The Planning, Construction, and Operation of an Aquifer Recharge and Recovery Infiltration Basin in Grand Forks County, North Dakota

By
William M. Schuh, Jon Patch, and Ben Maendel

Water Resources Investigation No. 47
North Dakota State Water Commission

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Newly-Constructed North (Rectangular) Infiltration Basin (1994)

Coffer Dam and Intake for the First Point of Diversion (1993)

Coffer Dam and Intake for the Final Point of Diversion (2009)

ACKNOWLEDGEMENT

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EXECUTIVE SUMMARY

An Aquifer Recharge and Recovery (ARR) infiltration basin and well field facility was planned, tested, and operated by the Forest River Hutterite Community near Fordville in Grand Forks County, North Dakota, from 1992 through the present (2009). Two infiltration basins were constructed: a triangular basin of 3.4 acres and a rectangular basin of 3.7 acres, for a total of 7.1 acres of active infiltration area. Basins were excavated to two feet below land surface, and spoil was used to construct a border berm having a slope ration of one foot rise per three feet of run. Bottom materials were predominantly of fine sand.

1. The basin facility successfully recharged more than 10,000 acre-feet of water from 1993 through 2007. Recharge varied from a minimum of 180 acre-feet in 1993 to a maximum of 1085 acre-feet in 2002. The mean recharge was 642 acre-feet/year.

2. Spring flows in the Forest River were analyzed for two climate scenarios. Recoverable waters for 45 days of operation under a 1940 through 1961 climate scenario would allow for 200 acre-feet of recharge with a 2,500 gpm pumping capacity, and 600 acre-feet with a 5,000 gpm pumping capacity in 80% of the years. Recoverable waters under a 1962 through 1996 climate scenario would allow for 500 acre-feet of recharge with a 2,500 gpm pumping capacity, and 800 acre-feet with a 5,000 gpm pumping capacity in 80% of the years. The documented period of basin operation (1993 through 2009) would correspond to a wet climate scenario.

3. Water permits, under the doctrine of appropriation as applied under North Dakota Century Code and Administrative Code, were applied to the river water rather than to later recovery from ground water. Conditions for the water permit allowed for pumping from the Forest River only when remaining flows after pumping maintained a minimum of 7.5 cfs. Pumping was allowed from April 1 through June 15. The operators were required to construct a monitoring-well network as designed by the staff of Water Commission (SWC), and to monitor the basin and groundwater according to an annual operational plan provided by the SWC. The plan for each year included requirements for the timing and frequency of ground-water measurements, and the acquisition of water samples from the river, the basin and neighboring ground water for evaluation of general chemistry and pesticide residues.

4. A major concern was retention of recharge waters in the aquifer. Concerns were primarily over potential spring losses to the river, about a half-mile from the basin. Concerns over ET loss were less because of the relatively deep water table (*approx.* 30 feet below land surface). Lacking detailed hydrologic data on loss factors, initial plans required a surplus of 20% of recharged waters in the first year, plus an annual surplus of 20% for unpumped water at the end of the year. Later plans were modified to require a surplus of only 5% of first-year recharge plus 20% of unrecovered waters at the end of each year, up to a maximum of 300 acre-feet. Carryover of more than 300 acre-feet was not allowed. The net effect was 80% overall recovery of recharged waters from 1993 through 2007. Aquifer retention was examined using a hydrologic model. Results are reported by Schuh and Patch (WRI No. 48, 2009).

5. Basin infiltration using turbid river water usually follows a declining infiltration, or "decay" curve that can be approximately described using a power function. Initial design specifications for the basin were based on infiltration decay curves derived from test basins operated near Oakes, in Dickey County, ND. While the Oakes facility generally had a coarser (predominantly medium sand) infiltration surface than the Forest River facility (predominantly fine sand), and therefore a larger initial permeability; and while the James River at Oakes generally had higher dissolved solids (~50 mg/L) compared with the Forest River (~15 mg/L), predictions of cumulative infiltration over the operational period were very close for both facilities, indicating that the cumulative infiltration relationships are reasonably robust. The cumulative infiltration (I) curve for the Forest River basin was: $I = 5.37t^{0.76}$, where t is the time of infiltration.

6. The primary cause of decreasing infiltration during operation was a "filter cake" which was deposited on the basin floor during application of turbid water. A reasonably robust relationship was derived for I vs. time (t) based on suspended solids (SS) in the river water. For both Oakes and Forest River facilities, the exponent (b) of the power function was found to be approximately related to SS as: $b = \frac{SS}{79}$. The resulting equation was: $I = \frac{Kt^{1-0.013SS}}{0.1^{-0.013SS}(1-0.013SS)}$, where K is the measured hydraulic conductivity of basin floor materials. This equation should provide a reasonable "first cut" for design estimates in future basin facilities in North Dakota. All ARR infiltration basins must be carefully monitored and management must be adjusted to provide for optimal efficiency of operation.

7. The Forest River Community chose to employ a smooth and unamended basin-floor operational plan in which the filter-cake was allowed to form freely. This option minimizes the depth of clay penetration, and facilitates cleaning. Following each operation, the filter cake on the basin floor was allowed to dry and crack. It was then "scraped" from the floor using a grader with less than one inch of penetration. "Windrowed" scrapings were then removed using a "scraper." These cleaning operations allowed for effective basin renovation for 17 years without having to replace the bottom materials. It is expected that a few more years of renovation may be possible without the need for replacement.

8. Water samples for water chemistry evaluation were collected from the Forest River, the basin, and nearby ground water. Results indicated no adverse impact on ground water quality. Slightly elevated nitrate detected in April river-water samples was detected in the basin, but all detections were below the EPA-Maximum allowable Contaminant Level (MCL). Infiltration effects on nitrate concentrations in nearby shallow ground water were almost non-detectable, likely due to dilution. During the first year of operation there were some spikes of elevated nitrate that occurred near the basin and which were higher than the river or basin waters. These occurred only one year, and were attributed to the elevation of the hydraulic mound formed by basin operation into the vadose zone, and dissolution of stored vadose nitrate. No pesticides were found to be reaching ground water during basin operation.

9. Estimated cost of recharge water delivered to the aquifer was $80.00 per acre-foot to $105.00 per acre-foot. After adjustment for the 80% surplus required for natural water discharge losses, the estimated cost would be about $100.00 per acre-foot to $131.00 per acre-foot. In gallon equivalents, the cost would be 0.03 to 0.04 cents (three to four hundredths of a cent) per gallon. These estimates do not include well construction and recovery costs, administrative costs, or treatment costs which would likely be required for municipal waters and human consumption.

10. The Forest River Community ARR facility has been effectively operated for 17 years. Storage of water in shallow unconfined aquifers, however, is short-term storage and long-term carryover cannot be applied to an extended drought. This means that during an extended dry period effective recharge would be heavily curtailed. The retention capability of the Inkster aquifer has been examined in a companion report (Schuh and Patch, WRI No. 48, 2009).

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INTRODUCTION

The Constitution of the State of North Dakota, Article XI, states that:

"All flowing streams and natural watercourses shall forever remain the property of the state for mining, irrigation and manufacturing purposes."

On this constitutional basis waters of the state are allocated for the beneficial use of its citizens according to the doctrine of prior appropriation, under provisions of Chapter 61-04 of the North Dakota Century Code, and Article 89-03 of the North Dakota Administrative Code, which govern water appropriation. In principle, water permits are granted for the beneficial use of water on the basis of priority date, established by the date of application. Within the same application date, water permits are granted by preference in the order of municipal, livestock, irrigation, industrial, and recreation. Water sources are managed on the basis of sustainability, a concept that is generally meant to insure against long-term mining and the eventual depletion of the state's water resources. However, we are increasingly understanding that issues of sustainability are complicated considerably by the uncertainties imposed by long-term climate variability, and by the response of aquifers to that variability (Theis, 1957; Bredehoeft and others, 1982; Bredehoeft, 1997; Devlin and Sophocleous, 2005).

In the early 21st century, the appropriation of water is approaching limits of sustainability in many areas of the state. In recent years the needs of growing cities, agricultural production and processing, and energy industries, have placed increased demands on surface and ground-water resources, to the point where planning for water supplies has become a critical factor in siting new enterprises. Development of works for conveyance of waters from the few remaining plentiful sources, like the Missouri River, to points of need, and methods for conserving and optimizing waters from sources approaching appropriation limits have become increasingly important. One management tool that may help to optimize the use of water resources in some locations is "Aquifer Recharge and Recovery" (ARR).

Aquifer Recharge and Recovery was previously commonly known as Artificial Recharge, and is alternately labeled as Aquifer Storage and Recovery (ASR). ARR involves the capture of waters from rivers and streams during periods of high flow, and storage of the waters in aquifers for later pumping recovery and use. Waters are frequently placed in aquifers by surface infiltration through excavated basins, or by use of injection wells (in confined aquifers, or aquifers with low permeability caps too deep to excavate.

In North Dakota ARR has previously been used or tested in several instances. Beginning in 1932, the city of Valley City recharged local ground water for later well recovery with water pumped from the Sheyenne River during intermittent high flows. During the 1950s, the city of Minot supplemented water in a local aquifer with water pumped from the Souris River. The U.S. Bureau of Reclamation and the Garrison Conservancy District supplemented ground water in the Oakes aquifer using spring infiltration of water pumped from the James River during the late 1980s and early 1990s. Water was pumped to low areas of the landscape, or applied through irrigation pivots (Frietag and Esser, 1986). During the late 1980s the North Dakota State Water Commission, in cooperation with the U.S. Bureau of Reclamation, conducted studies on a pilot recharge basin, infiltrating water from the James River to the Oakes aquifer in Dickey County, southeastern North Dakota (Schuh and Shaver, 1988; Shaver and Schuh, 1988; Shaver and Schuh, 1989a; Shaver and Schuh, 1989b). The feasibility of augmenting ground water in the Englevale Aquifer (Ransom and Sargent Counties, southeastern North Dakota) was explored, and results published by Cline and others (1993). Most recently, Solc (2000) has described ARR as a "water banking" concept, and proposed its' application as a part of an integrated plan for stabilizing water supplies in the Red River Valley.

In 1992 the Forest River Hutterite Community expressed an interest in using ARR technology to pump waters from the Forest River during spring high flows, and store them in the Inkster aquifer in Grand Forks County for later irrigation use. In the process of granting and perfecting a water permit, several issues of concern were identified. From the standpoint of cost-effectiveness for the Community, the feasibility of successfully storing the water, and of maintaining a facility capable of storing the water for long-term use, were major concerns. From the standpoint of the state, the ability of the aquifer to hold stored waters for effective well recovery so that pumping would not deplete existing ground water, and the potential water quality impacts of placing Forest River water in the aquifer, were of particular concern.

The Forest River Community (FRC) agreed, as a condition of its water permit, to construct a system of observation wells near the basin, and to monitor those wells according to an annual plan provided by the State Water Commission. The purpose of the data acquisition was to provide sufficient information to enable: (1) an assessment of the effective recovery and retention times of ARR waters; (2) an evaluation of ARR effects on local ground water quality, and; (3) an evaluation of the effectiveness of basin management practices that might provide useful information for potential future practitioners of ARR in North Dakota. This report is an evaluation of the results of 15 years of ARR operation by the Forest River Community, from 1993 through 2007.

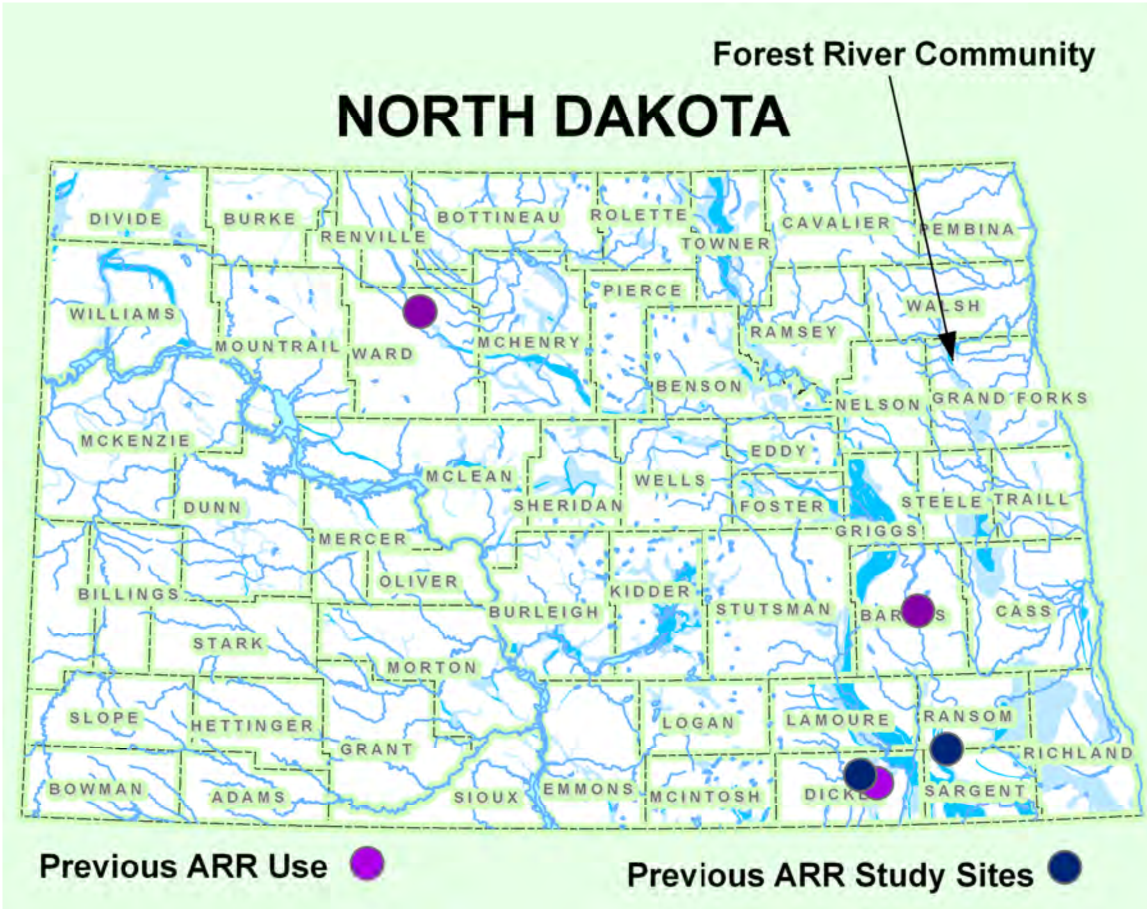


Figure 1. Location of the Forest River Community, and previous aquifer recharge and recovery (ARR) recharge facilities and studies in North Dakota.

PURPOSE AND SCOPE

The purpose of this report is to describe the initial design, the construction, and the operation of the FRC basin facility; and provide an assessment of its practicality and cost-effectiveness for other potential water users who may wish to attempt to use ARR technology to enhance water supplies. This report includes: (1) information concerning initial exploration and design of the basin; (2) a description of the methods used for placing water in the aquifer, and their effectiveness; (3) a discussion of water quality effects of basin recharge on the aquifer, including nitrate, total dissolved solids, sulfate, and pesticides; (4) cost of basin operation; and (5) regulatory requirements imposed to insure aquifer protection during operation of the basin. A second report (SWC-WRI No. 48, Schuh and Patch, 2009) examines the capability of the Inkster aquifer to retain ARR waters for beneficial use.

LOCATION AND NUMBERING SYSTEM

The location and numbering system used in this report is based on the public land classification used by the U.S. Bureau of Land Management. The system is illustrated in Figure 2. The first number denotes the township north of a base line, the second number denotes the range west of the fifth principal meridian, and the third number denotes the section in which the well or test hole is located. The letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract). For example, well 154-055-05ADD is located in the SE 1/4 SE 1/4 NE 1/4 Sec. 5, T. 154 N., R. 55 W. Consecutive terminal numerals are added if more than one well or test hole is located within a 10-acre tract.

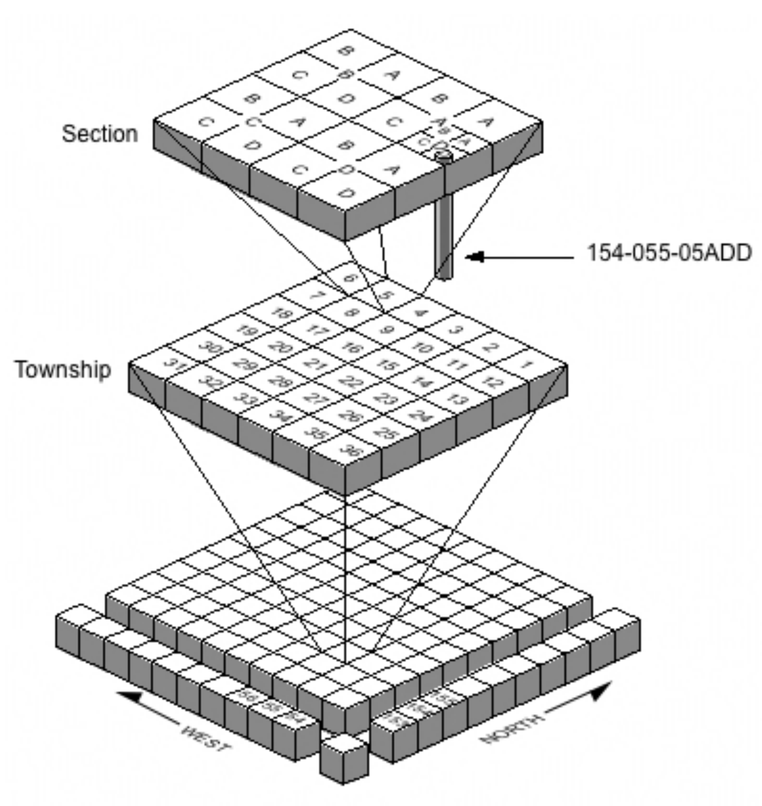


Figure 2. Description of U.S. Bureau of Land Management location system.

CLIMATE

The climate of Grand Forks County, North Dakota is continental, having cold winters and hot summers. The onset of cold weather usually begins in early November. The frost usually leaves the soil in mid-April. The moisture regime is sub-humid, with a long-term average annual precipitation of about 18 inches. The mean annual evaporation (for shallow lakes and reservoirs) is about 30 inches (USDA-SCS, 1980).

THE INKSTER AQUIFER

The Inkster aquifer (Figure 3) was formed through a complex history of depositional events and processes of glacial origin. Channels incised into glacial drift by meltwater were subsequently filled with glacial outwash and deltaic deposits from glacial Lake Agassiz in the latter part of the Pleistocene epoch. The land surface overlying the aquifer is flat to gently sloping eastward. The Inkster aquifer is, for the most part, unconfined with a common saturated thickness of 20 to 50 feet. The aquifer has an overall areal extent of about 12 to 15 square miles, all in Grand Forks County. The aquifer is comprised primarily of fine- to coarse-grained sand with some localized deposits of gravel. The aquifer matrix is generally composed of quartzose sand, detrital shale sand, and detrital bedrock and shield silicate gravels.

The Inkster aquifer is bounded on the west by the long ridge-like Edinburg moraine, on the north by the South Branch of the Forest River, and pinches out to land surface on the east and south. The aquifer is geologically and hydrologically similar to the Elk Valley aquifer which lies directly to the west. The two aquifers are separated by the Edinburg moraine. There does not appear to be a direct hydraulic connection between the two aquifers. Lithologic logs for SWC and some commercial drilling sites on the Inkster aquifer are provided in Appendix B of SWC-WRI No. 48 (Schuh and Patch, 2009).

The soils overlying the Inkster aquifer are primarily a sandy loam of the Maddock series (sandy, mixed, frigid Entic Hapludolls). The Maddock soils are highly permeable and readily absorb snowmelt and excess rainfall, and transmit water to the aquifer as recharge. There is typically no thick barrier of clay to impede the movement of water from the surface to the water table. The water table is generally 5 to 20 feet below land surface. As a result of the highly permeable soils, there is little surface drainage over most of the aquifer, and most of the surplus water is absorbed rather than shed as runoff.

Discharge from the Inkster aquifer occurs mainly through evaporation and transpiration during the growing season. Also, natural discharge occurs through springs and seeps where the North Branch of the Forest River is connected to the aquifer through incised coulees. A third means of discharge occurs from the pumping of high capacity wells for irrigation and rural water supply purposes.

The aquifer parameters, determined from an aquifer test in the NW1/4 NE1/4 Section 23, T. 154N., R. 55 W. (154-55-23AB), ranged from T=5,500 to 9,200 ft^2/day and S = 0.13 to 0.22.

There are currently 12 active water permits which allow annual withdrawals from the Inkster aquifer, for a total of 3,586 acre-feet. Irrigation accounts for 83% of the water allocations.

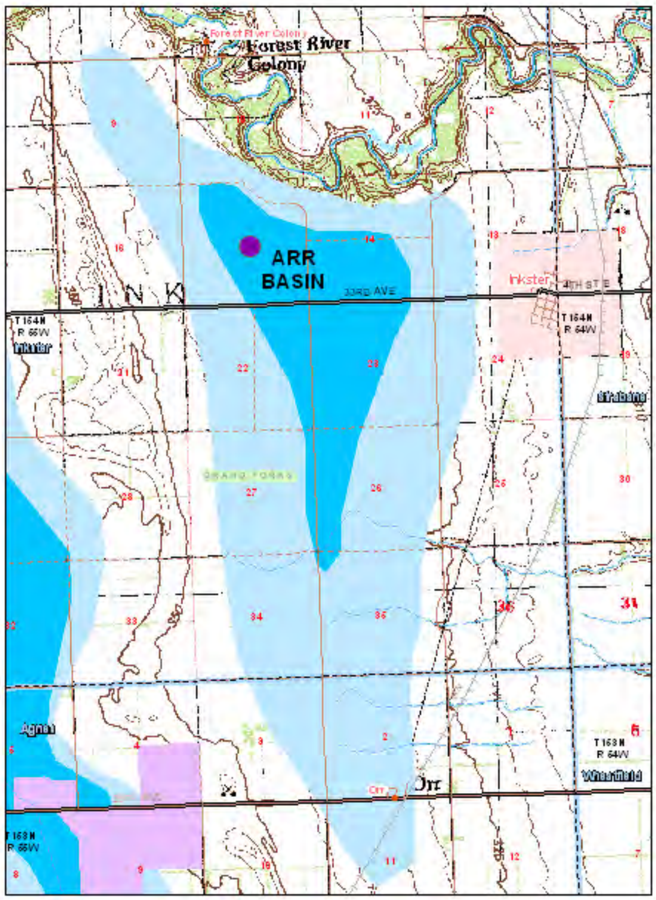


Figure 3. Map of the Inkster aquifer in relation to the Forest River and other topographical features.

SYNOPSIS OF ARR PRACTICES AND PROBLEMS IN NORTH DAKOTA

Aquifer Recharge and Recovery is a sophisticated process, and it has been thoroughly studied and tested by many researchers over a long period of time. Some important considerations will be briefly discussed in this section. An extensive literature review was published in a previous SWC report (Schuh and Shaver, 1988). For brevity we will, therefore, avoid repetition and refer the reader to that report for more detailed discussion and for citations of most of the individual researchers. We will also, specific to the Forest River facility, limit our discussion to infiltration basins, and avoid digression into discussion of injection wells.

History of ARR in North Dakota

Historically, ARR has been used sporadically in North Dakota, usually to solve local problems of municipal water supply. All major projects have been of the infiltration basin or shaft type, rather than injection wells. All have involved the injection of turbid river water rather than treated water. Most have operated for a few years, and then have been terminated because of alternative supplies, or in some cases because of problems with clogging.

In the 1960s the city of Minot supplemented municipal water supplies by recharging local ground water using water from the Mouse River. Recharge was implemented by boring 30-inch "hydraulic connectors" to the aquifer through an overlying clay "aquiclude" and filling the connectors with gravel (Pettyjohn and Fahy, 1968). While initially successful, the connectors eventually became clogged with river sediment, and the project was abandoned because of the costs of deep excavation required for renovating the connectors. The Minot experience has illustrated some important issues concerning design and maintenance of infiltration facilities for long-term operation. Many researchers have examined the relationship between the depth of clay penetration and the coarseness of the filtering medium during "rapid filtration," and have found that deep penetration is highly correlated with approach velocity (flux rate) and the coarseness of the filter (Deb, 1969; Harmeson and others, 1968; Ives, 1970; and Kovenya and others, 1972). Schuh and Shaver (1988) found that a matrix of medium or fine sand will cause silt and clay to filter out on the surface, and will limit deep penetration so that a basin surface can be easily maintained with a surficial cleaning, often requiring the removal of an inch or even less. They have suggested that the overall lower rate of infiltration on medium or finer sands is justified by the advantages offered in ease of cleaning and management, and avoidance of costs of deep excavation with deep clogging in gravels and coarse sands.

Aquifer recharge and recovery was successfully used to provide water for Valley City from 1932 through 1965 (Kelly, 1966). The Valley City ARR facility was used to capture winter flows (January to June) from the Sheyenne River during the extended dry period of the 1930s. Water was pumped from the Sheyenne River, chlorinated, and recharged through an abandoned gravel pit about a quarter-mile from the river. Artificial recharge increased the ground-water surface elevation by 18 feet between 1936 and 1940. Beginning in 1941 rainfall and natural recharge increased. Unlike the Minot facility, the Valley City recharge facility was not terminated because of problems with clogging, but rather because the climate changed, ground-water elevation eventually rose to within eight feet of land surface, and recharge was no longer required to maintain a sufficient supply at the city wells.

Studies aimed at implementing ARR technology as a component of major water projects in North Dakota have been investigated in the late 1980s and the early 1990s. The Garrison Diversion Unit Reformulation Act of 1986 mandated the investigation of ARR as one means of storing water for operation of the Oakes Test Area of the Garrison Diversion Unit. To meet this requirement, the U.S. Bureau of Reclamation, in cooperation with the North Dakota State Water Commission, conducted feasibility studies for ARR of James River water into the Oakes aquifer, in Dickey County, ND. Initial phase studies included an evaluation of the hydrogeological feasibility of ARR (Shaver and Schuh, 1988, 1989a), and the operation of a test infiltration basin (Schuh and Shaver, 1988). Feasibility was discussed in an executive summary (Shaver and Schuh, 1989b). A design and cost analysis was performed for a project-scale recharge facility (Shaver, 1989). Results indicated that ARR was feasible, but high initial water tables in recharge areas required an initial evacuation of the aquifer prior to recharge. That is, the management scheme would be one of debit use and replacement. The prospect of altering natural water table conditions from the debit scenario gave rise to opposition from some local landowners who wished to maintain pastures using natural sub irrigation.

Full-scale irrigation development through the Garrison Diversion Unit in the Oakes Test Area has not been authorized as of 2009. However, a 5,000-acre irrigation test plot overlying the Oakes aquifer continues to be used to evaluate the long-term feasibility of irrigation project development. In the absence of water from the Missouri River, ground water from the Oakes aquifer provided the source of water for the project. A part of the water was supplied by supplemental ARR. The means for supplying interim water for operation of the test area was studied by Shaver (1990). Water for operation of the test area has been retrieved using 82 wells. Water from the James River during spring high flows was used to recharge the Oakes aquifer by surface spreading in natural depressions, and by applying through stationary center-pivot irrigation towers. A total of 5,359 acre-feet was added to the Oakes aquifer from 1989 through 1993, with a maximum annual application of 2,402 acre-feet, and a minimum annual application of 671 acre-feet. Following large rains in 1993, water tables rose and ARR was discontinued. Since then flooding, rather than water supply, has been the main water problem in the Oakes area, and for a while wells were being being used to pump water from the aquifer to the James River. Large-scale development and use of ARR in the Oakes area has not occurred as of 2009.

Recharge and recovery from the Sheyenne River was proposed and investigated as a means for providing additional water to the Englevale aquifer in Ransom County, during dry periods, and for expanding irrigation development in the Englevale area (Cline and others, 1993). It was found that river water supplies were sufficient to irrigate about 1,800 to 3,000 acre-feet in nine years out of ten. An aquifer storage time of about three years following recharge was found to be possible before substantial losses to local wetlands would occur. Depending on the scale of development and management practices, the cost of ARR water for irrigation delivered to the pivot was estimated to be between $88.00 and $144.00 per acre. The Sheyenne River project was not implemented.

Other research conducted on ARR in North Dakota has included an evaluation on the use of organic-mat filters to enhance recharge (Schuh, 1991). Results indicated that the use of organic-mat filters substantially increased the infiltration rate, but also increased the depth of clay movement into the sand matrix. It was concluded that organic mats would be useful on short-term facilities, but that they would exacerbate deep clogging and the expense of renovation on long-term facilities. The effect of algae on clogging through calcium carbonate cementation of basin floors in North Dakota was studied by Schuh (1990). Results demonstrated that increased pH of basin water caused by algal photosynthesis could increase calcium carbonate deposition and decrease infiltration rate. Management measures, such as operating the basin at lower ponded depths, and possible use of grazing insects to feed on algae were discussed. While no injection-well recharge facilities have been operated in North Dakota, Shaver and Wucetich (1994) have evaluated the causes and solutions for clogging of injection wells (used for heat pumps) from precipitation of oxidized iron caused by the injection of oxygenated water into the Oakes aquifer. These findings are directly applicable to problems associated with operation of injection wells for ARR.

Design and Operational Requirements for ARR

The first challenge of ARR is to get the water into the aquifer. The first limitation is that of the initial porosity of aquifer and overlying materials. The infiltration surface must be sufficiently porous and conductive to move waters at an acceptable rate. ARR is generally limited to sandy or gravelly materials. Surficial materials, particularly topsoils and materials within the zone of soil development, frequently have concentrations of finer materials derived from organic matter deposition, and clays deposited and placed by runoff and eluviation which can impede percolation of waters. Topsoils are also more likely repositories of nutrients and pesticides which are undesirable solutes in recharge waters. For this reason, infiltration basins are usually excavated to below the solum, or in some cases to greater depths to expose a coarse substratum. In some cases, where the coarse materials are more deeply placed, “hydraulic connectors” consisting of gravel or sand-filled holes bored through the finer layer have been used. These, however, provide only a limited infiltration surface.

The second limitation is that of aquifer transmissivity. Allowing that the infiltration surface is sufficient to conduct substantial water to the aquifer, a hydraulic mound will usually begin to form early during the recharge process (Glover, 1964; Hantush, 1967). The mound is caused by the inability of the aquifer to move waters laterally from beneath the basin at a rate equal to the vertical influx rate. The hydrologic system compensates by increasing storage through elevating the local water level, and increasing the lateral hydraulic gradient. The mound will frequently intersect, and eventually rise above the basin floor. Once the hydraulic mound has reached the limit of basin carrying capacity, water delivery to the basin will have to be adjusted to a lower level to prevent overflow of the basin. In this way, the recharge rate is limited by the mound height. Mound formation is partially dependent on basin geometry, and is generally larger with a compact geometry, such as that of a circle or square. Rectangular geometries minimize mound formation, and length:width ratios of about 4 are usually recommended. (See Schuh and Shaver, 1988, for research citations.) Incremental decreases in mound formation are very small for ratios above length:width 4.

The third limit for infiltration is imposed by suspended solids in river water which seal the surface and impede infiltration. The process of sealing proceeds as follows: (1) during early stages of infiltration larger (silt and sand) suspended particles filter at the surface while colloidal clays move more deeply into the basin substratum; (2) silt particles eventually bridge surficial pores and form a “filter cake” which, in turn, filters out clay particles; and (3) the filter cake, once formed, gradually thickens through deposition and filtration, and increases the impedance of the surface layer. Increasing impedance of the surface layer will first cause the water-table mound to recede (if it has formed). Eventually, surface impedance will cause desaturation of the underlying sand. Thus, infiltration rate usually decreases as an approximate power function of time as the filter cake forms. From the Oakes recharge basin (Schuh and Shaver, 1988), estimated the decreasing infiltration rate (i), in ft./d, during clogging was approximated as:

$$i = 10.23t^{-0.59} \qquad (1)$$

where 10.23 would be the approximate mean saturated conductivity (K) of the infiltration matrix in ft./d. Integration of equation (1) derives equation 2 for cumulative infiltration (I) in feet:

$$I = 24.95t^{0.41} \qquad (2)$$

Several studies have found the final infiltration rate after 30 to 60 days of study to be between *approx*. 0.5 and 1.0 ft./d.

Limitations imposed by the filter cake require special management. The simplest procedure is to dewater the basin, allow the filter cake to dry, and then remove it by a shallow scraping of the surface. Usually the filter cake does not penetrate more than an inch or so into the matrix material. This generally allows for full rejuvenation of the basin. In some cases, operators have just allowed the floor to dry and crack and then resumed operation. This greatly enhances basin infiltration for a short while, but the rewetted filter cake reforms on the bottom relatively quickly, and enhanced recharge is short-lived. This measure would be most appropriate where only a short additional surge of water is required. Several workers have tried organic-mat filters on the top to break up the filter cake and enhance infiltration. Materials have ranged from cotton residues to composted sunflower seed hulls, and have been relatively successful in maintaining a higher infiltration rate. In addition to disorienting the filter cake through interception of silts and clays in the highly porous organic mat, and protecting the grain matrix from filter-cake formation, organic acids from the decomposing organic mat have been found to provide a microbial substrate for reduction of the oxygen fraction of entrapped air ahead of the wetting front to carbon dioxide, which then dissolves in pore water. It has been shown that the resulting increased macroporosity of about 4% can increase the hydraulic conductivity of the sub-basin materials by two orders of magnitude, and the infiltration rate by a substantial rate (Schuh, 1991).

Unfortunately, increased macroporosity and sustained high infiltration rates, along with the prevention of filter-cake formation, result in deeper deposition of clays, as deep as two feet below the basin surface. The deep-deposited clays will eventually clog the basin, requiring an expensive excavation to remove the deeper materials, and the importation of porous fill materials. For this reason, we believe that the best option is to design a basin of sufficient size to achieve the infiltration goal within the limits imposed by the clogging function, and provide a shallow cleaning after each operation. A thin post-operational scraping of the surface is much easier and, we believe, much more cost effective than a deep excavation. For the same reason, a surface composed of fine or medium sand is preferable to a coarse sand or gravel, since the latter will cause deeper penetration of clogging materials, while the former will intercept them through a filter cake formed at the surface. In most cases, long-term sustainability should be preferable to short-term recharge gains provided by the organic mats or gravelly sediments.

A fourth limitation is imposed by biological processes. These are highly variable and often unpredictable. They can be very influential. They are, however, usually manageable once identified. The example of oxygen reduction by microbial combustion of organic residues was given above. Some other examples are: (1) Formation of an algal mat; sunken algal mats have been documented to cause clogging of basin floors. Conversely, they have been observed, on occasion, to renovate the basin floor by floating the filter cake on air bubbles formed underneath by oxygen released through photosynthesis. (2) Photosynthesis by algae and diatoms have been documented to increase the pH of basin waters. This, in turn, has caused the deposition of carbonates from waters that are near saturation with calcium and magnesium carbonate, causing a substantial decrease in infiltration through sealing by the carbonate crust on the basin floor (Schuh, 1990). These are observed as a "clearing" of the basin waters. Conversely, the presence of *daphnia (sp)* beetles or other grazing aquatic fauna that can consume algae, decrease the pH, and might, perhaps, slowly decrease sealing, although infiltration enhancement initiated by *daphnia* addition has not been observed in short-term tests. The introduction of fish that consume daphnia beetles would reverse the process, again enabling algae proliferation. Carbonate clogging has been found to be a serious problem in the southwest U.S (Bouwer and Rice, 1989). It has been limited and managed by maintaining basin waters at shallow levels to allow intensive sunlight to kill algae. For the most part, biological processes have not been a major impediment to ARR operation in North Dakota, although carbonate clogging has been observed at Oakes.

A fifth limitation is that of hydraulic head management. It is axiomatic that once a filter cake forms, a higher water level in the basin should increase the rate of water movement across the impeding layer. However, effective use of increased head is limited by other factors. The previously discussed limitation of algae-induced carbonate deposition was mainly caused by (deep) high-head management practices which enhanced proliferation of algae. In addition, excessively large hydraulic heads overlying unsaturated sediments under a filter cake could cause excessive stress and partial collapse of the grain matrix, impeding infiltration rates and causing permanent damage to the porous matrix. This would be particularly important for fluvial deposits, where buoyancy during deposition might have caused a partially metastable packing structure. Usually, basin heads of up to a few feet should not cause consolidation.

The second major challenge of ARR is to ensure that influent waters do not harm the aquifer, and that a safe and desirable water product will be recovered from the aquifer. There are two aspects to this challenge. The first is that the quality of influent waters should be considered. If river waters are laden with nutrients or pesticides, ground-water contamination could occur. The dissolved constituents of waters should be considered and appropriately monitored in planning for the management of an ARR facility.

The second concern is that of water chemistry compatibility. Oxidized surface waters introduced into reduced aquifers having large reduced metal constituents in the dissolved fraction, can cause serious problems through clogging of aquifer pores, and through mobilization of metals in the recovered waters. For example, reduced iron or manganese in aquifer waters are highly soluble and mobile, but will precipitate as red or black minerals in the recovery waters once exposed to oxidized recharge waters. These will cause staining of clothes, utensils and fixtures. They may also cause clogging of pipes. Introduction of higher pH waters into a lower pH aquifer waters saturated with respect to carbonates could cause carbonate deposition and scaling. In some cases, mobilization of toxic metals, like arsenic, could occur. Sampling of receiving waters and recharge waters for chemical analysis, and particularly for analysis of trace elements is critical for the safe design of facilities, particularly where human consumption is involved. Changes in pH, dissolved oxygen, and temperature could be very important. Appropriate analyses can be accomplished using available chemical equilibrium models like WATEQ (Truesdell and Jones, 1974; Plummer and others, 1978) or PHREEQ (Parkhurst, 2009).

The last challenge is the recoverability of recharged water. The transmissivity of the aquifer must be sufficient to extract the influent waters, and the well-field must be appropriately designed to pump recharged waters at an acceptable rate. But in addition, a major concern is the retentiveness of the aquifer with respect to influent waters. Recharge will be of little value if recharged waters are lost to drains, springs or evapotranspiration before they can be pumped for beneficial use. This is particularly important when facilities are operated with waters pumped from nearby gaining streams. It is also important where ground-water is shallow and subject to evapotranspiration. Shaver (1990) recommended that ARR be operated on a deficit replacement basis in a shallow water-table area of the Oakes aquifer. If water tables are too shallow, elevated water tables caused by recharge may place water within the zone of evaporative loss. In such a case, long-term retention of waters would be rendered impossible by evaporative loss, and immediate pumping would be required to optimize recharged waters. Even where water tables are sufficiently deep, the flow system interaction with natural discharge areas must be clearly understood. For example, Cline and others (1993) determined that the Englevale aquifer, while sufficiently deep to retain recharge waters, would begin to lose waters through evaporation at Lone Tree Lake about three years after recharge.

FOREST RIVER WATER AVAILABLE FOR ARR

Availability of water is one critical component of ARR. Effective implementation of ARR using spring seasonal river flow is a matter of opportunity; that is, of taking advantage of high flows when they are available for capture. The period of the proposed water permit for pumping from the Forest River was March 1 to June 15. During this period, it was determined that a minimum flow of 7.5 cfs had to be maintained in the river downstream of the basin to ensure accommodation of water users in the lower reaches of the river. The 7.5 cfs estimate included 2 cfs estimated loss of water from the river, 2 cfs estimated maximum use for livestock, and 3.5 cfs needed to provide for the water rights of prior appropriators along the river. After June 15, low summer flows and prior water rights would preempt FRC rights of water use.

Probability of Available Water

Primary water-supply limitations affecting potential recharge include: (1) natural variations in spring river flow, and (2) pumping capabilities at the point of diversion. Other secondary factors include the chemistry and sediment load of the river water, which can affect the recharge capability of the basin; and the condition and maintenance of pumps and equipment, which will affect the ability of the operators to capture flow at critical times.

Probability plots of spring flows in the Forest River through 1996 are shown on Figure 4. The data distribution indicates that the amount of water available for capture during the time period allowed for pumping varies widely, from almost no pumpage in years like 1958 and 1961, to as much as 750 acre-feet in 1950 (pumped at 2,500 gpm). This means that recharge facility operators must consider the probability of flows, recognizing that in some years there will be ample water available for recharge, while in others there will be much less.

Second, the data indicate that climatic changes can have a significant effect on operation during different periods of operation. Figure 4 shows a significant upward trend in flows available for capture from 1940 through 1996. Regression analysis indicates that the moving mean usable flow has about doubled from 360 acre-feet pumped at 2,500 gpm, and 614 pumped at 5,000 gpm in 1945, to 666 acre-feet pumped at 2,500 gpm, and 1,164 acre-feet pumped at 5,000 gpm in 1995.

Third, the data indicate that doubling the pumping rate nearly doubles mean potential recharge throughout the period of operation. This is because variations in river flow include little or no flow, and periodic very large flows. Larger pumping capability allows the operators take advantage of the opportunity offered by large flows. The fact that the increase in water available for recharge is nearly proportional to the pumping rate indicates that river flows for a great many of the periods of pumpage are capable of providing water at 5,000 gpm or more. While even higher pumping capacity would further increase total yield of water from the river, the unit of additional yield per unit of increased pumping capacity would be expected to decrease, as a smaller proportion of occurrences would be expected for each successively larger flow rate.

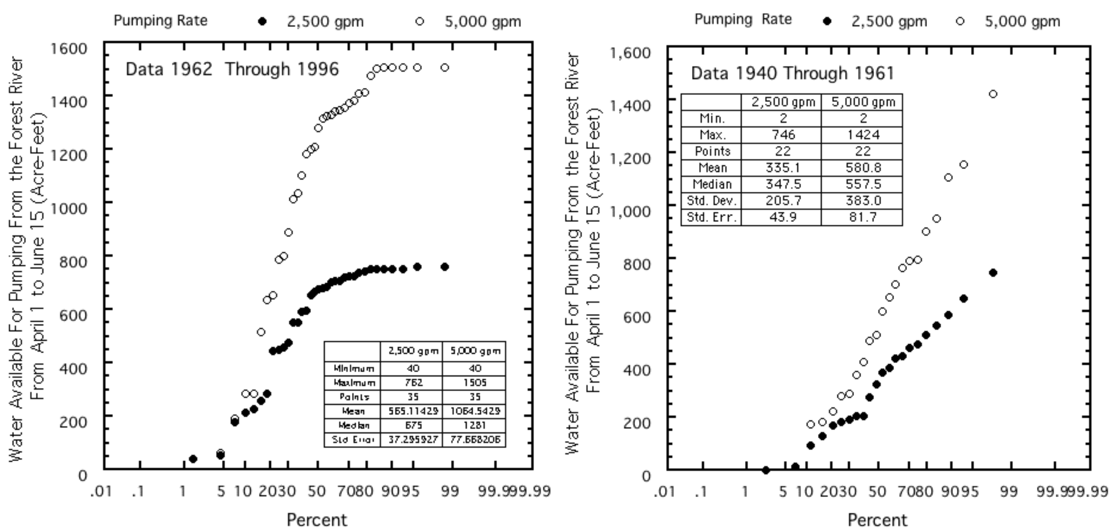


Figure 4. Probability of recoverable flows from the Forest River during April 1 to June 15.

In Figure 4 the opportunity for ARR is viewed in terms of probability, for the period from 1940 through 1961, and for the period from 1962 through 1996. For each time period, the maximum potential recharge was about 1,500 acre-feet, pumped at 5,000 gpm, and the minimum was close to no recharge. Under conditions characteristic of the 1940 to 1961 period, only about 200 acre-feet would be assured for recharge in 80% of the years at both pumping rates. Higher rates of recharge would be possible at lesser frequencies. Under conditions characteristic of the 1962 to 1996 period, at least 400 acre-feet of water would be available for recharge 80% of the time at the 2,500 gpm pumping rate, and more than 600 gpm would be available 80% of the time at the 5,000 gpm pumping rate.

From the standpoint of the water supply at the river, a basin design capable of recharging 400 to 600 acre-feet per year during a 75-day period, would accommodate flow available for diversion in eight years out of ten under current climatic conditions. If it is considered desirable to capture water storage opportunities occurring on a less frequent basis, then more pumping capacity would be desirable. It is understood, however, that as climate fluctuates there will be periods when the frequency of occurrence of these capture opportunities will decrease considerably, as in the period prior to 1962 where only 200 acre-feet per year could be obtained with 80% certainty.

Operators should be aware of such changing windows of opportunity, and should be prepared to accommodate them when considering the cost-effectiveness of operation.

Water Permits

Two water permits were approved for pumping from the Forest River to the FRC recharge basin. In 1993, the first water permit (#4561) authorized pumping of up to 520 acre-feet of water per year at a rate of 2,500 gpm prior to June 15. A minimum flow of 7.5 cfs in the Forest River after pumping was stipulated to maintain livestock use and prior water rights, and to offset river losses (Odenbach, 1993). In 1996 a second water permit (#4980) authorized an additional 400 acre-feet of pumping at a maximum pumping rate of 2,500 gpm. Restrictions were the same as those placed on Water Permit #4561 (Odenbach, 1996). A total withdrawal of up to 920 acre-feet, at a maximum pumping rate of 2,500 gpm was thus authorized. Pumping was authorized from April 1 through June 15.

PRELIMINARY INVESTIGATIONS AND SITE SELECTION

Effective recharge through an infiltration basin requires: (1) a suitable supply of surface water near an aquifer of sufficient aerial extent and thickness to store the desired amount of water; (2) a suitably permeable medium from the recharge surface to the aquifer; (3) aquifer storage and transmissive properties conducive to pumping of water from the aquifer in sufficient quantities when needed; and (4) sufficient distance from discharge areas, such as springs or wetlands, to prevent loss of recharge water before it can be used.

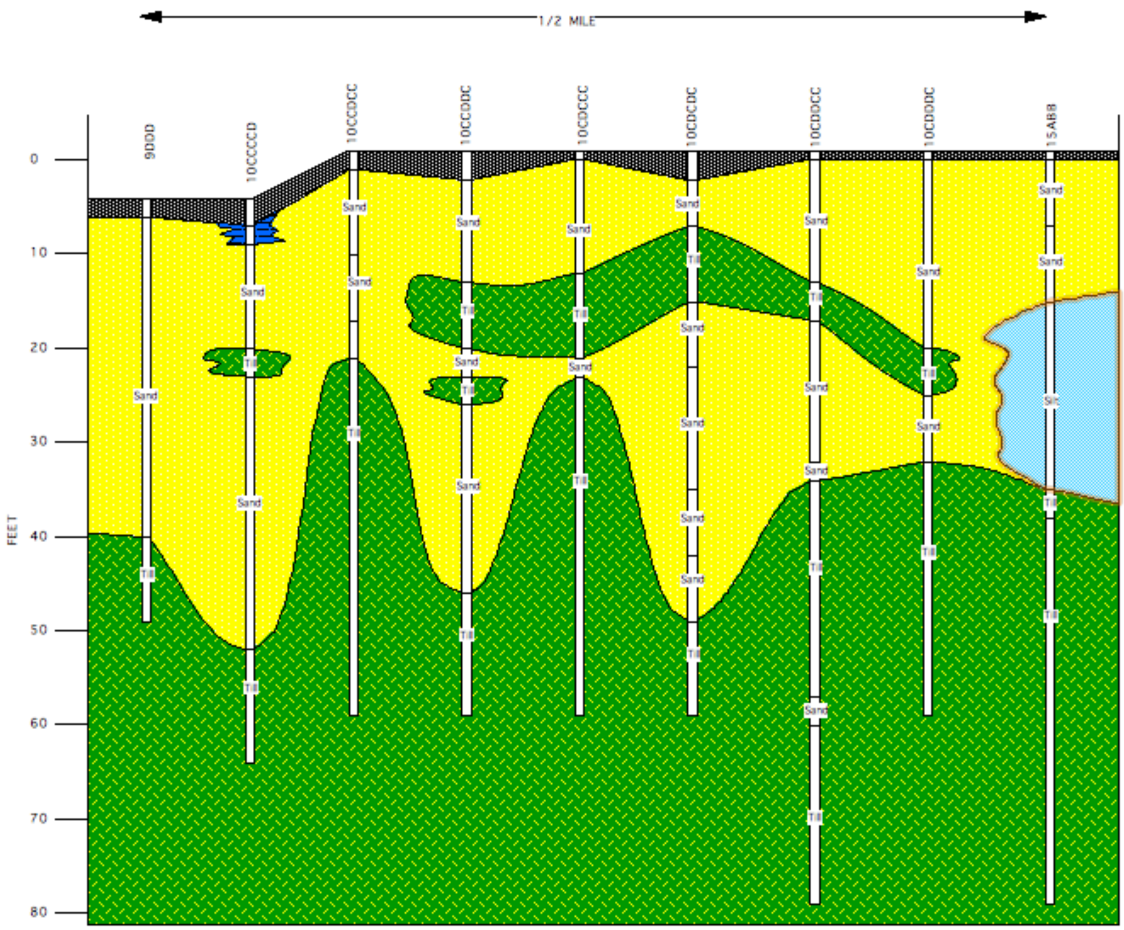


Figure 5. Stratigraphic cross section for the northwest boundary of the northwest quarter of 154-055-15.

Aquifer Suitability Limitations

The Inkster aquifer near the FRC consists of glaciofluvial sediments bordering the Forest River. The aquifer, near the river, is heterogeneous, with sediments ranging from coarse gravel and stones to fine sands and silt. Some areas near the river appear to have been deposited in a braided stream environment. A geological cross section from exploratory drill logs indicates that the aquifer thickness is highly variable, and that the thickness in the east-to-west direction is defined by an undulating aquitard, the troughs of which appear to have been formed as braids of an anastomosing stream (Figure 5). There are a local layers of silt (about four feet thick) at some locations, indicating a lower energy depositional environment, such as a backwater during some periods of deposition. If fine (clay or silt) layers are discontinuous lenses, and sufficiently deep, they may not effectively prevent recharge. However, extensive fine layers, with relatively shallow placement (less than 20 feet) would cause the formation of a perched ground-waster mound under recharging conditions, and would prevent efficient operation of a recharge basin. Conversely, a layer of fine materials that is thin and placed shallow could be removed through excavation. If surface clay and silt layers are too thick, excavation could be quite expensive.

Pilot Site Evaluations: Permeability and Saturated Thickness

Initial intentions of the FRC were to construct the basin in Section 9 of 154-055. Initial exploration was conducted by digging slit trenches with a backhoe, and by exploratory drilling using an auger rig. A thick layer of silt at 14 feet made the site unsuitable. In the SE corner of Section 9, two trenches indicated a fine to very fine sand dominant material to a depth of about 4 feet in the first hole and 6.5 in the second. Two laboratory falling head permeameter tests on 2.1-inch length x 2.1-inch diameter undisturbed core samples indicated a permeability of 1.52 and 1.82 feet per day, too low to sustain artificial recharge. Beneath the surface sands there was a layer of iron cemented stony materials, underlain by an assortment of pea gravels and mixed sand and gravel to a depth of about 8 feet. Large infiltration would be possible through these materials, but deep influx of clay and substantial clogging would be expected. At 8 to 9 feet, a layer of indurated stones, cobbles, and gravels were located. Treatment with 0.1 N hydrochloric acid indicated that the cementation was non-carbonate. Samples placed in cups of water and dilute hydrochloric acid did not decrease in cohesion. Cementation was likely siliceous. Permeability was tested by chiseling a "dish" into the top of a large sample, and dripping a steady known quantity of distilled water on the sample. The permeability was measured to be about 2,400 feet per day. While deeper strata are suitable for artificial recharge, the need (and expense) for excavation to a depth of about 7 feet to avoid fine surface materials rendered this site unsuitable. The southwest corner of Section 9 was found to have silt, underlain by an impermeable clay at about 17 feet, making the site unsuitable.

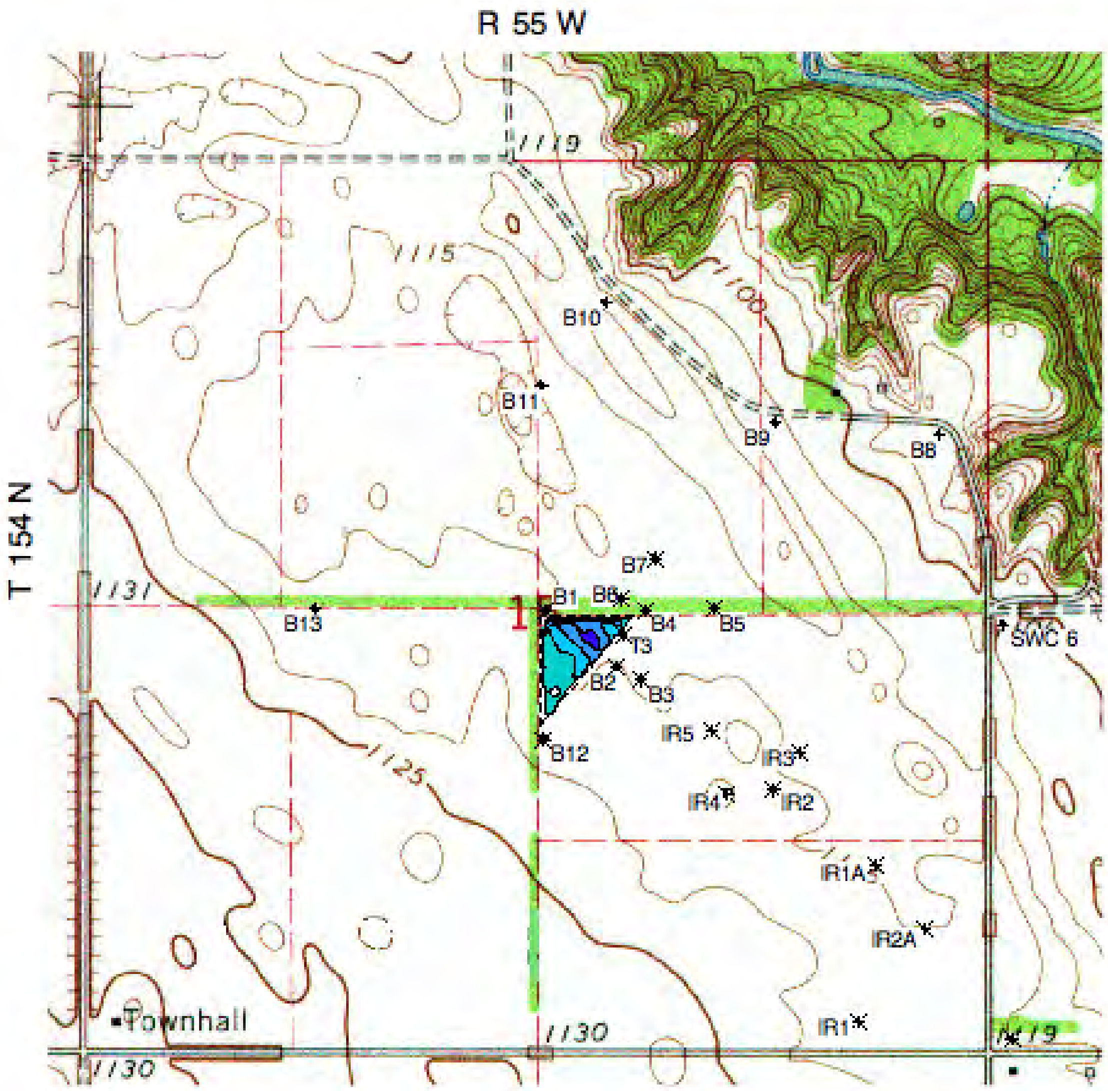


Figure 6. Pilot basin site in the center of Section 154-055-15. Wells labeled "IR" are the locations of irrigation wells before basin construction. Sites labeled "B" are observation wells placed to monitor water levels affected by ARR.

The center and south of Section 15 (154-055-15) were evaluated for suitability. Auger drilling of sites in the south (154-055-15DCC and 154-055-15CDD) indicated a homogeneous fine and medium sand, overlying a two-foot silt layer at nine to 13 feet below land surface. Deeper strata consisted of sand and gravel to about 38 feet. Laboratory hydraulic conductivity through silt on four 6-cm length by 5-cm diameter core samples was measured using the standing head method (Klute, 1965). Results are shown on Table 1. Low K for the silt layer, and location of silt at a depth that would require large excavation, rendered construction of the basin at this site impractical.

Table 1. Hydraulic conductivity measurements for sediments in 154-055-15.

Location	Sediments	Sample K (ft./d)	Mean K (ft./d)
SW corner of SE quarter	deep silt	0.25	
		1.21	
		0.3	0.59
SW corner of SE quarter	shallow silt	0.8	
		0.81	0.81
NW corner of SE quarter	gravel	124	
		104	
		250	159
SE corner of NW quarter	medium + coarse	14.9	14.9
	sand		
SE corner of NW quarter	sand + clay	8	8
SW corner of NE quarter	sand + some clay	4.1	
		3.1	3.6
SE corner of NW quarter	sand	10.3	10.3

Auger holes drilled in the center of Section 15 indicated that the clay aquitard was located at depths ranging from 30 to 43 feet below land surface. The initial water table was at about 30 feet below land surface. There was a general trend of greater depth to aquitard in the northeastward direction. High reflectance on an aerial infrared photograph (Figure 7) taken on September 17, 1993 showed the trace of what appeared to be a coarse paleo channel oriented from northwest to southeast, and skirting the northeast borders of the SW corner of the NE quarter of Section 15, and the NW corner of the SE quarter of Section 15. The presence of the paleo-channel is further supported by the east-to-west transect at the north boundary of the NW quarter of Section 15 (Figure 5), which indicates the presence of undulating deep channels. The location and orientation of FRC irrigation supply-wells (prefix IR) on Figure 6, also corresponds to the location and orientation of the high reflectance zone observed on the infrared photo. The bottoms of well screens on irrigation wells were at about 70 to 80 feet, compared with depths to till of 42 feet or less in the center of Section 15 (Appendix B in SWC-WRI No. 48, Schuh and Patch, 2009). These observations indicate that water recharged in the center of Section 15 would be recoverable by the irrigation wells. They also indicate that sufficient saturated thickness and transmissivity to enhance water storage and prevent excessive mounding of water during recharge is to be found southeast of the basin. Aquifer conditions northeast of the basin were less clearly understood.

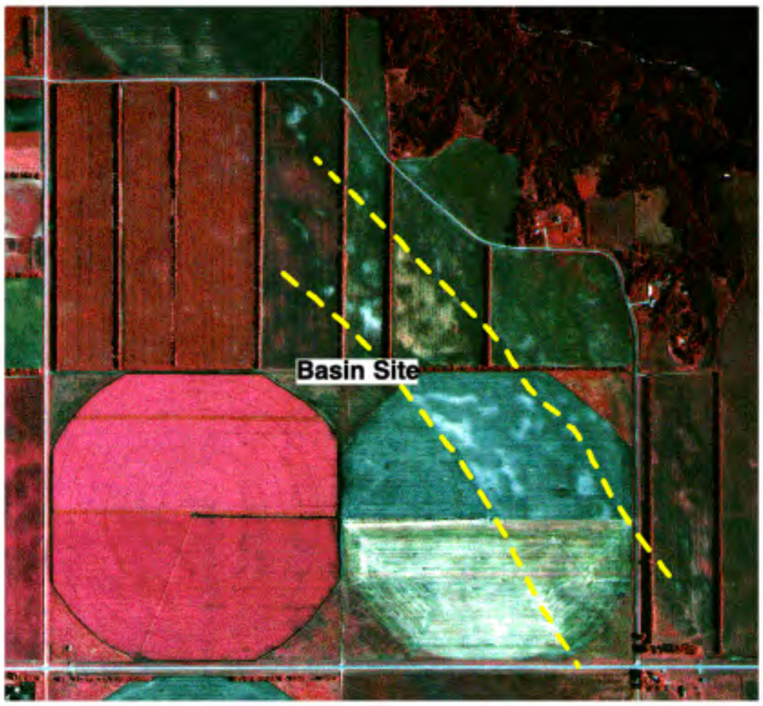


Figure 7. Aerial Infrared photo of 154-055-15 indicating the likely presence of a paleo-river channel near the proposed basin site.

Shallow sediments beneath the topsoil in the center of Section 15 consist of fine and medium sand. Auger-hole samples indicated that vadose and aquifer materials vary from fine sands, some mixed with clay, to fine gravel. A substantial part of the sand fraction consists of detrital shale. Some of the apparent sand and clay mixes may have been caused by slaking of the shales by mechanical abrasion of the auger stem during exploratory drilling. Fine layers did not appear to have sufficient depth or continuity to impede recharge.

Preliminary soil core samples taken at the two-to three-foot level in the center of Section 15 indicated that the hydraulic conductivity of sand materials is highly variable (Table 1). If the three pea gravel samples are weighted as a single average (because they were not characteristic of most of the center area) the average K is about 17.8 cm/h (14.9 ft./d). Without clogging, this would be expected to be the approximate initial steady-state recharge rate. Preliminary data indicated that the permeabilty of the vertical profile should be adequate to allow for effective recharge in the center of Section 15. The center of section 15 was selected as the location for the pilot basin.

Pilot Site Evaluations: Potential Retention Limitations

While aquifer storage characteristics and the properties of the overlying infiltration medium appeared to be adequate for artificial recharge in the center of Section 15, the proximity of this location to the Forest River caused some concern over possible losses through return to the river. The forested zone along the river is likely a major sink for aquifer water. The river is incised through the aquifer and into the underlying till, so that the aquifer discharge to the river occurs through springs at exposed till contacts at elevations above the river bed. Of particular concern is Inkster Spring, located about six-tenths of a mile east of the center of Section 15 (Figure 6). Spring discharges along the river would likely vary directly with changes in piezometric head of the aquifer caused by artificial recharge. It would not seem likely that increases in tree transpiration from rises in piezometric head near the river would be large. Evaluation of spring losses are an important component in assessing the effectiveness of recharge at the center of Section 15.

PILOT BASIN DESIGN AND OPERATIONAL PLAN

The purpose of this section is to describe the procedures used in basin design, and in establishing a preliminary operational plan. These can be compared with pilot basin, and long-term operational results.

Basin Design Objectives

Basin design should conform to recharge objectives. Based on analysis of water available from the Forest River, under current climatic conditions it was estimated that about 600 acre-feet of water would be available for recharge in about 80% of years. This seemed to be a reasonable goal for a minimum basin capacity. Basin design must consider many factors, including long-term infiltration based on limitations imposed by basin mounding, the clogging process caused by sealing of the basin surface from the addition of sediment laden water, biological and chemical processes which can affect the basin infiltration rate, and short-term changes in pumping from the river, which can increase the amount of required basin storage. Because of the many factors involved, and because of the sensitivity of basin operations to management, Shaver and Schuh (1989b) recommended that ARR projects should be implemented in stages. They recommended that a conservative preliminary design be made to account for all potential limitations, but that the design be implemented in modular form to allow for only partial construction if that proves to be sufficient. They also recommended that the basin project then be implemented in stepwise fashion, beginning with a pilot-scale project, and working to optimize basin effectiveness through management practices. Basin operation should be expanded based on requirements determined by the pilot operation.

Preliminary Specifications

Previous work in North Dakota (Schuh and Shaver, 1988) and elsewhere has indicated that an average recharge rate of at least 2 ft. per day should be feasible for a specified recharge period. Total time allotted for recharge from the Forest River was estimated at about 76 days, from the beginning of April to June 15. However, spring thaw in North Dakota is not reliable, and contingencies and breakdowns must be considered, so a conservative estimate of 45 operational days was used for preliminary assessment. Using this infiltration rate and period of operation, a basin area of about 6.7 acres would be needed to meet the 600 acre-feet/y recharge goal. An initial projected design for a total of 7 acres was therefore used for preliminary assessment. It was proposed that two rectangular basins of 800 x 200 feet in dimension comprise the initial full design, and that the project begin with construction and operation of a pilot basin of half this size, or about 3.5 acres.

Estimated Recharge Limitations from Mound Interference

One of the most common limitations imposed on basin recharge is caused by ground-water mound interference during early (fast) infiltration. Mounding effects were described under the subsection **Design and Operational Requirements for ARR.** As the basin surface clogs, the infiltration rate through the surface becomes limiting and the mound dissipates. Mound-imposed constraints usually occur during the earliest times of operation, before substantial clogging has occurred.

A Hantush (1967) simulation for a 800- x 200-foot rectangular basin was used to evaluate the likelihood of mound-imposed limitations on the proposed basin operation. The geometric mean vertical hydraulic conductivity for non-gravel sediment samples collected in the center of Section 15 (Table 1) was used for computation. The local water-table surface was about 30 feet below land surface, and the depth to the aquitard varied from about 40 feet to greater depths on the east extreme of the proposed construction site. Hantush simulations were calculated for infiltration rates of 15, 10, 5, and 4 feet per day, using a transmissivity of 2,000 ft^2 /d, and a drainable porosity of 0.18. Results (Figure 8) indicated that an expected maximum infiltration rate of 15 ft./d could be maintained for about a half-day before the mound would intersect the basin surface. After five days mound-imposed constraints would limit recharge to about four feet per day. This is still more than the rate of infiltration that would occur if 2,500 gpm were delivered to the basin. Under half-scale conditions (2,500 gpm delivered to a 3.7 acre basin), mound formation would not, therefore, limit recharge. If the full 5,000 gpm were delivered to a 3.7 acre basin, the mound would begin to limit recharge after about 2.5 days.

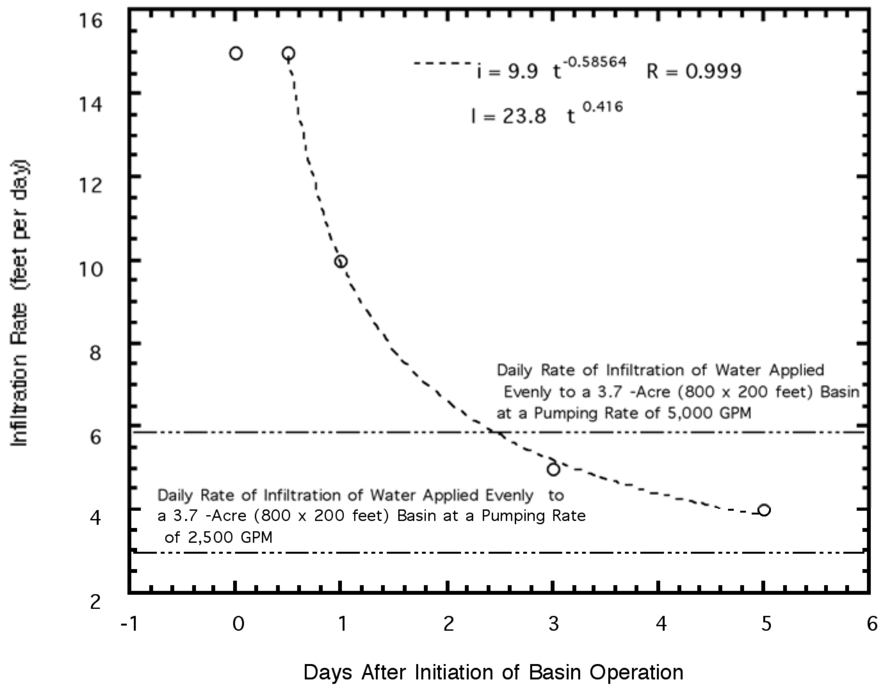


Figure 8. Infiltration rates at which the recharge mound underlying the recharge basin will intersect the basin surface (at 30 feet above the water table) after a specified number of days of operation during the fall 1992 pilot test.

Recharge Limitations from Filter Cake Formation

In 1987 and 1988 effects of soil clogging from sediment deposition, biological effects, and changes in water chemistry on basin recharge were examined in a 50- x 50-ft. test basin, using water from the James River (Schuh and Shaver, 1988). Clogging effects can usually be described using a power function:

$$i = kt^{-b} \qquad (3)$$

where i is the infiltration rate, K is the saturated hydraulic conductivity of the unclogged material, and b is an empirical factor. Cumulative infiltration (I) can be described in the integrated form:

$$I = \frac{k}{(1-b)} t^{(1-b)} \qquad (4)$$

The exponents for the Oakes test were described in equations (1) and (2). Using equation (3), total recharge for 45 days of operation in a seven-acre basin complex would allow 830 acre-feet of recharge; more than enough to meet the goal of 600 acre-feet.

The James River and the Oakes project (Schuh and Shaver, 1988) differ from the proposed FRC project in sediment load, aquifer materials, and vadose matrix. The James River is larger than the Forest River, and flows through a watershed of predominantly fine materials for most of its course. The Forest River near the FRC flows through the coarse beach sediments of former Lake Agassiz. In addition, the Forest River is impounded behind the Fordville Dam, about three miles (ten river miles) west of the FRC, which causes it to drop much of its suspended solids. For this reason, suspended solids in the Forest River during the recharge period are often lower (about 15 mg/L) than the 50 mg/L average measured for the James River (Schuh and Shaver, 1988). Conversely, basin floor materials on the proposed FRC construction site were considerably less permeable (Table 1) than those of the Oakes test basin, which began operation with an overall infiltration rate of 40 ft./d, and which varied locally within the basin from as low as 5 ft./d to more than 100 ft./d (Schuh and Shaver 1988). Based on measured K values, initial infiltration rates at the FRC facility would be expected to be about 15 ft./d (Table 1). After one day of clogging on the Oakes basin, infiltration was already reduced to 10 ft./d. This would be identical to the infiltration rate expected on the Forest River basin after one day of operation, from constraints imposed by basin mounding (Figure 8). In fact, the expected cumulative infiltration curves calculated for the Oakes basin affected by clogging (Equation 2) , and the simulated FRC basin based on mound formation (Figure 8) are almost identical. The identity is coincidental, and is not physically based. Clogging dynamics measured for a basin at Oakes, ND indicate that the preliminary design area of 7 acres should be sufficient to attain the recharge goal.

PILOT BASIN: CONSTRUCTION, OPERATION AND MONITORING

A pilot basin of approximately 3.4 acres was constructed in the summer of 1992. The excavated depth was approximately 2 feet below land surface. Excavation was deeper in the center of the basin to remove localized sediments having a higher clay content. In general, the deep center of the basin had material of lower permeability than the peripheral areas of the basin. A triangular, rather than rectangular, shape was used to fit the space available in the NW corner of the SE quarter of Section 15, which was the uncropped corner of a center-pivot irrigation system. After excavation, a subsoiler was used to relieve deep compaction caused by construction. This left deep ridges of about one foot in the basin floor (Figure 9A). The ridges were left in place during basin operation. Previous research (Jones and others, 1974, 1981) has indicated that the ridges can enhance infiltration capacity. Ridging increases the basin infiltration surface. In addition, sediment tends to move downward into the valleys of the ridge complex, which serves to maintain a higher infiltration rate on the upper portions of the ridges. The pilot basin is shown after construction and during operation on Figure 9.

Methods for Monitoring Infiltration Rates and Surface Clogging in the Pilot Basin

During initial operation of an artificial recharge basin, infiltration through, and clogging on the basin surface is non-uniform. When the pumping rate is limiting, early infiltration occurs through a limited area (A) having the lowest elevation, such that i x A equals water received at the intake. Clogging first begins in the initial ponded area, and the ponded area gradually spreads over new clean surface to compensate for clogging. This continues until the basin is fully covered. At the time of full coverage the basin begins to fill. Once full, it becomes necessary to gradually reduce the rate of water delivered to the basin.

In order to monitor the initial infiltration capabilities and changes in basin capacity caused by long-term clogging, the following procedures were used. Staff gauges were placed in the deepest portion of the basin floor to monitor water level elevations during operation. The entire basin was then flagged in a 2,500 square-foot (50 x 50 ft. increments) grid for analysis of recharge rates. Flag colors were alternated (yellow and pink) in each direction, to help provide a clear frame of reference for visual mapping of the flooded area of the basin floor. The basin layout is illustrated on Figure 10.

A

B

Figure 9. Pilot ARR basin: (A) prior to the pilot basin operation in the fall of 1992; and (B) during the water spreading phase of the spring 1993 pilot basin operation.

During the filling of a basin, the creep rate of water on the basin floor can be used to calculate overall infiltration rate through the basin according to:

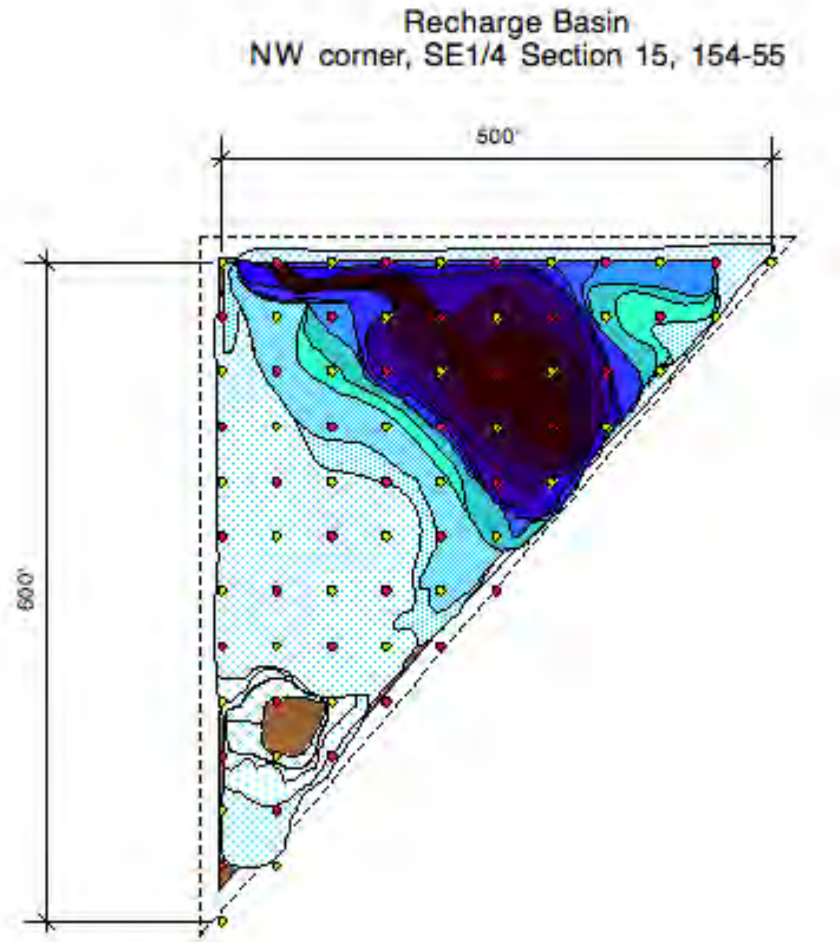
$$i = \frac{(Q_i - \Delta S)}{\overline{A}} \qquad (5)$$

where Q_i is the rate of water introduced to the basin at the inlet, $\overline{A}$ is the average area covered by water during the time increment of measurement. ΔS is the change in basin storage estimated from:

$$\Delta S = (d_f - d_i)A_i + \frac{(d_f - d_i)}{2}\Delta A \qquad (6)$$

where ΔA is the difference between final and initial area of basin floor covered with water for a given time interval, and d_f and d_i are final and initial water heights in the basin, respectively, for the same time interval. For early periods of basin operation in 1992 and 1993, the flooded area of the basin floor was mapped on graph paper using the flagged grid in the basin as reference. Water levels in the basin were measured at the time of each grid mapping. A rating curve for (Figure 11) was developed and used to calculate area for use of equation 6.

Initial estimates of the hydraulic conductivity of the basin using laboratory cores indicated an expected approximate geometric mean infiltration rate of about 14 feet per day. However, variability was high (from 3 to 5 feet per day in areas where clay was mixed with sand) to as high as 277 feet per day in the pea gravel. In general, it was expected that infiltration rates would be low in the clayey sands in the deep center of the basin, and that the higher infiltration rates would be located on the far southwest corner of the basin where pea gravel was sampled for the laboratory tests. More precise estimates of the relative extent and locations of materials of different coarseness were desirable.



DATE	TIME	days	area (ft2)	Δ area	staff gage	Δ gage	storage (ft3)	I (ft/day)	I (per step)
4/6/93	13:45	0.0104	9688	9688	0.70	0.70	3391	4.16	
4/6/93	14:34	0.0444	19691	10003	1.68	0.98	17787	-1.75	-2.47
4/6/93	15:40	0.0903	25565	5874	2.36	0.68	33174	-0.07	3.07
4/6/93	16:46	0.1361	32521	6956	2.87	0.51	47985	0.41	5.58
4/6/93	17:40	0.1736	36971	4450	3.15	0.28	57714	0.90	14.80
4/7/93	10:41	0.8826	30864	-6107	2.85	-0.30	47539	(n/a)	-6.05
4/7/93	12:45	0.9688	41990	11126	3.50	0.65	71217	2.46	12.07
4/7/93	13:44	1.0097	45175	3185	3.80	0.30	84291	2.24	44.95
4/7/93	15:11	1.0701	49489	4314	4.05	0.25	96124	2.12	34.82
4/7/93	17:06	1.1500	56839	7350	4.30	0.25	109415	1.96	21.92
4/7/93	19:02	1.2306	62457	5618	4.58	0.28	126117	1.84	30.53
4/8/93	8:40	1.7986	76101	13644	5.38	0.80	181540	2.14	16.54
4/8/93	11:37	1.9215	84101	8000	5.45	0.07	187147	2.06	31.16
4/12/93	10:00	5.8542	137649	53548	6.38	0.93	290261	2.07	6.89
4/13/93	8:30	6.7917	140790	3141	6.42	0.04	295830	2.10	137.83
4/14/93	8:30	7.7917	143508	2718	6.51	0.09	308623	2.11	163.16
4/15/93	8:39	8.7979	146515	3007	6.60	0.09	321674	2.11	150.29

Figure 10. Map of basin floor water spreading on April 15 during the spring 1993 basin pilot test. "I (per step)" is the localized infiltration rate for the time dependent floor spread increment. Negative (red) values are erroneous measurements.

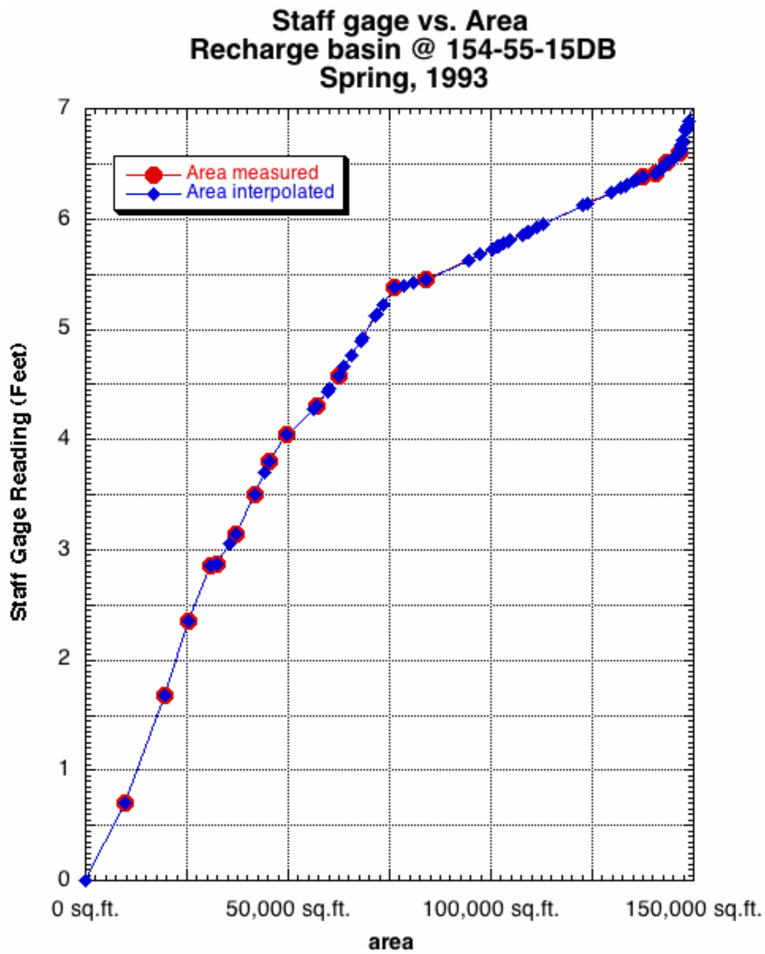


Figure 11. Basin area vs. staff gage measurement.

Because the water entering the basin was relatively clean (suspended solids between 8 and 18 mg/L), the clogging rate was assumed to be slow during the initial phase of basin operation. It was assumed that the change in overall basin infiltration rate did not decrease greatly due to clogging over the time of each individual measurement interval (usually one-half to one hour). While this assumption is not rigorously true, it provided an approximation for evaluation of relative conductivity of the basin floor. Because the hydraulic gradient of the basin vadose zone should approximate one, infiltration rate should be approximately equal to K. Infiltration rate for each local newly-flooded, actively-recharging area of basin area was estimated using equation 7,

$$i_j = \frac{\left(A_j \bar{i}_j - A_{j-1} \bar{i}_{j-1}\right)}{\left(A_j - A_{j-1}\right)} \qquad (7)$$

where i_j is the infiltration rate for the area of the basin floor flooded over the last time increment, A_j is total basin floor area covered with water at the end of the last measured time period, $\bar{i}_j$ is the overall average basin infiltration rate measured during the last time period, A_{j-1} is the total area covered with water at the completion of the previous measurement time interval, and $\bar{i}_{j-1}$ is the average basin infiltration rate measured during the previous time interval.

Pilot Basin Operation and Maintenance

Two pilot tests were conducted to evaluate the feasibility of the full-scale basin project. These included a short (one-day) test in the fall of 1992, and a full period of operation in the spring of 1993.

First Pilot Basin Test (Fall 1992)

On October 27, 1992, a brief (24-hour) basin test was conducted to provide initial hydraulic data for evaluating basin effectiveness. Water was pumped from the Forest River to the pilot basin at 1,000 gpm. Almost all infiltration measurements were about 6 feet per day, varying from an early measurement of 5.68 ft./d to a value of 6.21 ft./d six hours later. A single low value 3.51 ft./d followed by a single large value (8.48 ft./d) averaged together yield 5.96 ft./d, which indicates that there was likely an error of flooded area estimation at the time between the two measurement periods. Water pumped to the basin naturally flowed to the lowest elevation in the center of the basin. Surface materials in the center of the basin were finer than other areas, and it was considered likely that the average initial infiltration rate for the full basin test would be slightly larger than the 6 ft./d measured value in the first pilot test.

Second Pilot Basin Test (Spring 1993)

About one-third of the basin floor had been covered during the fall 1992 basin test. Because the water had appeared clear, and because the infiltration rate had not decreased greatly during the first test, the second test was conducted without cleaning the basin floor from the previous test. However, there did appear to be some residual clay filter cake in the previously flooded part of the basin. On April 21, 1993, the pumping rate was measured at 1,900 gpm near the basin intake, using a Panametrics™ ultra-sound propagation flowmeter. Basin floor area covered, height of water on the staff gauge, average infiltration rates, and individual local infiltration rates for the period of initial filling of the basin between April 6 and April 15 are illustrated on (Figure 10). Ponded area was hand mapped on April 6 and April 15 using the flagged intervals on the basin floor at times corresponding to water level readings. During this time period the basin was nearly completely filled. Maps were then digitized and areas quantified. A calibration curve for area versus elevation was developed (Figure 11) and used for measurement of basin storage and infiltration rates according to equations 5 and 6.

A total of 179.7 acre-feet was recharged to the Inkster aquifer during the spring pilot test. Average infiltration rates are summarized for the basin test on Figure 12. The first several days of the test were characterized by advancement of the recharge pool over increasing areas of clean basin floor, as clogging slowly proceeded in the initially flooded areas of the basin floor (Figure 10). Infiltration rate decay due to clogging is described shown on Figure 12. Infiltration rates can be described as:

$$i = 4.08t^{-0.24} \qquad (8)$$

and cumulative infiltration is described as:

$$I = 5.37t^{0.76} \qquad (9)$$

Infiltration rates shown on Figure 12 were calculated using actual measured infiltration surface area. However, the full infiltration surface was not used for recharge during the entire test. There were periods during which pumping was discontinued to repair the pump, to repair a leaky pipe, and to perform other required maintenance operations. Rest times are seen on Figure 14 as times of decreasing water level elevations.

Effect of Wet and Dry Cycles

Periods of increased infiltration rate following rests from pumping were caused by drying and cracking of the basin floor in the areas where the water had receded. However, despite discontinued pumping and temporary renovation of the basin floor during dry periods, a single overall decay curve (Figure 12, equation 9) could still be used to represent the overall clogging process of the basin floor. This is similar to the results reported by Schuh and Shaver (1988) for the artificial recharge basin at Oakes, ND. The return to the characteristic decay curve is caused by resettling of sediment on the basin floor. Despite the drying and cracking of the basin surface during periods of rest, the total amount of sediment in the basin, and in the filter cake which is a primary determinant of clogging, does not change. While desiccation fractures in the sealing layer temporarily increase infiltration, once the layer rewets, sediment gradually resettles and reseals the floor. The basin floor then returns to a condition similar to that before drying.

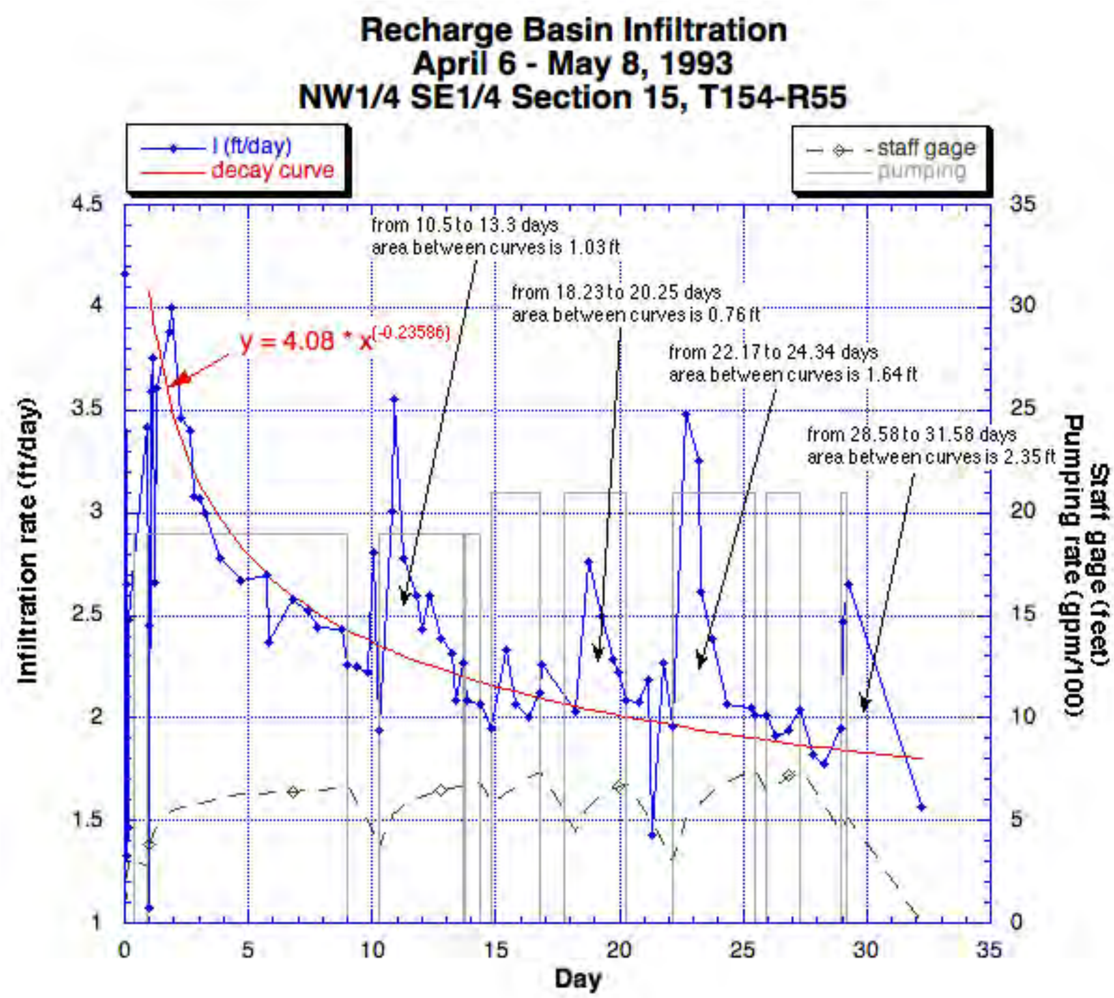


Figure 12. Infiltration during the spring 1993 pilot operation on ARR Basin 1 (the triangular south basin).

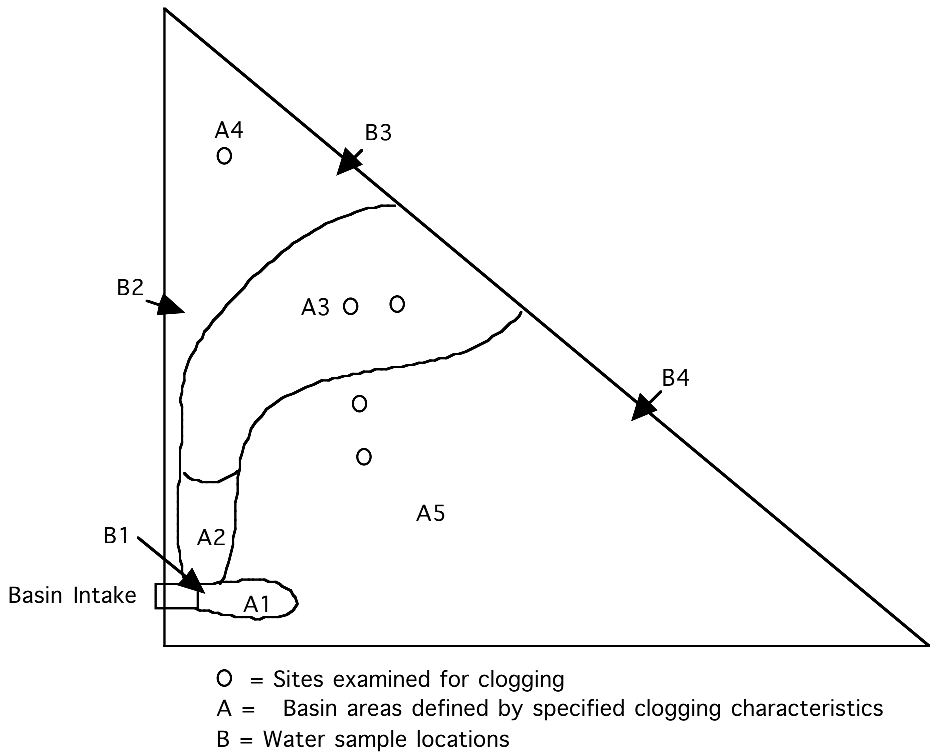
We wished to know whether short-term increases in infiltration caused by drying increased overall recharge. The cumulative additional infiltration per acre over that expected without drying of the basin is represented by the area between the power curve and the infiltration curve on Figure 12. The sum total of increased infiltration per acre of basin is 5.78 feet. If an average of about 2.5 acres of basin floor remained in operation during the drying and rewetting cycles, then the portion of total recharge attributable to the temporary renovation of the floor due to drying was 14.45 acre-feet, or about 8 % of the total recharge measured. While drying the basin increased recharge per unit of active surface area, the delay in water delivery caused a corresponding decrease in active recharge surface area. By applying equation 9 for a full 32-day operational period, an estimated 224 acre-feet would have been recharged for a full three acres of operating basin. This is about 44 acre-feet more than the total recharge with dry cycling. Of course during the first few days the basin was not full, but the basin was recharging at its full intake rate of 8.4 acre-feet per day as it expanded due to the clean basin floor.

From these data it would not seem beneficial to allow the basin to dry and crack as long as the basin can recharge at the full rate of water delivered by the pump. If the delivery rate exceeds basin recharge capacity, such that reducing the pumping rate is needed, it would then seem likely that longer drying cycles, rather than more frequent short cycles would be desirable to optimize recharge. For example, if the basin infiltration rate decreases by 30% (to about 6 acre-feet per day), it would be more beneficial (on a ten-day operational cycle) to allow the basin to dry for three days, followed by seven days of refilling and operation, than to operate the basin for 17 hours following a seven-hour hiatus seven times with no substantial drying. This would allow for a longer period of full operation with additional recharge, and it would also allow for greater convenience of operation with a substantial block of rest time for both equipment and personnel.

Basin Floor Condition After Spring Operation

Rates of infiltration are determined by the condition of the basin floor. After the Spring 1993 test operation the condition of the pilot-basin floor varied. These varying conditions are shown by area on Figure 13 as: (A1) nearest the inlet pipe there was a heavily scoured sandy area; (A2) in the primary flow path toward the deep center of the basin, there was a thin filter cake, but the floor was scoured and sandy; (A3) in the center of the basin, the deepest and first-flooded area, there was a thick and well-defined filter cake on the surface; (A4) in the eastern corner of the basin; and (A5) in the south corner of the basin the surface was smooth, and was characterized by a cemented surface rather than by a well-defined separate filter cake.

A



B

Figure 13. Schematic diagram (A) and photograph (B) of basin floor conditions after the spring 1993 pilot operation. Clogging characteristics for (A) are described in the text.

In basin section A1 (Figure 13A), located in the immediate flow path from the inlet pipe, there was a one-inch sandy crust overlying a darkened sandy soil that looked like topsoil to a depth of about 18 inches. Below the 18 inch level was clean sand. In section A2, there was a thin filter cake of about 0.07-inch thickness, with a range of about 0.03 inch to 0.12 inches. Underlying this was about 8 inches of medium sand, which overlay a dark fine sand to about 18 inches. The clean sand appears to have been deposited later in operation, after an initial period of infiltration. In section A3, the deep portion of the basin, there was a filter cake with an average thickness of about 0.29 inches, with thickness varying from 0.18 to 0.48 inches. Underlying the clay filter cake was a horizon of dark sandy soil to a depth of 12 inches. Beneath the top 12-inch layer were gravel and stones, intermixed with some clayey aggregates. Sections A4 and A5 had a thick crust rather than a filter cake. The cemented crust was about one-inch thick. Under the crust there was about seven inches of black soil in some cases, but usually there was no black soil at all. Below the seven-inch black soil, or in some cases immediately below the crust there was clean sand. There were large cracks to as deep as five inches in the cemented areas, and the internal portions of the cracks were lined with crust. Observation of the basin during operation indicated that the cracks were frequently present under water during operation. Their cause was uncertain.

Table 2. Dissolved Oxygen (DO) values, and Saturation Indices for calcite, dolomite, and Fe(OH)3 calculated using WATEQF (Plummer and others 1976) for the Forest River and for basin water samples (B1 through B4), measured in May of 1993.

Dissolved Oxygen Sample Location	Calcite Log (IAP/KT)	Dolomite Log (IAP/KT)	Fe(OH)3 Log (IAP/KT)	Dissolved Oxygen mg/L	pH
154-055-10D (Forest River)	1.09	1.87	0.913	8.2	8.63
154-055-15DBB (B1)	1.24	2.43	1.74	8.2	8.7
154-055-15DBB (B2)	1.25	2.55	1.69	8.8	8.65
154-055-15DBB (B3)	1.25	2.55	1.69	8.7	8.68
154-055-15DBB (B4)	1.24	2.47	1.63	12.2	

The filter cake was caused by silt and clay deposition. The cementation was likely caused by calcium carbonate precipitation on the floor of the basin. Previous tests at Oakes, North Dakota have indicated that cementation of similar appearance was caused by calcite precipitation (Schuh, 1990). Mineral species saturation indices for water samples collected at four positions on the basin (designated A1 through A4 on Figure 15) were calculated using WATEQF (Truesdale and others, 1974; Plummer and others, 1976). Results indicated that water in the basin was oversaturated with respect to calcite at all sampled positions.

Implications of Clogging Profiles for Long-Term Basin Operation

In general, larger amounts of suspended solids cause earlier formation of a filter cake on the basin surface. While later delayed filter-cake deposition allows for more rapid recharge, it also facilitates deeper deposition of clay within the basin floor. The slower clogging rate on the Forest River basin floor, compared with previous tests at Oakes on the James River (Schuh and Shaver, 1988), may indicate that some sediment is moving deeper in the soil profile. There is some darkening of the basin floor profile to depths of 18 inches. However, the cause of the dark coloration is unclear. Possible causes are manganese reduction and clay deposition. Hand texturing did not give clear indication of the presence of clay. Also the deeper coloration was spatially discontinuous and did not occur at all positions on the basin floor.

One problem in the initial basin tests was that the corrugations from subsoiling the basin were left in place. These likely enhanced the recharge capabilities of the basin by increasing surface area and a tendency of sediment to move into the troughs of the corrugations. However, they made later cleaning more difficult. Because most clogging occurs in a thin surface filter cake (a fraction of an inch), or in a surficial crust (usually less than an inch thick), most ARR basins can be easily renovated by simply removing the top inch of the basin. This cleaning operation requires little earth moving, and minimizes the progressive deepening of the basin. When the surface is corrugated, deep removal of soil (up to 1 foot) is necessary. It was recommended that in future operations corrugations from tillage or subsoiling be leveled with a harrow or drag to enable shallow and more cost-effective cleaning. The level floor would likely conduct less recharge water. But the expense of deep excavation and the problem of excessively deepening the basin was of greater concern.

A

B

Figure 14. Surface sediment filter cake: (A) immediately after operation of the rectantular (2nd) basin, and (B) after desiccation of the basin floor.

A GENERAL RELATIONSHIP BETWEEN BASIN INFILTRATION CAPACITY AND SUSPENDED SOLIDS

The rate of basin clogging, and the subsequent decrease in infiltration rate, is strongly related to the amount of suspended solids in the water entering the basin. This is the source of the filter-cake which forms on the surface, and which decreases basin floor permeability. While other clogging factors, such as carbonate cementation, algae deposition, and bacterial clogging, are usually delayed because of the need for biological adjustment, filter-cake formation begins immediately and has a substantial impact on the early and highly productive period of basin operation. The wet (A) and dried (B) sediments formed in the second (rectangular) basin, constructed in 1994, are shown on Figure 14.

The infiltration rate curve for preliminary design (equation 1) and for describing the pilot basin test (equation 8) are both of the form of equation 3, where K is the initial infiltration rate, and b is an exponent quantifying the rate of decay. Because ‘b’ is quantifying the effects of clogging, it is physically related to the amount of suspended solids entering the basin in the influent water. A generalized relationship between suspended solids (SS) and would be useful for initial designs of future ARR facilities.

Two sets of water samples were collected at the basin intake in 1993 for measurement of suspended solids (labeled SS). The first set, collected on April 13, averaged 27.5 mg/L. The second set, collected on May 5, averaged 8 mg/L. From these, an average of 17.75 mg/L is used to estimate the overall suspended solids input to the basin. Measurements of SS were similar in 1994, with 37 mg/L measured in April, and 7 mg/L measured from samples collected on May 5. Using equation 8, the infiltration-rate decay exponent measured for the Forest River basin in 1993 (b= -0.24) was lower than the exponent (b = -0.59) used for initial basin design which was based on the performance of the Oakes test basin (Schuh and Shaver, 1988). The suspended solids in the Oakes basin water were higher than those of the Forest River, averaging about 50 mg/L. Despite differences in coarseness of the sandy basin floors (overall the Oakes basin was coarser), the ratios of exponent (b) to suspended solids for both basins were similar (Oakes b/SS = 0.0118, Forest River b/SS = 0.0135). Thus, an average b/SS of 0.0127 or,

$$b = \frac{SS}{79} \qquad (10)$$

can be used as a rough approximation of expected infiltration decay rate exponents for sandy soils during application of turbid water in North Dakota.

Use of an infiltration function of the form used in equation 8 also requires an initial matching or scaling coefficient (k). While k is related to the initial permeability of the clean basin sediments, the scaling coefficient for a power function during clogging cannot be a true initial infiltration rate because of time dependence and the properties of logarithms. In using a power function, the initial value is the y intercept (x = 0) of a linear log/log function, which means that log(x) must equal 0, or in this case the log of time must equal 0. In all cases 0 = log 1. The use of a value of one is, in turn, dependent on the unit of time measurement, and represents the completion of a single unit of time measurement past the initiation of the basin test. Thus, if hours are used, the K coefficient is the infiltration rate of the basin floor after one hour of operation. If day units are used the K coefficient is the infiltration rate of the basin floor after one full day of operation. Under conditions where clogging is occurring, the time units themselves must have a considerable effect on the value of K used.

Normally, the data or information used to match initial infiltration curves for design purposes consists of laboratory or field measured hydraulic conductivities (K) or infiltration rates (which under conditions of unit field gradient should be identical). Laboratory or field measured saturated K can be related to time dependent k as:

$$k = \frac{K}{t^{-b}} \qquad (11)$$

In Situ K measurements, and initial measured infiltration rates for the Oakes basin averaged about 40 ft./d. From the exponent of -0.59, and from the fitted day-unit k coefficient of 10.23 (equation 1), a t_o value of 0.1 days, or 2.4 hours is calculated using equation 11. If equation 11 is then applied to the Forest River data using the same (0.1 d) t_o value, and applying k = 4.08 and b=-0.24, then K = 7.09 ft./d. This compares with an initial infiltration rate of about 6 ft./d for the basin floor measured during the fall 1992 test with low suspended solids in the water, and an overall geometric mean of about 14 ft./d (with large margin of error) measured for the laboratory cores. Thus, the 0.1 d time for t_o seems to be a good estimate for establishing a power function from initial K data for a basin floor. The practical identity of field K for clean soil and an initial time of about 2.4 hours is strictly empirical. Why the approximation seems to work is not clear. However, after two and a half hours the amount of clogging is not large in most cases, and it is also necessary that enough of the basin floor be flooded to provide an adequate representative sample area for the basin floor.

In summary, a general estimate of the cumulative recharge (I) for t days of operation can then be calculated from measured or estimated suspended solids in the influent water and an initial field or laboratory K measurement as:

$$I = \frac{Kt^{-b+1}}{0.1^{-b}(-b+1)} \tag{12}$$

or, using suspended solids:

$$I = \frac{Kt^{1-0.013SS}}{0.1^{-0.013SS}(1-0.013SS)} \tag{13}$$

REDISTRIBUTION OF FOREST RIVER ARR WATER IN THE INKSTER AQUIFER

Effective recharge requires that influent waters be placed for effective pumping and use, so that expanded use does not infringe on prior appropriators. Requirements for effective recovery are: (1) Water must be placed in an aquifer unit where it can be effectively recovered for the desired use. Recharged water must not be placed, or eventually move to locations where it cannot be pumped for the intended use. (2) The water must not be lost to external non-use sinks such as springs or evaporation. The greatest concern for the FRC facility is loss to seeps or springs along the Forest River. The effectiveness of placement and storage of recharge water will be considered as indicated by an initial assessment of storage during pilot operations of the basin; a long-term evaluation of losses through Inkster Spring and associated springs along the Forest River; and an evaluation of long-term retained storage of water near the basin. This section examines the short-term (measured) redistribution of basin water. The capability of the Inkster aquifer to sustain long-term storage of ARR water for beneficial use is examined in another report (SWC-WRI No. 48, Schuh and Patch, 2009).

Monitoring Well Network

To evaluate the effectiveness of artificial recharge, monitoring wells were placed in all directions from the pilot recharge basin, and water levels were measured during and following basin operation. Monitoring well locations are shown on Figure 6. Wells designated ‘B’ are those constructed specifically for basin monitoring. Wells designated ‘T’ are dedicated for pesticide sampling and were not used for water level monitoring. Wells designated SWC or USGS are those placed previously by the State Water Commission or the U.S. Geological Survey for piezometric monitoring, and used in our tests to monitor aquifer response to recharge. Wells designated ‘IR’ are irrigation wells. All monitoring wells were measured before the initiation of the basin test, twice a day during the early operation of the basin, and semi-weekly and eventually weekly after the completion of the basin test.

Aquifer Retention and Distribution of Water: Fall 1992 Basin Operation

During the fall of 1992, the recharge basin was operated for 24 hours at a delivery rate of 1,100 gpm. Ground-water levels were monitored for approximately 3,700 hours following the initiation of basin operation. Results (Figure 15) indicated a preferential flow in the eastward direction, a significant component of flow in the southeastward direction, and apparent insignificant flow in the southern and westward directions. Particularly perplexing was the complete absence of response in wells located right next to the basin on the northwest (B1) and southwest (B12) corners.

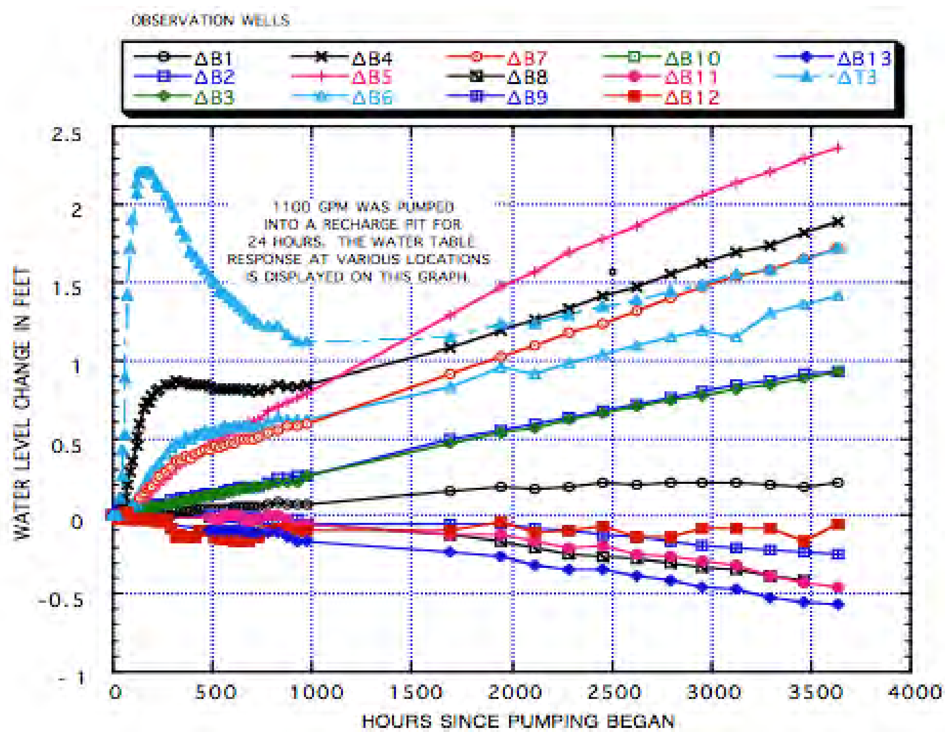


Figure 15. Changes in water levels in monitoring wells following the 24-hour pilot test on the south (triangular) basin in the fall of 1992.

From the fall 1992 basin operation it appeared that there was a strong eastward flow component, and a significant southeastward flow component based on the propagation of the 24-hour recharge pulse. The path of flow moving eastward was complex and possibly tortuous, and there were limitations to flow in the westward directions. It also appeared that no water from the limited pulse reached Inkster Spring in four months.

During the winter following the 24-hour test, there were no changes in piezometers at distance from the basin, including those near Inkster Spring. Delayed stronger hydrographic response on wells farther east of the basin (B5) which exceeded response at a closer well (B4) in line with the basin indicated that the flow path was likely tortuous and indirect.

It was hypothesized that the underlying aquifer consisted of interconnected channels of coarse sediment divided by till ridges that extend in places above the saturated zone. This hypothesis is consistent with aquifer characteristics discussed previously in the section titled **Pilot Site Evaluations: Permeability and Saturated Thickness**. When the ground-water mound rises in response to recharge, water redistributing outward follows the paths that are governed by: (1) overflow or breaching of the till ridges by rising water, and (2) indirect flow through a series of interconnected braids which provide conduits through the till barriers at varying distances from the position of recharge. It was further hypothesized that larger mounding resulting from longer operation might provide sufficient depth of water to breach barriers and cause flow in other directions, such as westward or northward.

Aquifer Retention and Distribution of Water: Spring 1993 Basin Operation

The pilot artificial recharge basin was operated for 32 days, beginning April 6, 1993. Pumping was terminated on May 5, 1993. The pumping rate was approximately 1,900 gpm. A total of 179.7 acre-feet was recharged, for an overall average recharge of 2.14 ft./d, and an average of 6.42 acre-feet per day of total recharge. The overall average pumping rate, including times of hiatus, was 1,357 gpm.

Water levels in monitoring wells following the spring basin operation are shown on Figure 16. Unlike the fall 1992 test, the monitoring well on the northwest corner of the basin (B1) responded quickly with a large mound that elevated 25 feet after about 200 hours of operation. The deep sample well immediately southeast of the basin (T3) responded quickly, forming a 20-foot mound after about 500 hours of operation. The nearest monitoring well east of the basin (B4) also responded quickly, but unlike the previous fall test, the later responding B5 well, which was placed farther east, did not exceed the water level in the closer well in final mound height. Wells in the southeast direction (B2 and B3) responded in linear order with distance but mound heights were not large, and did not rise more than two-to-three feet. This may have been due to increased transmissivity in the deeper and coarser sediment channel southeast of the basin (Figures 6 and 7). The nearest well south of the basin (B12) again failed to respond for the duration of the test. The well far north of the basin (B11) and the well near Inkster Spring (SWC6) did not respond significantly during the 16-week period from the initiation of the basin operation. The spring 1993 water-level response in some monitoring wells near the basin, that had previously failed to respond in the fall of 1992 under much smaller recharge stress, indicates that an irregular aquifer bottom causes tortuous redistribution of water at low influx rates. However, once mound elevation exceeds the height of the till divides, waters redistribute freely.

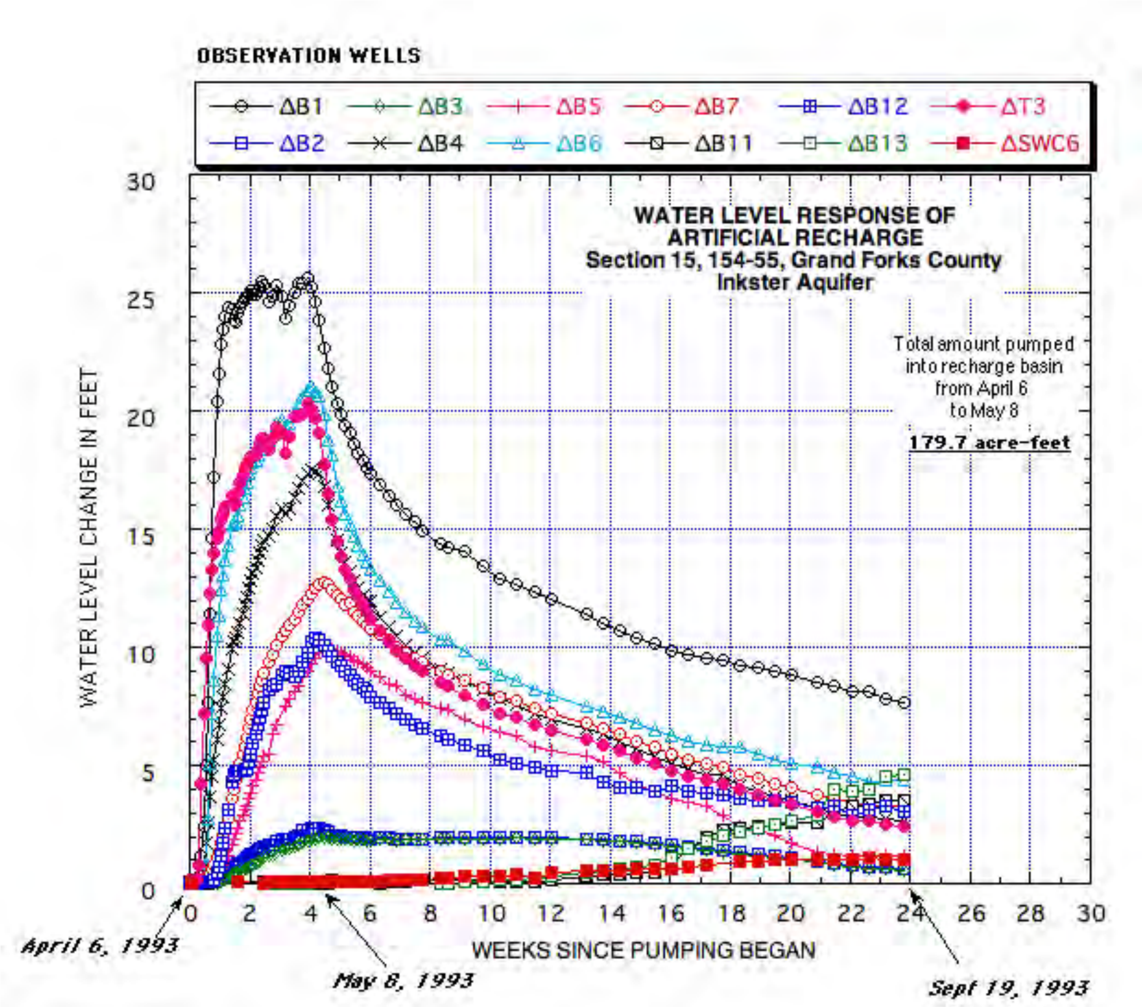


Figure 16. Changes in water levels in monitoring wells following the 24-hour pilot test on the south (triangular) basin in the spring of 1993. Basin operation was initiated on April 6, and terminated on May 8.

FULL ARR FACILITY OPERATION

After completion of the pilot operations on Basin 1 in 1992 and 1993, a second 800 x 200 ft. basin (labeled Basin 2) was constructed directly north of Basin 1. Two irrigation wells, labeled #4561 and #4980 were constructed nearby in the east and northeast direction from the two basins, to best enable recovery of the mounded waters and to optimize recovery and prevent loss through springs discharging to the Forest River. The two basins, and the two dedicated recovery wells are shown on Figure 17.

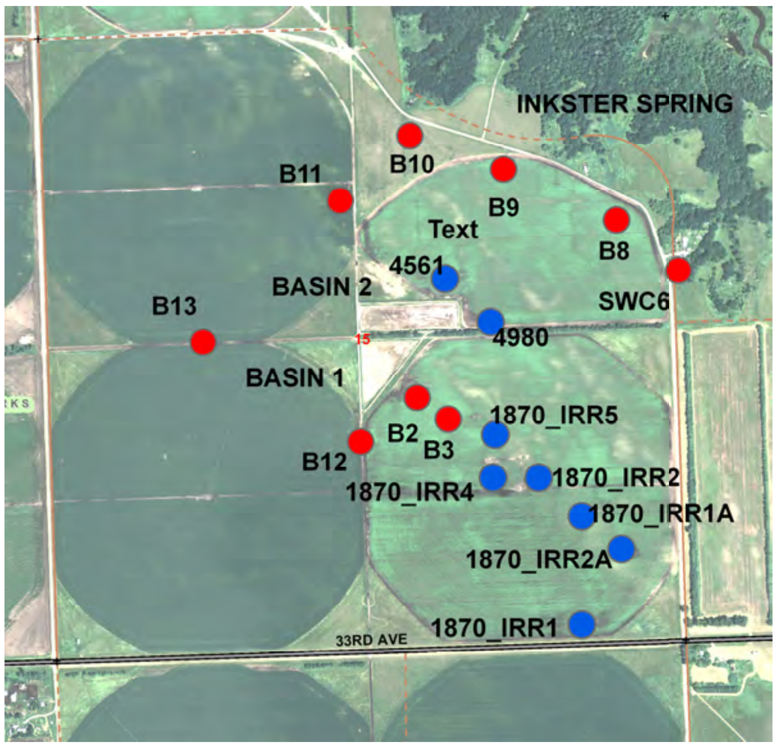


Figure 17. Location of the Forest-River Community ARR basin(s) in the center of 154-055-15, with irrigation wells (blue) and monitoring wells (red).

Basin Operational Requirements

The ARR basins have been operated annually since 1993. Conditions for Water Permits #4561 and #4980 required that the Forest River Community submit a recharge plan each spring. For each year since 1993 the SWC has provided an operational plan, including: (1) a computation of water available from the previous year for pumping; (2) an estimate of total water available after the year's recharge; (3) a ground-water monitoring plan, which is conducted by the Community; and (4) water quality sampling requirements for the year. Initially, the SWC deducted 20% of the water pumped immediately for estimated spring and evaporation loss, and an additional 20% of residual unrecovered waters for each year to account for further losses over the winter. After 1998 the formula was changed to 5% immediate deduction, with 20% loss of available waters left in the aquifer at the end of each irrigation season, up to a maximum of 300 acre-feet (acre-feet). All waters above 300 acre-feet were considered as loss after 1998. Estimated loss adjustments were based on guesswork. The adequacy of the estimated natural losses will be examined using a transient-flow hydrologic model in another report (SWC-WRI No. 48, Schuh and Patch, 2009).

Annual Recharge and Recovery

The result of 16 years of pumping was 10,021 acre-feet recharged, of which 7,944 acre-feet/year, or about 80%, was recovered for irrigation use (Table 3). The maximum recharge was 1,085 acre-feet/year, and the minimum was 180 acre-feet/year. The mean (discounting 1992) was 642 acre-feet/year. The maximum withdrawal was 1,021 acre-feet/year, and the minimum was 80 acre-feet/year. Mean withdrawal was 530 acre-feet/year.

Table 3. Reported recharge and recovery for the FRC facility.

Year	Recharge Acre-feet	Recovered Acre-feet	Year	Recharge Acre-feet	Recovered Acre-feet
1992	6	0	2000	708	813
1993	180	90	2001	770	901
1994	315	80	2002	1085	519
1995	410	182	2003	739	734
1996	514	288	2004	825	728
1997	451	233	2005	1029	669
1998	389	609	2006	815	1021
1999	788	318	2007	997	759

Points of Diversion From the Forest River

Points of diversion from the Forest River are shown on Figure 18. From 1993 through 1998, water was pumped from the "original" point of diversion using a diesel pump at an average rate of about 1,850 gpm. Water was impounded using a low-head porous dam constructed of rocks, and a deep pool was excavated behind the dam for placement of a screened intake. In 1999 the "final" point of diversion was constructed, and both sites were pumped. The "final" point of diversion was pumped using two electric pumps (100 hp and 200 hp), having pumping capacities of 1,300 and 2,900 gpm. During 1999, 188 acre-feet were pumped from each site. After 1999 only the final point of diversion was used. In 2002 the maximum combined pumping capacity was upgraded to 3,700 gpm. The SWC required an inline flowmeter for measurement of recharge water. Discharge to the basin was monitored at least daily, and frequently more often. An annual report of recharge water and recovered waters was required.

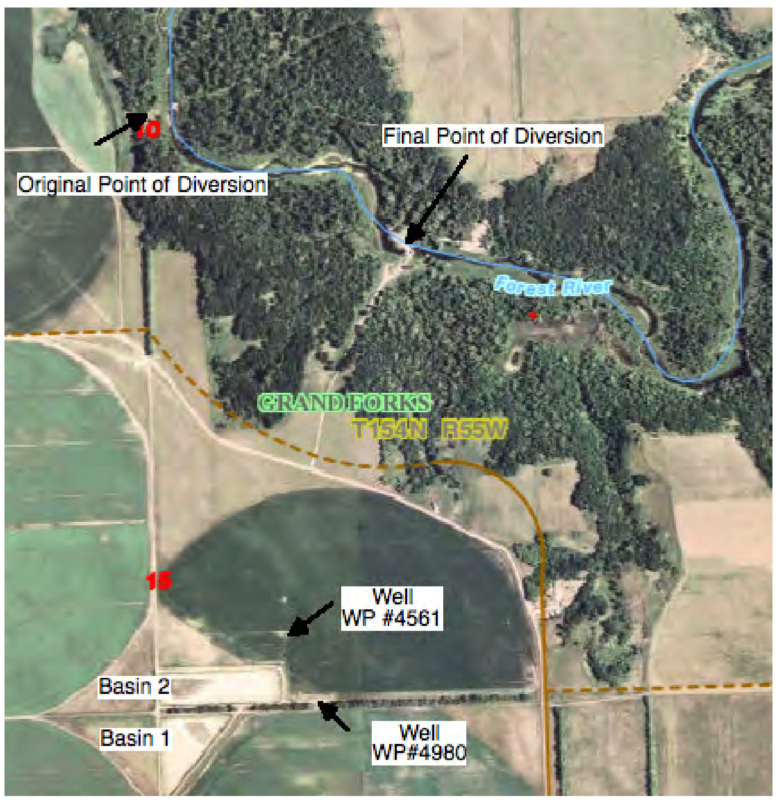


Figure 18. Location of ARR points of diversion on the Forest River.

Basin Cleaning and Maintenance

Each year the filter cake caused by deposition of suspended sediment must be cleaned from the basin floor to renovate it for further use. The Forest River Community has elected to use no surface infiltration enhancement measures, such as organic mats, and to maintain a smooth infiltration surface. The advantage of this renovation plan is that sediment movement is confined to the near-surface layer, and only an inch of surface need be removed annually.

Renovation is conducted as follows: A John Deere 770™ grader is used to "peel" the top inch from the basin floor. Operators grade from the "right" edge to the center, and then from the "left" edge to the center, leaving a pile of sediment in the center. The pile is then removed using a John Deere JP 868™ self-loading scraper. The result is a clean smooth floor that, after a year of weathering, provides an even surface for renewed operation. The residues have been placed against the outer berm of the basin to thicken it. Photos of basin cleaning operations are provided in Appendix B.

The Community has been able to operate in this manner for 17 years without having to replace the materials. Eventually the bottom will have to be rebuilt. Replacement will require excavating enough sand from a neighboring location to replace about two feet of the basin floor. Excavated areas may then be reclaimed using the cumulative sediments removed from the basement floor.

Weed Control

It was recommended that weeds be controlled and prevented from going to seed in the basin. Weed seeds are deposited by wind, by local weed infestations, and from deposits in recharge sediment; but most can be removed before or soon after germination by timely removal of the filter-cake layer. If cleaning is delayed, then precision of shallow cleaning can be impeded by the roots of the established weeds. Also, if other weed control measures, such as harrowing or undercutting, are implemented before cleaning the basin, surface sediment deposits are mixed in with subsoil sands and reduce basin permeability. Finally, if weeds are allowed to go to seed they will increase in the basin with each year. Thus, the proper order of maintenance should be: (1) early cleaning of the basin floor, followed by (2) periodic harrowing or undercutting to prevent weeds from going to seed. However, it is important that no chemical applications be made at any time for weed or pest control in or near the basin. This is essential to ensure that pesticide contamination of the aquifer does not occur. Introduction of contaminants to the aquifer will jeopardize the usability of the water, and will threaten the legality of continuing recharge.

EFFECTS OF ARR ON AQUIFER WATER QUALITY

Possible adverse changes in water quality of the Inkster aquifer from addition of artificial recharge water are a concern. Potential adverse impacts include addition of agricultural chemicals from runoff, such as pesticides, nitrate, excessive sulfate, and other inorganic chemical species. Protection of the aquifer is particularly important with respect to Agassiz Water Users District wells, located about one mile southeast of the basin, at 154-55-23.

Water samples were collected from the Forest River near the intake for the basin, from the basin itself, and from 21 wells in the vicinity of the basin. Dissolved oxygen (DO) was measured at several basin positions using an in situ DO meter (Figure 19B). Water samples were collected from the basin using a polytetrafluoroethylene (PTFE) dipper. Inorganic chemical analyses for river and basin water samples are summarized in Appendix Table A-1. Inorganic chemical analyses for samples from wells are in Appendix Table A-2. Organic analyses for river and basin water samples, and for samples from a sampling well near the basin (T2) are in Table 4.

A sample well network was designed to monitor water quality changes using existing observation wells, irrigation wells near the basin, and an additional set of thirteen wells designed and constructed specifically for measuring water levels and taking water samples near the basin. Well locations are shown on Figure 6. All wells were sampled using a PVC bailer.

Four sets of wells were used for collecting water samples:

(1) Two observations wells had been used for measuring water levels prior to construction of the basin (Figure 19A). Dissolved oxygen was measured at several basin positions using an in situ meter (Figure 19B). The first is located at 154-055-15CBB (also labeled SWC6), near Inkster Spring (Figure 6). The second is located at 154-055-15DBBD, about a half-mile from the basin and between the basin and the Agassiz Water Users District wells. These were constructed of 2-inch polyvinyl chloride (PVC) bonded using methyl-ethyl ketone solvent-weld glue. Well screens were near the bottom of the aquifer. These wells were used for measuring water levels and for collecting water samples used to evaluate general water chemistry.

(2) Irrigation wells (labeled with the prefix 'IR', Figure 6) were used for irrigation pumpage, and were constructed and used prior to operation of the basin. IR wells were used for some general chemistry assessments, and also for measurement of some water levels.

(3) Twelve wells were constructed specifically for monitoring the effects of basin recharge. These wells (labeled with the prefix 'B', Figure 6) were used for monitoring water levels, and for taking water samples used in assessment of inorganic water

chemistry. Basin monitoring wells were constructed of PVC fastened with solvent-weld glue, and had screened intervals placed just above the aquitard.

(4) One nest of three wells (labeled with the prefix 'T' in Table A-1 and on Figure 6) was adjacent to, and southeast of, the Pilot Basin (Basin 1). These wells were constructed of 2-inch PVC casing, fastened with stainless steel screws. Well screens were placed with bottoms immediately above the aquitard, six feet below land surface, and midway between the aquitard and the six-foot depth. All T-wells were covered by a removable 4-inch PVC protective casing. The T-wells were used only for sampling organic chemicals, and after initial basin tests were dedicated for sampling purposes only. Water samples were collected from the well having the screened interval nearest the surface of the ground-water mound. Usually well T2 was sampled during basin operation.

Water samples were collected using "clean-clean" procedure. The 4-inch PVC protective cover was removed, a polyethylene sheet apron was placed over the sampling site to hold down dust, and the 2-inch PVC well-stem was washed using low-phosphate soap. The cap was then removed, and the threaded portion of the inside of the top of the casing was wiped with a clean wet rag. The bailer from the previous sampling (left in the well) was used to bail five well volumes of water from the well. A new, disposable polyethylene bailer was then used (with a new 1/8-inch nylon rope) to sample water in the well. Water samples were placed in three amber 1-liter bottles. All contact with the bailer was limited to the "clean" worker, who wore clean vinyl gloves. The clean worker was assisted by a "utility" worker, who performed all tasks requiring contact with the surrounding environment. Water samples were placed on ice, and were sent to Minnesota Valley Testing Laboratory (New Ulm, MN) in chilled coolers for receipt within 24 hours. Results of analysis for water samples collected from well T2 are in Tables A-1 (river and basin chemistry), A-2 (monitoring well chemistry), and Table 4 (organic analysis).

A

B

Figure 19. Collecting a water sample near the basin inlet (A) for water chemistry measurements; and (B) measuring dissolved oxygen in Basin 1, using an in situ DO meter.

Nitrate Concentrations

Large concentrations of nitrate can be toxic. Toxic effects include methemoglobinemia (blue-bay syndrome) for infants, and possible carcinogenic effects at large concentrations. The EPA Maximum Contaminant Level (EPA-MCL) for nitrate is 44 mg/L (10 mg/L as N). Nitrate concentrations are of particular concern at the Agassiz Water Users District well field, about a mile and a half southeast of the basin. **All nitrate concentrations are reported as NO_3 unless specified otherwise.**

There are two possible sources of increased nitrate in ground water near the Forest River Community ARR basin. Nitrate can originate in the river water added to the basin, or in the vadose zone overlying the aquifer. Under dryland farming practices and climatic conditions common to North Dakota, salts and surface-applied agricultural chemicals tend to accumulate just beneath the root zone (Schuh and others, 1993). During periods of large rainfall, recharge water moving through the zone of accumulation dissolves salts and moves them to the water table, temporarily increasing solute concentrations in the top of the saturated zone. Usually, solute concentrations quickly return to previous characteristic concentrations, unless recharge events are exceptionally large and prolonged. Thus, dissolution and transport of vadose solute under wet conditions can cause temporary increases in solute concentrations at the water table.

Direct influx of nitrate to the Inkster aquifer during infiltration of water from the Forest River should not exceed the nitrate concentrations of the source water. Nitrate concentrations from the Forest River, and in the basin are on Table A-1. Water samples were collected in 1993, 1994, and 1998. Nitrate concentrations from river samples collected in April were below 15 mg/L (less than 3 mg/L as N). Nitrate concentrations from river samples collected in May were below 2 mg/L (0.5 mg/L as N).

Water samples were collected from the basins in 1993, 1994, 1996, and 1998. In 1993 water samples were collected from Basin 1. In 1994, 1996 and 1998 water samples were collected from Basin 2. Water samples collected in April of 1993 and 1994 were replicated from different parts of the basin. Single water samples were collected from the basin intake in 1996 and 1998. Nitrate concentrations from two water samples collected in April of 1993 were similar to the river samples. In 1996 the nitrate concentration was 4.7 mg/L (1 mg/L as N). All other samples were found to have either non detects, or nitrate concentrations below 1 mg/L (0.23 mg/L as N).

None of the water samples collected from the river or the basins exceeded the EPA-MCL of 44 mg/L. In general, nitrate contamination in water samples collected earlier in the pumping season (April) were higher than those collected in May, which tended to be at or below 1 mg/L. Larger April nitrate concentrations in the Forest River were likely caused by runoff from farm fields. As might be expected, nitrate concentrations in river water and in the basin water were similar at corresponding sampling times. The median nitrate concentration from the river was 0.8 mg/L (0.2 mg/L as N). Direct influx of nitrate from the river would thus be unlikely to cause large increases in ground-water nitrate concentrations.

Nitrate concentrations were measured for a few water samples collected from irrigation and sampling wells before construction of the basin. The maximum pre-construction nitrate concentration was 1.4 mg/L, and most were about 1 mg/L or non detectable (Table A-1 and A-2). Water samples collected from observation wells at 154-055-14CBB near Inkster Spring, and at 154-055-14CCC (between the basin and Agassiz Water Users District wells) indicate that between 1985 and 1997 nitrate concentrations were less than 1 mg/L, and that no increasing trend was observed. There is no evidence of adverse impact from ARR on Inkster Spring or on the Agassiz Water Users District wells.

Water samples from monitoring wells near the basins showed temporary increases in nitrate. Generally, nitrate concentrations decreased with distance from the basin. For example, a water sample collected from Well T2, a well designated specifically for sampling at the water table immediately adjacent to Basin 1, had a nitrate concentration of 14 mg/L (3 mg/L as N) in mid-April 1993. Nitrate concentrations in Well B2, southeast of the basin, briefly increased to 30 mg/L (6.8 mg/L as N, more than the highest measured nitrate concentration in the river or basin water) in May of 1993, but then declined to less than 1 mg/L (0.226 mg/L as N). Nitrate concentrations in Well B3, near but more distant than B2 from Basin 1, did not increase. Nitrate concentrations in Well B4, at the east corner of Basin 1, increased from a non detectable level to 8.8 mg/L (2 mg/L as N) in April of 1993, but by May returned to less than 1 mg/L and did not increase again. Nitrate concentrations in Well B5, east of Basin 1, but more distant than B4, increased from non detection to 1.3 mg/L in April of 1993, but then declined and remained low.

Characteristic nitrate concentrations indicate likely flushing of vadose nitrate rather than direct influx from the river water. Evidence of this includes: (1) nitrate increases that are transitory, and quickly return to previous lower nitrate concentrations; (2) lesser increases in nitrate concentration with distance from the basin; and (3) temporary nitrate concentrations in ground-water measurements that are larger than river or basin nitrate concentrations. It would appear that as the ground-water mound from basin recharge rose and intercepted the previous vadose zone near the basin, it dissolved nitrates from beneath the root zone. These larger nitrate concentrations again decreased when the ground-water mound dissipated. It seems that nitrate flushed from the vadose zone in the first basin operation may have depleted local nitrate supplies in the vadose zone. No flushing of nitrate was observed after 1993.

Total Dissolved Solids (TDS) and Sulfate Concentrations

Total dissolved solids (TDS) and Sulfate concentrations are of concern, although less so than nitrate and pesticides. TDS and specific conductance are indicators of total salt content. Large TDS is undesirable for drinking water and for irrigation. TDS in the Inkster aquifer near the recharge basins varied from about 400 mg/L to a maximum of 2,200 mg/L. Most TDS concentrations were between 400 and 700 mg/L. Total dissolved solids concentrations in the Forest River were generally lower and less variable than ground water, with a mean and median near 540 mg/L, and a 95% confidence interval of the mean between 515 and 565 mg/L. River water added to the basin thus has low TDS, and should not adversely affect ground water with respect to salinity.

The chemical composition of the water is primarily of calcium and magnesium bicarbonate and sulfate. In the Forest River water bicarbonate and sulfate are of about equal concentration, while in the aquifer the ratio of bicarbonate to sulfate is somewhat more variable. While not highly toxic, sulfate is of secondary concern as a contaminant, and in large concentrations can cause some loosening of stool. The EPA has assigned sulfates a non-enforced secondary MCL of 250 mg/L. The sulfate concentration in the river and in the basin samples was consistent, with a measured minimum of 170 mg/L, a measured maximum of about 260 mg/L, a mean and median of about 210 mg/L (median is 212 mg/L), and a 95% confidence interval for the mean between 195 and 225 mg/L. Water added to the aquifer through recharge is thus not highly sulfatic.

Trends of sulfate concentrations from the Inkster aquifer during and following 1993 were variable. Sulfate concentrations decreased with time at sites B1, B3, B5, T2, IR and IR5 (Figure 6, Table A-2). They remained about the same at sites B1, B2 and B7; and increased at sites B4, IR2A, and at outlying observation wells 154-055-14CBB and 154-055-14CCC. In general, sulfates tended to decrease or change less nearest the basin, while largest changes were in the outlying wells. Both the distance from the basin, and some large concentrations (a temporary measurement of 1,400 mg/L at B7) indicate that increased sulfate concentrations were likely caused by flushing of sulfates from the vadose zone. The temporarily large increase of sulfate at B7 may have been caused by the rising of the basin ground-water mound into the vadose zone. Less dramatic and more gradual increases of sulfate in water samples from wells 154-055-14CBB and 154-055-14CCC were likely caused by flushing of vadose sulfates following wet conditions in 1993. These conditions also caused a natural rise in ground-water elevations. Addition of Forest River water through basin recharge water did not contribute significantly to increases of TDS and sulfate in ground water.

Other Inorganic Constituents

Calcium and magnesium concentrations in the aquifer increased and decreased proportionately with sulfate concentrations. Sodium did not vary. Other constituents, including boron, chloride, fluoride, iron, and magnesium did not change. pH varied somewhat during recharge. Effects of pH on infiltration were discussed previously in relation to water chemistry effects on basin-floor clogging.

Organic Agricultural Chemicals

Contamination of the Inkster aquifer with organic agricultural chemicals carried in river water was of concern. Surface waters in North Dakota sometimes carry trace organic residues in runoff from agricultural lands. In almost all cases chemicals detected are acid extractable and highly soluble. For example, South Washington Lake and Lake Coe in Eddy County have been shown to have a consistent trace level of picloram, which is used in the uplands surrounding the lake for leafy spurge control (Schuh, 1993). In previous work, monthly water samples taken from the Sheyenne River at Fort Ransom in the spring and summer of 1993 for assessment of pesticide load, indicated that the only detections were in the spring. All of these were highly soluble acid extractables such as 2,4-D, dicamba, MCPA, and picloram (Cline and others, 1993). None of these water samples have been above EPA-MCL.

Water samples were collected for assessment pesticide contamination from recharge in each year (1993-1998) except 1997. Four water samples were collected in 1993. Two were collected from the Forest River near the river intake (April 15 and May 5) and two were collected from the basin on the same dates. All samples after 1993 were collected from Well T2 (Figure 7). Results (Table 4) indicate no detections of organic chemicals in the river, the basin(s), or in the sample well adjacent to Basin 1 during the period of basin operation.

Because repeated samples were found to have no indications of organic contamination of ground water, the sampling frequency was decreased from annually to once in every five years.

Summary of Water Quality Impact

From the beginning of basin recharge in the spring of 1993 through spring of 1998, there has been no evidence of adverse impact of artificial recharge on ground-water quality through introduction of organic agricultural chemicals, nitrate, sulfate, or other inorganic chemical substances.

Table 4. Summary of pesticide detections in water samples collected from the Forest River and from a sample well near recharge Basin 1.

Pesticide (Common Name)	Forest River 4-15-93	Forest River 5-5-93	Well T2 4-15-93	Well T2 5-5-93	Well T2 5-5-94	Well T2 5-31-95	Well T2 5-23-96	Well T2 5-13-98
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Acetochlor	NS	NS	NS	NS	NS	NS	< 1	< 0.5
Alachlor	<0.5	<0.5	<0.5	<0.5	<0.5	<0.1	<0.5	<0.5
Atrazine	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 0.5
Butylate	<1	<1	<1	<1	<1	<1	<1	NS
Chlorpyrifos	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Cyanazine	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.2
Deethylatrazine	NS	NS	NS	NS	NS	NS	NS	< 0.5
Deisopropyl - atrazine	NS	NS	NS	NS	NS	NS	NS	<0.5
Di-Methoate	<0.5	<0.5	<0.5	<0.5	<0.5	NS	NS	NS
Diallate	<0.5	<0.5	<0.5	<0.5	NS	NS	NS	NS
EPTC	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 0.5
Ethalfluralin	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Ethyl Parathion	NS	NS	NS	NS	NS	NS	NS	NS
Fonofos	<0.5	<0.5	<0.5	<0.5	<0.5	<1	<1	<0.5
Linuron	<0.5	<0.5	<0.5	<0.5	<0.5	NS	NS	NS
Methyl Parathion	<0.5	<0.5	<0.5	<0.5	<0.5	<0.03	NS	
Metolachlor	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Metribuzine	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pendimethalin	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Phorate	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.3
Prometon	<1	<1	<1	<1	<1	<1	<1	<0.5
Propachlor	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	NS	NS	< 0.5
Propazine	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5
Simazine	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 0.5
Terbufos	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.2
Tri-Allate	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Trifluralin	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
2,4,5-T	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1
2,4,5-TP	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1
2,4-D	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	NS**	<0.5
2,4-DB	**0.95***	<0.5	<0.5	<0.5	<0.5	<1.6	<0.5	<0.5
Bentazon	NS	NS	NS	NS	NS	NS	NS	<0.5
bromoxynil	NS	NS	NS	NS	NS	<20	NS	NS
Chloramben	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	NS
Dicamba	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1
MCPA	NS	NS	NS	NS	NS	NS	NS	<3.0
Picloram	<0.1	<0.1	<0.1	<0.1	<0.1	<0.5	<0.1	<0.1
Triclopyr	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1

* Concentration not confirmed. Below ELCD-MDL

** Impurity in sample, blocked detections

COST ESTIMATES FOR CONSTRUCTION, OPERATION AND MAINTENANCE OF THE FOREST RIVER COMMUNITY ARR FACILITY

The purpose of this section is to provide a general estimate of the cost per acre foot of water that would be incurred by most parties in building and operating an ARR facility similar to the Hutterite facility in North Dakota. Some cost elements, including electrical costs and pump purchase and maintenance costs were based on estimates provided by the operators. The pump construction and maintenance costs were based on a 10-year replacement cycle. The Forest River Community, however, has some cost benefits inherent to its communal structure. For example, conveyance pipes were not purchased, but rather were excavated and removed from the decommissioned CENDAK irrigation pilot project in South Dakota using labor and equipment belonging to the Community. Similarly, annual basin cleaning costs were performed by FRC personnel, using equipment belonging to the Community. For this reason, more standardized construction and maintenance costs estimates were considered to be more useful for other parties considering a similar project.

Electrical costs for pumping are not now available for before 2002. NODAK electric cooperative provided an approximation of the rate schedules for 1991, 2001, and 2002 through 2009. Exact pumping costs and measured pumpage were available for 2002 through 2007. Not only rates, but methods for calculating rates changed during the pumping period. For example, before 2003 rates were calculated using a facility charge ($/mo.) and an energy charge ($/kwh). Beginning in 2003 a dual energy charge rate was employed, including a first charge rate up to 500 kwh, and a second for use above 500 kwh. For simplicity, a multiple regression of pumpage (acre-feet) vs. two variables: (1) the facility charge, and (2) the product of annual pumpage (acre-feet) times the first charge rate ($/kwh) was found to predict 96% of the variability of 2002 through 2007 costs. The resulting relationship is shown on Figure 20.

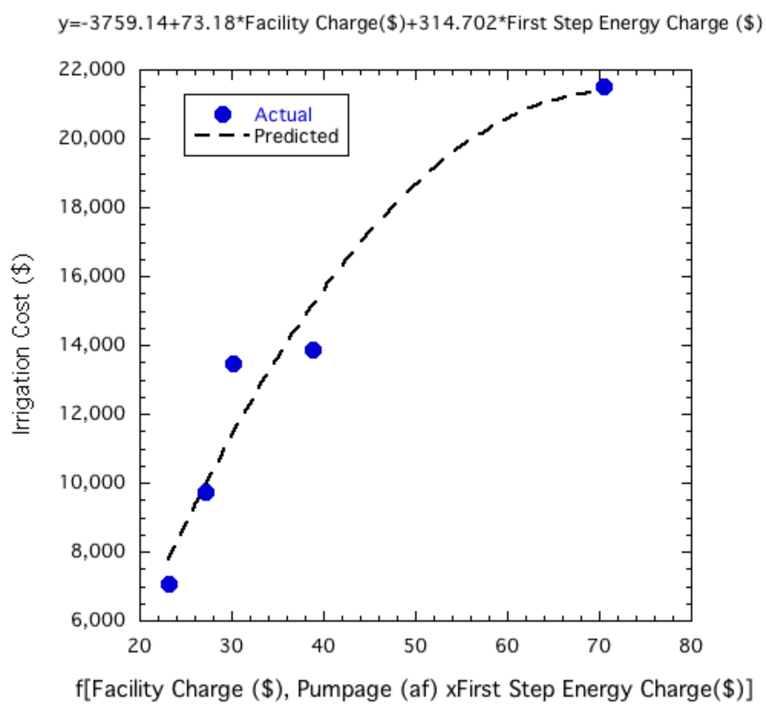


Figure 20. Electrical costs vs. actual and estimated electrical rates for pumping from the Forest River during 2002 through 2009.

The resulting estimated electrical costs ranged from $5.8 to $19.7/acre-foot over the operational period, with a steadily increasing rate. The overall median rate was $9.90 /acre-foot, and the mean was $11.20/acre-foot, with a 95% confidence interval of about $8.80 to $13.60/acre-foot. The regression estimate was applied to the 1993 through 2007 pumping period (Figure 21) to provide estimates of pumping costs before 2002. For the operating cost computations (Table 5) we used actual cost when available, and supplemented the pre-2002 period with estimated costs.

Construction cost estimates for 3,800 linear feet of pipeline using 16-inch PVC pipe placed at a depth of 4 feet, and for excavation of seven acres to two feet, using the spoil to form border dikes, were provided by Ron Swanson, a design engineer with the North Dakota State Water Commission, with price assistance from Northern Water Works Supply (Fargo, ND). These costs were annualized by amortizing over a 20-year period and a 30-year period. A longer period of operation, which is almost certain, would result in lower annual cost estimates.

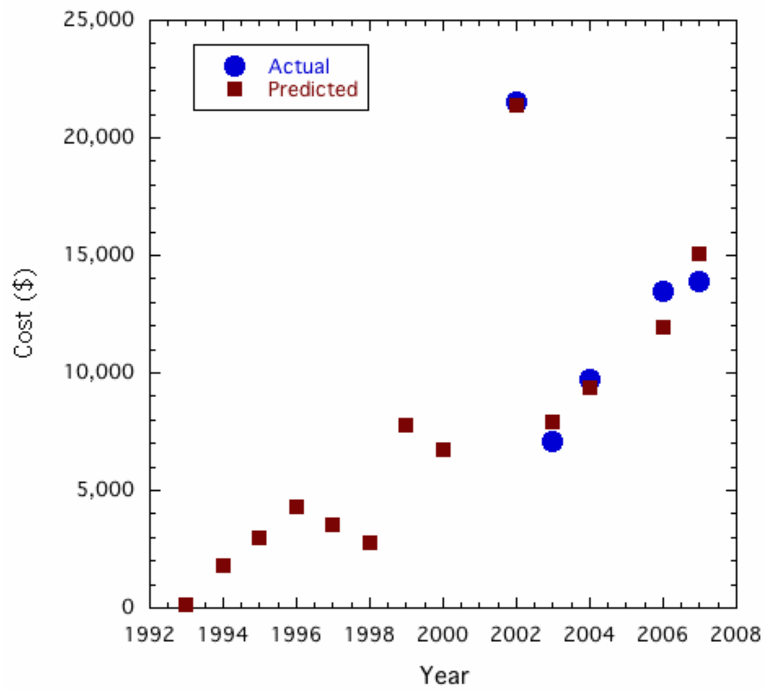


Figure 21. Actual (2002-2007) and estimated (1993-2007) annual electrical costs for pumping from the Forest River.

Cost estimates for annual basin maintenance (one-day grader, three-day scraper with mobilization) were provided by Weisz Contracting (Bismarck ND), based on 2009 rates. Cost estimates for pump purchase and maintenance were provided by the Forest River Community.

Cost estimates for initial water quality samples were based on two organic contaminant analyses ($500.00 each), five general chemistry and trace element analyses (*approx.* $200.00 each), and $500.00 collection cost for each sampling. The annual sampling costs were based on half of the initial sampling intensity, sampled once every five years.

Cost for monitoring wells is based on construction of eight 2-inch diameter polyvinyl chloride (PVC) wells screened from 30-35 feet, with $800 mobilization cost and drilling cost ($8/ft.). Monitoring and maintenance costs for the basin during operation are based on labor and benefits for 20 hours per week for two months.

Annualized costs were estimated by amortizing construction costs for 20- and 30-year payments at 4% and 8% interest, and adding the annualized payments to the annual operating costs (Table 6). Total annual costs were then estimated for each of the operational-year scenarios of the Forest River Community facility (Table 7). Table 8 provides estimated cost per acre-foot recharged to the aquifer, and Table 9 provides an estimate of the cost per acre-foot of "extractable" water. Extractable water is the amount that can be pumped and used by the Community after subtracting 20% for natural loss.

Table 5. Fixed cost for construction of the ARR basin and pipeline.

CATEGORY	SUBCATEGORY	ITEM	DESCRIPTION	COST
Construction Cost				
	Pipeline and Basin			
		Mobilization		$10,000.00
		Pipeline	3,800', 16" d PVC, buried 4' $30.00/ft. pipe x 2 for placement	$114,000.00
		Basin	Excavate 7 acres 2', spoil used for banks - 23,000 cy x $3.00/cy	$69,000.00
		Seeding and stabilization	8 acres x $750.00/acre	$6,000.00
	Pump Placement	Coffer Dam	3 days backhoe x $130.00/d 2 days dump truck x $80.00/day	$550.00
		Materials	Pipe and Screen + labor	$7,000.00
	Engineering			$20,000.00
	Monitoring Wells	Mobilization		$800.00
		Drilling	8 wells x 35' x $8.00/ft.	$2,240.00
Initial Water Quality Sampling			2 organic contaminant x $500.00 5 general and trace x $200.00 $500.00 sampling cost	$2,000.00
Electrical Hookup (1998 cost)			6,207 ft. Cable Type #3-3/O 220 mil XLP Jacketed	$28,708.00
Contingencies				$21,000.00
Subtotal (Construction)				$281,298.00

Table 6. Annualized fixed cost, and annual operating costs for the ARR facility operation.

CATEGORY	SUBCATEGORY	DESCRIPTION	Annualized Cost 20 year, 4%	Annualized Cost 20 year, 8%	Annualized Cost 30 year, 4%	Annualized Cost 30 year, 8%
Annual Cost						
	Annualized Construction Cost		$20,698.00	$28,650.00	$16,267.00	$24,987.00
	Annualized Pump Cos	Purchase and Maintain (10 y replacement)	$4,305.00	$4,305.00	$4,305.00	$4,305.00
	Cleaning Basin Floor					
		Mobilization	$1,200.00	$1,200.00	$1,200.00	$1,200.00
		Grader - one day $95.00/h	$760.00	$760.00	$760.00	$760.00
		Scraper (3 days) $140.00/h	$3,360.00	$3,360.00	$3,360.00	$3,360.00
	Cleaning Subtotal		$5,320.00	$5,320.00	$5,320.00	$5,320.00
	Operational Maintenance	3 mo. 20 h/wk. x $15/h	$3,600.00	$3,600.00	$3,600.00	$3,600.00
	Annual Pump Setup	Backhoe 1/2 day ($130.00/h)	$520.00	$520.00	$520.00	$520.00
Electrical Cost	Pumping Year	Acre-Feet Pumped	Cost	Cost	Cost	Cost
	1993	180	900.00	900.00	900.00	900.00
	1994	315	1,816.10	1,816.10	1,816.10	1,816.10
	1995	410	3,011.90	3,011.90	3,011.90	3,011.90
	1996	514	4,321.10	4,321.10	4,321.10	4,321.10
	1997	451	3,528.00	3,528.00	3,528.00	3,528.00
	1998	389	2,747.60	2,747.60	2,747.60	2,747.60
	1999	788	7,770.20	7,770.20	7,770.20	7,770.20
	2000	708	6,763.20	6,763.20	6,763.20	6,763.20
	2001	770	13,707.00	13,707.00	13,707.00	13,707.00
	2002	1085	21,502.00	21,502.00	21,502.00	21,502.00
	2003	739	7,089.00	7,089.00	7,089.00	7,089.00
	2004	825	9,733.00	9,733.00	9,733.00	9,733.00
	2006	815	13,458.00	13,458.00	13,458.00	13,458.00
	2007	997	13,875.00	13,875.00	13,875.00	13,875.00

Table 7. Total estimated recharge cost per year for water delivered to the aquifer from operation of the FRC ARR facility.

Year	Recharge (acre-feet)	Amortization 1 20 year, 4%	Amortization 2 20 year, 8%	Amortization 3 30 year, 4%	Amortization 4 30 year, 8%
1993	180	$40,663.00	$48,615.00	$36,232.00	$44,952.00
1994	315	$41,579.10	$49,531.10	$37,148.10	$45,868.10
1995	410	$42,774.90	$50,726.90	$38,343.90	$47,063.90
1996	514	$44,084.10	$52,036.10	$39,653.10	$48,373.10
1997	451	$43,291.00	$51,243.00	$38,860.00	$47,580.00
1998	389	$42,510.60	$50,462.60	$38,079.60	$46,799.60
1999	788	$47,533.20	$55,485.20	$43,102.20	$51,822.20
2000	708	$46,526.20	$54,478.20	$42,095.20	$50,815.20
2001	770	$53,470.00	$61,422.00	$49,039.00	$57,759.00
2002	1,085	$61,265.00	$69,217.00	$56,834.00	$65,554.00
2003	739	$46,852.00	$54,804.00	$42,421.00	$51,141.00
2004	825	$49,496.00	$57,448.00	$45,065.00	$53,785.00
2006	815	$53,221.00	$61,173.00	$48,790.00	$57,510.00
2007	997	$53,638.00	$61,590.00	$49,207.00	$57,927.00
Mean	642	$47,636.01	$55,588.01	$43,205.01	$51,925.01

Table 8. Total estimated recharge cost per year for one acre-foot of water delivered to the aquifer from operation of the FRC ARR facility.

Year	Recharge (acre-feet)	Amortization 1 20 year, 4%	Amortization 2 20 year, 8%	Amortization 3 30 year, 4%	Amortization 4 30 year, 8%
1993	180	$225.91	$270.08	$201.29	$249.73
1994	315	$132.00	$157.24	$117.93	$145.61
1995	410	$104.33	$123.72	$93.52	$114.79
1996	514	$85.77	$101.24	$77.15	$94.11
1997	451	$95.99	$113.62	$86.16	$105.50
1998	389	$109.28	$129.72	$97.89	$120.31
1999	788	$60.32	$70.41	$54.70	$65.76
2000	708	$65.71	$76.95	$59.46	$71.77
2001	770	$69.44	$79.77	$63.69	$75.01
2002	1,085	$56.47	$63.79	$52.38	$60.42
2003	739	$63.40	$74.16	$57.40	$69.20
2004	825	$60.00	$69.63	$54.62	$65.19
2006	815	$65.30	$75.06	$59.87	$70.56
2007	997	$53.80	$61.78	$49.36	$58.10
Mean	642	$89.12	$104.80	$80.39	$97.58

Table 9. Total estimated recharge cost per year for one acre-foot of water delivered to the aquifer from operation of the FRC ARR facility that is recoverable for use after a 20% deduction for loss.

Year	Recharge (acre-feet)	Amortization 1 20 year, 4%	Amortization 2 20 year, 8%	Amortization 3 30 year, 4%	Amortization 4 30 year, 8%
1993	180	$282.38	$337.60	$251.61	$312.17
1994	315	$165.00	$196.55	$147.41	$182.02
1995	410	$130.41	$154.66	$116.90	$143.49
1996	514	$107.21	$126.55	$96.43	$117.64
1997	451	$119.99	$142.03	$107.71	$131.87
1998	389	$136.60	$162.15	$122.36	$150.38
1999	788	$75.40	$88.02	$68.37	$82.21
2000	708	$82.14	$96.18	$74.32	$89.72
2001	770	$86.80	$99.71	$79.61	$93.76
2002	1,085	$70.58	$79.74	$65.48	$75.52
2003	739	$79.25	$92.70	$71.75	$86.50
2004	825	$74.99	$87.04	$68.28	$81.49
2006	815	$81.63	$93.82	$74.83	$88.21
2007	997	$67.25	$77.22	$61.69	$72.63
Mean	642	$111.40	$131.00	$100.48	$121.97

Estimated recoverable water costs (Table 9) vary widely with recharge quantities, with a minimum in the range of $60 to $80 per acre-foot for 1,000 acre-feet of recharge, but as high as $300 per acre-foot for the minimum (180 acre-feet) recharge scenario. Economies of scale are thus very important.

The estimated costs apply only to recoverable water delivered *to the aquifer*. They do not include the cost of additional wells constructed to extract recharged waters. They also do not include administrative costs. Other parties wishing to attempt a similar project would need to account for the cost of wells to recover the recharged water.

The cash cost of recharge for the Forest River Community would be much lower than the estimates above, because of their labor structure. The economic structure of the FRC consists of a broad spectrum of agriculturally-based enterprises, so that there is access to some of the required machinery, to in-house repair facilities, and to an ample labor pool. Much of the construction cost was defrayed using in-house labor. For example, the pipeline materials were salvaged from the CENDAK project in South Dakota using FRC labor and equipment. The tables above provide an estimate of costs that would be incurred by a party dependent on contractors for construction.

Potential costs for a municipal user are calculated using Table 9, and adjusting acre-feet to gallons (325,829 gal./acre-foot). Estimated costs for recharge alone range from 0.03 cents/gal. to 0.04 cents/gal. Additional costs for administration, ground-water pumping, and in most cases the cost of water treatment before recharge would have to be added.

CONCLUSIONS

An ARR facility was constructed, operated and monitored by the Forest River Hutterite Community from 1993 through 2009. The FRC was able to recharge more than 10,000 acre-feet from 1993 through 2007.

Forest River flow records indicated that, for 45 days of pumping during a 1940 through 1961 climate scenario, about 200 acre-feet would be available for recharge 80% of the time pumped at 2,500 gpm, and about 600 acre-feet would be available pumped at 5,000 gpm. For a 1962 through 1996 climate scenario, 80% probabilities for 2,500 and 5,000 gpm pumping capacities would be 500 acre-feet and 800 acre-feet, respectively. The mean pumping rate for 1993 through 2007 was 642 acre-feet, with two years above 1,000 acre-feet. And 80% of recharge operations exceeded 400 acre-feet. The operational period occurred during a wet climatic cycle, including two of the largest historical floods on the Red River, and a record water-level elevation in Devils Lake.

Regulatory requirements included the issuance of two water permits for pumping from the Forest River. Water Permit conditions included the requirement for an annual management plan to be stipulated by the SWC for each operational year. Annual plans included a schedule for monitoring ground-water elevations during operation, pumping records using an in-line flow meter, and acquisition of water samples for measurement of water chemistry in the basin and nearby ground water. The SWC required initially that 20% of the water recharged initially, and 20% of unpumped water at the end of each operational year be left in the aquifer. Requirements were later modified to require that 5% of initial recharge and 20% of unpumped waters at the end of the year, up to a maximum of 300 acre-feet, be left in the aquifer. The combined average of unpumped water at the end of 2007 was about 80% of the amount recharged. Two recharge basins, with a total area of 7.1 acres, were operated simultaneously. The first basin was triangular, with an area of 3.4 acres. The second was rectangular (800 x 200 ft.) with an area of 3.7 acres. Basins were excavated to a depth of two feet. Spoil was used to form border dikes having a 1:3 rise:run ratio. Starting times varied from early March to early April.

Infiltration rates decreased over each year's operational time due to clogging of the basin floor with sediments, and cementation caused by deposition of carbonates. Basins were usually operated without draining, and without use of amendments, such as organic mat filters. Basin floors were level rather than corrugated. Cleaning at the end of each operational year consisted of scraping the top inch (the filter cake formed from river sediments), and removal of the detritus from the basin. Cleaning operations were sufficient to maintain sustainable infiltration through the basin for 17 years without having to restore the basin floor. At the time of this report, several more years without renovation appear to be feasible.

Predictive power functions for basin infiltration during operation with turbid water were developed. Relationships for cumulative infiltration vs. time and vs. suspended solids were fairly robust, and similar to equations developed for a test basin in the Oakes Test Area, despite differences in basin floor texture (finer for the Forest River facility) and river suspended solids (cleaner for the Forest River facility). The predictive equations should provide a reasonable “first estimate” for future infiltration designs in North Dakota.

Water samples collected from the Forest River, the basin during operation, and shallow ground water near the basin during operation indicated that no adverse water quality impacts were occurring. Temporary increases in ground-water nitrate and sulfate occurred near the basin during first operation, but concentrations were all well below the EPA-MCL, quickly subsided, and were not repeated in subsequent years. A likely source was stored vadose nitrate and sulfate which was mobilized and depleted by the hydraulic mound formed by the basin. Water samples collected from the Forest River, the basin and local ground water during spring ARR operation indicated no detections of pesticides.

Cost estimates for recoverable ARR water ranged from \$100 to \$131 per acre-foot, or 0.03 to 0.04 cents per gallon. These cost estimates include the expenditures required to construct and operate facilities to pump water from the river, place the water in the aquifer, and monitor the ground-water movement and chemistry resulting from operation. They do not include administrative costs, or costs for pumping recovery or water treatment for human consumption.

CITATIONS

Bouwer, H. and R.C. Rice. 1989. Effect of water depth in groundwater recharge basins on infiltration rate. Irrig. Drain. Eng., Am. Soc. Civ. Eng., 115:4:566-568.

Bredehoeft, J.D., S.S., Papadopulos and Cooper, H.H. 1982. Groundwater: The Water Budget Myth. Scientific Basis of Water Management, National Academy of Sciences Studies in Geophysics, pp. 51-57.

Bredehoeft, J.D. 1997. Safe Yield and the Water Budget Myth. Ground Water. 35:6, 929.

Cline, Royce, Craig Odenbach, Preston Schutt, and William Schuh. 1993. Feasibility of stabilization of water levels and expansion of water use from the Englevale aquifer using water conservation, well field modification, and artificial recharge. Water Resource Investigation No. 23. North Dakota State Water Commission. Bismarck, ND. 151 pp.

Deb, A.K. 1969. Theory of sand filtration. Journal of Sanitary Engineering Division. ASCE 95:399-420.

Devlin, John F. and Marios Sophocleous. 2005. The persistence of the water budget myth and its relationship to sustainability. Hydrogeology Journal. 13:549-554.

Frietag, Arden and Dale Esser. 1986. Artificial recharge and drainage management in the Oakes Test Area. ASCE North American Water and Environment Congress. Anaheim, CA. June 22-28.

Glover, R.E., 1964. Ground water movement. U.S. Bureau of Reclamation, Engineering Monograph 31, 67 pp.

Hantush, M.S. 1967. Growth and decay of groundwater-mounds in response to uniform percolation. Water Resour. Res. 14:844-856.

Harmeson, R.H., Roger L. Thomas, and R.L. Evans. 1968. Coarse media filtration for artificial recharge. AWWA Annual Conference.

Ives, K.J. 1970. Rapid filtration. Water Research. 4: 201-223.

Jones, O.R., D.W. Goss, and A.D. Schneider. 1974. Surface plugging during basin recharge with turbid water. Trans. ASAE 17:1011-1019.

Jones, O.R., D.W. Goss, and A.D. Schneider. 1981. Management of recharge basins on the southern high plains. Trans. ASAE. 24:977-987.

Kelly, T.E. 1966. Artificial recharge at Valley City, North Dakota, 1932 to 1965. Proceedings of the National Water Well Exposition, Columbus Ohio, Oct. 2-6, 1966. pp. 20-25.

Klute, A. 1965. Conductivity of Saturated Soil. In A. Klute (ed.) Methods of soil analysis. Part 1. Agronomy 9: 210-221.

Kovenya, S.V., M.K. Melnikova, and A.S. Frid. 1972. A Study of the role of mechanical forces and geometrical conditions in the movement of highly dispersed particles in soil columns. Sov. Soil Sci. Engl. Transl. 10, 133-140.

Odenbach, Craig. 1993 *(dated August 27)*. Memorandum to the North Dakota State Engineer RE: Water Permit #4561.

Odenbach, Craig. 1996 *(dated August 8)*. Memorandum to the North Dakota State Engineer RE: Water Permit #4980.

Parkhurst, David. 2009. PHREEQ.
http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/index.html

Pettyjohn, Wayne A. and Vernon Fahy. 1968. Artificial recharge solves water problem. Public Works. pp. 82-85+.

Plummer, N.L., B.F. Jones, and Alfred H. Truesdell. 1978. WATEQF-a FORTRAN IV version of WATEQ, a computer program for calculating chemical equilibrium of natural waters. U.S. Geological Survey Water-Resources Investigations 76-13.

Schuh, W.M. and R.B. Shaver. 1988. Feasibility of artificial recharge to the Oakes aquifer, southeastern North Dakota: evaluation of experimental recharge basins. Water Resources Investigation No. 7. North Dakota State Water Commission. Bismarck, ND. 248 pp.

Schuh, W.M. 1990. Seasonal variation in clogging of an artificial recharge basin in a northern climate. J. Hydrol. 121:193-205.

Schuh, W.M. 1991. Effects of an organic mat filter on artificial recharge with turbid water. Water Resour. Res. 27:6:1335-1344.

Schuh, W.M., D.L. Klinkebiel, J.C. Gardner, and R.F. Meyer. 1993. Tracer and nitrate movement to groundwater in the Northern Great Plains. J. Environ. Qual. 26:1335-1347.

Shaver, Robert B. 1989. Feasibility of artificial recharge to the Oakes aquifer, southeastern North Dakota: preliminary cost analysis of a project-scale and pilot-scale well field and artificial recharge facilities. Water Resources Investigation No. 8. North Dakota State Water Commission. Bismarck, ND. 113 pp.

Shaver, Robert B. 1990. An interim water supply for the Oakes aquifer test area of the Garrison Diversion Unit: evaluation and selection of well-field sites and well-field design. Water Resources Investigation No. 15. North Dakota State Water Commission. Bismarck, ND. 539 pp.

Shaver, R.B., and W.M. Schuh. 1988. Feasibility of artificial recharge to the Oakes aquifer, southeastern North Dakota. *In (Ed.) A.I. Johnson and Donald J. Finlayson, Artificial Recharge of Ground Water.* Proceedings of the International Symposium on the Artificial Recharge of Ground Water. ASCE. New York. pp. 74-84.

Shaver, R.B., and W.M. Schuh. 1989a. Feasibility of artificial recharge to the Oakes aquifer, southeastern North Dakota: hydrogeology of the Oakes aquifer. Water Resources investigation No. 5. North Dakota State Water Commission. Bismarck, ND. 121 pp.

Shaver, R.B., and W.M. Schuh. 1989b. Feasibility of artificial recharge to the Oakes aquifer, southeastern North Dakota: Executive summary. Water Resources Investigation No. 8. North Dakota State Water Commission. Bismarck, ND. 79 pp.

Shaver, R.B. and Joe Wucetich. 1994. An evaluation of injection well plugging from a ground-water heat pump system in southeastern North Dakota. *In (Ed.) Johnson, A.I., and David G. Pyne, Artificial Recharge of Ground Water, II.* Proceedings of the Second International Symposium on the Artificial Recharge of Ground Water. ASCE. New York. pp. 720-731.

Solc, Jaroslav. 2000. Artificial recharge and the concept of aquifer storage recovery. Our Basin Home: Managing our Society Within Nature. Proceedings of the 17th Annual Red River Basin Land and Water International Summit Conference. January 11-13, 2000, Winnipeg, CA. p. 3.

Theis, C.V. 1957. The source of water derived from wells: essential factors controlling the response of an aquifer to development. Ground Water Notes: Hydraulics. 34 pp.

Truesdale, A.H. and B.F. Jones. 1974. WATEQ, a computer program for calculating chemical equilibria of natural waters. U.S. Geol. Survey Jour. Research. 2:233-248.

USDA-SCS. 1980. Hydrology Manual for North Dakota. USDA-NRCS. Bismarck ND. 163 pp.

APPENDIX A: Water Chemistry

Table A-1. General Chemistry for water samples collected from the Forest River and the Forest River Community ARR basins.

Site	Location	Date	SiO2	Fe	Mn	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl	F	NO3	As	TDS	CH*	NCH*	%Na	SAR	Spec. Cond. (mmho)	T oC	pH
			mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L					
River Samples																								
154-055-10D	River	04/15/93	17	0.02	0.15	73	29	45	8.3	209	0	210	15	0.2	13	0.04	514	300	130	24	1.1	732	7	8.78
154-055-10D	River	04/05/94	18	0.04	0.3	65	30	48	10	210	0	200	15	0.2	12	0.05	502	290	110	26	1.2	712	10	
154-055-10D	River	05/04/94	7.2	0.04	0.34	88	38	49	7.9	304	0	210	17	0.2	0.8	0.06	569	380	130	22	1.1	855	9.2	9.04
154-055-10D	River	05/13/98	-	0.03	0.08	86	39	53	7.0	282	0	250	16	0.2	1.4	-	623	380	140	23	1.2	897	19.6	8.14
Basin Samples																								
154-055-15DBB(b)	Basin 1 (rep 1)	04/15/93	17	0.03	0.15	75	29	45	9.2	207	0	210	15	0.2	14	0.05	534	310	140	24	1.1	819	6	8.52
154-055-15DBB(b)	Basin 1 (rep 2)	04/15/93	16	0.02	0.12	73	29	45	8.3	200	0	210	15	0.2	16	0.04	508	300	140	24	1.1	744	8	8.56
154-055-15DBB(b)	Basin 1 (rep 1)	05-04-93	4.9	0.05	0.22	76	34	45	8.3	271	0	190	18	0.2	0.8	0.11	525	330	110	22	1.1	1080	19.2	8.63
154-055-15DBB(b)	Basin 1 (rep 2)	05-04-93	2.2	0.04	0.18	66	34	47	8.3	242	0	180	18	0.1	0.0	0.05	494	300	110	24	1.2	819	23	8.7
154-055-15DBB(b)	Basin 1 (rep.3)	05-04-93	2.9	0.04	0.12	72	35	47	8.1	253	1	170	18	0.1	0	0.05	501	320	110	23	1.1	792	20.9	8.65
154-055-15DBB(b)	Basin 1 (rep 4)	05-04-93	2.98	.04	.11	70	34	46	8.2	253	2	190	18	0.1	0.0	0.05	494	310	100	24	1.1	781	20.3	8.68
154-055-15ACC1	Basin 2 Disch	05/04/94	5.3	0.03	0.16	82	38	51	9.6	282	0	220	21	0.2	0	0.06	566	360	130	23	1.2	828	10.5	8.27
154-055-15ACC2	Basin 2 Middle-South	05/04/94	4.7	0.03	0.11	78	38	50	8.5	275	0	220	19	0.2	0	0.06	554	350	130	23	1.2	826	10.5	8.79
154-055-15ACC3	Basin 2 East End	05/04/94	3.8	0.02	0.06	76	38	51	8.1	264	0	220	19	0.2	0	0.06	546	350	130	24	1.2	805	10.3	9.35
154-055-15ACC1	Basin 2 Disch	05/23/96		0.05	0.02	68	31	55	9.8	216	0	250	17	0.2	4.7		542	300	120	28	1.4	720	14	
154-055-15ACC1	Basin 2 Disch	5/13/98	-	0.03	0.03	80	38	57	7.2	269	0	260	16	0.2	0.9	-	618	360	140	25	1.3	880	17.8	8.18

Table A-2. General Chemistry for the Inkster aquifer near the Forest River Community ARR basins.

Site	Location	Date	SiO2	Fe	Mn	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl	F	NO3	As	TDS	CH*	NCH*	%Na	SAR	Spec. Cond. (mmho)	T oC	pH
			mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L					
154-055-14CBB	SWC6	09/26/85	23	0.01	0.51	84	25	3.5	2.6	264	0	94	2	0.2	1	0.06	366	310	96	2	0.1	650	7	
154-055-14CBB	SWC6	07/13/88	30	0.02	0.52	85	24	4	2.1	270	0	93	6.2	0.2	1	0.05	379	310	89	3	0.1	619	8	
154-055-14CBB	SWC6	06/03/92	26	0.02	0.52	85	24	4	1.7	268	0	93	5.3	0.2	0	0.06	372	310	91	3	0.1	958	8	
154-055-14CBB	SWC6	04/06/93	29	0.01	0.54	89	25	4	2	271	0	110	8.3	0.2	0	0.05	401	330	100	3	0.1	784	8	8.32
154-055-14CBB	SWC6	05/05/93	26	0.03	0.58	90	25	4.5	2	268	0	110	7.5	0.2	0	0.03	398	330	110	3	0.1	638	8.4	7.93
154-055-14CBB	SWC6	08/24/93	28	0.01	0.69	110	30	5	2.5	266	0	160	15	0.2	0	0.04	480	400	180	3	0.1	704	9	8.24
154-055-14CBB	SWC6	07/06/94	29	0.04	0.62	100	29	3	1.7	267	0	150	9.1	0.2	0	0.03	455	370	150	2	0.1	661	9	
154-055-14CBB	SWC6	07/26/94													0.1									
154-055-14CBB	SWC6	07/23/97		0.07	1.3	230	65	6	3.7	331	0	580	6	0.2	0.09		1060	840	570	2	0.1	1420	8	
154-055-14CCC	OBS	07/13/88	23	0.07	0.33	79	25	4	2.5	285	0	100	5.4	0.2	1	0.16	381	300	67	3	0.1	627	9	
154-055-14CCC	OBS	06/03/92	25	0.38	0.57	87	26	5	1.9	261	0	120	3.7	0.1	0	0.05	399	320	110	3	0.1	925	9	
154-055-14CCC	OBS	04/06/93	28	0.24	0.76	120	38	5.5	2.7	261	0	270	6.1	0.1	0	0.05	600	460	240	3	0.1	1016	8	8.11
154-055-14CCC	OBS	05/05/93	26	0.49	0.76	120	35	5.5	2.2	264	0	210	3.7	0.1	0	0.03	534	440	230	3	0.1	1208	8.7	7.88
154-055-14CCC	OBS	08/24/93	26	0.09	0.9	140	42	5.5	3.2	272	0	280	6.7	0.1	0.2	0.04	639	520	300	2	0.1	844	10	7.94
154-055-14CCC	OBS	07/06/94	28	0.53	0.77	130	41	4.5	2.1	274	0	270	5.9	0.1	0	0.05	618	490	270	2	0.1	822	8	
154-055-14CCC	OBS	07/26/94													0.2									
154-055-14CCC	OBS	06/01/95		0.37	0.66	100	32	5	2.2	264	0	190	6.5	0.1	1		468	380	160	3	0.1	690	8.5	7.84
154-055-14CCC	OBS	07/23/97		0.54	0.68	110	34	5.5	2.4	276	0	190	9.8	0.2	0.09		489	410	190	3	0.1	787	9	
154-055-15ACCC	B1	04/06/93	25	0.02	0.39	110	31	8	3.3	271	0	180	8.5	0.2	0	0.11	500	400	180	4	0.2	680	7	7.15
154-055-15ACCC	B1	04/14/93	26	0.03	0.24	95	33	4.5	2.8	343	0	99	2.8	0.2	0	0.06	433	370	92	3	0.1	673	9	7.07
154-055-15ACCC	B1	05/04/93	25	0.05	0.21	100	35	5.5	2.8	373	0	90	3.5	0.2	0	0.06	446	390	88	3	0.1	660	8.4	7.57
154-055-15ACCC	B1	06/01/95		0.03	0.22	120	42	4.5	2.9	396	0	160	12	0.2	1		538	470	150	2	0.1	806	12.8	7.26
154-055-15ACCC	B1	05/23/96		0.03	0.35	120	41	4.5	3.5	393	0	170	14	0.2	0.1		548	470	150	2	0.1	748	7.8	
154-055-15ACDB	B7	04/06/93	24	0.01	0.69	160	37	5.5	2.7	245	0	320	4.5	0.2	0	0.04	676	550	350	2	0.1	961	8	8.26
154-055-15ACDB	B7	04/15/93	23	0.01	0.38	160	40	6	2.2	263	0	350	3.2	0.2	0	0.03	715	560	350	2	0.1	934	9	8.02
154-055-15ACDB	B7	05/05/93	26	0.04	2.3	470	120	9	3.5	336	0	1400	5.5	0.1	0.2	0.03	2200	1700	1400	1	0.1	2290	9.1	7.47
154-055-15ACDB	B7	08/24/93	26	0.02	0.9	160	42	5.5	2.6	251	0	360	8.7	0.1	0	0.04	730	570	370	2	0.1	925	9	6.84
154-055-15ACDB	B7	04/05/94	27	0.02	1.2	140	37	4	1.9	235	0	310	3.2	0.2	0	0.05	641	500	310	2	0.1	841	8	
154-055-15ACDB	B7	05/04/94	29	0.02	1.1	160	40	5	2.1	255	0	330	1.4	0.2	0	0.06	693	560	350	2	0.1	907	8	
154-055-15ACDBC	IR10	07/26/94	29	0.16	0.8	140	37	4.5	1.8	302	0	260	6.4	0.1	4.6	0.05	633	500	250	2	0.1	802	8	
154-055-15ACDD	B5	04/06/93	27	0.17	1.6	290	70	6	3.1	353	0	710	3.6	0.1	0	0.04	1290	1000	720	1	0.1	1456	11	7.43
154-055-15ACDD	B5	04/14/93	25	0.32	1.9	310	74	6	3.1	366	0	740	3.7	0.1	1.3	0.04	1350	1100	780	1	0.1	1623	10	6.81
154-055-15ACDD	B5	05/04/93	26	0.4	2.2	360	86	7	3.5	437	0	880	3	0.1	0.4	0.04	1580	1300	890	1	0.1	1705	9.6	7.48
154-055-15ACDD	B5	08/23/93	28	0.2	1.1	150	38	5.5	2.9	329	0	250	14	0.1	0	0.03	652	530	260	2	0.1	887	12	7.04
154-055-15ACDD	B5	04/04/94	29	0.09	1	130	33	3	2.3	275	0	230	14	0.1	0	0.05	578	460	230	1	0.1	808	8	
154-055-15ACDD	B5	05/04/94	28	0.18	1.1	150	37	3.5	2.4	362	0	220	13	0.1	0	0.03	633	530	230	1	0.1	877	9	
154-055-15ACDD	B5	05/31/95		0.17	0.97	140	31	4.5	2.1	266	0	260	16	0.1	1		587	480	260	2	0.1	808	15.8	6.71
154-055-15CCC	OBS. (DES)	07/24/85	24	0.09	0.37	87	28	4	2.4	233	0	110	7	0.2	1.5	0.03	380	330	140	2	0.1	1760	9	
154-055-15C	MERGE IR 2,3,4,5	07/24/85	26	0.26	1.1	160	49	6	3	276	0	320	11	0.1	1	0.04	714	600	380	2	0.1	1064	9	

APPENDIX B: Basin Cleaning Operations

Figure B-1. John Deere 770™ grader used to "peel" filter cake. The grading operation begins on two edges of the basin, and the filter cake is scraped toward the center, where a single pile is collected for removal.

Figure B-2. John Deere JP686™ self-loading scraper, used to collect the filter-cake pile deposited by the grader.

Figure B-3. John Deere JP686™ self-loading scraper depositing the filter-cake residue collected from the basin floor on the outside of the basin berm.

Figure B-4. Post-cleaning basin floor, 2009.