EVALUATION OF GROUNDWATER RESOURCES

EASTERN SOUTH DAKOTA AND BIG SIOUX RIVER,

SOUTH DAKOTA AND IOWA

TASK 11: ARTIFICIAL RECHARGE POTENTIAL

FINAL REPORT

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INTRODUCTION

This report is part of a series of studies being conducted by the U.S. Army Corps of Engineers to evaluate water resources in South Dakota and the Upper Big Sioux River in South Dakota and Iowa. The output contained in this report, however, is restricted to that part of South Dakota east of the Missouri River and only that part of the Big Sioux Basin located in South Dakota. The following task is the output for this report.

TASK 11 -- Determine potential artificial recharge capabilities of all aquifers by open pit or surface spreading, injection well method, and low-head dams.

a. Search literature to determine possible range of artificial recharge rates for comparable aquifers or hydrologic systems.

b. Devise a rating system by which feasibility of artificial recharge can be used to compare various aquifers.

c. Prepare a report which identifies those aquifers with the greatest potential for artificial recharge.

DATA AVAILABILITY AND PRESENTATION

The availability of hydrologic data may vary considerably from one county to the next in eastern South Dakota. In general, those counties which have a county water resource study completed have the most data available. Exceptions to this do occur, however, where local interest and/or ground-water development has prompted the State's Division of Water Rights to establish an observation well monitoring network prior to the completion of a county-wide study. The number of Water Rights observation wells (piezometers) has markedly increased since the drought of 1976 and the ensuing interest in irrigation. As a result, nearly all of the aquifers and/or management units have at least some observation well data.

For this report, the observation well data were reviewed in each aquifer and management unit. In particular, the thickness of aquifer overburden was compared to water levels in the observation wells to determine if specific portions of the aquifer exist under confined or unconfined conditions. Then the individual well data were compiled by aquifer and/or management unit so that general conclusions could be drawn about the unit.

ARTIFICIAL RECHARGE

Objectives

Artificial recharge is a means of augmenting the natural infiltration of surface water into a ground-water reservoir and has been used for a variety of purposes (Lehr, 1982):

1. Ground-water (well field) management

2. Reduction of land subsidence

3. Renovation of waste water

4. Improvement of ground-water quality

5. Storage of stream waters during periods of high or excessive flow

6. Reduction of flood flows

7. Increasing well yield

8. Decreasing the size of areas needed for water-supply systems

9. Reduction of salt-water intrusion or leakage of mineralized water

10. Increasing stream flow

11. Store fresh water derived from rain and snowmelt. If the existing ground water is saline, the less dense fresh water lens will float on the saline water

12. Secondary recovery of oil

It is conceivable that artificial recharge could be used for all listed purposes in eastern South Dakota, except for no. 12. However, for the purposes of this report the discussion is limited to a combination of ground-water management (no. 1) and increasing well-yield (no. 7) to provide Class I or II drinking water to municipalities or rural households. While the U.S. Army Corps of Engineers is vitally concerned about property damaging floods (no. 6), this purpose is not a mandate of this particular TASK. Furthermore, those areas susceptible to major flooding and which are underlain by porous and permeable material, are naturally filled to capacity by the flood waters. Thus, structures and/or diversion facilities would be required to move the water to a different location that has available storage capacity.

Types of Artificial Recharge

Artificial recharge can be classified into two general categories:

1. Infiltration of water into an aquifer under

atmospheric pressure (surface spreading), and

2. Injection of water into an aquifer at some pressure greater than the pore pressure in an aquifer (injection wells).

The first type is usually accomplished by two methods. These are either:

a. The use of a man-made recharge or infiltration basin or canal, or

b. The use of low-head dams on a drainage way, stream, river or lake.

There are technical and operational problems associated with all types of artificial recharge, but a discussion of difficulties and their remedies are beyond the scope of this report.

Surface Spreading

Assuming the aquifer has room to be recharged (i.e., the aquifer is not full or the rate of use is equal to the recharge rate) the surface spreading method can be used anywhere the aquifer is near the land surface, and there is sufficiently permeable material connecting it to the aquifer. Surface spreading basins are generally man-made structures into which water is periodically placed and allowed to infiltrate into the underlying aquifer. Surface spreading methods can also be used on floodplains under certain conditions.

Primary criteria for location of a spreading basin are groundwater gradient and depth, aquifer characteristics including degree of saturation, site specific geologic data such as depth to top of the aquifer and the presence of any low permeability layers, and proximity to a dewatered portion of the aquifer, or proximity to active pumping.

Low-Head Dams

Although low-head dams are similar to spreading basins, they are unique because of their locations and because it is assumed that recharge will collect naturally behind the dam as a result of precipitation and runoff. However, if water is placed behind the dam by other than natural means (i.e., pumped) then the low-head dam would be viewed as a hybrid of the low-head dam and other spreading basin methods.

Because normal streamflow passes over an aquifer relatively quickly, low-head dams are a useful way to delay the water and allow more time for infiltration into the aquifer. Recharge by low-head dams would normally be most effective in late summer when ground-water levels are low.

The presence of an aquifer at or near the land surface, the ground-water gradient, aquifer characteristics including degree of saturation, the presence or absence of any low permeability layers, and proximity to a dewatered portion of the aquifer are all criteria to consider when locating a low-head dam.

Low-head dams can be located along drainage ways, streams, and rivers where topography and cultural features will allow construction. The dam should cause ponding of water a few feet in depth. Structures can also be used on lakes to increase the lake's capacity and to increase infiltration into any aquifer that may be hydraulically connected to the lake.

Injection Wells

Injection wells are a possible method of artificial recharge to any aquifer. They are wells through which water is pumped into an aquifer at some pressure greater that the aquifer's pore pressure. This type of recharge is used primarily where aquifers are under confined hydrologic conditions or in aquifers under unconfined hydrologic conditions where:

1. The water level is deep enough to provide adequate storage capacity and prevent unacceptable evapotranspiration losses.

2. The ground water is separated from the land surface by restricting layers, or

3. Cultural features or surface topography makes recharge basins impractical (Bouwer, 1978).

Development of artificial recharge using the injection well method requires detailed site-specific testing and evaluation and is dependent on many technical variables. Legal and institutional constraints must also be considered when artificial recharge by the injection well method (or any other artificial method) is contemplated.

Todd (1980) states that the most widely used method of artificially recharging ground water is by various types of water spreading. Although not stated by Todd, it might be further concluded that, at least in a general sense, this is also the most cost effective method. When discussing recharge well methods using high quality wastewater (Todd, 1980, p. 476) states: "The high cost of recharging effluent of this quality into wells can only be economically justified where some special purpose such as control of land subsidence, control of sea water intrusion, or delayed development of a costly alternative water supply source can be served."

In November, 1978, a ground water recharge symposium was held in Phoenix, Arizona. At this symposium various authors (Signor, 1978; Skilitzke, 1978; Bianchi, 1978) enumerated instances where recharge injection wells have been used successfully. Todd (1980) also lists several areas where artificial recharge by injection wells has been successful. Testament by these authors prove the technical feasibility of this method of artificial recharge, but they also state that artificial recharge by any method is generally a matter of economics. Sherman (1978, p. 2) states: "Obviously, surface spreading is far less expensive [than injection wells] if the situation is right." Signor (1978, p. 16) in a comparison of spreading basins and injection wells concludes: "Recharge by use of spreading basins may be more feasible than recharge by use of wells." The theme of the symposium and statements by Todd (1980) strongly suggest that artificial recharge by the injection well method is practical in only special cases. From a technical and economic viewpoint this method of artificial recharge is not a likely alternative in eastern South Dakota. Therefore, this method of artificial recharge will not be further discussed in this Task.

Retention Time

When artificially recharging an aquifer, the intent is that the recharged water will remain in the aquifer or in a particular area of the aquifer long enough to be of use. This is called retention time and is dependent upon the geohydrologic setting.

Determination of retention time requires prior knowledge of an aquifer's hydrologic characteristics and usage patterns. More commonly, however, only the grain size of aquifer material and the general ground-water gradient are known. Consequently, an approximate relationship between grain size and hydraulic conductivity is used to estimate retention time (table 1).

The actual rate at which a particle of water will travel in an aquifer can be estimated if the following parameters are known:

1. Hydraulic conductivity (K) of the aquifer (table 1),

2. Ground-water gradient (i) in the aquifer, and

3. Effective porosity (n) of the aquifer.

This rate of movement can then be applied to actual situations and the length of time (t) that it will take for a particle of water to travel a given distance (d) can be calculated. The method of calculation is as follows:

$$t = \frac{d}{\frac{K\,(i)}{n}}$$

TABLE 1

Relationship between grain size class and hydraulic conductivity

Grain size class	Range of hydraulic conductivity (ft/day)
Clay or silt	< 20
Sand, very fine	10- 80
Sand, fine	70- 140
Sand, fine to medium	70- 400
Sand, medium	130- 400
Sand, fine to coarse	70- 600
Sand, medium to coarse	130- 800
Sand, coarse	400-1,000
Sand and gravel	400-1,200
Sand, coarse, and gravel	400-1,400
Gravel	800-2,000

Table after Koch (1980)

Table 2 lists the time in days that it would take for a particle of water to move a given distance at a given hydraulic conductivity assuming a ground-water gradient of 5 feet per mile and an effective porosity of 15 percent. The hydraulic conductivities listed across the top of the table are the midpoints for the different grain size classes of very fine sand through gravel.

Consider that the average glacial outwash (aquifer) is comprised of material ranging in grain size class from medium sand to coarse sand and gravel. Thus, this type of aquifer material which is common in eastern South Dakota, has hydraulic conductivities ranging from 265 to 900 feet/day (table 2). Assuming that average distance of travel for recharge water ranges from 0.25 to 0.75 miles from the recharge point to a discharge point means that retention time would range from 232 to 2367 days if the gradients were 5 ft/mi. Most artificial recharge situations, however, would result in gradients exceeding 5 ft/mi. Because time is inversely proportional to the gradient, doubling the gradient would reduce the time by one-half. Thus, under artificial recharge conditions where higher gradients are maintained, the travel times shown in table 2 would be some factor less than shown.

TABLE 2

Travel time (in days) of water through varying distances with varying hydraulic conductivities (assuming a hydraulic gradient of 5 ft/mi and an effective porosity of 15 percent).

Distance (in miles)	Hydraulic Conductivity (feet/day)									
	45	105	235	265	335	465	700	800	900	1400
0.25	4646	1991	890	789	624	450	299	261	232	149
0.50	8659	3711	1658	1470	1163	838	557	487	433	278
0.75	13939	5974	2669	2367	1872	1349	896	784	697	448
1.00	18586	7965	3559	3156	2497	1799	1195	1045	929	597
1.50	27878	11948	5338	4734	3745	2698	1792	1568	1394	896
2.00	37171	15931	7188	6312	4993	3597	2390	2091	1859	1195
3.00	55757	23896	10677	9468	7490	5396	3584	3136	2788	1792
4.00	74342	31861	14236	12624	9986	7194	4779	4182	3717	2390
5.00	92928	39826	17795	15780	12483	8993	5974	5227	4646	2987

AQUIFERS OF EASTERN SOUTH DAKOTA

Classification for Artificial Recharge

In TASK 7 the aquifers in eastern South Dakota were divided into two major groups: Surficial and Bedrock aquifers. The Surficial aquifers and/or management units were further subdivided into three types. That same subdivision is also appropos to the discussion of artificial recharge. The subdivision is as follows:

1. Unconfined aquifers that are non-buried (app. A),

2. Unconfined aquifers that are buried (app. B), and

3. Confined aquifers (app. C).

To be classified as buried, an aquifer must be overlain by more than 10 feet of low-permeability materials. All bedrock aquifers are considered to be under confined hydrologic conditions. It is recognized that many aquifers are under both confined and unconfined hydrologic conditions. Plates 1 through 4 show all of the known surficial aquifers in eastern South Dakota and delineates those portions that are both confined and unconfined.

Aquifer Suitability for Artificial Recharge

Suitability of an aquifer for artificial recharge by a particular method was determined by considering the aspects of the different methods described in a preceding section entitled "Types of Artificial Recharge." Two conditions that were not considered as criteria for the suitability classification (apps. A, B, and C) are:

1. Whether or not an aquifer presently has any potential storage capacity for recharge water, or

2. Whether recharge water is available.

This is because an aquifer's potential storage capacity and water availability situation will vary spatially and in magnitude with time. An example would be an aquifer that is presently undeveloped and has little potential storage capacity for artificial recharge because of a high water level. Thus, should the aquifer become developed, the potential storage capacity would increase.

Only a few of those aquifers and management units listed as suitable for either the low-head dam or spreading basin method (app. A and B) are presently capable of being artificially recharged. This is because necessary additional storage capacity in the aquifers is not generally available under present use conditions.

All aquifers are suitable to some degree for recharge by injection wells. Because artificial recharge by injection wells in confined aquifers has been assumed to be impractical the aquifers and management units in appendix C (confined hydrologic conditions) were categorically deemed unsuitable for artificial recharge. Exceptions are noted on plates 1 through 4 where aquifers classified as confined have unconfined areas. Thus, the following more detailed discussion will be restricted to unconfined aquifers.

Limitations of Unconfined Aquifers

In eastern South Dakota three major characteristics of unconfined aquifers limit their practical development as artificial recharge sites. The aquifers are generally thin, or they have water tables near land surface, or they have insufficient retention times.

Thin Aquifers

Thin aquifers are considered to be those less than 25 feet thick. Because they are thin, their additional storage capacity is obviously quite limited. With sustained pumping, drawdowns may become so severe that well capacities are reduced by as much as one-half to two-thirds of original capacity following a recharge cycle. Up to a point this problem could be partially remedied by installation of additional discharge wells or using some special type of horizontal well construction method.

Aquifers with Water Table near Land Surface

Aquifers with shallow water tables (less than 15 feet deep) are limited by their general absence of significant storage capacity. Additionally, potential problems may occur when the water level approaches 5 feet because of possible water-logging and salt buildup in the root zone. Also, water losses by evapotranspiration could negate artificial recharge when water tables rise to with 5 feet of the land's surface.

Retention Time

Most water table aquifers are associated with drainageways or lakes which serve as discharge points throughout most of the year. In eastern South Dakota, the discharge points are generally only a few tenths of a mile to 2 to 3 miles from the aquifer boundary with a resulting retention time of only a few months to a maximum of a few years. At those sites where retention time would be measured in years this factor would be minimal. Unfortunately, many potential recharge sites in eastern South Dakota would have probable storage times measured in months or 1 to 2 years maximum.

Discussion

One or more of the preceding limitations apply to most of the unconfined aquifers in eastern South Dakota. Because of these limitations, it is not practical to consider many of the aquifers for artificial recharge. To become practical as recharge reservoirs, they would require delivery of recharge water close to time of actual use. Should this become the case, then a strong argument could be made for using the water as it is delivered and eliminating the recharge-discharge cycle. The construction of specialized discharge structures (in thin aquifers) would be at least a partial solution to this problem but would probably be economically impractical.

If economics are ignored, most unconfined aquifers could sustain some degree of artificial recharge. If this limitation is ignored, then the limiting factors of aquifer thickness, water levels, and storage time could be determined on a site by site basis.

AQUIFER REQUIREMENT FOR ARTIFICIAL RECHARGE

The following discussion in this report attempts to evaluate the surficial aquifers in terms of need or potential need for artificial recharge. "Need" is defined as estimated natural recharge (a minimum-maximum range) versus actual estimated water use and appropriations. The data shown in appendices D and E were prepared by manipulating data compiled for TASK 2 (aquifer extent) and TASK 7 (estimation of natural recharge rates).

Water Use Versus Natural Recharge

Appendix D shows calculated water use versus estimated minimum-maximum recharge rates. Examination of this data reveals that 25 aquifers use more water than their estimated minimum recharge rate. Of these, 21 are from confined aquifers and 4 are from unconfined aquifers. If the estimated maximum recharge rate is used for comparison, calculated water use from only five aquifers exceeds natural recharge. Of these, four are from unconfined aquifers.

In TASK 7 the recharge rates for confined aquifers were estimated to range from .15 to .60 inches per year. This relatively wide estimated range is due to two factors:

1. Lack of data documenting actual recharge rates, and

2. Due to local hydrologic conditions the actual recharge rates to confined aquifers probably does vary over a relatively wide range.

Thus, those 21 confined aquifers that exceed the estimated minimum recharge rate have potential "need" for artificial recharge in terms of use versus recharge.

Of the four unconfined aquifers where use exceeds the estimated recharge rate, two of them, the Big Sioux : Sioux Falls and the Missouri : Pierre, have hydraulic connection to streams capable of supplementing the recharge deficit. However, the Cow Creek and Vermillion East Fork : Montrose may currently have a "need" for artificial recharge.

Appropriation Versus Natural Recharge

Appendix E shows appropriation versus estimated minimum-maximum natural recharge rates. Examination of these data indicates that appropriations exceed the minimum annual recharge in 65 aquifers. Of these, 27 are unconfined. Appropriation exceeds the maximum estimated recharge in 33 aquifers. Seven of these are unconfined.

To evaluate a current "need" for artificial recharge on an aquifer basis a list (table 3) based on two criteria was developed. The criteria are, first, those aquifers where use exceeds estimated minimum natural recharge and second, those where appropriation exceeds estimated maximum natural recharge.

TABLE 3

List of aquifers with potential need for artificial recharge

AQUIFER NAME : MANAGEMENT UNIT NAME (if applicable)
Choteau : Tyndall
* Vermillion East Fork : Montrose
Upper Vermillion Missouri
Warren : Wolsey
* Floyd : Pearl Creek
Lower Vermillion-Missouri
Cow Creek
Choteau : West
Warren : West James
Choteau : Middle
Gray Goose
Geddes
Tulare : Hand
Ethan
Elm : Northern Brown
* Big Sioux : Sioux Falls
Elm : Ipswich
Brule Creek
Floyd : East James
Missouri : Pierre
Choteau : East
Plum Creek

* Aquifers which contain Class I or II water that could be used for drinking water.

Water Quality

One of the objectives of the U.S. Army Corps of Engineers study is to identify those areas or aquifers that contain Class I or II water that is used or may be used for drinking purposes. The upper limit of Class II drinking water is 1,000 mg/L total solids residue. To identify those aquifers, a statistical water-quality evaluation was made of all the aquifers in eastern South Dakota where adequate data were available (TASK 5). Tables 4 and 5, which were compiled from that report, list those aquifers that may contain significant water supplies where the total solids residue is less than 1,000 mg/L.

For the purposes of this report, those aquifers of potentially acceptable water quality (listed in tables 4 and 5) can be compared with those tables evaluating natural recharge rates, water use, and appropriations, to determine which aquifers may have a potential "need" for artificial rechage under assumed development scenarios.

POTENTIAL ARTIFICIAL RECHARGE SITES

During preliminary planning stages the U.S. Army Corps of Engineers identified several aquifers or areas for preliminary evaluation as artificial recharge sites. These sites were chosen by the Corps because of a reported good quality water (less than 1,000 TDS) analysis at or near these sites. However, the aquifers at these sites do not necessarily qualify for inclusion in table 3 (aquifers with potential need for artificial recharge) because criteria for inclusion on this table is based on water use or appropriation. These sites are discussed individually in the following section. In addition, a general discussion on the entire Big Sioux Aquifer is included to provide an example for some of the problems that might be encountered in developing artificial recharge sites.

Warren : West James; Northeast Jerauld and Beadle County Artificial Recharge Site

Geology

The extreme northeast corner of Jerauld County and the adjacent few square miles in north central Beadle County are generally underlain by the Warren : West James aquifer. The aquifer is discontinuous, but where present is generally overlain by relatively impermeable glacial till ranging from a few feet to several tens of feet thick. A series of interconnected drainages in this area are former meltwater channels. Sand and gravel deposits on the floor of these channels are also generally thin and discontinuous. However, in some areas the channels cross buried portions of the Warren : West James aquifer. At these locations considerable thicknesses of sand and gravel directly underly the channel floor or may be present beneath several feet of alluvium.

A collapsed outwash plain with an area of about 2 square miles is located 1/2 to 2 1/2 miles south of Alpena (fig. 1). Here, surface sand and gravel (collapsed outwash) or till overlies additional sand and gravel, part of which is probably the buried

TABLE 4

Aquifers in which the mean total solids is less than 1000 mg/L

AQUIFER NAME : MANAGEMENT UNIT (if applicable)
Antelope Valley
Big Sioux : Aurora
Big Sioux : Brookings
Big Sioux : Middle Skunk Creek
Big Sioux : Moody
Big Sioux : North
Big Sioux : North Deer Creek
Big Sioux : Northern Skunk Creek
Big Sioux : Sioux Falls
Big Sioux : Six Mile Creek
Big Sioux : South
Big Sioux : Southern Skunk Creek
Big Sioux : Unnamed Creek
Bowdle : Edmunds
Bowdle : Hoven North
Bowdle : Hoven South
Bowdle : Lebanon
Chapelle Creek
Coteau Lakes
Crow Creek
Delmont
Floyd : Pearl Creek
Hillsview
Java
Lesterville
Missouri : Elk Point
Parker-Centerville
Selby
Spring Creek : Artas
Spring Creek : Herreid
Tulare : Hyde
Tulare : Western Spink
Vermillion East Fork : Montrose
Vermillion East Fork : Antelope Lake
Vermillion East Fork : Spirit Lake
Vermillion East Fork : Willow Lake
Wilmont

TABLE 5

Aquifers in which 95 percent confidence interval is less than 1000 mg/L total solids residue

AQUIFER NAME : MANAGEMENT UNIT (if applicable)
Antelope Valley
Big Sioux : Aurora
Big Sioux : Brookings
Big Sioux : Middle Skunk Creek
Big Sioux : North
Big Sioux : North Deer Creek
Big Sioux : Sioux Falls
Bowdle : Hoven North
Bowdle : Hoven South
Parker-Centerville
Vermillion East Fork : Willow Lake
Middle James : Columbia

Warren : West James Aquifer. The total thickness of sand and gravel may exceed 40 feet.

Hydrology

The Warren : West James aquifer is usually a buried and confined aquifer. Locally, the aquifer may be unconfined where it occurs near land surface, or where it has hydraulic connection to surface sands and gravels. These areas of hydraulic connection usually occur in the creek bottoms, or in the area of the collapsed outwash plain.

A water sample was collected from a 59-foot deep private well located in SE SE SW SE sec. 20, T. 109 N., R. 62 W, Beadle County during 1963. A chemical analysis revealed a total solids concentration of 865 ppm. This chemical quality makes it a Class II water and therefore worthy of consideration for drinking water purposes. However, other chemical analyses of water from the Warren : West James show poorer quality water as evidenced by the absence of this aquifer from tables 4 and 5. There is no log or water level available for this well, but its reported depth is consistent with other wells in the area known to be part of the Warren : West James aquifer. Other test hole or well logs within a 1-mile radius show the Warren to be absent, or composed primarily of fine or fine- to medium sand less than 25 feet thick.

A Water Rights observation well (JE-77B) was drilled in the collapsed outwash plain during 1977 (fig. 1). An abbreviated log of that well follows:

FIGURE 1

FEET	DESCRIPTION
0- 6	Gravel, fine to medium
6- 12	Clay, yellow-brown, gravelly
12- 14	Clay, gray, silty, gravelly
14- 43	Gravel, fine to coarse and
43- 55	Clay, gray, silty, sandy

The well was completed to a depth of 35 feet with the water level fluctuating between 12 and 18 feet. A water sample collected in 1977 yielded a total solids concentration of 572 ppm. Other test holes in the area had up to 40 feet of sand and gravel in them with less than 5 feet of overburden (fig. 1).

Conclusions

The area around the private well located in SE SE SW SE sec. 20, T. 109 N., R. 62 W., Beadle County, probably would not be a favorable area to consider for artificial recharge for the following reasons:

1. The aquifer is discontinuous and is likely to have small potential reservoir volume; and

2. The aquifer is probably too fine grained to serve as a practical recharge reservoir.

The area of collapsed outwash plain is, however, a potential artificial recharge site. Favorable geohydrologic conditions include:

1. Unsaturated sand and gravel at or near land surface;

2. Adequate thickness of aquifer to allow practical operation of discharge wells;

3. Water table conditions which are favorable for either recharge pits or injection wells;

4. Water quality with less than 1,000 ppm total dissolved solids, and

5. Assuming 5 feet of unsaturated sand and gravel over approximately a 2-square-mile area, a potential of about 250 acre-feet of storage is available.

If this latter site receives further consideration as an artificial recharge project, then further detailed testing would be required. Those items that should be further investigated are water quality, thickness and aquifer extent, overburden distribution, and water levels.

It should further be pointed out that other sites in or near this area have a high probability of being potential artificial recharge sites if water quality, which is unknown, is not a factor.

Vermillion East Fork; Lake County Artificial Recharge Site

Geology

The Vermillion East Fork management unit extends from northern Turner County to north-central Kingsbury County (Hedges and others, 1982, pl. 7). That part of it occurring in Lake County is the object of discussion here and typifies complicated and unpredictable glacial geology. The shape of the valley varies from a flat-bottomed, steep-walled, narrow gorge one-quarter mile wide; to a one and one-half mile wide valley with walls sloping down to a narrow floodplain. Outwash comprised of sand and gravel occurs erratically throughout. Sand and gravel is rarely present in the upper 25 feet of the valley floor sediments. Here deposits of alluvium, till, and fine grained outwash predominate. The sloping valley walls are composed primarily of till with scattered occurrences of sand and gravel. There are two small areas on the sloping valley wall, Area A and Area B (fig. 2) where total thickness of sand and gravel reaches a maximum of 33 and 26 feet, respectively. The extent of the sand and gravel and the stratigraphic relationship of these deposits to other aquifers in the area are unknown. Sand and gravel may be present at depths greater than 25 feet below the valley floor, but it is not known whether these deposits are restricted to the valley-fill sequence or are part of a more extensive aquifer system which has been incised by the down-cutting stream.

Hydrology

Observation well LK-67B located in SW corner sec. 9, T. 106 N, R. 54 W (fig. 2) was cased to a depth of 38 feet. The following log was recorded at that location:

FEET	DESCRIPTION
0- 3	Topsoil
3- 10	Tan clay
10- 35	Gray clay with fine sand streaks
35- 49	Coarse sand and gravel; rock at 49 feet

Logs from other test holes in that general area reflect a similar absence of sand or gravel in the upper 25 feet. A water sample was found to have a total dissolved solids concentration of 760 ppm in 1972. A subsequent sample in 1982 revealed a total dissolved solids concentration of 1252 ppm.

Water levels measured in well LK-67B fluctuate between 13 and 18 feet below the measuring point. This places it at the same

FIGURE 2 -- FOLDOUT -- FOLLOWING PAGE 17

level as the gray clay recorded from 10 to 35 feet in the test hole. The tan clay from 3 to 10 feet and the gray clay provide at least a semi-confining, if not an impermeable layer above the aquifer material.

Because there are no observation wells in Area A (fig. 2), saturated thickness and water quality for this area are unknown. One observation well (LK-67A) is present in Area B with sand and gravel logged from 2 to 19 feet. The water level in this well fluctuates about 3 to 8 feet below land surface. A 1980 water quality analysis from observation well LK-67A yielded a total dissolved solids concentrations of 420 ppm.

Conclusions

Geologic and topographic conditions do not appear favorable for potential artificial recharge in the area around observation well LK-67B using recharge pits or low head dams.

Both Area A and Area B have only limited potential as artificial recharge sites using recharge pits. Area B is particularly attractive due to the good quality water reported at the site. However, before conclusions on water quality are made, an additional water sample should be obtained from observation well LK-67A and other wells should be installed and sampled. Water quality determinations should also be made in Area A before potential desirability as an artificial recharge site is established.

The major drawback to both of these areas is their probable limited areal extent, and thus limited storage capacity. If Area A is assumed to cover 320 acres and Area B 160 acres, then for each 5 feet of unsaturated sand and gravel present there would be approximately 64 and 32 acre feet respectively of water storage. Thus, with present data it seems unlikely that there would be significant storage capability for artificial recharge.

The sporadic occurrence of sand and gravel throughout the East Fork Vermillion River in Lake County mandates extensive additional testing to determine if any of the three sites discussed have any practical potential for artificial recharge.

<u>Tulare : Hitchcock; Hitchcock Artificial Recharge Site</u>

Hydrogeologic Analysis

Two observation wells were drilled for the Water Rights Division (South Dakota Department of Water and Natural Resources) near Hitchcock, South Dakota, located at NW NW NW NW section 5, Township 113 North, Range 63 West. The first well (BD-76A) was drilled and cased during 1976 to a depth of 70.25 feet. A laboratory analysis of a water sample from that well showed a total dissolved solids value of 728 ppm. During 1980 this location was redrilled and observation well (BD-80J) was completed at a depth of 145.7 feet. A chemical analysis of water from that well showed a total dissolved solids of 1756 ppm. An abbreviated log of the 1980 test hole follows:

FEET	DESCRIPTION
0- 39	Clay (till)
39- 42	Coarse sand to fine gravel
42- 44	Clay (till)
44- 46	Boulder
46-132	Clay (till)
132-150	Coarse sand
150-173	Clay (till)
173-180	Shale

It should be noted that the first well (BD-76A) was completed in non-aquifer material (clay, till) at a depth of 70.25 feet while the second well (BD-80J) was completed in aquifer material (coarse sand) at a depth of 145.7 feet.

The sand encountered in observation well BD-80J at 132 to 150 feet may or may not be part of the Tulare aquifer. Because of its lower depth and high total dissolved solids, it is suspected that this sand may be an isolated lense and not in hydraulic connection with the Tulare aquifer.

Conclusions

It is recommended that this site should not be considered for artificial recharge because of the following reasons:

1. The depth (70.25 feet) at which the better quality water sample was obtained does not have a suitable recharge reservoir since geologic materials at that depth are nearly impermeable.

2. The aquifer material at 132 to 150 feet may be a small isolated sand lense and not of sufficient size for a practical artificial recharge project.

3. If the aquifer material at 132 to 150 feet is in fact part of the Tulare aquifer system, the poor water quality (1756 ppm total dissolved solids) far exceeds the limits of 1000 ppm total dissolved solids imposed by this study.

Miscellaneous Management Unit; Wessington Artificial Recharge Site

Geology

The Pearl Creek floodplain in east-central Hand County and extreme western Beadle County (fig. 3) represents the path of a former glacial meltwater channel that formed during a stillstand of ice as the glacier retreated from the Ree Hills area. The meltwater channel was cut 35 to 55 feet through relatively impermeable clay (glacial till). Subsequently, meltwater and recent stream-flow events deposited 30 to 35 feet of sand and gravel outwash and alluvium in the channel.

Hydrology

The sand and gravel fill in this part of Pearl Creek has been included as part of an aquifer designated as a Miscellaneous Management Unit in east-central Hand County. Water levels in this part of the aquifer are generally 3 to 7 feet below the land surface and fluctuate 2 to 3 feet annually as recorded in observation wells HD-73W and HD-73V. Water quality analyses of samples from these same wells indicate total dissolved solids less than 1000 ppm.

The sand and gravel underlies approximately 800 acres bounded on the south by the section line 1 mile north of Wessington. The north boundary terminates at the center of the west section line in section 11, T. 112 N., R. 66 W. (fig. 3). Natural recharge to this part of the aquifer is probably 2 to 4 inches per year or about 135 to 270 acre-feet per year.

Potential for Artificial Recharge Site

The evaluation of this site as an artificial recharge site is made without the assurace of an adequate water-supply to justify construction. For this discussion, however, an adequate supply of acceptable quality of water is assumed. With this qualification, the aquifer at this site would have the potential to be artificially recharged by a low-head dam or installation of recharge pits.

LOW-HEAD DAM OPTION

The construction of a low-head dam approximately 1400 feet long across the floodplain at the southeast corner of sec. 25. T. 112 N., R. 66 W. to the southwest corner of sec. 30, T. 112 N., R. 65 W. (fig. 3) with a maximum weir elevation of 1400 feet above MS1 would inundate approximately 625 acres of floodplain to a maximum depth of about 12 feet. Water behind this dam would then percolate downward into the underlying sand and gravel

FIGURE 3

deposits and spread laterally under the outwash terrace deposits (fig. 3). Discharge wells could be constructed on manmade islands overlying the floodplain, or on the outwash terrace deposits, preferably as close as maximum high water mark as is possible.

RECHARGE PITS OPTION

A series of recharge pits could be dug either on the floodplain or on the outwash terrace deposits with discharge wells constructed at appropriate locations for extraction of the water. The location, size, and number of recharge pits would depend on method of delivery and quantity of available recharge water as well as the hydrogeologic characteristics at each specific site.

Conclusions

The general geologic conditions, water table elevation, water quality, and topographic configuration indicate favorable conditions exist for development of an artificial recharge project at the Wessington site. However, more detailed testing and evaluation is required before a final decision is made. It is recommended that the following testing procedures be completed to help determine the feasibility of an artificial recharge project.

1. Determine potential source, amount, and method of delivery of recharge water.

2. Determine if there is any underlying aquifer material that is hydraulically connected to the outwash terrace deposits or the sand and gravel outwash deposits underlying the floodplain.

3. Determine the extent and thickness of the outwash terrace deposits and the degree of hydraulic connection to the sand and gravel outwash underlying the floodplain.

Due to the lack of detailed data at the Wessington site, a quantified proposal cannot be made at this time. The limiting factors for a sustained annual yield would depend primarily on two factors:

1. The amount and timing of recharge water availability, and

2. The actual geohydrologic conditions that exist as determined by the recommendations listed above.

Under optimum conditions, it would not be unreasonable to expect a sustained annual yield of 1000 to 2000 acre feet of water.

Floyd : Pearl Creek; Artificial Recharge Site

Geology

A report by Iles (1979) defined the thickness and extent of the Pearl Creek management unit. The management unit is comprised of glacial outwash which lies in a narrow bedrock valley eroded into the Pierre Shale. Varying thicknesses of relatively impermeable glacial till overlie the outwash throughout most of its areal extent. The southern half of the management unit is generally more deeply buried than the northern half (fig. 4).

The extent of the management unit as shown on plate 5 in Hedges and others (1982, TASKS 1, 2, and 3) is likely in error. The connection between the East James and Pearl Creek management units of the Floyd aquifer at the north end of the Pearl Creek management unit probably does not exist. Test hole data from Iles (1979) support this interpretation.

Hydrology

The Pearl Creek management unit has a north to south groundwater gradient and occurs under both confined and unconfined hydrologic conditions. The transition from unconfined to confined occurs approximately in sections 20 and 21, T. 110 N., R. 59 W. Unconfined conditions predominate north of this area while confined conditions predominate to the south.

Middle Pearl Creek, an intermittent stream, flows over the management unit at or just south of the transition from unconfined to confined hydrologic conditions. The potential for natural recharge that might be contributed by the creek to the outwash cannot presently be assessed. This is because it is not known whether the creek is directly connected to the outwash and if it is, whether it loses water to or gains water from the outwash.

Artificial Recharge

The use of a low-head dam on Middle Pearl Creek has only limited potential. Just west of the creek in sec. 29, T. 110 N., R. 59 W., the outwash is buried by only 9 feet of glacial till (fig. 4). In this same general area a low-head dam on the creek may provide recharge to the outwash if the following conditions are met:

1. The creek has cut through the till,

2. There is good hydrologic connection between the creek and outwash, and

3. The outwash is under unconfined hydrologic conditions.

FIGURE 4

Even though the creek may have cut through the till to the outwash, an effective seal may be provided by the presence of alluvium, thereby limiting recharge. Data elsewhere in the area where Middle Pearl Creek flows over the outwash show burial of the outwash by as much as 32 feet (fig. 4) which would eliminate the use of a low-head dam for recharge. It should be noted, however, that specific data are lacking on the hydrogeologic relationship between the creek and the outwash.

There is no potential for artificial recharge using a low-head dam on South Fork Pearl Creek. This is because the outwash is too deeply buried and is under confined hydrologic conditions beneath the creek.

Recharge using man-made infiltration basins is possible and would be most effective in that part of the management unit north of Middle Pearl Creek, an area of approximately 8 square miles. Here, the outwash is locally at or very near the land's surface (fig. 4) and is under unconfined hydrologic conditions.

Limited data are available on the thickness of the unsaturated outwash north of Middle Pearl Creek. Three observation wells in this portion of the management unit (fig. 5) show 13, 2, and 6 feet, respectively (from north to south), of unsaturated sand and gravel. Five feet of unsaturated outwash over the 8 square mile area will be assumed for discussion purposes. The specific yield of the outwash is assumed to be 0.20. Using the above assumed numbers, the present storage capacity for artificial recharge in the unconfined portion of the management unit is estimated to be approximately 5,000 acre-feet.

Figure 5 shows the total thickness of outwash (aquifer plus overlying dry sand and gravel). Using this figure along with figure 1 and the above mentioned thicknesses of unsaturated outwash, it is calculated that the saturated thicknesses of outwash at the above three mentioned wells are 27, 53, and 34 feet, respectively, from north to south. When there is more than 25 feet of saturated thickness, high capacity wells can normally maintain nearly constant production rates until or unless excessive drawdowns are created. Thus, the saturated thickness is great enough to allow pumping from the aquifer to create more storage capacity prior to or during artificial recharge, while still maintaining enough saturated thickness to allow removal of the water with conventional wells.

Conclusions

There is presently an assumed storage capacity of approximately 5,000 acre-feet available in that portion of the Pearl Creek management unit of the Floyd Aquifer which lies north of Middle Pearl Creek. This potential capacity along with adequate thickness of saturated sand and gravel make this area a good candidate for artificial recharge.

FIGURE 5

Any efforts in developing this area as a recharge site however must be preceded by a detailed hydrogeologic investigation to fully delineate the thicknesses of saturated and unsaturated outwash sand and gravel. Artificial recharge could be accomplished with man-made recharge pits. If recharge pits are used, they should be located upgradient from discharge points, and in areas where the best combination of unsaturated sand and gravel is present with minimum thickness of glacial till overburden.

Spring Creek : McPherson; Artificial Recharge Site

The U.S. Army Corps of Engineers expressed an interest in the McPherson management unit of the Spring Creek aquifer both as a potential primary water source and as a possible artificial recharge area. The ensuing sections will address both of these items.

Geology

The Spring Creek : McPherson aquifer in McPherson County is composed of two glacial geomorphic features: a collapsed outwash plain and a outwash valley train. Together they cover a total area of approximately 158 square miles (fig. 6). These features are composed primarily of sand and gravel, although till and lake sediments may be present. The collapsed outwash is present in approximately the eastern one-half of the area and the valley train is present in the western one-half (fig. 6). Thickness of the outwash ranges up to as much as 82 feet. Hamilton (1982) reports the aquifer at depths to 200 feet, but for purposes of this report the thickness of Spring Creek is restricted to that which occurs within 100 feet of the surface and is under water table conditons.

Hydrology

The surface of the collapsed outwash is undulating while the underlying water table is relatively flat, therefore, depth to water varies with the topography. There are not enough observation wells to construct a useful water table map, however, it can be assumed that water entering the aquifer flows toward lakes and sloughs which are discharge points most of the year. Natural recharge to the Spring Creek : McPherson aquifer (assuming 3.5 inches) may be as much as 29,000 acre-feet per year.

Table 6 shows location, depth, and conductivity of water from the Spring Creek : McPherson aquifer. Those wells for which conductivity values were less than 1,000 had an average depth of about 45 feet. By contrast, those wells which had an average depth of about 70 feet exceeded 1,000 micromhos. Thus, the better quality water is more likely to be found at shallower depths.

FIGURE 6 -- FOLDOUT -- FOLLOWING PAGE 27

TABLE 6

Location, depth, and conductance of water in the Spring Creek : McPherson aquifer

Location	Depth (ft)	Electrical Conductivity (micromhos)
127-70- 5 ACBB	20	965
127-70-18 BAB	70	803
127-71-22 ACC	22	718
127-71-23 BBBB	83	400
127-72-10 C	72	592
127-72-15 BB	12	592
128-69-30 DDDD	32	950
128-69-32 DCCB	50	945
126-71- 4 BBBC	100	2,450
127-70- 3 DCCB	82	1,920
127-71-16 DDDD	62	1,250
127-71-28 ADC	35	1,672
127-72-15 BBBB	64	1,550
127-72-24 AAAA	73	1,900

For location, see aquifer map, figure 6. Data from Hamilton, 1982.

Examination of thickness data from unpublished test hole logs, shape, and aquifer area shown on figure 6, suggests that in terms of quantity, the eastern portion of the aquifer would be most likely to sustain high capacity wells.

Conclusions

The present data strongly indicate that the Spring Creek : McPherson aquifer would probably be capable of yielding as much as several thousand acre-feet of water per year with total solids residue under 1,000 mg/L. However, much more detailed testing would be required to locate well field sites.

Assuming availability of water, artificial recharge would be a technically feasible method of augmenting water supplies from the Spring Creek : McPherson aquifer. The eastern portion would be more suitable because that part of the aquifer is wider and thicker.

Due to the relatively high relief of the collapsed outwash, natural ground-water flow patterms are localized and generally indicate discharge to lakes or sloughs. Correspondingly, there are many local ground-water divides and water quality changes could occur both horizontally and vertically over short distances. For these reasons, siting of either a well field or combination well field-recharge facility would necessitate detailed water table maps.

Big Sioux

The Big Sioux aquifer is a shallow, primarily water table aquifer that stretches southward along the axis of the Prairie Coteau, from its headwaters in Marshall County to its mouth at Sioux City, Iowa. Because it is a shallow water-table aquifer with highly permeable sand and gravel at the surface over much of its extent, it would seem likely to be a good prospect for artificial recharge. However, the Big Sioux aquifer is thin, has water table near land surface and has short retention time, all of which limit the practicality of artificially recharging the Big Sioux aquifer. In addition to its physical limitations, there is no apparent "need" for artificial recharge. This conclusion is based on total use estimates of 57,000 acre feet per year versus 258,000 acre feet per year natural recharge. The one potential area where a "need" exists for artificial re- charge is the Sioux Falls management unit. The City of Sioux Falls currently obtains its water supply from wells in this area. However, as detailed in TASK 7, the "need" is presently being satisfied by induced infiltration from the Big Sioux River.

The difficulties encountered in using shallow unconfined aquifers in eastern South Dakota for artificial recharge are exemplified by an attempted pilot artificial recharge project at Sioux Falls (see Siegel, 1984, app. F). This project was initiated in 1977 and terminated in 1984 without ever accomplishing the objective of diverting water from the Big Sioux River to that test area. The two conclusions resulting from this project are:

1. During the seven-year period that this project existed, the water table never dropped far enough below land surface for a sufficient length of time, even through drought years, to warrant implementation of artificial recharge. The project participants concluded that natural recharge, plus inadvertent induced recharge from the diversion channel and sediment traps which were part of the project structures, already were accomplishing a very efficient job of recharging the aquifer in this area, and

2. If a severe enough drought occurred to necessitate artificial recharge to the Sioux Falls well field there probably would be inadequate flow in the Big Sioux River to allow diversion.

It should be recalled from discussion earlier in this report that aquifers with water tables generally less than 10 feet deep were not considered practical for artificial recharge. To determine how water levels in the entire Big Sioux aquifer compared to this limitation, appendix G was compiled as a computerized analysis of most observation wells for each management unit in the Big Sioux aquifer. This data show average depth to water for each observation well, however, the averages are not weighted for time. This simple compilation shows that 71 of of 192 observation wells (37 percent) have average water levels more than 10 feet below land surface. A cursory glance at the table shows that a high proportion of these 71 wells exceed the 10-foot limitations by only 1 to several feet. This quick and simplified analysis indicates that shallow water-table conditions exist over a substantial portion of the Big Sioux aquifer. Thus, favorable sites for artificial recharge are not too likely within the Big Sioux.

GENERAL CONCLUSIONS

A variety of limitations for shallow, unconfined aquifers in eastern South Dakota makes artificial recharge, in general, impractical. Local areas could successfully use artificial recharge as a management option if the right combination of storage, water use patterns, and water availability (natural or imported) were available. However, determination of these areas would depend on a detailed evaluation for each specific site.

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APPENDIX A

Unconfined aquifers and management units that are non-buried

Aquifer : Management Unit	Suitable for Low-Head Dam	Suitable for Spreading Basin
Antelope Valley	yes	yes
Big Sioux : Aurora	yes	yes
Big Sioux : Brookings	yes	yes
Big Sioux : Middle Skunk Creek	yes	yes
Big Sioux : Moody	yes	yes
Big Sioux : North	yes	yes
Big Sioux : North Deer Creek	yes	yes
Big Sioux : Northern Skunk Creek	yes	yes
Big Sioux : Sioux Falls	yes	yes
Big Sioux : Six Mile Creek	yes	yes
Big Sioux : South	yes	yes
Big Sioux : Southern Skunk Creek	yes	yes
Big Sioux : Unnamed Creek	yes	yes
Bowdle : Edmunds	?	?
Bowdle : Hoven North	yes	yes
Bowdle : Hoven South	yes	yes
Bowdle : Lebanon	yes	yes
Chapelle Creek	?	?
Coteau Lakes	yes	yes
Cow Creek	no	yes
Crow Creek	no	no
Delmont	yes	yes
Elm Creek	yes	yes
Highmore-Blunt	yes	yes
Missouri : Elk Point	no	yes
Missouri : Greenwood	no	yes
Missouri : Peoria	no	yes
Missouri : Pierre	no	yes
Missouri : Tower	no	yes
Okobojo Creek	no	no
Parker-Centerville	yes	yes
Selby	no	yes
Spring Creek : Artas	yes	yes

Spring Creek : Herreid	yes	yes
Spring Creek : McPherson	yes	yes
Vermillion-East-Fork : Antelope Lake	no	yes
Vermillion-East-Fork : Montrose	yes	yes
Vermillion-East-Fork : Reid Lake	no	yes
Vermillion-East-Fork : Spirit Lake	no	yes
Vermillion-East-Fork : Willow Lake	no	yes
Vermillion-West-Fork	yes	yes

NOTES:

All aquifers and management units are as defined in the following reference unless otherwise noted.

Hedges, Lynn S., Burch, Stephen L., Iles, Derric L., Barari, Rachel A., and Schoon, Robert A., 1982, Evaluation of ground-water resources eastern South Dakota and upper Big Sioux River, South Dakota and Iowa: Prepared by the South Dakota Geol. Survey for the U.S. Army Corps of Engineers, Contract DACW45-80-C-0185.

The Missouri aquifer and its management units were defined as part of the basal aquifer system in Hedges and others, 1982.

Missouri : Elk Point -- This part of the Missouri aquifer had no management unit designation in Hedges and others, 1982. It was simply identified as 'M'.

Vermillion-East-Fork : Montrose -- This part of the Vermillion-East-Fork aquifer had no management unit designation in Hedges and others, 1982. It was identified as 'VEF'.

APPENDIX B

Unconfined aquifers and management units that are buried

Aquifer : Management Unit	Suitable for Low-Head Dam	Suitable for Spreading Basin
Choteau : East	no	yes
Floyd : Pearl Creek	yes	yes
Gray Goose	no	no
Tulare : East James	yes	yes
Tulare : Hitchcock	no	yes

NOTES:

All aquifers and management units are as defined in the following reference.

Hedges, Lynn S., Burch, Stephen L, Iles, Derric L., Barari, Rachel A., and Schoon, Robert A., 1982, Evaluation of ground-water resources eastern South Dakota and upper Big Sioux River, South Dakota and Iowa: Prepared by the South Dakota Geol. Survey for the U.S. Army Corps of Engineers, Contract DACW45-80-C-0185.

APPENDIX C

Confined aquifers and management units

QUATERNARY AQUIFERS

<u>Aquifer</u> : <u>Management Unit</u>

Altamont

Bad-Cheyenne
Brule Creek

Choteau : Middle
Choteau : Tyndall
Choteau : West
Corsica
Crow Lake

Deep James

Elm : Ipswich
Elm : Northern Brown
Elm : Southern Brown
Ethan

Fairmount
Floyd : Alexandria
Floyd : East James

Geddes
Grand

Harrisburg
Hillsview
Howard
Hubonmix

Intermediate

Java

Lennox
Lesterville
Lower-James-Missouri : Jamesville
Lower-James-Missouri : Scotland
Lower-Vermillion-Missouri

Middle James : Aberdeen
Middle James : Columbia

Newton Hills

Onaka

Plum Creek
Prairie Coteau

Shindler
Sioux Falls

Tulare : Hand
Tulare : Hyde
Tulare : Miller
Tulare : Ree Heights
Tulare : Sully
Tulare : Western Spink
Twin Lakes

Upper-Vermillion-Missouri

Veblen

Wakonda
Wall Lake
Warren : Morris Creek
Warren : West James
Warren : Wolsey
White Lake
Wilmot

BEDROCK AQUIFERS

Codell Sandstone

Dakota Formation

Greenhorn Limestone

Igneous and metamorphic rocks
Inyan Kara Group

Madison Group

Niobrara Formation

Sioux Quartzite
Split Rock Creek Formation

NOTES:

All aquifers and management units are as defined in the following reference unless otherwise noted.

Hedges, Lynn S, Burch, Stephen L., Iles, Derric L., Barari, Rachel A., and Schoon, Robert A., 1982, Evaluation of

ground-water resources eastern South Dakota and upper Big Sioux River, South Dakota and Iowa: Prepared by the South Dakota Geol. Survey for the U.S. Army Corps of Engineers, Contract DACW45-80-C-0185.

Lower-James-Missouri : Jamesville -- This part of the Lower-James-Missouri aquifer had no management unit designation in Hedges and others, 1982. It was identified as 'LJM'.

Sioux Falls -- This aquifer was absent in Hedges and others, 1982.

Tulare : Sully -- This part of the Tulare aquifer had no management unit designation in Hedges and others, 1982. It was identified as 'T'.

APPENDIX D

Water use versus recharge. (a)

Aquifer and/or Management Unit (1)	Water use vs estimated minimum annual recharge (in percent) (2)	Water use vs estimated maximum annual recharge (in percent) (3)
Choteau : Tyndall	477	119
Vermillion East Fork : Montrose	364	364 (b)
Upper Vermillion Missouri	357	89
Warren : Wolsey	317	79
Floyd : Pearl Creek	310	62
Lower Vermillion Missouri	251	63
Cow Creek	238	238
Lower James Missouri : Scotland	196	49
Choteau : West	184	50
Warren : West James	163	41
Choteau : Middle	158	40
Gray Goose	150	30
Geddes	147	37
Tulare : Hand	144	36
Ethan	143	36
Lennox	140	35
Wall Lake	140	34
Elm : Northern Brown	137	34
Big Sioux : Sioux Falls	131	131
Elm : Ipswich	130	32
Brule Creek	129	32
Floyd : East James	124	31
Missouri : Pierre	122	122
Choteau : East	120	30
Plum Creek	108	27
Grand	86	22
Tulare : East James	86	86
Bad-Cheyenne	81	20
Hillsview	80	20
White Lake	79	20
Hubonmix	78	20
Middle James : Aberdeen	77	19
Lower James Vermillion : Scotland	75	19
Crow Lake	64	16
Middle James : Columbia	57	14
Tulare : Hyde	54	14
Veblen	52	13

(1)	(2)	(3)
Tulare : Hitchcock	52	52
Newton Hills	51	13
Okobojo Creek	49	49
Wilmot	47	12
Parker-Centerville	44	44
Howard	43	11
Elm : Southern Brown	43	11
Floyd : Alexandria	41	10
Big Sioux : Southern Skunk Creek	40	40
Big Sioux : Northern Skunk Creek	40	40
Tulare : Western Spink	39	43
Tulare : Sully	39	10
Tulare : Miller	37	9
Twin Lakes	37	9
Java	36	9
Big Sioux : Six Mile Creek	36	36
Intermediate	36	9
Missouri : Elk Point	35	35
Big Sioux : South	35	35
Bowdle : Hoven South	35	35
Prairie Coteau	33	8
Harrisburg	33	8
Warren : Morris Creek	32	8
Big Sioux : North	32	32
Shindler	32	8
Big Sioux : Unnamed Creek	32	32
Tulare : Ree Heights	31	8
Onaka	31	8
Corsica	30	8
Big Sioux : Aurora	30	30
Highmore-Blunt	29	29
Altamont	28	7
Wakonda	28	7
Fairmount	26	7
Bowdle : Lebanon	26	26
Crow Creek	24	24
Big Sioux : Middle Skunk Creek	24	24
Deep James	23	6
Big Sioux : Brookings	23	23
Big Sioux : North Deer Creek	22	22
Big Sioux : Moody	21	21
Bowdle : Hoven North	18	18
Lesterville	18	4
Delmont	15	15

(1)	(2)	(3)
Vermillion East Fork : Spirit Lake ----------	14	14
Sebly -------------------------	14	14
Elm Creek --------------------	13	13
Vermillion East Fork : Willow Lake ----------	12	12
Missouri : Peoria -------------	12	12
Antelope Valley ---------------	9	9
Vermillion West Fork ----------	8	8
Bowdle : Edmunds --------------	8	8
Vermillion East Fork : Antelope Lake ---------	6	6
Chapelle Creek ----------------	5	5
Spring Creek : Montrose -------	3	3
Spring Creek : Artas ----------	3	3
Spring Creek : Herreid --------	2	2
Coteau Lakes ------------------	2	2
Missouri : Greenwood ----------	1	1
Vermillion East Fork : Reid Lake ------------	1	1
Missouri : Tower --------------	1	1

(a) Water use data used in compiling this appendix were taken from Hedges, Burch, and Iles, 1985. Recharge rates for individual unconfined aquifers were taken from tables 7 and 14 (Hedges and others, 1985). Natural recharge rates for all confined aquifers were calculated using 0.15 and 0.60 inches per year as the minimum and maximum recharge rates, respectively. The method for calculation of percentage water use versus recharge is by the following formula: water use ÷ average annual recharge X 100 = percent water use.

(b) For the purposes of this study, the minimum and maximum recharge estimates for all unconfined aquifers are considered to be equal.

APPENDIX E

Appropriation versus recharge. (a)

Aquifer and/or Management Unit (1)	Appropriation versus estimated minimum annual recharge (in percent) (2)	Appropriation versus estimated maximum annual recharge (in percent) (3)
Choteau : Tyndall -------------	3,853	963
Vermillion East Fork : Montrose -------------	2,950	2,950 (b)
Warren : Wolsey ---------------	2,451	612
Floyd : Pearl Creek -----------	2,234	447
Upper Vermillion Missouri -----	1,977	494
Elm : Northern Brown ----------	1,843	461
Lower Vermillion Missouri -----	1,572	393
Cow Creek ---------------------	1,253	1,253
Big Sioux : Six Mile Creek ----	1,194	1,194
Warren : West James -----------	1,186	296
Choteau : Middle --------------	1,087	272
Choteau : West ----------------	1,037	259
Elm : Ipswich -----------------	1,022	256
Ethan -------------------------	965	242
Missouri : Pierre -------------	939	939
Tulare : Hand -----------------	894	223
Big Sioux : Sioux Falls -------	893	893
Floyd : East James ------------	849	212
Lower James-Missouri : Jamesville ------------------	806	201
Brule Creek -------------------	713	178
Tulare : East James -----------	710	710
Wilmont -----------------------	687	182
Gray Goose --------------------	662	132
Big Sioux : Southern Skunk Creek ------------------	627	627
Plum Creek --------------------	615	154
Middle James : Aberdeen -------	580	145
Middle James : Columbia -------	526	131
Grand -------------------------	494	123
Choteau : East ----------------	467	117
Veblen ------------------------	456	114
Hillsview ---------------------	437	109
Tulare : Hitchcock ------------	424	424
Bad Cheyenne ------------------	423	106
Geddes ------------------------	399	100
Lennox ------------------------	397	99

(1)	(2)	(3)
Big Sioux : Northern Skunk Creek	349	349
Tulare : Western Spink	317	317
Okobojo Creek	311	311
Big Sioux : Aurora	299	299
Parker-Centerville	287	287
Big Sioux : Unnamed Creek	278	278
Bowdle : Hoven South	272	272
Crow Lake	270	67
Big Sioux : North	250	250
Wall Lake	240	60
Lower James Missouri : Scotland	236	59
Elm : Southern Brown	225	56
Missouri : Elk Point	218	218
Big Sioux : Brookings	216	216
Big Sioux : North Deer Creek	214	214
Altamont	200	50
Howard	195	49
Hubonmix	191	48
Prairie Coteau	188	47
Big Sioux : Moody	183	183
Big Sioux : South	157	157
Highmore-Blunt	153	153
Antelope Valley	151	151
Big Sioux : Middle Skunk Creek	150	150
Tulare : Hyde	147	37
Crow Creek	144	144
Warren : Morris Creek	129	32
Bowdle : Hoven North	122	122
Vermillion East Fork : Willow Lake	108	108
Vermillion East Fork : Spirit Lake	105	105
Fairmount	105	26
Vermillion West Fork	99	99
Bowdle : Lebanon	95	95
Selby	84	84
Intermediate	82	20
Vermillion East Fork : Antelope Lake	75	75
Delmont	69	69
Onaka	68	17
Missouri : Peoria	68	68
Deep James	67	17
Elm Creek	57	57
Corsica	27	7
Java	27	7

(1)	(2)	(3)
Bowdle : Edmunds ----------------	26	26
Coteau Lakes ----------------------	22	22
Tulare : Miller -----------------	20	5
Chapelle Creek ------------------	20	20
Spring Creek : Artas ------------	20	20
Spring Creek : McPherson -------	13	13
Spring Creek : Herreid ---------	3	3
Missouri : Greenwood ----------	3	3
Vermillion East Fork : Reid Lake -------------	0	0
Missouri : Tower ---------------	0	0
Lesterville ---------------------	0	0
Wakonda ------------------------	0	0
Tulare : Ree Heights -----------	0	0
Shindler -----------------------	0	0
Harrisburg ---------------------	0	0
Twin Lakes ---------------------	0	0
Tulare : Sully -----------------	0	0
Floyd : Alexandria -------------	0	0
Newton Hills -------------------	0	0
White Lake ---------------------	0	0

(a) Water use data used in compiling this appendix were taken from Hedges, Burch, and Iles, 1985. Recharge rates for individual unconfined aquifers were taken from tables 7 and 14 (Hedges and others, 1985). Natural recharge rates for all confined aquifers were calculated using 0.15 and 0.60 inches per year as the minimum and maximum recharge rates, respectively. The method for calculation of percentage appropriation versus recharge is by the following formula: appropriation ÷ average annual recharge X 100 = percent appropriation.

(b) For the purposes of this study, the minimum and maximum recharge estimates for all unconfined aquifers are considered to be equal.

APPENDIX F

Big Sioux aquifer recharge study at Sioux Falls *

* This appendix contains the entire text but does not contain the appendices.

FINAL REPORT

BIG SIOUX AQUIFER RECHARGE STUDY AT SIOUX FALLS

Prepared by

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EAST DAKOTA CONSERVANCY SUB-DISTRICT
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FIGURES

TABLE

INTRODUCTION

Scope of This Report -- This report is not inteneded to be a detailed treatise on aquifer recharge. Instead, it is an effort by the chairman of a multi-agency task force, created in 1977, to make a pilot aquifer recharge study, to document the group's efforts, and to summarize the conclusions drawn from this experience.

Basis for Study -- On June 22, 1977, a Citizens Water Advisory Committee appointed earlier by the Sioux Falls City Commission submitted a written report to the Commissioners.[1] The Committee's first short-term recommendation was that, "Immediate steps be taken by the city to initiate programs of annual recharge of the aquifer." The Committee further recommended that additional study be made to determine the most effective means of recharging the Big Sioux Aquifer.[2]

On June 10, 1977, John Velehradsky, Chief - Planning Division, Omaha District - Corps of Engineers (Corps), wrote to the East Dakota Conservancy Sub-District (EDCSD), U.S. Geological Survey (USGS), and City of Sioux Falls (C-SF) noting that the Corps was evaluating alternative sources of supplemental water supply for Sioux Falls as part of the Corps' Upper Big Sioux River and Eastern South Dakota Water Supply Study.[3] He proposed a multi-agency evaluation of artificial recharge and offered $5000 of Corps' funds to initiate the effort.

Representatives of the Corps, USGS, South Dakota Geological Survey (SDGS), and C-SF met with the EDCSD Board of Directors on July 21, 1977 and decided to jointly pursue a well-planned research program to evaluate the possibility of recharge of the Big Sioux River Aquifer north of Sioux Falls.[4]

These actions were taken because artificial recharge had been a popular concept in most discussions of alternatives for Sioux Falls' future water supply. In addition, the Sioux Falls Water Advisory Committee had hired Ed Lacey, a well driller/inventor from Trent, South Dakota, to run some preliminary recharge tests. The Committee felt that these test results warranted more intensive evaluation using pilot tests in a section of the city's wellfield.

Formation of Task Force and Pilot Study Proposal -- Initial task force participants were Carter Laing, Corps; Jerry Siegel and Wendell Wischer, EDCSD; John Powell and Ed LeReux, USGS; Merlin Tipton and Assad Barari, SDGS; Les Hash, Tom Molohan and Vern Winegarden, C-SF; and Gerald Moore, EROS Data Center.

It should be noted that Rick Miner, Paul Ziemba and Alan Johnson were later Corps participants as were Neil Koch and John Little with the USGS. In addition, John Wiersma, James Dornbush and Walter Hu, Engineering Professors at South Dakota State University, provided input. John Madden, DeWild Grant Reckert and Assoc. (DGR), as consultant to C-SF, assisted the task force with various technical aspects of the project.

All committee meetings were held at the Water Purification Plant in Sioux Falls. A brief summary of actions of the task force in planning and trying to implement the study follows.

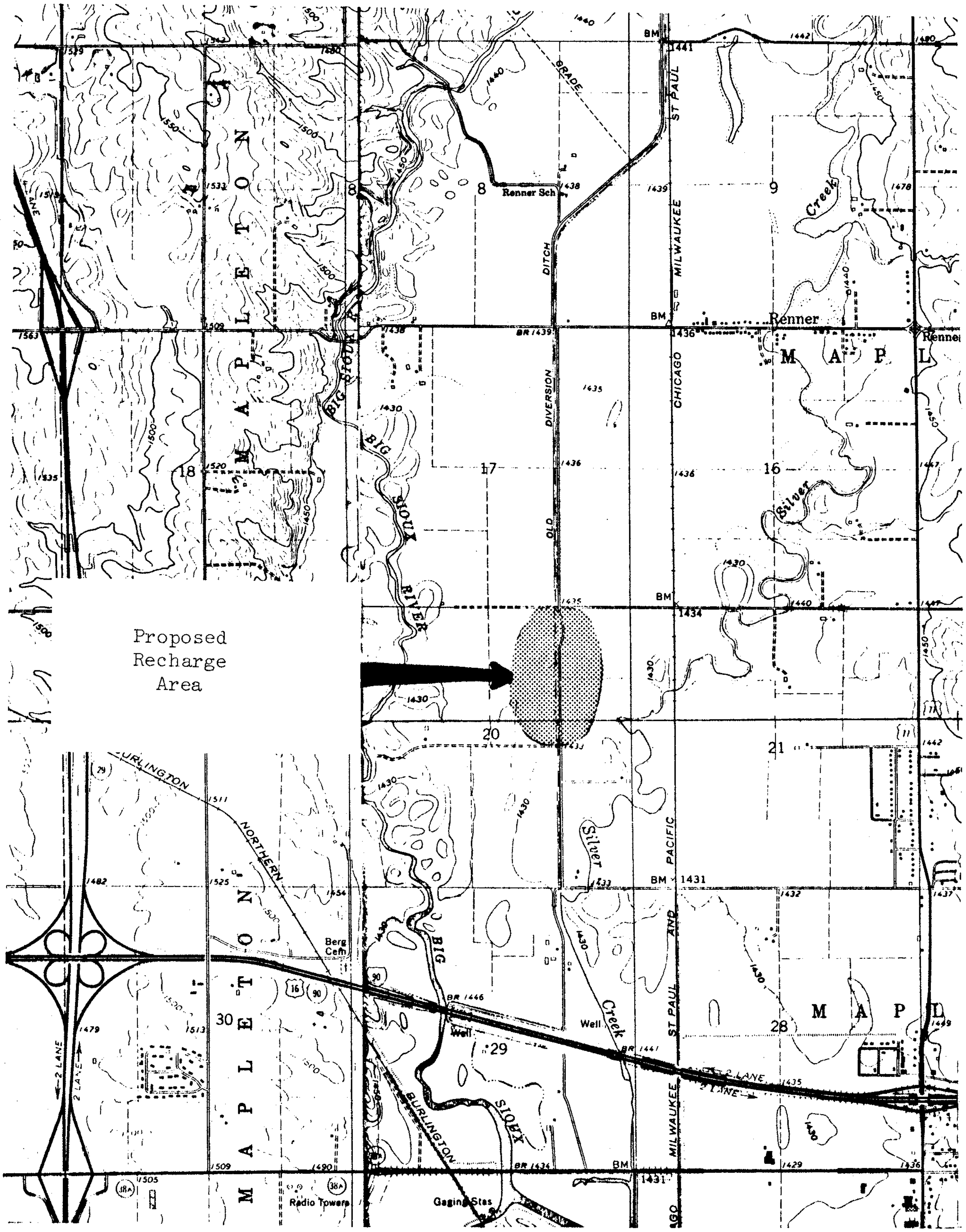
At the initial meeting, on August 4, 1977, Jerry Siegel was appointed task force chairman. Three possible pilot recharge sites in the Sioux Falls area were evaluated using maps and field inspections. A section of a drainage channel north of the city between the Big Sioux River and Silver Creek was tentatively selected as the best site. The task force decided to secure the following information: (1) maps showing location and capacity of all city wells; (2) the location of all existing observation wells; (3) sediment data from the Dell Rapids gauging station; (4) a detailed bibliography on past aquifer recharge efforts in the United States; and (5) a copy of the Silver Creek Watershed Improvement Plan.

At the second meeting, on September 1, a number of articles on artificial recharge were reviewed and the general concept of diverting Big Sioux River water via pipeline as the source of recharge was developed. The task force decided to ask the Sioux Falls Water Advisory Committee and two townships to participate in the task force, if they desired.

At an October 4 meeting, the task force learned from John Hatch, S.D. Division of Water Rights, that a temporary water permit was needed to run the proposed pilot recharge tests. In addition, the permit to divert Big Sioux River flows for the proposed Slip-Up Creek Project would be senior to any artificial recharge permit.

On October 27, Les Hash reported that water levels in their older wells in the airport area had risen six to eight feet recently when water began flowing again in the Big Sioux River. A rough cost estimate of $23,500 was made to install and operate a four-cell recharge system. A final site location was made along 160 acres owned by the C-SF in the NE½ of Section 20 (see Figure 1). Carter Laing was authorized to finalize a proposal for submission to the Corps' Missouri River Division Office in Omaha with a request for $15,000 of Corps' funding. By late December, the task force received word that the Corps had tentatively approved a $15,000 grant.[5]

Figure 1. Location Map of Proposed Artificial Recharge Test Area.



Final Study Proposal -- The general proposal agreed on by the task force and finalized by Carter Laing is summarized below:

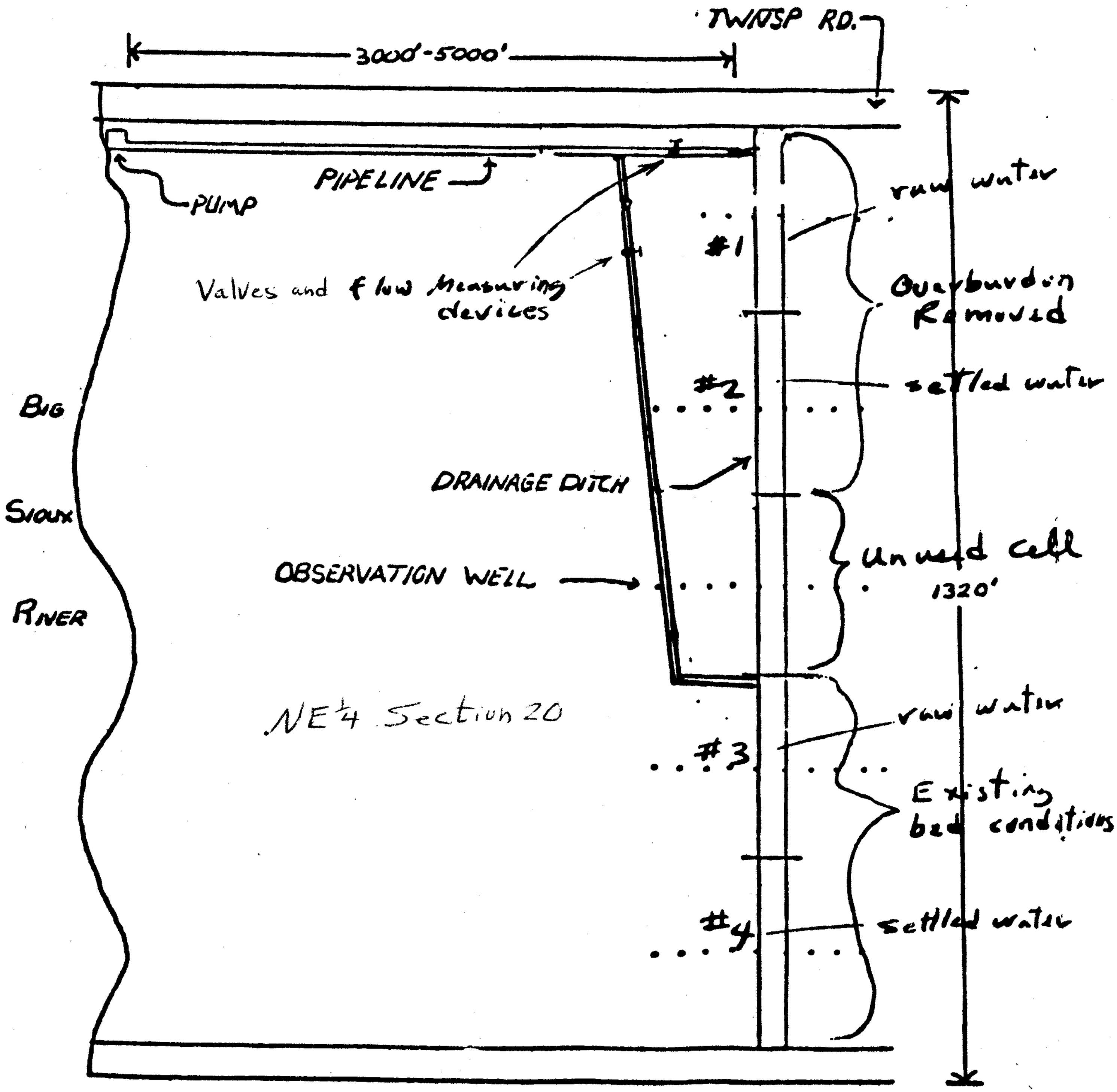
Materials for constructing the pits, power costs, and other direct costs would be financed by the Corps grant. The C-SF would provide equipment and labor to construct the pits and would be in charge of actual operation of the recharge tests.

The project called for construction of two two-cell recharge pits in a one-fourth mile reach of the old drainage ditch north of Sioux Falls between Silver Creek and the Big Sioux River, along land owned by the C-SF. The recharge tests would be conducted essentially as follows: Water would be diverted from the Big Sioux River to the drainage ditch by means of an irrigation pump and a T-ed pipeline which would allow metered discharge of water into the recharge test area at two separate points. Water would be impounded in the drainage ditch by means of six channel structures filled with flow measurement devices. The six channel structures would form four recharge impoundments. The first two impoundments would be prepared for the recharge tests by removal of 12 to 18 inches of soil from the drainage ditch bottom. The third and fourth impoundments would be left in their natural state. The first cell of each series would thus receive raw Big Sioux River surface water, whereas the second cell would receive better quality water with most of the suspended solids removed in the first cell (see Figure 2).

A total flow of about 600 gpm would be pumped into the recharge impoundment and allowed to infiltrate into the aquifer. The quantity of surface flow into and out of each recharge pit would be accurately measured. The quantity of water which infiltrated the recharge area would be determined by use of the continuity equation. The rate of recharge into the aquifer would be monitored by about 50 observation wells placed in five parallel rows in a semi-logrithmic pattern perpendicular to the drainage ditch. At least one row of wells would extend from Silver Creek to the Big Sioux River. Water would be applied to the recharge site in a cyclical manner during the critical phase of testing and in a continuous manner during the second phase of testing. Recharge tests would be run as soon as there was a combination of the following two conditions: (1) the water level in the recharge area was low enough to conduct reliable recharge tests, and (2) there were still sufficient flows in the Big Sioux River to allow diversion.

All participating agencies would assist in data collection for the first few days of the recharge tests. After that period, the C-SF would read the observation wells and river stage gauge on a regular basis in the manner approved by the other participating agencies. Data evaluation would be conducted to determine the rate of flow from recharge water into the aquifer under the variable conditions experienced during the recharge test.

Figure 2. Sketch Diagram Showing General Layout of Proposed Four Cell Recharge System.



Attempted Implementation of Project -- The committee met again on January 10, 1978 and approved the final study work plan. It was apparent, however, from the rising watertable that the pilot tests would be difficult to conduct during 1978. The task force felt strongly that the average water level in the recharge area should be at least five feet below the top of the gravel outwash material before reliable information could be secured from artificial recharge tests. The SDGS agreed to install the needed observation wells as soon as weather permitted. The Corps issued a three-party contract with the C-SF and EDCSD on May 4, 1978.

The task force met again, May 24, 1978, to finalize detailed plans for recharge cell size and location and the location and placement of observation wells. John Madden of DGR was authorized to survey the location and elevation of the observation wells, once installed (see Figure 3). The SDGS installed the observation wells in early June, 1978. High water levels continued through 1978 and early 1979, however, and prohibited the running of pilot recharge tests.

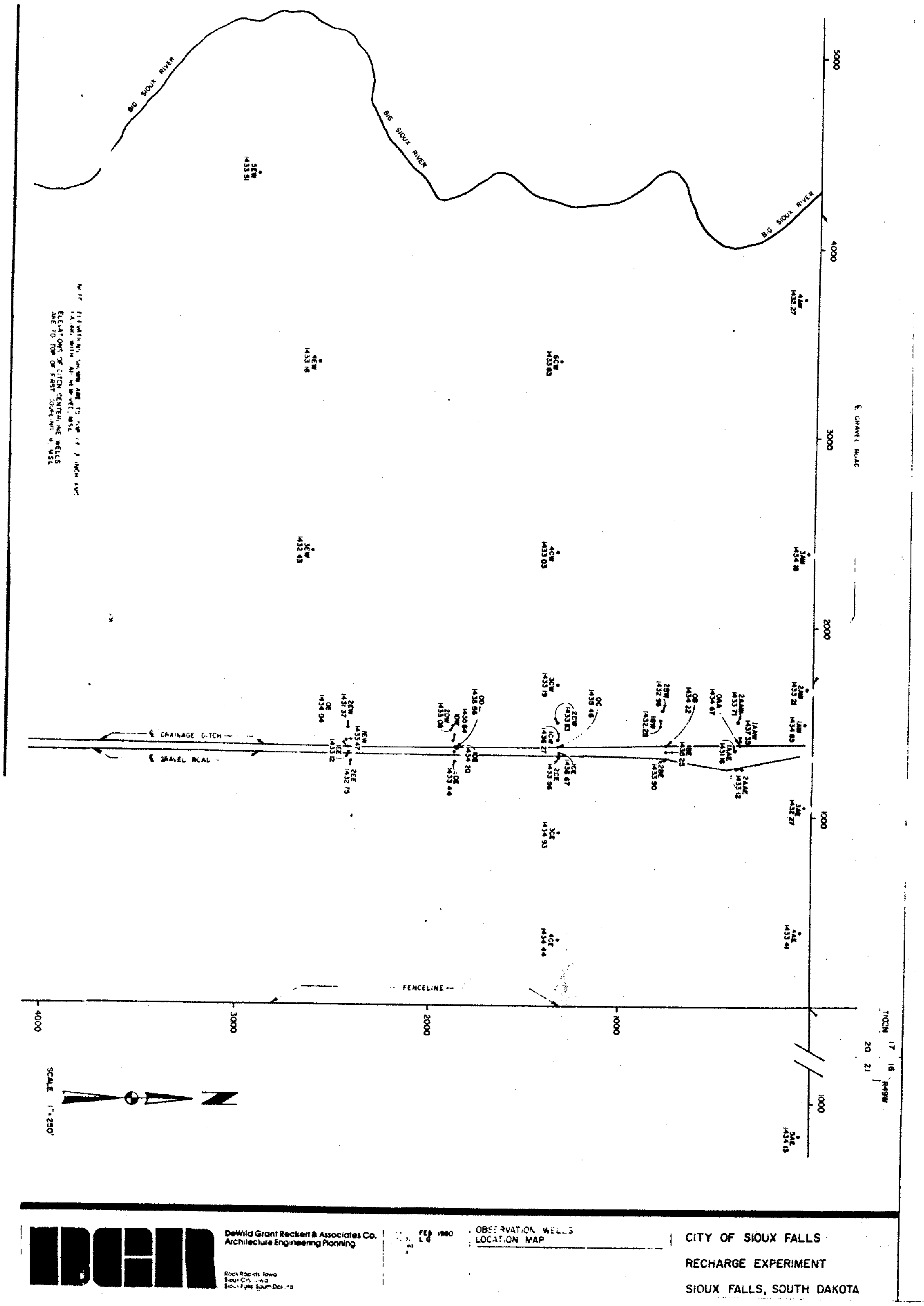
During late summer of 1979, water levels began to drop. On September 13, the task force met to update the proposed recharge project and determine whether to proceed with the pilot tests. Updated costs estimates prepared by DGR for purchase and fabrication of the channel structures were reviewed. Total costs had risen from $31,000 to $41,031.93. The task force asked the Corps to consider providing additional funds needed due to the rise in costs resulting from time delays.

The task force decided to purchase the materials and fabricate the structures so they would be ready to install once water levels were favorable. The Corps modified the three-party contract on October 12 so a $10,000 payment could be made upon installation of the observation wells and delivery of the assembled channel structures. The channel structures were fabricated by DGR and C-SF personnel. Water levels rose again, however; further delaying the actual tests.

On March 18, 1980, EDCSD billed the Corps for $10,000. A $1,428.40 payment was given to SDGS for installation of the observation wells and $7,706.11 to DGR for surveying, preparing cost estimates, and purchasing and partially assembling the channel structure materials.

The task force met April 22, 1980 to review the possibility for conducting tests during 1980. Although the aquifer and river were essentially full, the committee decided to apply for a temporary water permit in case water levels dropped later. A temporary permit for Sioux Falls to divert 0.865 mgd, as long as there was a 50 cfs by-pass flow, was approved June 10 by the State Division of Water Rights. On August 12, DGR noted that water levels might not drop the desired 5 feet below the top of the aquifer by the end of the year. The temporary recharge permit expired December 31, 1980.

Figure 3. Detailed Location Map of Observation Wells Installed by the S.D. Geological Survey for the Sioux Falls Aquifer Recharge Project.



On February 10, 1981, DGR billed the C-SF and EDCSD for $1242.12 of unpaid engineering services and materials and noted that high water levels precluded testing that spring. DGR was paid $865.49 remaining from the $10,000 Corps grant received earlier, leaving an unpaid bill of $376.63.

Task Force Chairman Jerry Siegel corresponded with the C-SF stating that no further expenses should be incurred until additional funds were secured.[6] He began pursuing funds through the Corps' Sec. 22 and Eastern South Dakota Water Supply Study programs. In late 1981, a strong request was made for a $15,000 allocation of Eastern South Dakota Water Supply Study funds for FY1982. The Corps indicated they might become available and asked for detailed cost estimates. The following breakdown was made for the remaining $5000 grant plus $15,000 of new funds.[7]

Purchase and installation of water delivery equipment	--	$13,000
Purchase and installation of flow measurement devices	--	1,000
Pumping power costs	--	1,000
Data interpretation and report preparation	--	5,000
Total	--	$20,000

This estimate continued to assume that the C-SF would honor an earlier commitment to get the site ready for testing and record most of the data, and that the EDCSD, SDGS and USGS would supervise the installation of equipment and the collection and analysis of data. On June 11, Mr. Siegel met with the Corps and learned that they were in the process of allocating the $15,000 to the aquifer recharge budget. Water levels remained high during 1982, however, and the recharge tests were further delayed.

During early 1982, the USGS was finalizing preparation of a digital model of the main Big Sioux River Aquifer in Minnehaha County, north of Sioux Falls. The task force shifted its efforts temporarily toward use of the digital model to analyze the potential for artificial recharge north of Sioux Falls. Several trips were made to Huron to consult with Neil Koch, who was responsible for preparation of the model. A discussion of these analyses is contained in the Analysis and Discussion section of this report.

During 1983, water levels remained high. Alan Johnson replaced Rick Miner as the Corps official responsible for the project. In late 1983 (November 7), the Corps processed payment for $372.63 engineering services which had been provided by DGR. Alan Johnson advised Task Force Chairman Jerry Siegel that the $15,000 allocation of Eastern South Dakota Water Supply Study funds for the recharge project would likely be lost if the tests could not be run during 1983.

In early 1984, it became apparent to everyone involved that reliable recharge tests at the selected site could not be achieved unless drought conditions returned. Alan Johnson advised Jerry Siegel, in an April 18 telephone conversation, that the $15,000 of additional Corps funding had reverted and asked him to utilize the $5627.37 remaining to summarize the efforts of the task force and to make a realistic appraisal of the potential for artificial recharge of the Big Sioux River Aquifer near the Sioux Falls wellfield area.

USGS and C-SF water officials were consulted. C-SF officials indicated they did not wish to prepare the final report but offered to provide water level data for their wellfield and to review the draft report. The EDCSD entered into a cooperative agreement with the USGS to provide $1000 of Corps funds for USGS analysis of flow records at the Dell Rapids gauging station.

SUMMARY OF EXPENDITURES FROM $15,000 CORPS FUNDING

Engineering Services - DeWild Grant Reckert & Assoc.		$ 4,847.37
Purchase of Channel Structure Materials		4,096.86
Installation of Observation Wells - SDGS		1,428.40
Preparation of Final Report - EDCSD		3,627.37
Flow Analysis -- Dell Rapids Gauging Station - USGS		1,000.00
	Total	$15,000.00

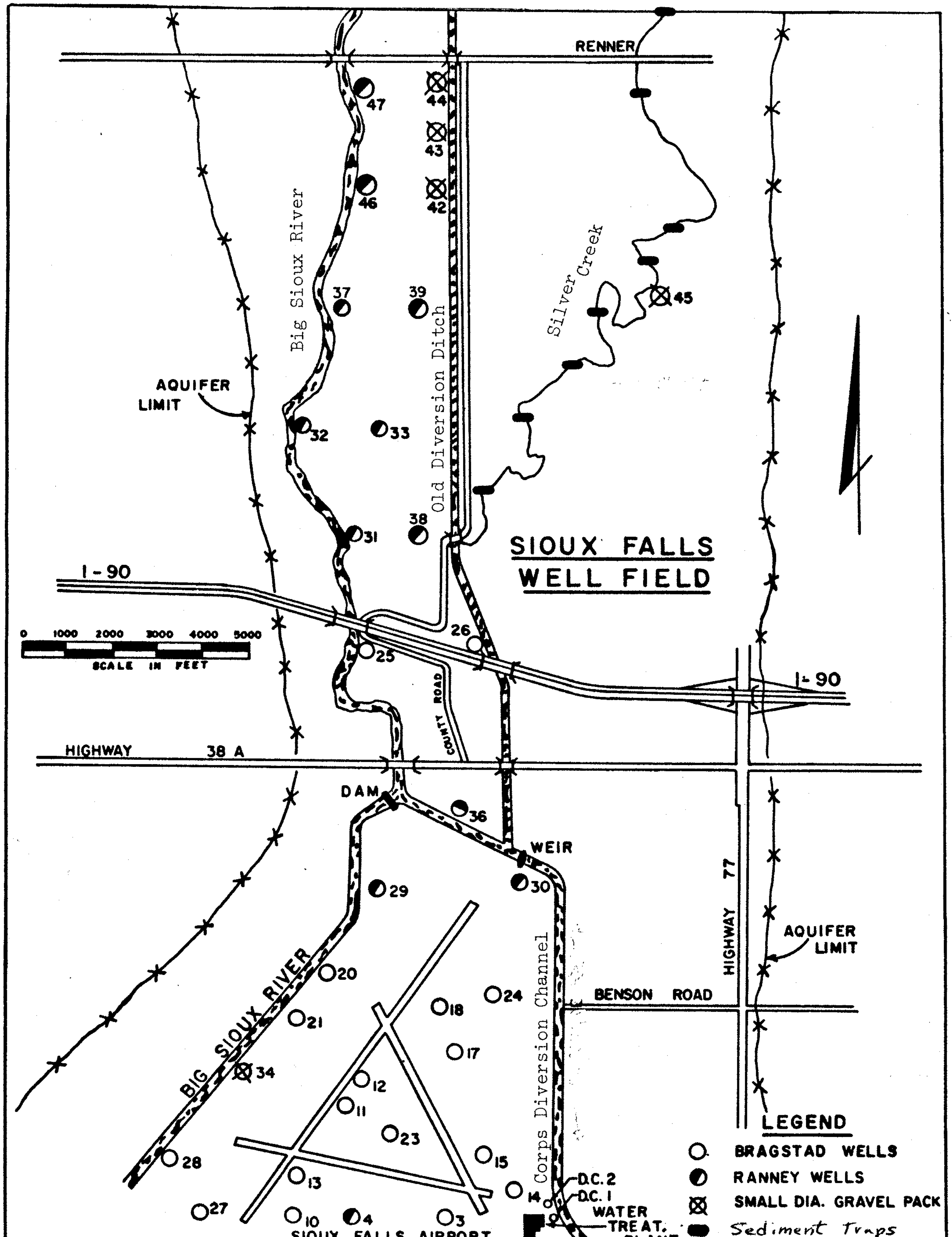
ANALYSIS AND DISCUSSION

The Artifical Recharge Paradox -- The fact that efforts to run aquifer recharge tests were frustrated for seven years because the aquifer water level never dropped more than five feet below the top of the sand and gravel, leads to an important conclusion. Natural recharge of the Sioux Falls wellfield area through precipitation and flooding plus infiltration through the bed of the Big Sioux River, Silver Creek and the old diversion ditch, and the flood diversion channel constructed by the Corps of Engineers is very efficient.

The favorable location of Sioux Falls' municipal wells in relation to the Big Sioux River, the old diversion channel and Silver Creek is shown in Figure 4. As a part of the Silver Creek PL566 Watershed Project, a series of over 25 sediment traps was constructed in the Silver Creek stream bed. Figure 4 notes the location of seven of these traps which lie in the wellfield area. Seven upstream dams, in conjunction with these traps, inadvertently provide effective artificial recharge of the northern portion of Sioux Falls' wellfield.

As long as there is flow in the Big Sioux River, it appears that the adjacent aquifer will be replenished. This was dramatically demonstrated in 1977. A severe drought occurred during 1975-1977 and water levels in Sioux Falls wells and the surrounding aquifer area dropped sharply. A number of experts predicted that it would take a major flood to bring the water level in the wellfield back up.

Figure 4. Location Map of Sioux Falls Municipal Wells and Sediment Traps Constructed as Part of the Silver Creek PL566 Watershed Project*



Source: Adapted from Sioux Falls Water Department Annual Report, 1980.

No major flood occurred during 1977. Yet, by late 1977, aquifer levels in the wellfield had risen to the high levels they were at in the spring of 1973 before the drought began (see water level charts for four wells in Appendix I).

During normal water years, it would be wasteful or foolish for Sioux Falls to pump water from the Big Sioux River to artifically recharge the aquifer near the wellfield for a number of reasons: (1) Power costs for pumping are expensive, (2) Mother Nature is recharging the wellfield very efficiently herself, (3) most of the time, the bulk of water would end up flowing naturally back to the river, and (4) if excess water were placed in the aquifer (creating high water-table conditions), surrounding farmers could sue for crop damages.

Even following abnormally dry summers, high river flows usually occur the following spring and replenish the aquifer. Thus, pumping river water to recharge the aquifer most years would involve wasted energy and money. The only scenario in which artificial recharge would make economic sense would be when an extended dry period occurred and the river level dropped to the point that it was not recharging the aquifer naturally. When that occurs, however, the city could very well face restrictions on diverting river water for recharge because of downstream water right considerations.

This brings us to the heart of the artificial recharge paradox for the city. When hydrologic conditions are such that the aquifer water level has dropped to the point where pumping Big Sioux River water to recharge the aquifer would be a reasonable economic gamble, there would not likely be enough flow in the river to allow diversion for artificial recharge. It must be remembered that the river and aquifer are not separate systems operating independently. They are closely inter-related parts of the same system.[8]

The remaining subsections contain additional information dealing with the artificial recharge paradox.

Digital Model Evaluation of Aquifer Recharge above Sioux Falls -- In 1982, as noted earlier, the task force decided to utilize the hydrologic digital model being finalized for the Big Sioux River Aquifer above Sioux Falls[9] to make an assessment of the potential and impacts of diverting Big Sioux River water for artificial aquifer recharge. Project Manager Neil Koch agreed to make the desired computer runs. Task force members Les Hash, Assad Barari, and Jerry Siegel met with him to reivew and discuss his results.

Using the model, water was pumped to the recharge site at a constant rate of 870 gpm or 1.94 cfs for four 30 day recharge periods. The model estimated the amount of the recharge water that would return to the river during these periods. In addition, the model was used to predict the amount of water that would return to the river during three 30 day recovery periods.

The outputs of the model run are summarized as follows:

Total water delivered during 120 day recharge period	150,336,000 gallons
Water returned to river during 120 day recharge period	24,429,600 gallons
Recharge water remaining in aquifer after 120 day recharge period ...	125,906,400 gallons
Water returned to river during 90 day recovery period	30,067,200 gallons

Thus, during the 120 day recharge and 90 day recovery period, the model predicted that 54,496,800 gallons out of 150,336,000 gallons delivered to the aquifer, or 36%, would return to the river.

Streamflow Analysis at Dell Rapids Gauging Station -- Daily streamflow data from the gauging station on the Big Sioux River near Dell Rapids for May 1, 1948 through October 24, 1983 are contained in Appendix II.

As noted earlier, the S.D. Board of Water Management determined that 50 cfs must be bypassed for any diversions from the Big Sioux River. Table I contains a listing of the dates when Big Sioux River flow at the Dell Rapids gauging station was less than 50 cfs. As the table shows, diversions of Big Sioux River flows for artificial recharge of the Sioux Falls wellfield would have been restricted during extended periods of most dry years. And, as noted earlier, diversion during normal years would have been wasteful.

A duration hydrograph prepared by the U.S. Geological Survey for the period 1954-1983 is shown in Figure 5. The hydrograph shows the percent of time which discharges were equaled or exceeded during any given time period. The 50 cfs bypass requirement has been superimposed on the diagram. Even though the hydrograph shows that 50 cfs is exceeded over 50% of the time between mid-March and early August, it is during the extended dry periods (when flow would most likely be less than 50 cfs) that artificial recharge would be beneficial.

Table 1. Dates When Big Sioux River Flow at Dell Rapids Gauging Station was Equal To or Less Than the 50cfs By-Pass Requirement

Water Year 1948*

12/18-2/25
7/18
7/19
7/21-7/25
8/13
8/14
8/19-9/2
9/5-9/10
9/12-9/30

Water Year 1949

10/1-3/23
7/25
7/28
7/29
8/1
8/2
8/7-8/11
8/17-9/20
9/27-9/30

Water Year 1950

10/6
10/8-10
10/13
10/15
10/16-17
10/20-2/23
3/5-3/26

Water Year 1951

1/11-1/14
1/18-2/10
2/28-3/18

Water Year 1952

11/2
11/4-3/10

Water Year 1952

12/4
12/11-2/8

Water Year 1954

10/17-11/5
11/13-3/1
3/6-3/9
5/23-5/26
6/1-6/17
6/25-9/30

Water Year 1955

10/1-3/24
3/29-3/30
5/21-6/3
6/6-6/22
7/5-7-12
7/19-8/7
9/9-9/30

Water Year 1956

10/1-3/21
8/16-8-22
9/3-9/19
9/22

Water Year 1957

10/1-10/30
11/19-2/24
3/5
3/8-3/22
7/1-9/30

Water Year 1958

10/1-3/6
4/7-5/4
5/6-5/27
7/1-7/6
7/8-9/30

Water Year 1959

10/1-3/28
7/22-8/24

Water Year 1960

10/2-2/20
7/20-8/3
8/10-8/22
8/31-9/30

Water Year 1961

10/1-3/25

Water Year 1962

12/9-3/15

Water Year 1963

12/8-3/11
7/18-9/30

Water Year 1964

10/1-3/14
3/18-3/31
8/16
8/18
8/31-9/18

Water Year 1965

11/26-12/11
12/19-2/8
7/7-7/17
8/3-8/19
8/30
9/4-9/10
9/17-9/30

Water Year 1966

10/1-11/10
11/12-2/29
8/6-8/25
9/3-9/30

Water Year 1967

10/1-10/22
10/24-3/17
3/20-3/22
3/30-4/2
5/23
5/26-6/24
7/15-9/30

Water Year 1968

10/1-10/15
12/7-12/10
12/13-4/2

Water Year 1969

12/9
12/21-12/25
8/24
8/28-9/30

Water Year 1970

10/1-10/9
10/24
10/27
12/17
12/20-2/17
2/20-2/23
7/28-9/30

Water Year 1971

10/1-10/29
12/17-12/19
12/28-3/11

Water Year 1972

7/17-9/28
9/30

Water Year 1973

10/1-10/8
10/18-2/19
6/24-9/30

Water Year 1974

10/1-4/7
6/3-9/30

Water Year 1975

10/1-2/26
3/5
5/24-9/30

Water Year 1976

10/1-3/9
5/11-6/17
7/14-9/30

Water Year 1977

1/9-3/12
9/28-29

Water Year 1978

10/13-3/17

Water Year 1979

1/29-3/13
9/14
9/16-9/30

Water Year 1980

10/1-3/7
5/9-9/30

Water Year 1981

10/1-2/22

Water Year 1982

None

Water Year 1983

None

*Water Year - begins October 1 and runs through September 30 of the following year.

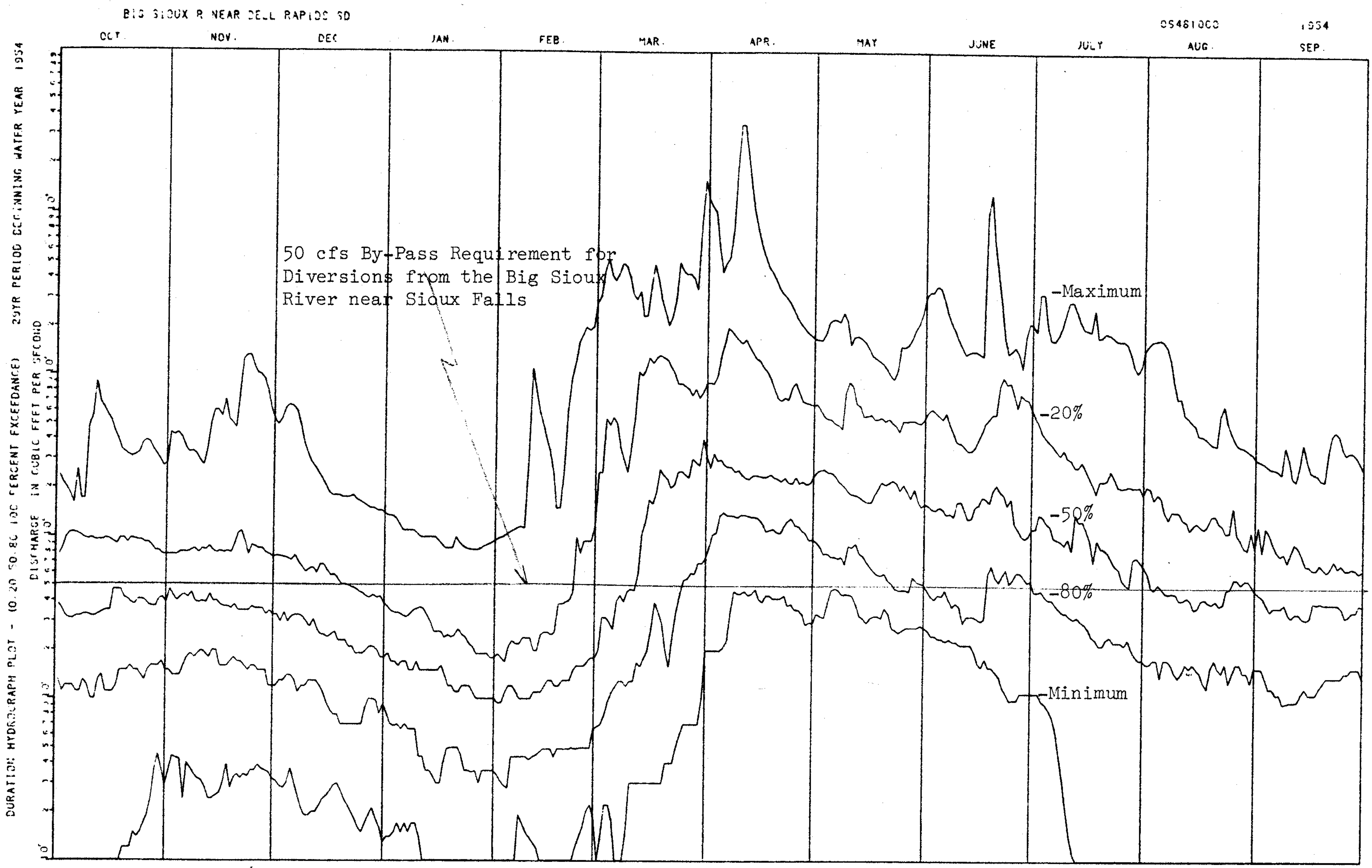


Figure 5. Duration Hydrograph for the Period 1958-1983, Big Sioux River Gauging Station near Dell Rapids, South Dakota.

REFERENCES

1 Report of the Citizens Water Advisory Committee to The City Commissioners, Sioux Falls, South Dakota, submitted June 22, 1977, p. 12.

2 Ibid, p. 15

3 10 June, 1977 Letter from John E. Velehradsky, Chief - Planning Division, Omaha District Corps of Engineers, to Jerry L. Siegel, Manager-Treasurer, East Dakota Conservancy Sub-District.

4 Minutes - East Dakota Conservancy Sub-District - July 21, 1977, pp. 1 and 6.

5 20 December 1977 Letter from Carter Laing, U.S. Corps of Engineers - Omaha District to Task Force Members.

6 March 3, 1981 Letter from Jerry L. Siegel, Manager-Treasurer, East Dakota Conservancy Sub-District, to Les Hash, Manager, Sioux Falls Water Department.

7 April 14, 1982 Letter from Jerry L. Siegel, Manager-Treasurer, East Dakota Conservancy Sub-District, to Rick Miner, U.S. Corps of Engineers - Omaha District.

8 The Big Sioux Aquifer Water Quality Study, First in a Series, East Dakota Conservancy Sub-District, 1983, pp. 6-8.

9 A Digital-Computer Model of The Big Sioux Aquifer in Minnehaha County, South Dakota, U.S. Geological Survey Water-Resources Investigations 82-4064, Prepared in cooperation with the East Dakota Conservancy Sub-District, the South Dakota Department of Water and Natural Resources, and Minnehaha County

10 Annual Report of Sioux Falls Water Department, 1980, p. 4.

APPENDIX G

Summary of water level data in the Big Sioux Aquifer

The water level file of the South Dakota Geological Survey data base was used as a source of water level information for this appendix. NATURAL programs were used to obtain all water level data for observation wells within unconfined portions of the Big Sioux aquifer by management unit. The maximum and minimum depth to water (in feet) from the land surface for each observation well was obtained over the entire record specific to each observation well. The average depth to water was obtained from averaging the minimum and maximum water level reading for each observation well.

Management Unit (1)	Location (2)	Depth of Aquifer (ft.) (3)	Depth to Water Max. (4)	Min. (ft.) (5)	Avg. (6)
AURORA Observation well					
BG-57F	110N-49W-26CCCC	6-58	19.7	13.5	16.6
BG-57G	110N-48W-33ABAB	8-40	10.3	2.3	6.3
BG-63C	111N-48W-35DAAA	2-38	---FLOWING WELL----		
BG-63D	110N-48W-07DAAA	8-21	8.0	2.3	5.2
BG-77H	110N-48W-20CCCC	18-80	26.6	23.6	25.1
BG-77I	110N-48W-31BBBB	1-45	21.7	19.9	20.8
BG-77J	110N-49W-36DDDD	4-45	5.9	3.0	4.5
BG-77R	110N-49W-33CCCC	1-20	7.3	2.0	4.7
BG-77S	110N-49W-20AAAA	2-18	7.3	2.5	4.9
BG-77T	110N-49W-15BBBB	4-10	6.9	3.6	5.3
BG-78D	110N-49W-14DDDD	0-37	33.0	----	33.0
BG-79C	110N-49W-11CCCC	4-28	11.0	8.6	9.8
BG-79D	110N-49W-29AAAA	1-42	9.8	2.4	6.1
BG-79E	110N-49W-22AAAA	2-35	14.7	10.5	12.6

Area of management unit (acres) -- 39,300

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Management Unit (1)	Location (2)	Depth of Aquifer (ft.) (3)	Depth to Water Max. (4)	Min. (ft.) (5)	Avg. (6)
BROOKINGS Observation well					
BG-57A	112N-50W-30BABB	5-53	6.9	2.2	4.6
BG-57B	111N-51W-36BBCC	3-18	7.1	1.4	4.3
BG-57E	110N-50W-18DCAB	4-34	7.0	1.9	4.5
BG-57H	109N-50W-25BBCC	3-17	5.0	0.1	2.6
BG-63F	109N-49W-31BBAB	4-25	6.5	2.4	4.5

(1)	(2)	(3)	(4)	(5)	(6)
BROOKINGS -- continued.					
BG-64A	109N-50W-15CBDB	----	----	----	----
BG-75D	112N-51W-01AAAB	2-28	9.1	3.5	6.3
BG-75E	112N-51W-35DDDD	0-42	15.0	10.1	12.6
BG-75F	111N-51W-12CDDA	6-25	8.8	4.7	6.8
BG-75G	112N-50W-18CBCC	3-39	6.2	1.5	3.9
BG-75H	112N-50W-18DCDC	3-30	7.7	3.5	5.6
BG-75I	112N-50W-30BCCC	3-29	5.6	1.1	3.4
BG-75J	112N-51W-24ABBB	5-47	16.1	12.4	14.3
BG-75K	112N-51W-24AAAA	2-41	9.7	5.4	7.6
BG-75L	112N-50W-19BCCC	2-41	4.4	6.4	5.4
BG-75M	112N-51W-25AAAA	2-37	8.3	3.7	6.0
BG-75N	112N-51W-25ABAB	5-50	11.2	7.0	9.1
BG-76B	112N-51W-19BBBB	71-112	39	34.8	36.9
BG-76C	112N-52W-25DDDD	35-55	5.7	2.2	7.9
BG-76D	112N-51W-21BBAA	33-77	22.8	14.6	18.7
BG-76E	112N-51W-04BAAA	?	32.6	23.9	28.3
BG-76F	112N-51W-09CBBB	?	29.6	19.8	24.7
BG-77A	112N-50W-05CDCD	8-40	13.9	8.7	11.3
BG-77B	112N-51W-20BBBB	44-84	36.3	28.7	32.5
BG-77C	111N-51W-04BBBB	40-65	5.6	1.4	3.5
BG-77D	111N-51W-10CCCC	2-25	8.6	5.7	7.2
BG-77E	110N-51W-02CCCC	32-60	39.2	36.7	37.9
BG-77F	110N-50W-05CBCB	5-30	6.2	2.9	4.6
BG-77G	109N-51W-11DDDD	3-44	15.0	13.1	14.1
BG-77L	110N-50W-18BBBB	1-24	5.2	1.2	3.2
BG-77M	110N-51W-11CCCC	2-26	9.8	6.8	8.3
BG-77N	110N-51W-16AAAA	3-35	6.5?	----	6.5?
BG-77O	110N-51W-11AAAA	1-15	4.1	0.9	2.5
BG-77P	110N-51W-23AAAD	1-16	9.3	7.2	8.3
BG-77Q	110N-51W-36CCCC	2-32	13.9	11.8	12.9
BG-80C	112N-50W-32BAAA	0-32	18.9?	----	18.9
DU-71A	115N-49W-23ABAA	1-13	5.2	2.8	4.0
DU-71B	115N-49W-04DDDD	1-27	4.3	1.6	3.0
DU-71C	115N-47W-17BBBC	11-34	15.1	9.8	12.5
DU-73B	115N-49W-10DCD	12-18	4.2	0.3	2.3
DU-75A	115N-48W-19ABBB	6-42	19.6	14.1	16.9
DU-76A	115N-49W-25BBBB	2-35	2.7	0.3	1.5
DU-77B	113N-50W-31AAAA	4-40	12.7	6.6	9.7
DU-77C	113N-50W-32AAAA	13-29	14.9	8.8	11.9
DU-77F	113N-50W-31DDDC	4-35	12.1	6.0	9.1
HN-57B	113N-51W-06BBAA	40-60	5.7	0.6	3.2
HN-63A	114N-51W-07BBBB	5-25	16.5	5.2	10.9
HN-57A	115N-52W-27DCCD	----	----	----	----
HN-63B	113N-51W-01ABBB	12-41	8.2	5.3	6.8
HN-71A	113N-51W-26DDDD	----	----	----	----
HN-75A	113N-51W-10CCDD	----	----	----	----
HN-75B	113N-51W-24BCBC	3-28	7.7	3.4	5.6
HN-76A	113N-52W-36CDDD	36-75	36.9	32.8	34.9
HN-76B	115N-52W-35CCCC	0-20	7.8	3.8	5.8

(1)	(2)	(3)	(4)	(5)	(6)
BROOKINGS -- continued.					
HN-76C	114N-53W-20CADC	2-44	21.5	16.4	19.0
HN-76D	113N-53W-08DCCC	1-55	8.5	5.2	6.9
HN-76E	113N-53W-22AAAD	----	----	----	----
HN-77A	113N-51W-34BCCC	8-54	21.0	25.6	23.3
HN-77B	114N-52W-04DDDD	27-14?	17.0	15.0	16.0
HN-77C	114N-52W-10CCCC	50-91?	19.5	17.9	18.7
HN-77D	114N-52W-29DAAA	2-35	9.3	5.3	7.3
HN-77E	114N-51W-28CCCC	2-32	4.1	1.3	2.7
HN-77F	114N-51W-27CCCC	38-65	27.1	30.8	29.0
HN-77G	113N-51W-19CCCC	2-35	11.4	9.6	10.5
HN-77H	113N-51W-23ABBB	2-35	7.3	2.6	5.0
HN-77I	114N-52W-01BBBB	1-16	7.3	3.1	5.2
HN-77J	113N-51W-15AAAB	1-35	8.0	4.5	6.3
HN-77K	113N-51W-30CCCC	1-35	17.7	14.3	16.6
HN-77L	114N-51W-06AAAA	----	----	----	----
HN-77M	114N-52W-06BBBB	----	----	----	----
MY-63F	108N-49W-07AADD	1-17	5.3	0.4	2.9

Area of management unit (acres) -- 191,100

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(1)	(2)	(3)	(4)	(5)	(6)
MIDDLE SKUNK CREEK Observation well					
MA-57B	104N-50W-20AAAB	8-18	7.6	2.9	5.3
MA-57E	103N-51W-35CCDD	8-62	9.9	4.6	7.3
MA-78A	104N-50W-04DCCC	2-47	12.7	9.2	11.0
MA-78B	104N-50W-21CCCC	3-18	8.1	5.7	6.9
MA-78C	104N-50W-31DCCD	2-32	4.2	1.5	2.9
MA-78D	103N-50W-18AAAA	4-31	4.0	1.2	2.6
MA-78E	103N-50W-19BCCC	3-28	8.5	5.0	6.8

Area of management unit (acres) -- 18,300

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(1)	(2)	(3)	(4)	(5)	(6)
MOODY Observation well					
MA-57A	104N-49W-03DDDD	----	----	----	----
MY-57A	108N-49W-22BBBB	0-14	7.2	1.0	4.1
MY-57B	106N-48W-05CCDD	4-27	13.3	4.3	8.8
MY-57C	105N-48W-18CBBB	4-13	8.2	2.3	5.3
MY-61A	107N-48W-05DCCC	8-42	11.4	3.9	7.7
MY-63A	108N-48W-19CCCC	8-22	8.7	1.3	5.0
MY-63B	107N-48W-16AAAA	10-20	10.1	1.1	5.6
MY-63C	107N-48W-23AAAA	20-28	14.8	8.3	11.6

(1)	(2)		(3)	(4)	(5)	(6)
MOODY -- continued.						
MY-63D	107N-48W-32ABBB		0-28	21.5	15.5	18.5
MY-63E	106N-49W-22DDDD		0-25	10.8	3.0	6.9
MY-78A	107N-47W-16CCCC		1-27	13.2	6.8	10.0
MY-78B	107N-48W-25BBBB		8-60	16.0	12.3	14.2
MY-78C	106N-49W-15DDDD		8-18	8.9	0.9	4.9
MY-78D	106N-49W-35BAAA		1-16	6.4	1.6	8.0
MY-78E	105N-48W-19AAAA		1-17	7.4	0.8	4.1
MY-78G	105N-49W-35AAAA		1-17	5.3	0.4	2.9

Area of management unit (acres) -- 35,500

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NORTH DEER CREEK Observation well						
BG-63A	111N-50W-21CCCC		38-77	13.3	7.6	10.5
BG-77K	111N-50W-30DDDD		4-15	6.8	2.8	4.8
BG-77O	110N-51W-11AAAA		4-54	6.2	1.1	3.7
BG-77V	111N-50W-17DDDD	2	4-54	4.5	0.2	2.3
BG-78C	112N-50W-13DDDD		0-33	7.7	5.0	6.4
BG-80F	111N-50W-04DCDD		8-59	9.4	9.1	9.3

Area of management unit (acres) -- 5,700

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NORTH Observation well						
GT-57A	121N-52W-01CBBB	R	3-38	12.1	5.3	8.7
GT-76A	120N-52W-09DDDD	R	1-48	18.2	14.7	16.5
GT-77B	121N-52W-08DCCC	R	2-34	9.1	6.4	7.8
GT-77D	121N-52W-29CCBB	R	2-28	9.4	5.3	7.4
HN-57A	115N-52W-27DCCD		3-15	6.1	1.8	4.0
CD-56A	120N-52W-28DDDD	R	3-33	11.0	5.0	8.0
CD-57A	118N-52W-21BBCB		3-42	16.6	6.0	11.3
CD-57B	116N-52W-28AAAA		0-38	19.5	13.3	16.4
CD-59A	117N-53W-24CCBB		4-35	15.5	11.4	13.5
CD-60A	119N-52W-33DCDC	R	2-18	9.7	5.2	7.5
CD-60B	117N-53W-02DDDC		6-39	9.0	3.0	6.0
CD-60C	116N-52W-06DCCC		5-30	8.9	1.8	5.4
CD-76B	118N-52W-30CDCD		2-30	8.8	6.5	7.7
CD-76C	118N-52W-11CBBC		3-30	5.1	3.1	4.1
CD-76E	118N-52W-01DCDC		1-32	14.9	9.0	12.0
CD-76F	119N-51W-31DDDD		1-13	6.4	1.0	2.7
CD-77B	119N-52W-04ADDD	R	1-11	7.2	4.4	5.8
CD-77C	119N-52W-10DDDD	R	2-16	8.0	6.2	7.1
CD-77F	117N-53W-12CDDD		1-18	8.2	6.8	7.5

(1)	(2)	(3)	(4)	(5)	(6)
NORTH -- continued.					
CD-78A	119N-55W-29AABB	5-15	5.7	7.1	6.4
CD-79A	117N-53W-28CCBB	0-22	4.9?	----	4.9?
CD-81A	117N-52W-06DDDD	2-47	6.5?	----	6.5?
CD-81B	118N-52W-33BBBB	2-23	13.7?	----	13.7?

Area of management unit (acres) -- 83,500

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(1)	(2)	(3)	(4)	(5)	(6)
NORTHERN SKUNK CREEK					
Observation well					
MA-57C	104N-49W-31CCCC	9-43	12.2	3.8	8.0
MA-57D	103N-49W-17DBDC	13-34	10.5	3.1	6.8
MA-57H	101N-49W-09BCBC	5-14	13.6	11.0	12.3
MA-80C	104N-49W-31CCCC	8-36	12.4	7.7	10.1
MA-80D	103N-49W-07BAAA 1	10-44	12.7	10.5	11.6
MA-80E	103N-49W-07BAAA 2	10-34	12.5	10.3	11.4
MA-80F	103N-49W-18ACBB	14-43	13.1	11.7	12.4
MA-80G	103N-49W-16BCCC	3-32	8.3	6.1	7.2
MA-80H	103N-49W-16ACCC	4-31	10.8	7.6	9.2
MA-80J	103N-49W-33BBBA	13-28	9.7		9.7
MA-80L	102N-49W-09BBAB	8-35	7.9	6.4	7.2
MA-80M	102N-49W-08CDCC	10-31	8.9	7.7	8.3
MA-80T	101N-50W-01ABBB 2	----	----	----	----
MA-80W	101N-50W-01CCCC 2	12-54	12.7	12.1	12.4
MA-80DA	104N-49W-20DDDA	10-27	10.0	9.1	9.6
MY-78F	105N-50W-29BBBB	2-51	16.6	11.4	14.0

Area of management unit (acres) -- 22,900

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(1)	(2)	(3)	(4)	(5)	(6)
SIOUX FALLS					
Observation well					
MA-57C	104N-49W-31CCCC	9-43	12.2	3.8	8.0
MA-57D	103N-49W-17DBDC	13-34	10.5	3.1	6.8
MA-57H	101N-49W-09BCBC	5-14	13.6	11.0	12.3
MA-80C	104N-49W-31CCCC	8-36	12.4	7.7	10.1
MA-80D	103N-49W-07BAAA 1	10-44	12.7	10.5	11.6
MA-80E	103N-49W-07BAAA 2	10-34	12.5	10.3	11.4
MA-80F	103N-49W-18ACBB	14-43	13.1	11.7	12.4
MA-80G	103N-49W-16BCCC	3-32	8.3	6.1	7.2
MA-80H	103N-49W-16ACCC	4-31	10.8	7.6	9.2
MA-80J	103N-49W-33BBBA	13-28	9.7	----	9.7
MA-80L	102N-49W-09BBAB	8-35	7.9	6.4	7.2
MA-80M	102N-49W-08CDCC	10-31	8.9	7.7	8.3
MA-80W	101N-50W-01CCCC 2	12-54	12.7	12.1	12.4

(1)	(2)	(3)	(4)	(5)	(6)
SIOUX FALLS -- continued.					
MA-80DA	104N-49W-20DDDA	10-27	10.0	9.1	9.6
MA-80R	101N-50W-07ABAB	4-15	7.5	7.3	7.4
MA-80X	101N-50W-16BAAA	0-14	11.0	10.3	10.7
MA-80AA	101N-49W-11BACB	0-32	11.9	11.3	11.6
MY-78F	105N-50W-29BBBB	2-51	16.6	11.4	14.0
MA-80Q	102N-48W-33DABA	12-44	9.6	9.4	7.5

Area of management unit (acres) -- 22,900

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SIX MILE CREEK Observation well					
BG-57C	111N-49W-32DCCD	5-49	9.2	1.0	5.1
BG-57D	110N-50W-13ABBA	8-30	11.9	1.5	6.7
BG-63E	110N-50W-22CCCB	4-45	5.1	1.4	3.3
BG-79A	110N-49W-05ABBB	4-68	9.0	6.3	7.7
BG-79B	110N-49W-07AAAA	6-52	6.2	3.7	5.0
BG-80H	111N-49W-27CCCD	1-84	16.2	15.4	15.8

Area of management unit (acres) -- 4,200

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SOUTH Observation well					
LN-57A	099N-48W-21BBAA	12-28	11.5	5.9	8.7
LN-57B	098N-49W-25CCBC	5-10	7.6	0.9	4.3
LN-57C	097N-48W-36CCBC	18-40	22.5	13.4	15.4
LN-57D	096N-48W-25BBAA	7-54	21.1	13.9	17.5
LN-80N	098N-48W-17DDCB 2	12-86	5.6	5.3	7.6
LN-80Q	099N-48W-32DCDD 2	4-65	12.9	----	12.9
MA-57J	101N-48W-16ADDA	16-29	19.3	11.1	15.2
MA-80Q	102N-48W-33DABA	12-24	9.6	9.4	9.5
MA-80AA	101N-49W-11BACB	0-32	11.9	10.3	11.6
MA-80CA	101N-48W-28BAAA	10-30	15.2	15.0	15.1
MA-80EA	102N-48W-30ADDD	20-27	11.0	----	11.0
MA-80FA	102N-48W-29DABB	6-26	18.6?	----	16.6?
MA-80GA	102N-48W-28CACB	2-93	19.9?	----	19.9?
UN-57C	095N-48W-34CBCC	12-28	13.9	4.6	9.3
UN-77F	094N-49W-01ADAA	18-25	7.4	5.6	6.5
UN-77G	093N-49W-24DAAA	6-45	17.8	9.0	13.4

Area of management unit (acres) -- 49,000

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(1)	(2)	(3)	(4)	(5)	(6)
SOUTHERN SKUNK CREEK					
Observation well					
MA-57F	101N-50W-07AABB	12-19	8.2	4.9	6.6
MA-57I	101N-50W-24CDAB	13-61	15.1	13.0	14.1
MA-78F	102N-50W-19BCDC	1-22	12.7	8.1	10.4
MA-80R	101N-50W-07ABAB	4-15	7.5	7.3	7.4
MA-80X	101N-50W-16BAAA	0-31	11.0	10.3	10.7
MA-80Y	101N-50W-23BBBA	9-51	15.3?	13.2?	14.3?
MA-80HA	101N-50W-23DADD				

Area of management unit (acres) -- 9,700

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(1)	(2)	(3)	(4)	(5)	(6)
UNNAMED CREEK					
Observation well					
BG-63B	111N-50W-34BCCC	4-62	15.3	1.3	8.3

Area of management unit (acres) -- 5,800

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