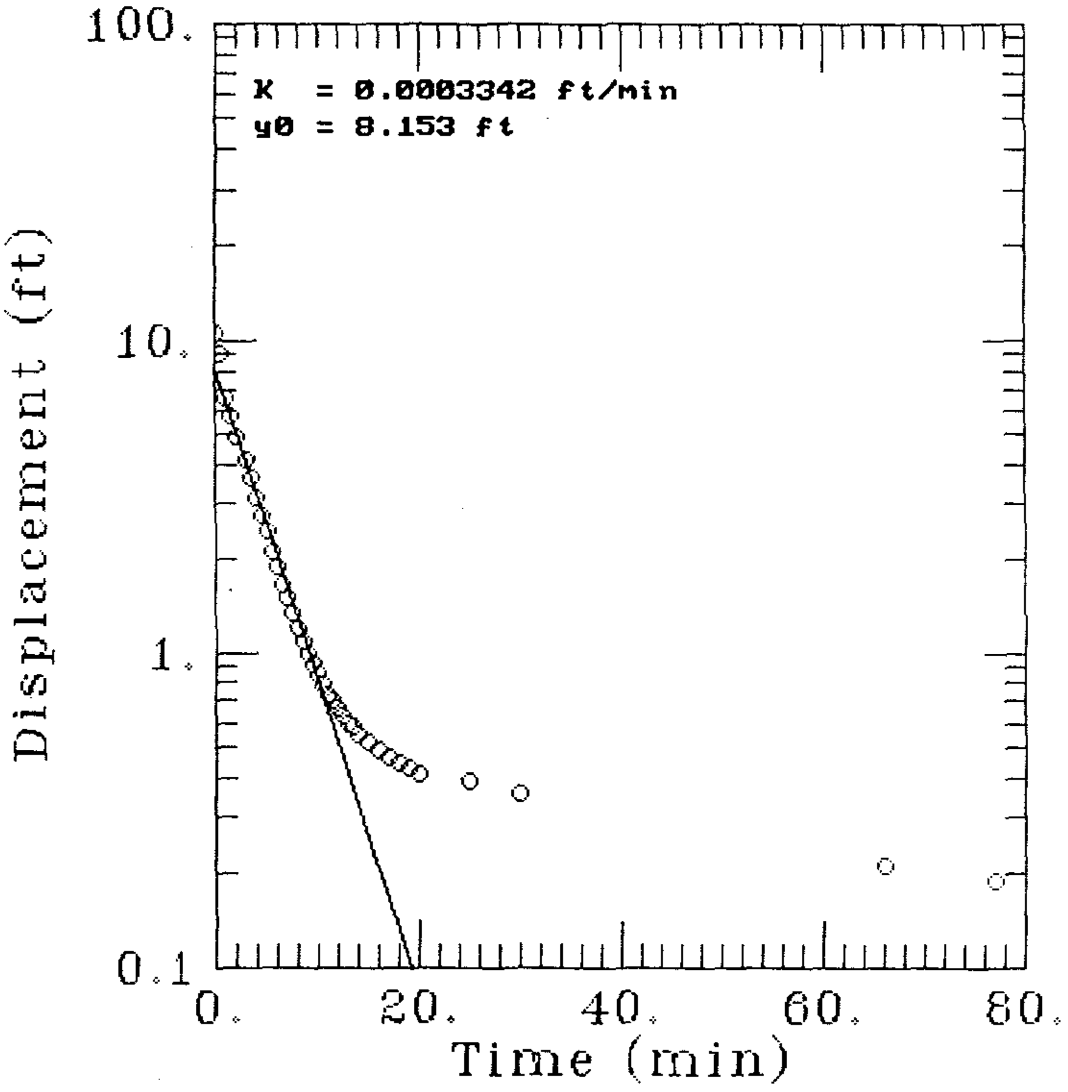


Figure 40. Bouwer-Rice analysis of SRC-CO2

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