# Retention of Aquifer Recharge and Recovery Water in a Shallow Unconfined Aquifer: Simulations of a Basin Recharge and Recovery Facility in Grand Forks County, North Dakota

By
William M. Schuh and Jon Patch

Water Resources Investigation No. 48
North Dakota State Water Commission

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RIVULET OF THE INKSTER SPRING COMPLEX, GRAND FORKS COUNTY, ND

## ACKNOWLEDGEMENT

The authors thank Ben Maendel, of the Forest River Community, for countless hours of field work in measuring basin and observation well water elevations, and hours spent locating and measuring spring discharges along the Forest River. We thank Jonathan Maendel for information on operational planning scenarios used in designing the models used in this study. We also thank Rod Bassler, North Dakota State Water Commission cartographer, for his assistance in coordinating a geographical information system interface with the model.

# EXECUTIVE SUMMARY

An aquifer recharge and recovery project (ARR) was implemented by the Forest River Hutterite Community near Fordville, North Dakota, from 1993 through 2009. Water was pumped each spring from the Forest River, and piped about a half mile to two infiltration basins (a total of ~7 acres). Recharge was conducted from March through the middle of June, with the starting date depending on thaw conditions and river flows. Annual recharge varied from as little as 180 acre-feet, to as much as 1,069 acre-feet. Recharged water was then pumped from the aquifer for irrigation using wells constructed near the basin.

One of the greatest concerns was the ability of the aquifer to retain recharged waters for future use. The Forest River is a gaining stream, and is fed by numerous springs along the Inkster aquifer. There was concern that recharge waters may be lost through the springs before they could be recovered. Natural discharge also occurs through evapotranspiration (ET) in shallower areas of the aquifer, and through ET sinks and seeps located beyond the eastern boundary of the aquifer. Although the water table near the river and at the basin was relatively deep, about 30 feet below land surface, an elevated hydraulic mound at the basin itself would also enhance ET near the basin during and immediately after operation. Finally, about 2.5 miles south of the basin there are natural drainageways that could discharge recharged waters, given sufficient time.

A hydrologic model, using MODFLOW™ was used to evaluate potential natural losses and retention characteristics of recharged waters. Findings are summarized below.

1. During the operational period, about 80% of the recharge water was recovered through pumping. A transient simulation of recharge, pumping and natural discharge using 1993 through 2007 recharge and pumping recovery data indicated that about 17% of the recharged water had been lost through various natural discharge sinks, very close to the 20% left in the aquifer.

2. The 1993-2007 simulation indicated that about 10% of the water recharged in any given year would be lost through natural discharge, regardless of pumping scenario, and about 35% of all unpumped waters at the end of the operational year would be lost through natural discharge.

3. The optimal pumping recovery efficiency for the 1993-2007 simulation was at 90% recovery, which resulted in only 13% loss. This, however, caused a deficit of 3% and would be unacceptable from the standpoint of aquifer management.

4. Most natural discharge (about 47% of the total loss) for the 1993-2007 simulation occurred through four spring complexes located within a mile of the basin. These included Inkster Spring, slightly more than a half-mile northeast of the basin. Losses through ET were about 31% of the total loss. Losses through ET and seepage beyond the eastern boundary of the aquifer (about 2.5 miles east of the basin) were estimated at about 12% of the total natural discharge loss. The remaining 10% were discharged through drains in the southern portion of the aquifer and seven additional spring complexes more distant from the basin.

5. A steady-state model using "particle-tracking" for each of nine cells representing the basin complex indicated that water and solute particle paths and destinations were strongly influenced by location within the basin.

6. Simulation of the destination of a "single-year" recharge pulse indicated that most ET occurred near the basin, and was caused by the elevated ground-water mound which brought the local water table to near land surface. Losses of ET beyond the eastern boundary of the aquifer began about a year after the recharge event, and peaked after about three and a half years. Losses through the south drains began about a year and a half after the event and peaked about five years after the event. Losses through the four nearest spring zones [Springs Zones 5 through 8, including Inkster Spring (5)] began within the year of the event and peaked within a year of the event. Peak discharge through more distant springs varied, with a maximum of up to eight years after the recharge event. After peak discharge, all discharge sinks continued to discharge recharged waters at some level for the entire 15-year operational period simulation.

7. Spring discharges were strongly influenced by hydrologic effects caused by the formation and propagation of the hydraulic mound at the basin during and following the recharge event, and its indirect effect on the flow system. The effect of the mound northwest of the basin was to "back up" the natural flow system and divert it, with increased local heads, toward springs northwest of the basin.

8. Total loss of recharged waters took many years. But waters not recovered through local pumping within two years were found to be effectively beyond local recovery. While some of these waters may be recoverable by other parties pumping between the basin and more distant discharge sinks, the location and fate of these waters and their effective recovery is uncertain and cannot be included within a reasonable recovery scenario.

9. A second proposed ARR basin and recovery-well complex was proposed for construction and operation about a mile south of the current operating basin. Simulated discharge losses in the operation year were negligible, compared with 10% for the north basin. However, a larger percentage (57% compared with 35% for the north basin) of non-recovered water at the end of the year was projected to be lost through natural discharge sinks.

10. The greatest portion (about 40%) of the natural discharge loss for the proposed south basin was simulated to be lost through ET. The second greatest portion (about 25%) was simulated to be lost through natural drainageways located south of the proposed basin. About 18% (each) of total natural discharge loss was simulated to occur through springs on the Forest River and through ET and seepage beyond the eastern aquifer boundary.

11. ET losses for the proposed south basin were simulated to peak about three years after the recharge event, indicating that main losses would be in shallow water-table areas somewhat distant from the basin. Spring losses were simulated to peak at about two to four years after the recharge event. Losses through the east boundary were simulated to begin about two years after the recharge event, and peak at three to eight years after the event. Losses through drainage were most immediate, beginning within the year of the recharge event, and peaking about two years after the event.

12. Combined operation of the two basins (north and proposed south) together were simulated to result in a higher proportional loss (approx. 20%) of total recharge, than either of the individual basins (17% loss north, 10% loss proposed south) under an 80% first-year pumping recovery scenario.

13. Simulations of the proposed south basin indicate that at least three wells, including two near (north and south) of the basin, and within the direct influence of the hydraulic mound, would likely be needed to effectively recover water.

14. **The principal finding of the model is that ARR storage in the Inkster aquifer is short-term storage. It must be applied principally from year to year.** The Inkster aquifer has a relatively deep water table (mostly deeper than 20 feet). Such deeper water tables, in North Dakota's shallow unconfined systems, are usually found only where streams or drainageways intersect the aquifer. This implies high risk of seepage and spring losses. Conversely, aquifers having shallower

water tables would likely be unable to store sufficient recharge water without first being evacuated through pumpage. Discharge losses through such shallow water-table systems would likely be primarily through ET near the basin. Management of such a system may require a program of deficit replacement: that is, pumpage and use followed by replacement. This was proposed by Shaver (1990) as a procedural plan for operation of an ARR facility in the Oakes aquifer in southeastern Dickey County, ND, but was never implemented. Simulation of such a system may be a worthwhile objective for future investigations of potential ARR use in North Dakota.

15. **In most cases, use of ARR in thin shallow unconfined aquifers must be viewed as a means for transferring unused surface waters to a ground-water reservoir for beneficial use within a short period of time, optimally within a year, of the time of capture. Aquifer recharge and recovery, in thin shallow unconfined aquifers, is not an appropriate means for providing long-term supplemental storage.**

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## INTRODUCTION

From 1992 through the present (2009) the Forest River Hutterite Community (FRC), near Fordville, North Dakota, has operated an aquifer recharge and recovery (ARR) basin and recovery project, in which water has been pumped from the Forest River during spring high flows and stored in the Inkster aquifer for later recovery and irrigation use (Figure 1). The location, planning, construction and operation of the FRC ARR facility has been described in detail in a companion report (WRI No 47, Schuh, Patch and Maendel, 2009).

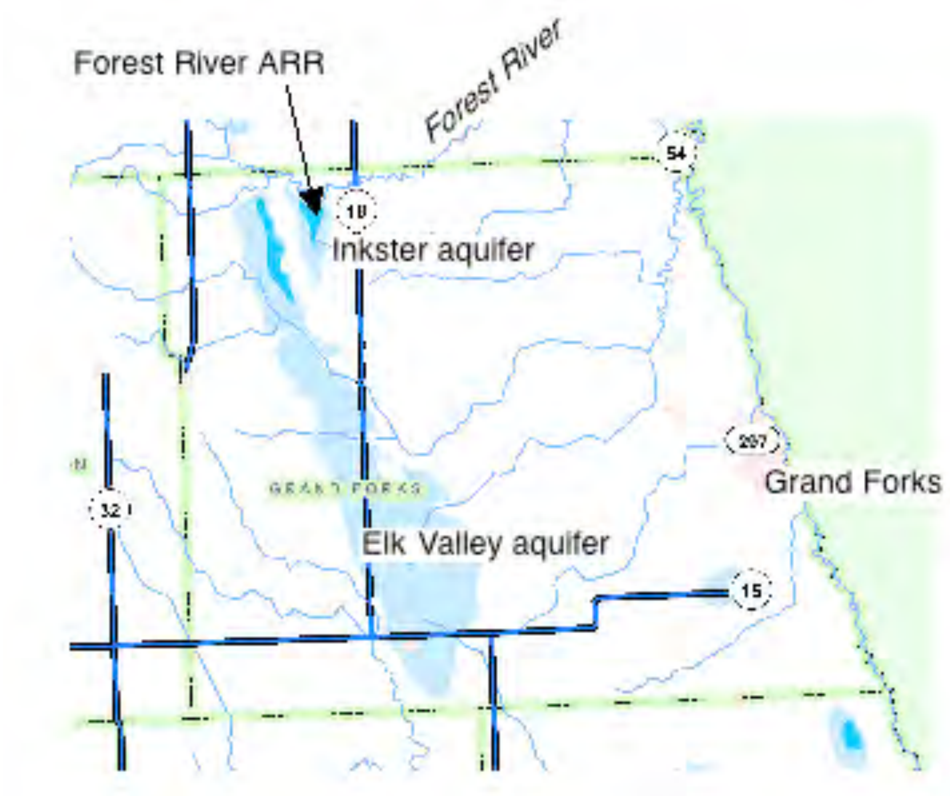


Figure 1. Location of the Forest River Community ARR facility in Grand Forks County, ND.

One of the primary concerns in implementation of ARR is the retention of water for beneficial use. The cost and labor of recharge is wasted if recharged waters cannot be retained in the aquifer long enough to be pumped for beneficial use; or if, from the standpoint of the ARR operators, retained waters move beyond recovery of their well field. From the regulatory standpoint, waters moved beyond immediate recovery are of uncertain fate and, depending on local hydrology, can be difficult to account for in the aquifer water budget.

The location of the Forest River Community ARR basin is about a half-mile from the Forest River; advantageous for transmission of water to the basin, but problematic for retention because of potential losses through springs. The water table near the basin is relatively deep, about 30 feet below land surface (bls) (Appendix A, 154-055-14CBB), because of drawdown accentuated by local pumpage and spring discharge. However, ET losses could occur locally during maximum mound elevations, and waters retained long enough can be lost through ET and seepage in areas characterized by shallow water tables along the eastern border of the aquifer, and in areas in the southern reaches of the aquifer. Long-term retention may also be decreased by discharge through natural drainageways in the southern areas of the aquifer.

As a preliminary precaution, the State Engineer has required that the State Water Commission (SWC) staff provide an annual operational plan for the FRC facility, as a condition for Water Permits #4561 and #4980, authorizing the basin facility. Since 1993 the SWC staff has required that the FRC provide water-level data for a set of nine monitoring wells constructed for the basin (Figure 2). The SWC initially (beginning in 1993) deducted 20% of water pumped from the river immediately for estimated spring and evaporation losses, and an additional 20% of residual waters for each year to account for further losses over the winter. After 1998 the formula was changed to a 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. All waters above 300 AF were considered as loss after 1998. Estimated loss adjustments were based on guesswork. The annual recharge and recovery implemented as a result of this plan has been discussed by Schuh, Patch and Maendel (2009) and has been summarized in Table 3 of that report.

Understanding the fate of recharged waters is critical for ARR management. Because of the many properties, boundary conditions and stresses affecting ARR interactions with the aquifer, a hydrologic model is best suited for evaluating the long-term effects of ARR. A steady-state model can provide a broad outline of relative water losses through various discharge sinks. It is also essential as the calibration step for a transient model. A steady-state model, however, is inadequate for simulating the effects of hydraulic mound formation during recharge, and the time-dependent aspects of pumpage. Because recharge and discharge are fully balanced at steady state, the steady-state model cannot be used to evaluate the temporal redistribution of water and time-dependent losses through various sinks. Both steady-state and transient models of the Inkster aquifer were developed to evaluate the spatial and temporal redistribution and loss of recharge waters under conditions of the Forest River Community ARR facility.

The purpose of this report is to describe the development, application and results of steady-state and transient models for ARR operation in the Inkster aquifer, and their implications for management of the FRC facility and for the planning of other similar facilities in similar hydrologic settings.

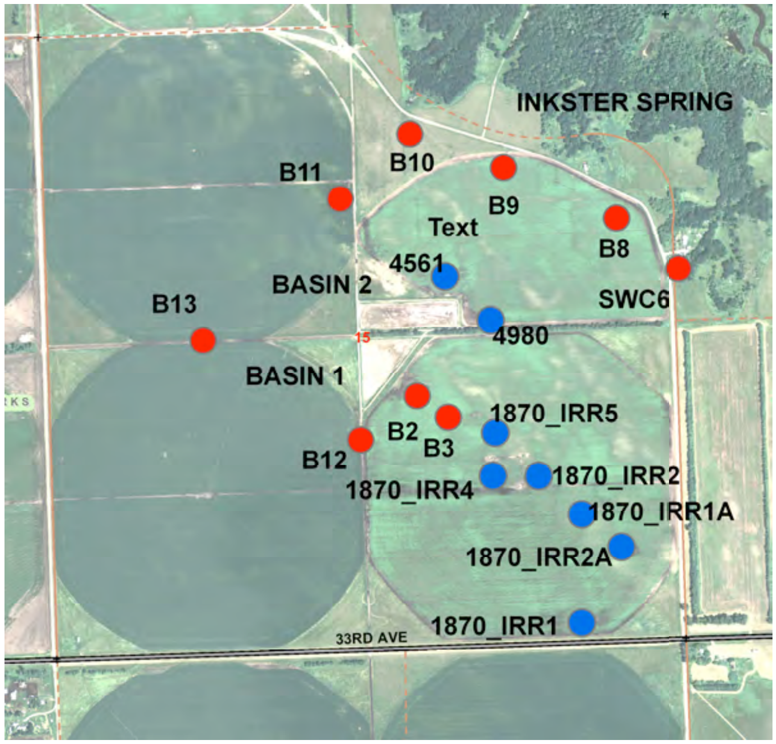


Figure 2. Location of the Forest River Community ARR basin(s) in the center of 154-055-15, with irrigation wells (blue) and monitoring wells (red).

## 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 3. 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 Section 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.

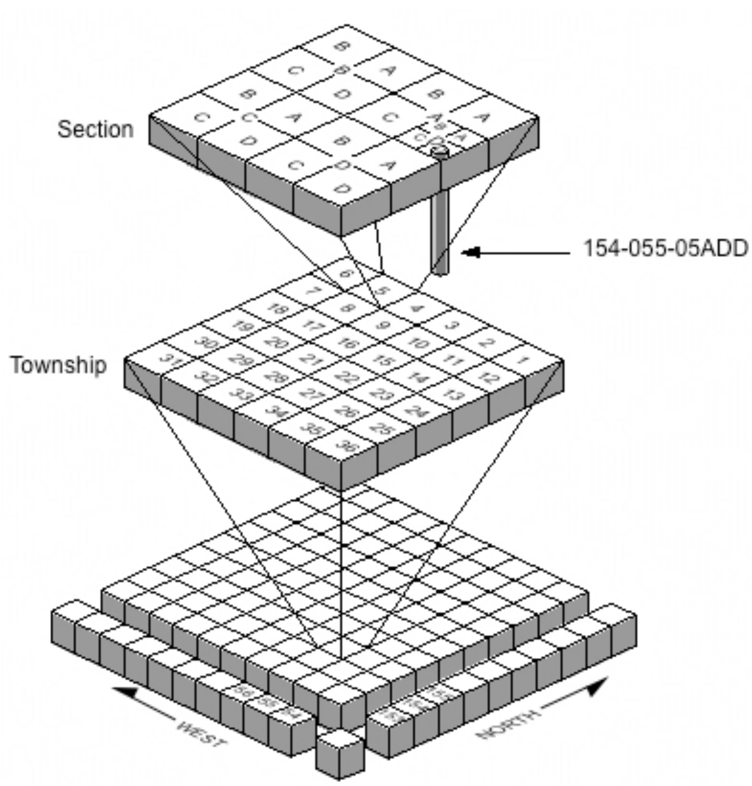


Figure 3. Description of U.S. Bureau of Land Management location system.

## 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 48 cm (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 4) 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 late Pleistocene epoch. The land surface overlying the aquifer is flat to gently sloping eastward. The aquifer has an overall areal extent of about 12 to 15 square miles, all in Grand Forks County. It is comprised primarily of fine- to coarse-grained sand with some localized deposits of gravel. Sediment composition includes quartzose sand, detrital shale sand, and detrital bedrock and shield silicate gravels. Gravels are, in some cases, cemented. Cementation is non-carbonaceous and is likely siliceous. The lithology is highly complex, characteristic of a highly active fluvial depositional environment. Individual locations frequently include a wide range of sediments, including clay stringers at some locations. Bottom topography is undulating in some areas, characteristic of an anastomosing stream depositional environment. Lithologic logs for SWC and some commercial drilling sites on the Inkster aquifer are provided in Appendix B.

The aquifer is bounded on the west by the long ridge-like Edinburgh Moraine, on the north by the South Branch of the Forest River, and pinches out to land surface on the east and south. The Inkster aquifer is geologically and hydrologically similar to the Elk Valley aquifer which lies directly to the west (Figures 1 and 3). The aquifers are separated by the Edinburgh Moraine. There does not appear to be a direct hydraulic connection between the two aquifers.

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.

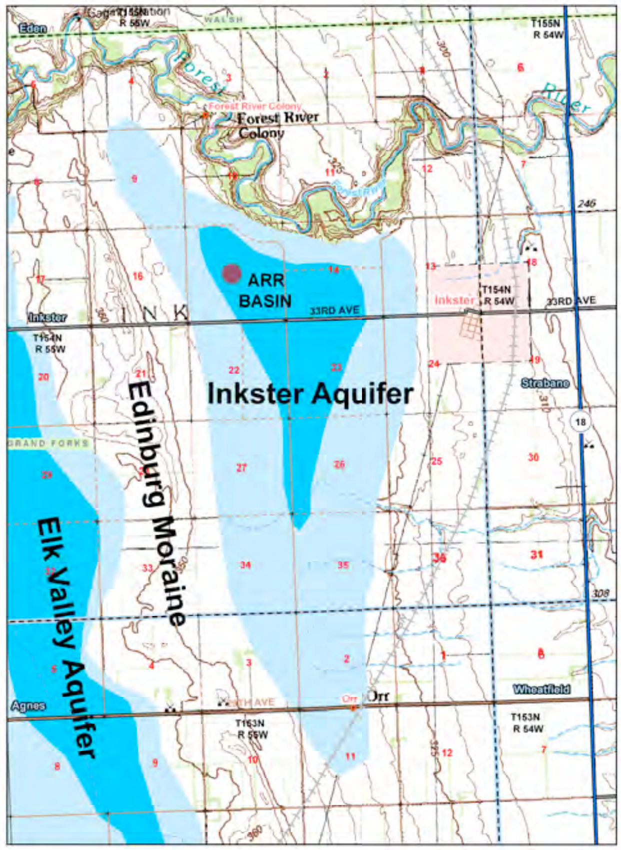


Figure 4. Map of the Inkster aquifer in relation to the Forest River and other topographical features.

The Inkster aquifer is, for the most part, unconfined with a common saturated thickness of 20 to 50 feet. Water tables commonly fluctuate about four feet annually. Hydrographs for 24 years of record are provided for three observation well sites in Appendix A. Discharge from the Inkster aquifer occurs mainly through evaporation and transpiration during the growing season; and through springs and seeps where 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. There are currently 12 active water permits which allow annual withdrawals from the Inkster aquifer amounting to 3,586 acre-feet. Irrigation accounts for 83% of the water allocations.

The aquifer parameters determined from an aquifer test in the NW1/4 NE1/4 Section 23, T154N-R55W (154-55-23AB) ranged from T=5,500 to 9,200 $ft^2$/day and S = 0.13 to 0.22. A saturated thickness of about 37 feet was measured at the test site. The hydraulic conductivity ranged from about 150 to 250 ft./d, although K would likely vary widely over the extent of the aquifer.

## STEADY-STATE MODEL OF THE INKSTER AQUIFER

The following paragraphs describe the steady-state Inkster ARR model, its parameterization, calibration, and results. The model was constructed using Visual MODFLOW, version 4.2 (Waterloo Hydrogeologic, 2006).

### Model Structure and Parameters

The Inkster aquifer model was discretized into a rectangular grid consisting of approximate 192 x 192 foot square cells. All cells were of uniform size. The aquifer boundary was set using the digitized North Dakota State Water Commission aquifer map, and imported as an image file using ArcMap 9.2 GIS software. A minimum boundary cell depth of 20 feet was specified.

**Recharge:** Recharge was applied in three zones. The main zone included the entire model, except for a tier of about 7 cells, 1,330 feet wide, along the entire length of the western boundary. Recharge through the main recharge zone was 7.5 inches per year. Although many models used for surficial aquifers in North Dakota have applied lower values, commonly in the range of 3 to 5 inches, the Inkster aquifer is distinctive in that the modern water table is deep for most of its aerial extent, and the capillary fringe of the water table does not intersect the root zone, and is therefore "uncoupled" with respect to evapotranspiration. Annual recharge has been measured at approx. 4.8 inches per year (+/- 1, $P<0.05$) on similar (Maddock series) soil at the Oakes experiment station (Derby, written communication, 8/15/02). Annual recharge to the Carrington aquifer, a shallow confined aquifer (20 feet to the upper boundary), through mixed till with a water table at about 8 to 11 feet bls (Heimdal soil series: coarse-loamy, mixed, superactive, frigid Calcic Hapludolls) was measured at about 8 inches per year (Schuh and others, 1993).

The western boundary of the Inkster aquifer receives runoff waters from the Edinburgh Moraine (Figure 5). To approximate runoff, the area of the eastern slope of the moraine was measured using a USGS 1:100,000 series topographical map. The 50% probability annual runoff map from the North Dakota Hydrology Manual (USDA-NRCS, 1980) indicated a likely local runoff of 35 to 40 acre-feet per square mile. Divided by the length of the linear boundary, expected average runoff would be about 500 cubic feet per year per linear foot of boundary. This runoff influx was applied over about a quarter mile (7 cells or 1,330 feet). Additional recharge was about 4 inches. Adding the runoff estimate to 7.5 inches of general recharge, boundary recharge was estimated as about 11.5 inches per year. As an approximation of this estimate, 10 inches per year were applied along the northern half of the western boundary, and 12 inches per year were applied along the southern half. Recharge zones are shown on Figure 6.

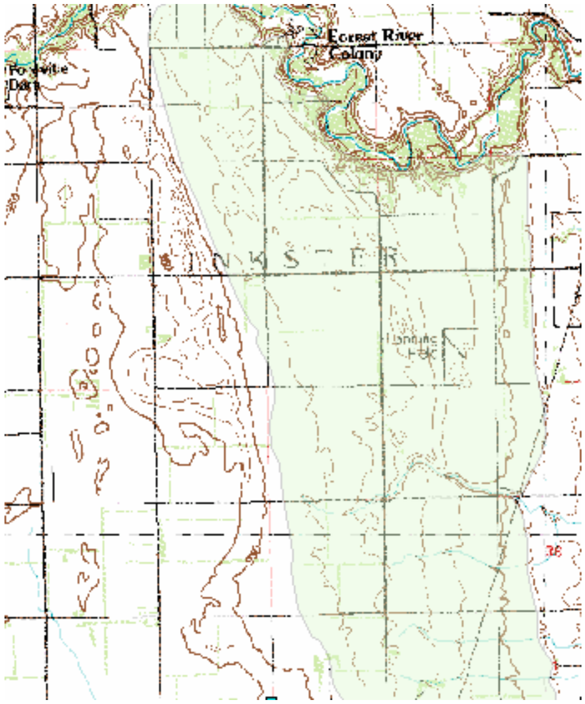


Figure 5. Topography of the Edinburgh Moraine on the western boundary of the aquifer.

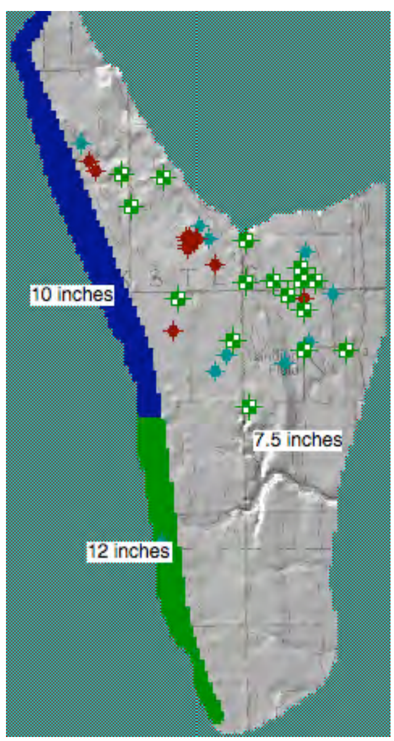


Figure 6. Location of recharge zones.

**Evapotranspiration:** Thirty (30) inches of evapotranspiration (ET) was applied to the model with a 6-feet linear root extinction function. Because the water table for most of the aquifer is deep (greater than 20 feet bls), the model decouples quickly and is not highly sensitive to ET. Most of the ET discharge occurs beyond the eastern boundary of the model. Poorly-drained sandy soils are located east of the aquifer boundary, as shown on Figure 7A. The position of the aquifer boundary was based on limits imposed by estimates of the pumping characteristics and the saturated thickness of the aquifer. Rather than extend the aquifer boundary to affect continuity, the model treated the eastern aquifer boundary as a general head (GH) boundary, with the specified head equal to the bottom of the boundary cell, and the flow distance of 500 to 1,000 feet beyond the boundary, to simulate flux into the evaporative discharge zone. Thus, the general head boundaries on the eastern border of the model should be understood predominantly as evapotranspiration loss occurring beyond the boundary, with some water likely lost through seepage in drainageways.

Some ET discharge areas are located in the southern portion of the aquifer (Figure 7A). Control points (observation wells) in the southern Inkster aquifer are inadequate, but it may be assumed, from soil drainage classifications, that water tables are shallower than in the north. The best defined evaporative discharge areas are located along drainageways in the southern Inkster aquifer. Drainageways are simulated using linear strings of drain cells with discharge elevations set at drain-bottom elevations which were estimated using the digital elevation model (DEM). Cell conductivities for both general head and drainage applications were adjusted in the calibration of the model.

General head (green) and drain cells (gray) are shown below on Figure 8A. Four drainageways are represented in the southeastern portion of the aquifer. The green cells along the eastern boundary are applied as described above, to simulate discharge of water through ET sinks east of the aquifer. The GH boundaries on the north (green) are used to simulate springs and are described in the next section. For analysis of the water budget, the eastern GH boundary is divided into four zones: (1) Zone 13 (red), (2) Zone 14 (magenta), (3) Zone 15 (yellow), and (4) Zone 16 (violet) (Figure 8B).

An approximate indicator of ET intensity is NET RECHARGE, shown on Figure 7B. Areas of low net recharge correspond approximately to the areas of shallow soils shown on Figure 7B, particularly along drainageways and along the northeastern border. It appears that ET is less well represented in the southern Inkster aquifer, and that water tables are shallower than represented by our model. But lacking precise control points in this area, further calibration would not be justified, particularly since the area of primary concern is in the northern portion of the aquifer.

A B

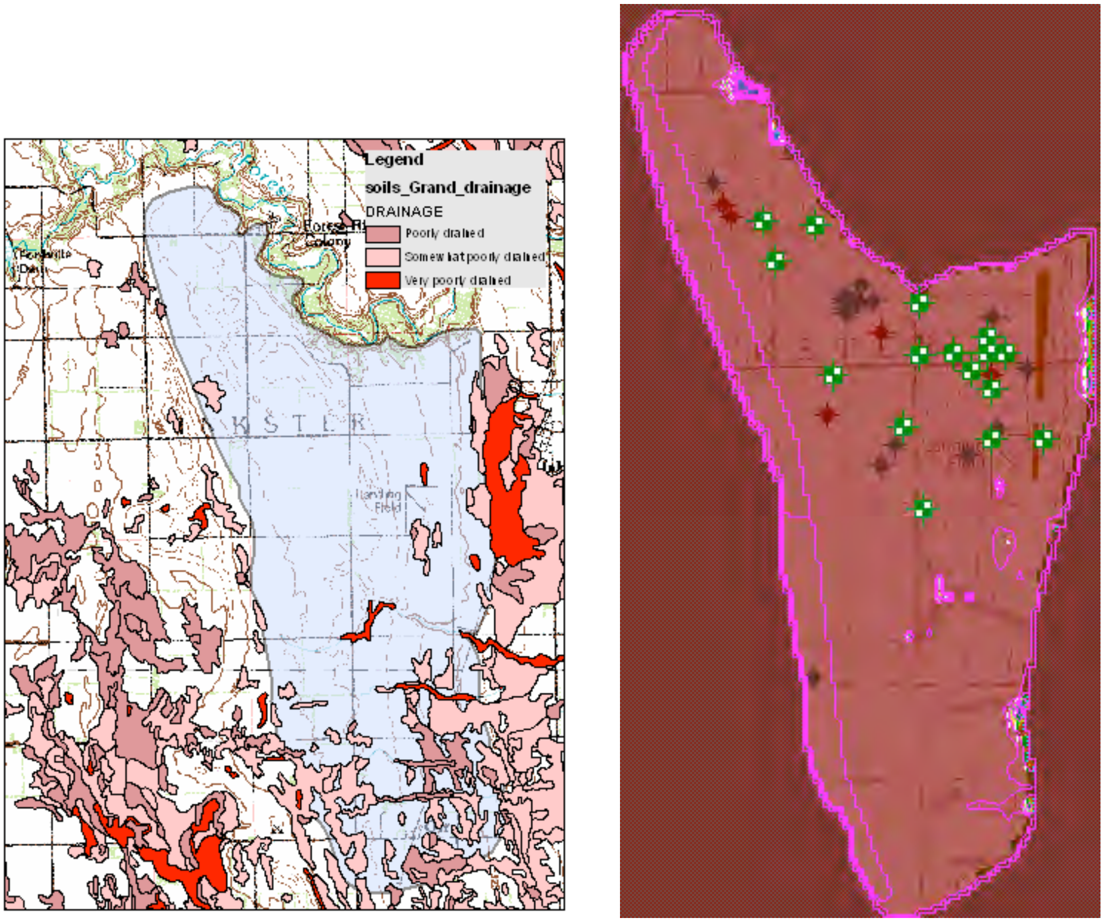


Figure 7. Comparison of evaporative soils (A) and evaporative areas represented by minimal net recharge (B) predicted by the model.

A B

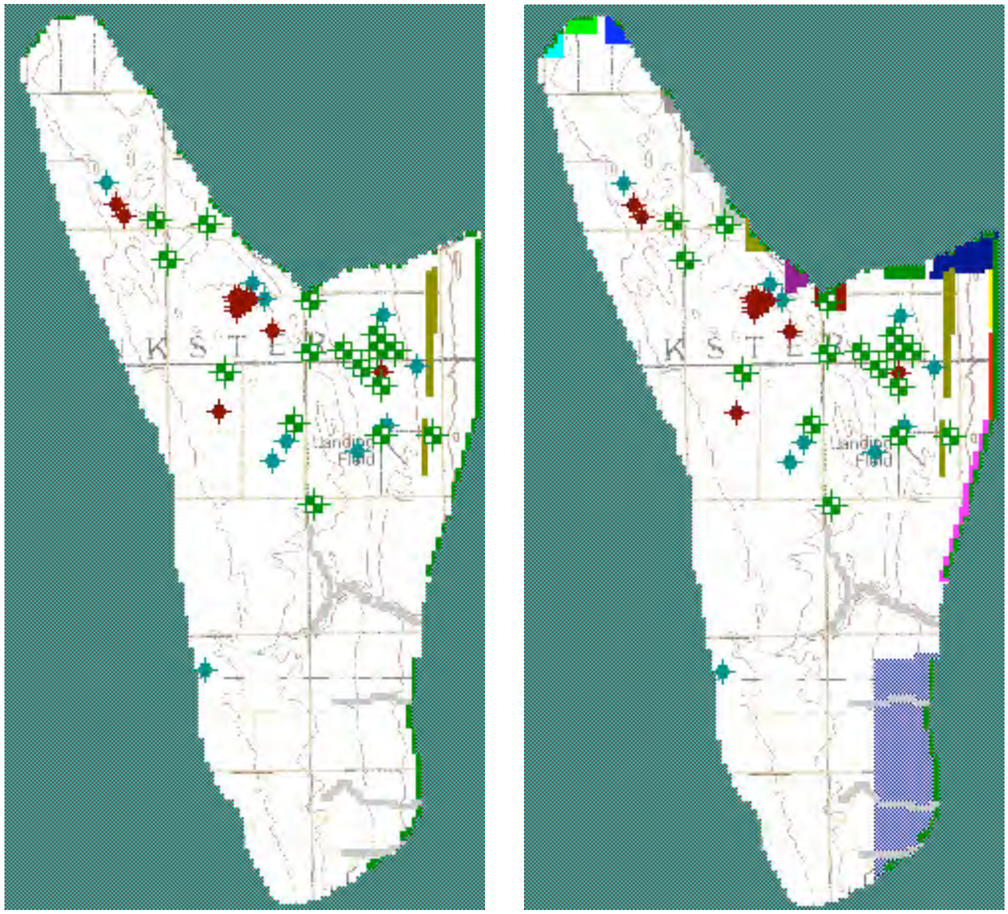

Figure 8. (A) Location of General Head boundaries (green), and; (B) General Head zones used for water budget analysis of external ET (Zone 13-red, Zone 14-magenta, Zone 15-yellow, and Zone 16-purple) along the eastern boundary, and for water budget analysis of spring discharge along the northern boundary (Zones 2 through 12, east to west). The north-south oriented linear strings of brown cells are wall cells, representing low-T barriers to flow in the west-east direction. Individual spring zones are shown on Figure 9.

**Spring Discharge:** One of the main management concerns for the FRC recharge project is retention time before loss to springs. The principal cause of deep water tables in the northern Inkster aquifer is a series of springs along the northern border which serve as discharge zones to the Forest River. These occur principally where the coulees draining to the river cut back through the till boundary, opening sand deposits for local flow. One of the largest single spring complexes is Inkster Spring, located about a half mile northeast of the basin. Kelly and Paulson (1970) reported: in 1964, springs in the segment of the Forest River that includes Inkster Spring discharged about 1,100 gpm (approx. 1,774 AF/y). The measurement was based on gaining flow in the Forest River. They reported that aquifer discharge through the Inkster Spring complex was between 200 and 700 gpm.

Between May 23 and October 20 of 1994 Jon Patch and Bill Schuh used a weir to measure discharge from one of the large discharge points of Inkster Spring, below a beaver dam. Discharge rates varied from 38 to 61 gpm with a mean of 50.5 gpm. On September 15, 2004 Ben Maendel and Bill Schuh walked the Forest River and mapped springs. Inkster Spring was estimated to have a discharge rate of about 100 gpm, based on a visual comparison with flows measured in 1994. Discharge had apparently increased substantially, possibly due to the recharge basin. A visual estimate was assigned to each of the other springs along the river, scaled to that of Inkster Spring. Eleven spring zones were identified. On September 20, 2004 Ben Maendel used a weir to measure discharge from Inkster Spring at 122 gpm. Visual estimates on all springs were scaled upward to adjust for the measured discharge. All individual springs were simulated using GH boundaries with the specified elevation at, or slightly greater than, the bottom of the boundary cell. Distances and conductances were adjusted in fitting the model. The spring discharge zones (labeled 2 through 12) are shown on Figure 9. Spring Zone 5 simulates the Inkster Spring complex.

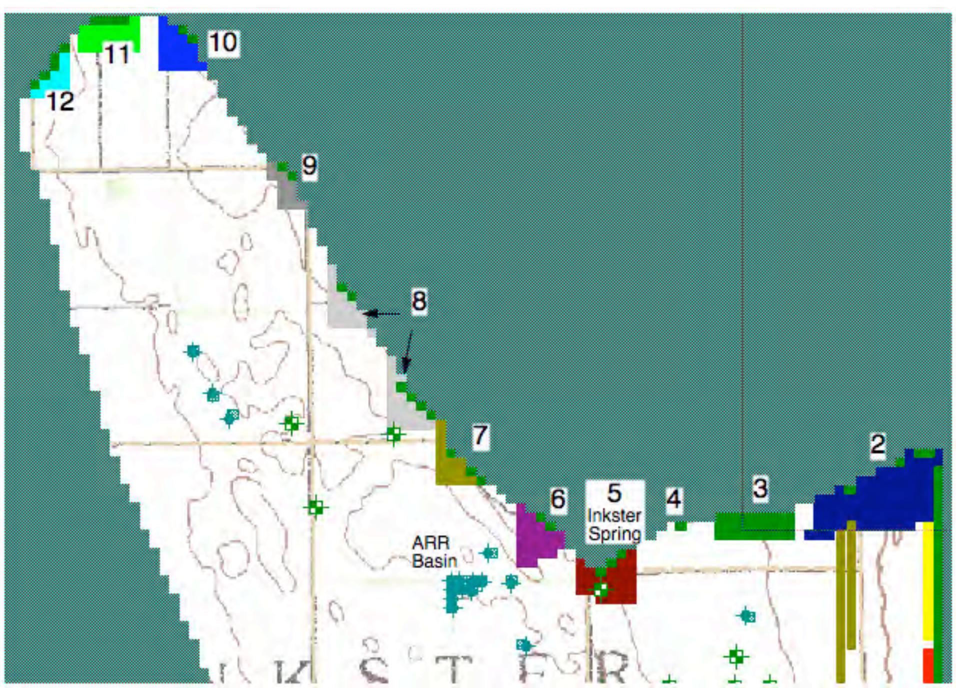


Figure 9. Location of spring discharge zones used in the model.

The correspondence of the simulated spring discharge values with field estimates in the calibrated model is shown on Figure 10. The large simulated discharge is in Zone 8, which was required to achieve a reasonable calibration. Total field-estimated discharges were 952 gpm and simulated discharges were 890, a discrepancy of 7%. If we combine the discharges into three composite zones: (1) Northeast (Zones 2 and 3), (2) Central (Zones 4, 5, 6 and 7) centered on Inkster Spring, and (3) Northwest (Zones 8 through 12), the combined totals are very close to a 1:1 correspondence, indicating that the calibrated distribution is generally reasonable, and that differences are mainly due to local variability (Figure 9B). It must be remembered that field estimates are approximate and not precise.

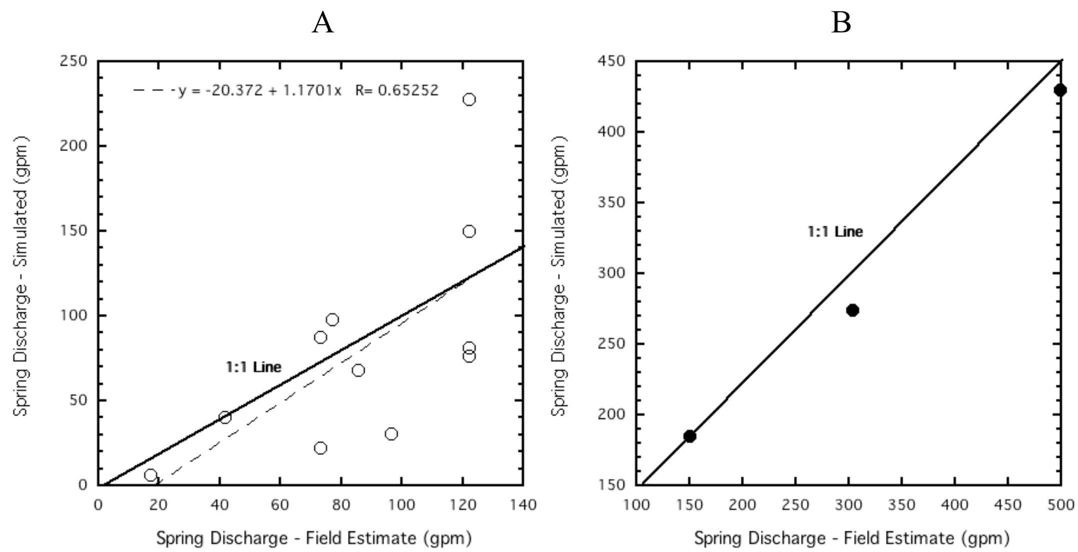


Figure 10. Comparison of field estimated and steady-state simulated spring discharge values for individual spring zones (9A), and for consolidated Northeast, Central, and Northwest spring zones (9B).

**<u>Model Calibration Control Points:</u>** Locations of the observation wells used for calibrating the steady-state model are shown on Figure 11. These 17 sites offer a reasonably good water-level representation within the area of primary concern, which is the north-central portion of the aquifer. Calibration data, however, are missing in the southern portion of the model, and in the far northwest corner.

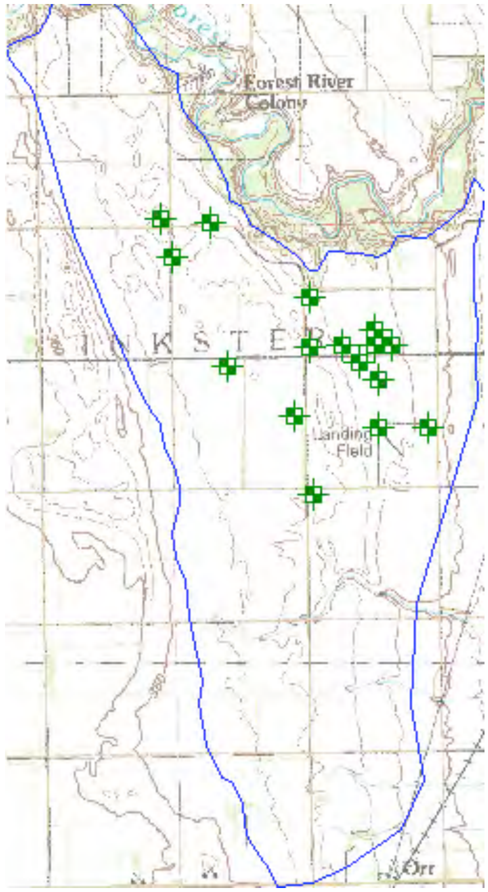


Figure 11. Locations of observation wells used as control points in model calibration.

**Pumping Wells:** The locations of pumping wells used for calibration are shown in red on Figure 12. They include wells for Water Permit #1840 for the Agassiz rural water system, and irrigation wells for Water Permits #1877, #3830, and #3892. All pumping wells simulated during calibration had been actively pumped during most of the 1980s. The two ARR recovery wells, shown near and northwest of the basin, were constructed after basin construction specifically for the purpose of recovering recharge waters before they are discharged through springs to the Forest River. Water for Water Permit #1877 is pumped from wells in both SE Section 15 and NW Section 22. To differentiate for discussion of our model, we will label the Section 22 well as Well No. 1877, and the Section 15 well group as Well No. 1877A. These wells, however, are both authorized under the same water permit. The 1877A well group consists of six wells, labeled IRR1, IRR1a, IRR2, IRR2a, IRR4 and IRR5, located on an approximate diagonal line from the center to the southeast corner of Section 15. For the purpose of the steady state model, total pumping for 1877A is treated as a single well at the center of the SE quarter of Section 15. For the transient model, the six wells are treated individually.

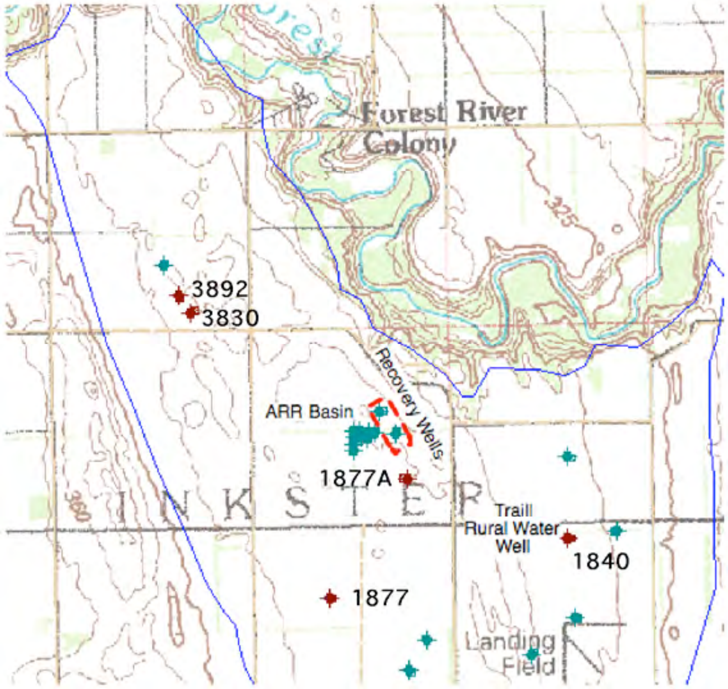


Figure 12. Locations of pumping wells. Red wells were used for calibration. The recovery wells (indicated by the red border) were used for recovery of ARR water.

**Aquifer Recharge Basins:** The ARR basin complex consists of two basins: (1) a triangular basin, having an area of 3.4 acres, and (2) a rectangular basin having an area of 4.2 acres, and length-to-width ratio of about 4:1. These are shown on Figure 13. Both the size and geometry affect basin infiltration capabilities, particularly during early operational times. Before clogging of the surface with suspended solids deposition governs the infiltration rate, recharge is governed by hydraulic mound formation, which is affected by basin size and geometry. These effects were described previously (Schuh, Patch and Maendel, 2009, WRI No. 47, p. 9) in the section titled "**Design and Operational Requirements for ARR**."

Two basins are operated simultaneously. The first basin is located in the NW corner of the SW quarter of Section 15, is triangular, and has a surface area of about 3.4 acres. Dimensions are shown on Figure 13. The second basin is located in the SW corner of the NW quarter of Section 15, is rectangular, and has a surface area of about 4.2 acres. The rectangular basin has a 4:1 length:width ratio. Basin recharge was simulated using injection well cells. To maintain a similar geometry, five cells were used for the triangular basin, and four for the rectangular basin as shown on Figure 14. The 4:1 length:width ratio was maintained on the rectangular basin. Areas, however, were approximately reversed, at 4 acres on the triangular basin, and 3.4 acres on the rectangular basin.

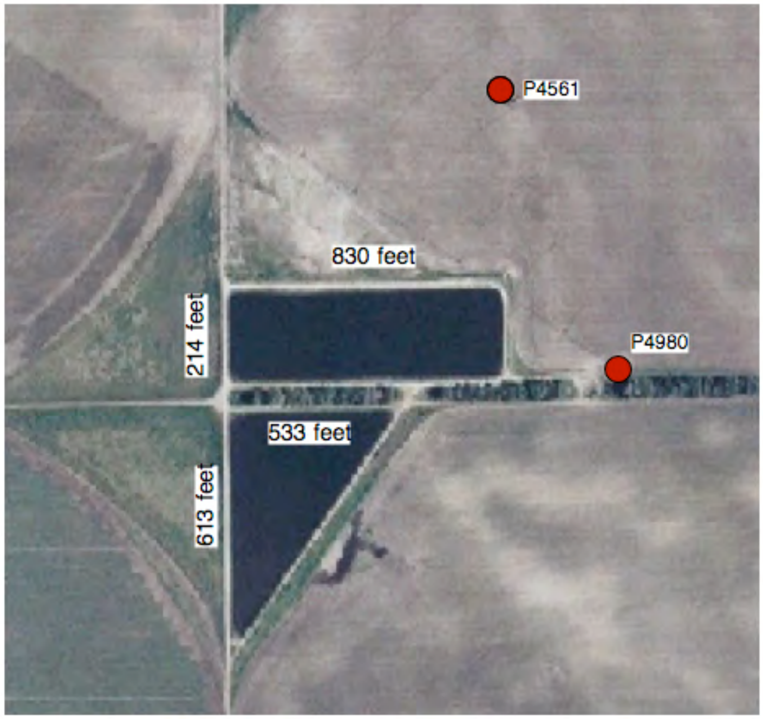


Figure 13. ARR recharge basins and local recovery wells (red).

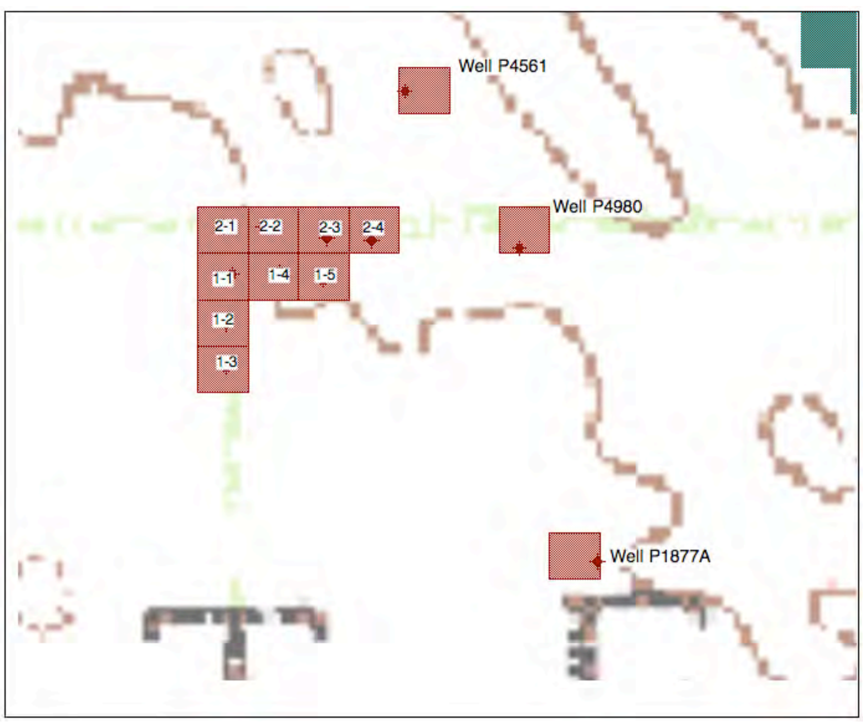


Figure 14. Injection-well cell configuration used to represent the basin recharge.

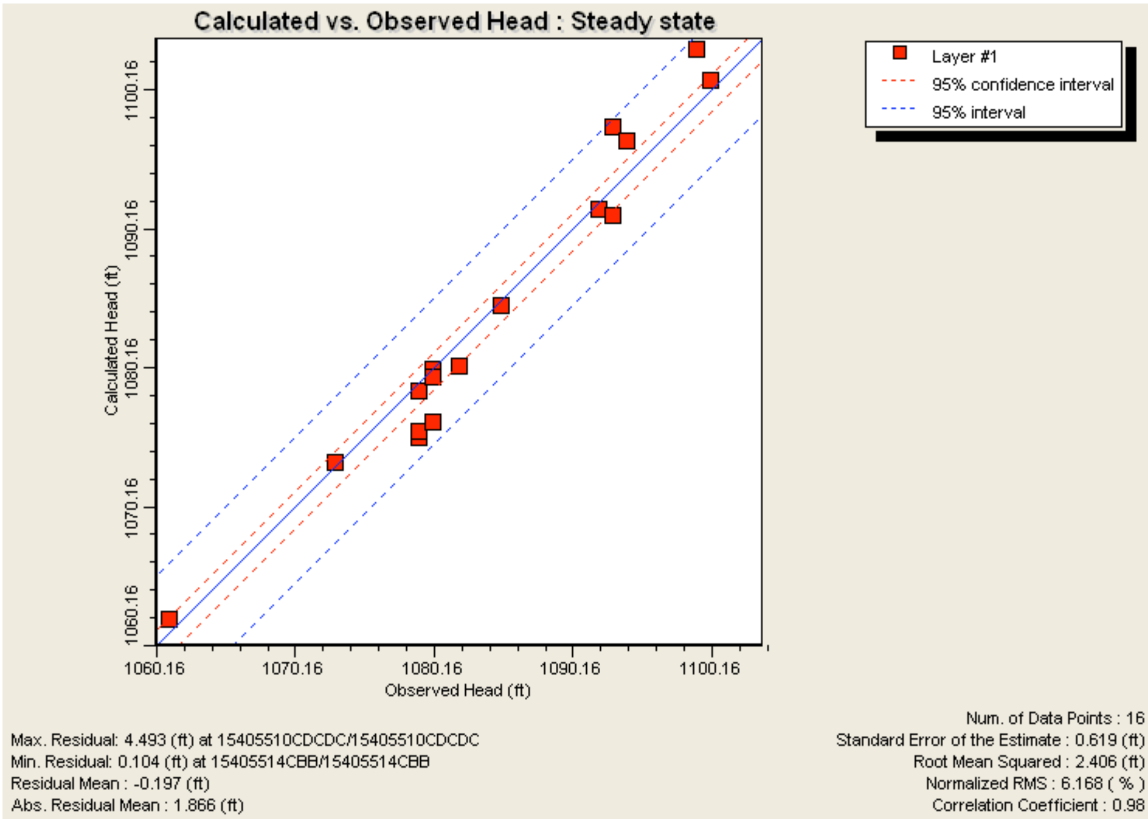


Figure 15. Calibration curve for simulated vs. measured aquifer head at control points shown on Figure 11.

**Parameters and Calibration:** The hydraulic conductivity (K) was isotropic at 55 ft./d with an effective porosity of 0.18. The calibration of simulated vs. measured head for the model is shown on Figure 15. The calibration of simulated head for observation well site 154-055-25DAA and maintenance of aquifer head below land surface on the eastern boundary required decreasing transmissivity (T) between the well and the eastern boundary. A north-south ridge in the aquifer bottom near the well was indicated by the kriged bottom representation (Figure 16). Because there are no control points east of the well, it is speculated that the ridge may be higher. Alternately, local sediments may have a lower K. A wall boundary was used to effect a lower T. The wall boundary was assigned a thickness of 10 feet, and a K of 1 ft./d (T = 10 $ft^2$/d). A simulated wall with an east-west impedance was also assigned along the northeastern boundary. The assigned wall locations are shown on Figure 8. Steady-state simulations were run for a maximum of 6,000 days, with a closure criterion of 0.01 feet.

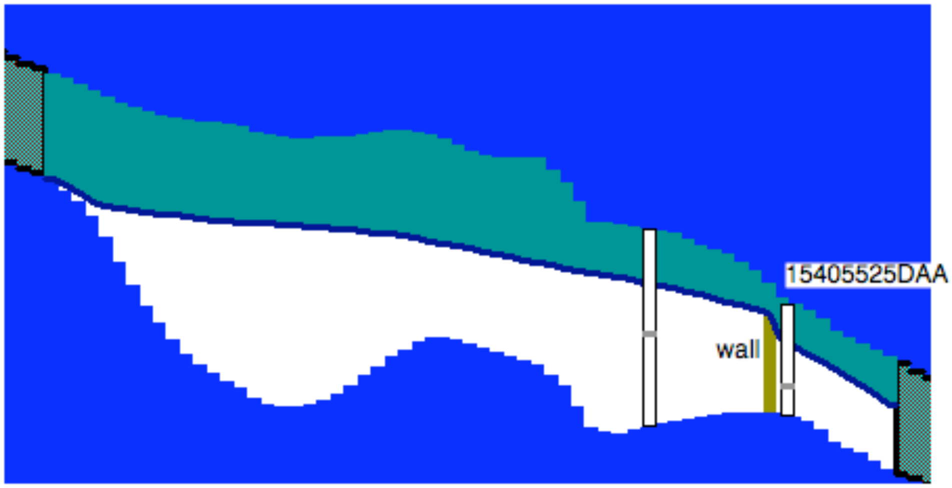


Figure 16. Illustration of the "wall" effect on simulated aquifer head at control point 15405525DAA.

**Sensitivity Analysis:** Model Sensitivity to parameters: hydraulic conductivity (K), evapotranspiration (ET), root depth, specific yield ($S_y$), and recharge is shown on Figure 17. The model is highly sensitive to small changes in K and recharge. Sensitivity to ET and root depth is very small, which is expected for an aquifer having a water table deep enough to decouple for most of its area. Sensitivity to effective porosity is small.

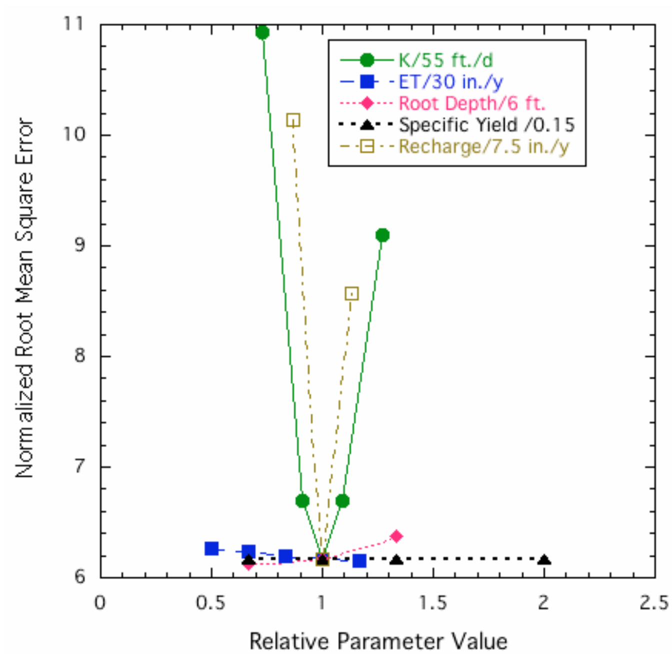


Figure 17. Sensitivity of model calibration to relative parameter.

**Results of Steady-State Model Simulations**

Under steady-state conditions all additional recharge water must be discharged. In the Inkster aquifer, the discharge is distributed between: (1) spring discharge, (2) ET discharge, and (3) discharge through drainageways. ET occurs predominantly in the southern portion of the aquifer, and along and beyond its eastern boundaries. In the model, ET is subdivided into two components: (2a) ET within the boundaries of the model, and (2b) ET through evaporative soils and wetlands beyond the eastern boundary of the model, represented by GH boundaries in Zones 13 through 16. To examine the distribution of discharge in response to ARR, basin recharge was simulated at rates of 180 AF/y (1993), 315 AF/y (1994), 514 AF/y (1996), 787 AF/y (1999), and 1,085 (2002) AF/y. For each basin recharge rate, local recovery through ARR pumping near the basin was simulated at rates varying from 0 to approx. 100% of the recharge rate. At larger recharge rates pumping cells began to dry at pumping rates approaching maximum recharge.

**Composite Spring Discharge of ARR Waters:** The simulated fraction of discharge through springs can be described for varying recharge rates using second-order polynomial functions (Figure 18). The larger the recharge rate, the smaller the portion of recharge lost through springs, and the more that is lost through ET and drainage. Maximum differences occurred near zero pumping (x-axis: Local Pumpage/Basin Recharge = 0), for which 27% of recharged waters were lost through springs at a recharge rate of 1,086 AF/y, compared with 40% lost through springs at 514 AF/y (Figure 18). The difference decreases with increasing pumping recovery, and for recoveries greater than 60%, differences in spring losses between recharge rates are insignificant. The differences are caused by basin recharge geometry, which results in radial flow at the time of recharge. Larger rates tend to redistribute more water that is oriented westward and away from the springs, to greater distances from the springs, and enhance flow toward more distant discharge zones. With greater pumping recovery, less water will move beyond the influence of spring discharge zones. Flow system effects of no pumping and 950 AF/y pumping recovery are compared for ARR recharge of 1,085 AF/y, and for no recharge or pumpage, are shown on Figures 19A, B and C.

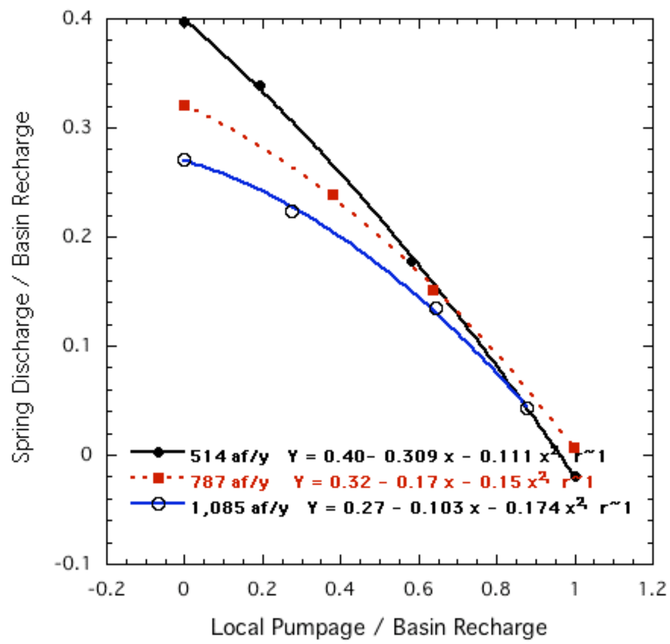


Figure 18. Relative loss of ARR recharge water through springs at varying rates of pumping recovery.

**<u>Local Distribution of Spring Discharge of ARR Waters:</u>** Changes in spring discharge at varying pumping rates for 514 AF/y, 788 AF/y and 1,085 AF/y recharge rates are shown on Figure 19A,B and C respectively. Almost all of the simulated steady-state spring discharge occurs in the central segment of the northern boundary, through spring discharge Zones 5 through 8. A small fraction of ARR water, up to a maximum of about 5 to 6%, is discharged through the northeast spring zones (Zones 2 and 3), which are generally downgradient of the basin location in the natural flow system. Negligible discharge of recharged waters occurs in the northwestern spring zones (Zones 9 through 12), which is upgradient of the basin, distant from effects of recharge redistribution, and for which intervening irrigation wells dampen the effects of recharge. It is interesting that spring discharge under near maximum pumpage actually decreases at spring Zones 5 (Inkser Spring) and 6. This occurs because the recovery wells are placed to intervene between the basin and the springs, and all of the pumping recovery occurs between the basin and Spring Zones 5 and 6, whereas basin redistribution is radial. The result is that spring losses in Zones 5 and 6 are compensated upriver in Zone 8, through which enhanced discharge occurs, even under optimal pumping.

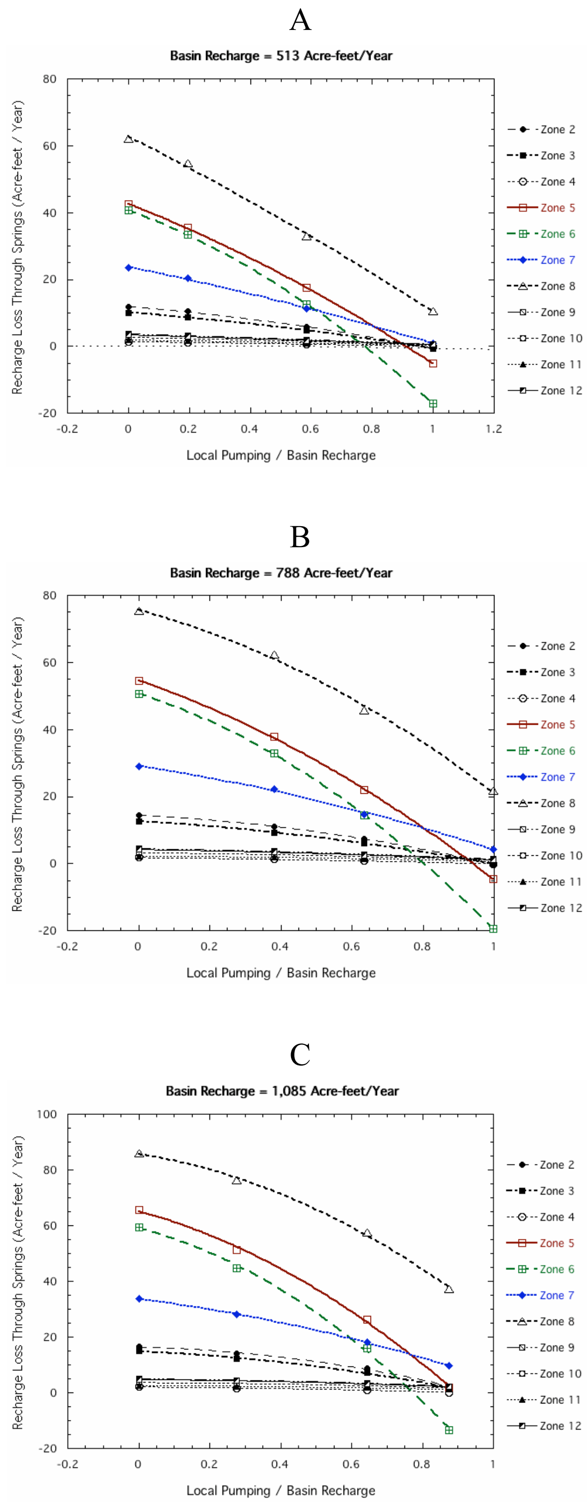


Figure 19. Discharge of ARR waters through individual spring zones under varying relative pumping recoveries for ARR recharge of: (A) 513 AF/y, (B) 788 AF/y, and (C) 1,085 AF/y.

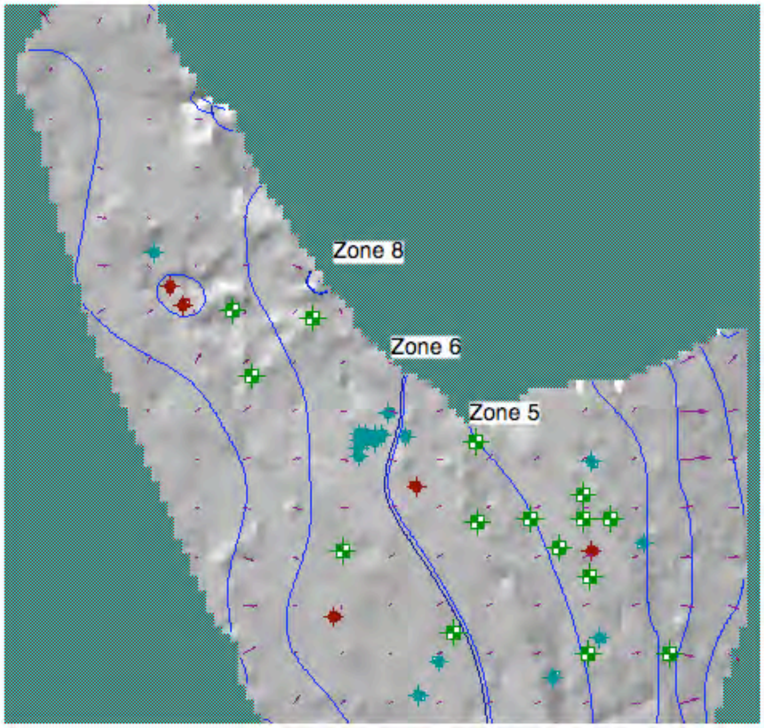


Figure 20(a). Aquifer flow system under no ARR. Red arrows are flow vectors, and contour intervals are 10 feet.

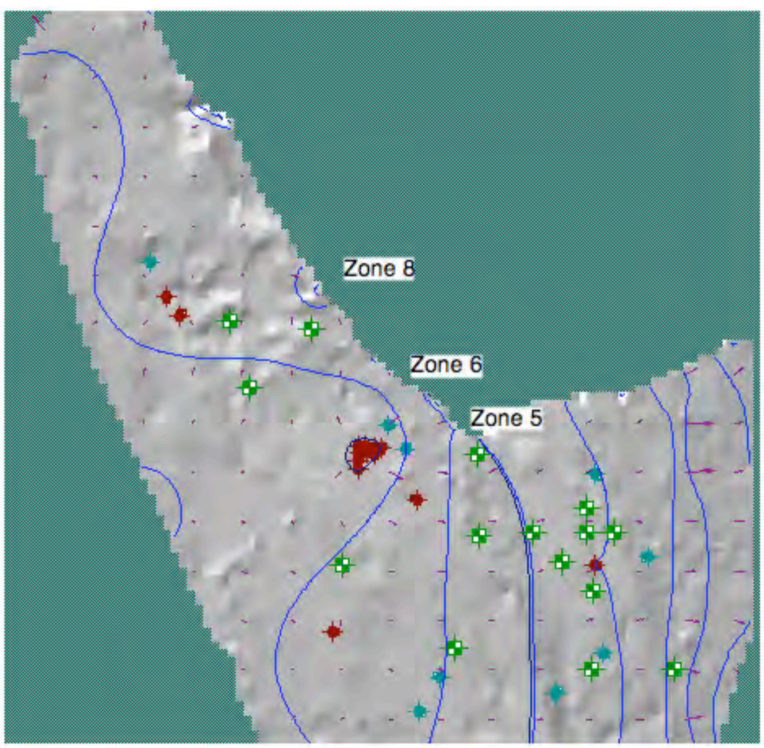


Figure 20(b). Aquifer flow system under 1,085 AF/y ARR recharge with no pumpage. Red arrows are flow vectors, and contour intervals are 10 feet.

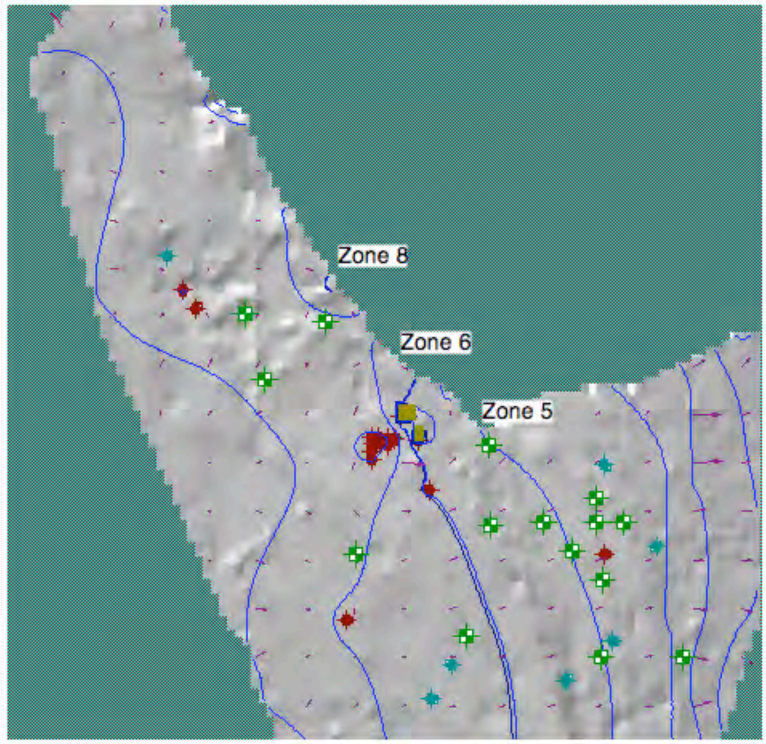


Figure 20(c). Aquifer flow system under 1,085 AF/y ARR recharge with 950 AF/y ARR pumpage. Red arrows are flow vectors, and contour intervals are 10 feet.

**Composite Discharge Water Budget:** Under steady-state conditions, recharge must equal discharge. Inkster ARR recharge is apportioned between pumpage, drainage, springs and total ET. Predominant discharge sinks are important because they indicate, in a general sense, the approximate time of storage of unpumped waters. Predominant ET sinks occur along the eastern boundary of the aquifer about 1.75 miles from the basin. The predominant spring discharge zones range from 0.6 miles at Inkster Spring (Zone 5) and Zone 6, to 1.3 miles at Zone 8. Distance to the drains is greater than 2.4 miles. Longer distances should allow for longer detention times.

The relative proportion of discharge of unpumped waters through different sinks is shown on Figure 21. Total ET includes amounts occurring within the aquifer boundaries, and amounts discharging beyond the eastern boundary. At low rates of pumpage recovery the largest proportion of discharge is though ET. Highest ET loss occurs with highest recharge rates. At greater than 60% well recovery, however, ET losses at all recharge rates are effectively the same.

Simulated basin recharge losses through spring discharge are second highest. Greatest loss occurs with lowest recharge rates for reasons discussed above, related to the relative positions of pumping recovery and the redistribution of water from the basins.

As with ET, spring losses at all recharge rates converge at greater than 60% pumping recovery. Also, spring losses and ET losses converge and are effectively the same at greater than 60% pumpage recovery. This occurs because with high local pumpage, less ARR water enters the natural flow system toward the distant ET sinks. Drainage losses, even with no local pumpage, never exceed 10% of ARR recharge. Drainage discharge for all three pumping rates are so similar, that they are treated as a single function.

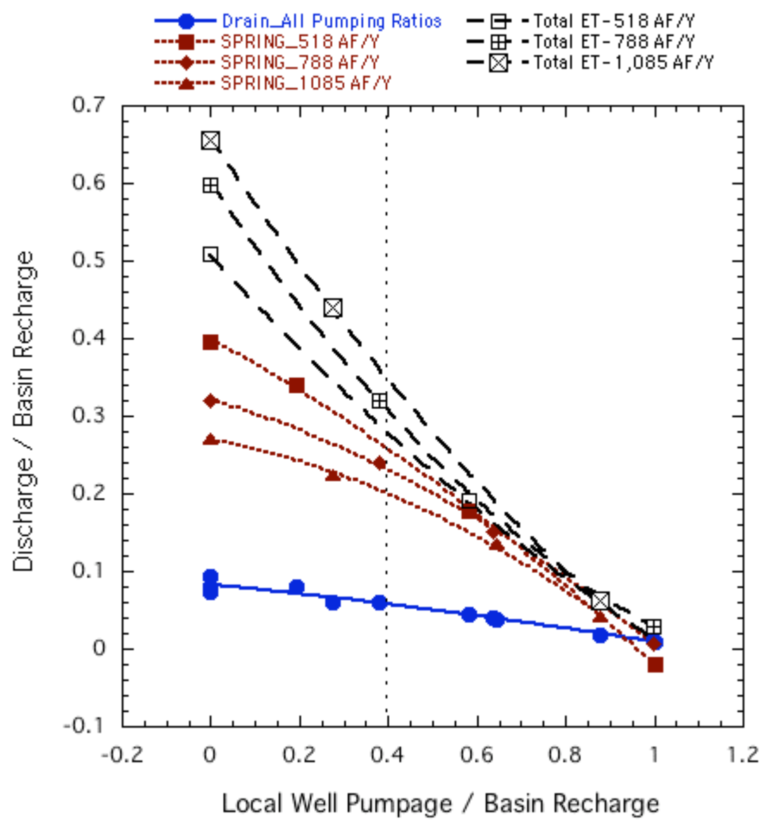


Figure 21. Proportion of ARR recharge that is discharged through ET and through springs, indicated by steady-state simulations recharge rates of 518 AF/y, 788 AF/y and 1,085 AF/y.

**Estimated Time of Influence:** Approximate time of effect from recharge on respective discharge zones can be estimated using:

$$t = \frac{Sd^2}{2.25T} \qquad (1)$$

Where T is transmissivity, S is the aquifer specific yield, d is distance, and t is time. Using a saturated thickness of about 30 feet for the aquifer between the basin and the springs, with a specific yield of 0.15 and K of 55 ft./d, the time of effect would be about 1.1 and 1.2 years for Spring Zones 5 and 6, and about 5.5 years for Spring Zone 8. Using a saturated thickness of 37 ft., the time of effect would be about 7.8 years for ET at and beyond the eastern border of the aquifer. Using a saturated thickness of 44 ft., the time for recharge effect at the drain would be 11.8 years.

Greater detention times indicate longer aquifer storage. They do not necessarily indicate, however, that the waters can be recovered within the property of the basin operators with later pumpage. If sufficient time elapses before recovery, recharged waters may have escaped influence of local pumping, and may or may not be captured by other water users before discharge though distant sinks. **Storage dynamics need to be examined more closely using a transient model.**

**Indications of Steady-State Particle Tracking**

Effects of long-term ARR operation on ET and spring discharge may be of two types: (1) direct losses through discharge of recharged waters; and (2) indirect losses affected by alteration of the flow system near the discharge point. "Direct loss" is defined as the discharge of water molecules that actually recharged through the basin. "Indirect loss" is defined as discharge of water molecules that are within the ambient flow system and which have a recharge source other than the ARR source, but which have been redirected toward a specified discharge sink by the hydraulic impact of the basin on the flow system. Direct losses can be examined using particle-tracking in the model. Indirect losses (discharge) cannot.

A simulated particle was placed in each recharge cell (9 cells), and tracked to discharge zones for 0, 40, 60, 80 and 90% (88% for 1,085 recharge) local pumping recovery on two basin recharge treatments: (1) 514 AF/y and (2) 1,085 AF/y).

**Particle-Analysis for 1,085 AF/y ARR Recharge:** Particle paths for individual cells are shown for 1,085 AF/y recharge and varying pumping recoveries on Figures 22(a-d). Individual path times and destinations are summarized on Table 1. Particle destinations were strongly dependent on the location of the injection point within the basin, and on well field recovery and location.

With 88% pumping recovery, direct losses of recharged waters are through local wells, and discharge is completed within two years. With 80% pumping recovery, all direct discharge of basin recharge water occurs through wells, except for one cell which discharges through Inkster Spring within two years. For 60% pumping recovery, three cells discharge through Inkster Spring and Spring Zone 6 north of the basin, within two to four years. The mean particle travel time for discharge to springs was 3.5 years. Particles from the six remaining cells discharge through local wells within two years. For no pumping recovery [Figure 22(d)] direct discharge for one cell occurs through the well

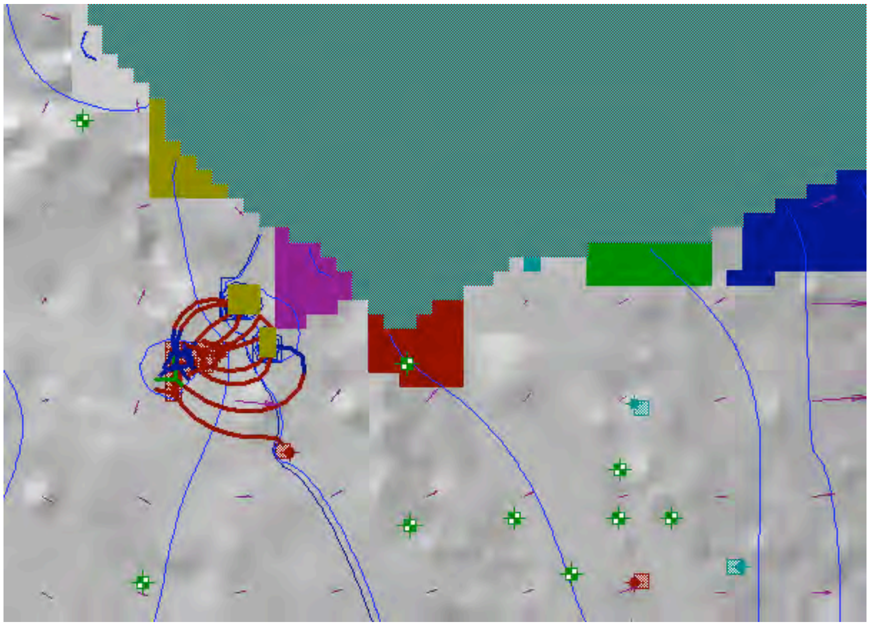

Figure 22(a). Particle track for ARR recharge of 1,085 AF/y and 88% (950 gpm) recovery through local pumping.

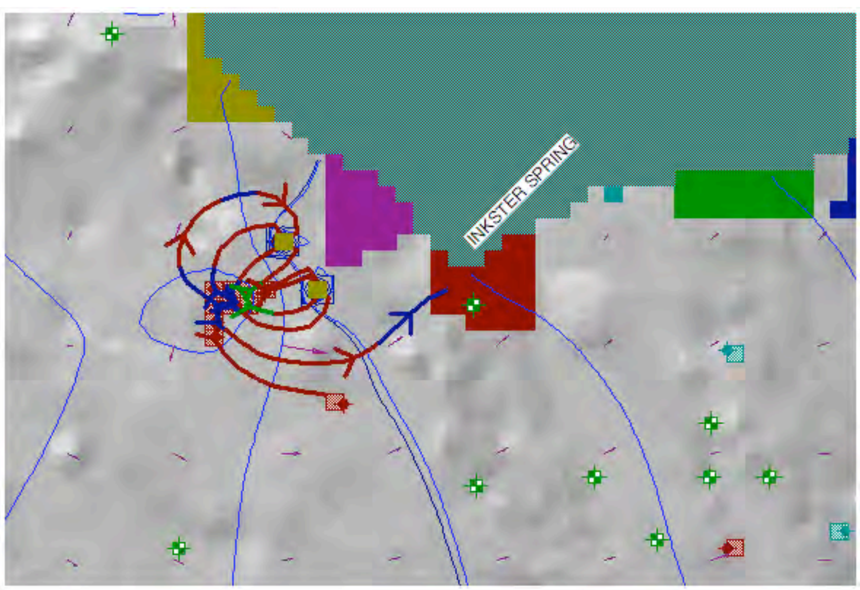


Figure 22(b). Particle track for ARR recharge of 1,085 AF/y and 80% (868 gpm) recovery through local pumping.

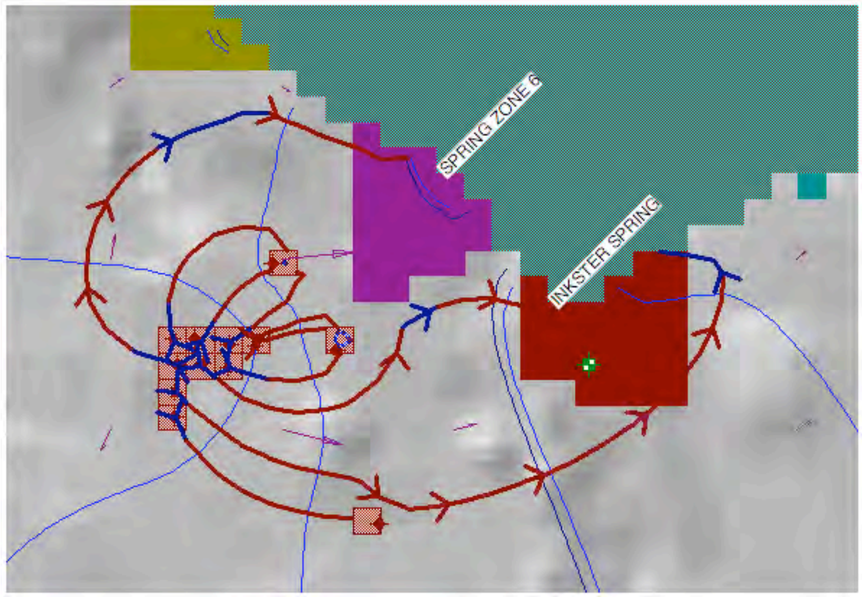


Figure 22(c). Particle track for ARR recharge of 1,085 AF/y and 60% (652 gpm) recovery through local pumping.

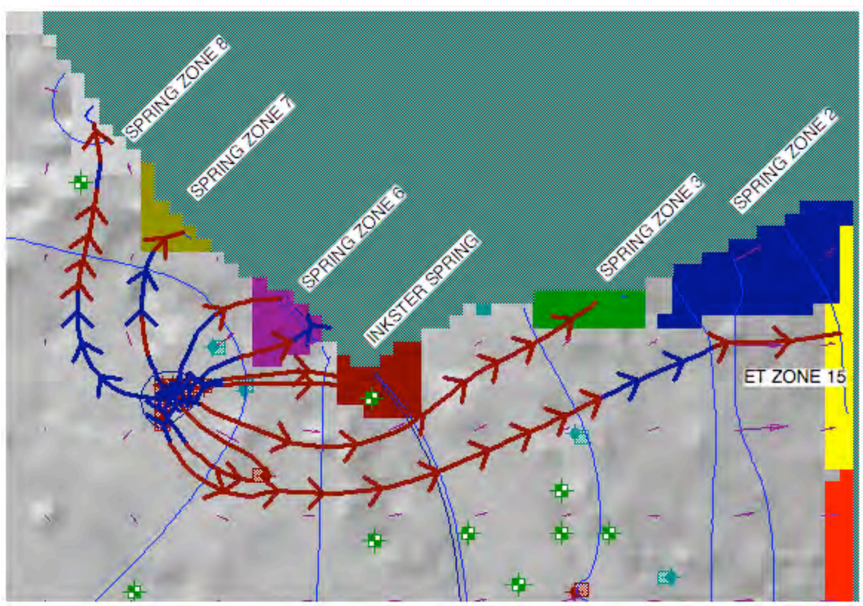


Figure 22(d). Particle track for ARR recharge of 1,085 AF/y and no recovery through local pumping.

field associated with a preexisting water permit (#1870A) in southeast Section 15; particles for one cell discharge through the eastern boundary of the aquifer after about four years; particles for another cell discharge through Spring Zone 3 about a mile northeast of the basin; and particles for the other six cells all discharge through Spring Zones 5 (Inkster Spring) through 8.

**Particle-Analysis for 514 AF/y ARR Recharge:** Particle paths for individual cells are shown for 514 AF/y recharge and varying pumping recoveries on Figures 23(a-b). Individual path times and destinations are summarized on Table 1. For 80% pumping recovery, only one basin cell discharged through a spring (Inkster Spring), with a travel time of three years. For 60% well recovery particles from two basin cells discharged through Inkster Spring (Spring Zone 5). The rest discharged through wells. With 40% local pumping recovery, particles from one cell discharged through Spring Zone 3, while two discharged through Inkster Spring [Figure 23(a)]. The mean travel for spring discharge was 2.3 years (Table 1). For no local well recovery, particles from seven cells discharged through Spring Zones 2, 3, 5 (three cells) and 6 (two cells).

Steady-state simulations indicate that basin position is important for determining the paths and destinations of recharge water particles. South-center basin cells are frequently recovered through irrigation well group #1877A, north-center cells (2-2 and 2-3) are usually recovered through irrigation well #4561, and eastern cells are usually recovered through irrigation well #4980. Northwestern basin cells are frequently discharged through springs north and northeast of the basin complex when there is no pumping recovery, and southwestern cells are frequently discharged through distant springs to the northeast of the basin complex. Higher basin recharge tends to increase discharge northwest of the basin complex, while at lower recharge rates, the tendency is toward spring discharge northeast of the basin complex. This, as previously discussed, occurs because at larger recharge rates more water tends to move westward under larger recharge mounds during the recharge period.

Table 1. Travel times and destinations for each basin cell, as affected by local pumping recovery fractions. * *The label 1877A identifies the well group used to pump water for Water Permit #1877 in SE Section 15.*

| (1) Basin Rech. AF/y | (2) Pump Recovery Fraction | (3) Basin Cells | (4) Discharge Zone | (5) Travel Time (y) | (1) Basin Rech. AF/y | (2) Pump Recovery Fraction | (3) Basin Cells | (4) Discharge Zone | (5) Travel Time (y) |
|---|---|---|---|---|---|---|---|---|---|
| 514 | 0.0 | 1-1 | 2 | 6 | 1,086 | 0.0 | 1-1 | 8 | 4 |
| | | 1-2 | 1877A* | 1 | | | 1-2 | 1877A | 1 |
| | | 1-3 | 1877A | 1 | | | 1-3 | 15 | 4 |
| | | 1-4 | 1877A | 1 | | | 1-4 | 1877A | 1 |
| | | 1-5 | 3 | 1 | | | 1-5 | 3 | 2 |
| | | 2-1 | 6 | 4 | | | 2-1 | 7 | 3 |
| | | 2-2 | 6 | 2 | | | 2-2 | 6 | 2 |
| | | 2-3 | 5 | 2 | | | 2-3 | 5 | 3 |
| | | 2-4 | 5 | 1 | | | 2-4 | 2 | 2 |
| 514 | 0.4 | 1-1 | 3 | 5 | 1,086 | 0.4 | 1-1 | 7 | 3 |
| | | 1-2 | 1877A | 1 | | | 1-2 | 1877A | 1 |
| | | 1-3 | 1877A | 1 | | | 1-3 | 1877A | 1 |
| | | 1-4 | 5 | 1 | | | 1-4 | 5 | 2 |
| | | 1-5 | 5 | 1 | | | 1-5 | 5 | 2 |
| | | 2-1 | #4561 | 1 | | | 2-1 | 6 | 4 |
| | | 2-2 | #4561 | 1 | | | 2-2 | #4561 | 2 |
| | | 2-3 | #4980 | 1 | | | 2-3 | 6 | 2 |
| | | 2-4 | #4980 | 1 | | | 2-4 | #4980 | 2 |
| 514 | 0.6 | 1-1 | 5 | 1 | 1,086 | 0.6 | 1-1 | 6 | 4 |
| | | 1-2 | 1877A | 1 | | | 1-2 | 5 | 3 |
| | | 1-3 | 1877A | 1 | | | 1-3 | 1877A | 2 |
| | | 1-4 | 5 | 1 | | | 1-4 | 5 | 4 |
| | | 1-5 | #4561 | 1 | | | 1-5 | #4561 | 2 |
| | | 2-1 | #4561 | 1 | | | 2-1 | #4561 | 2 |
| | | 2-2 | #4980 | 1 | | | 2-2 | #4561 | 2 |
| | | 2-3 | #4980 | 1 | | | 2-3 | #4561 | 2 |
| | | 2-4 | #4980 | 1 | | | 2-4 | #4980 | 1 |
| 514 | 0.8 | 1-1 | #4980 | 2 | 1,086 | 0.8 | 1-1 | #4561 | 4 |
| | | 1-2 | 5 | 3 | | | 1-2 | 5 | 3 |
| | | 1-3 | 1877A | 1 | | | 1-3 | 1877A | 1 |
| | | 1-4 | #4980 | 1 | | | 1-4 | #4980 | 2 |
| | | 1-5 | #4980 | 1 | | | 1-5 | #4980 | 2 |
| | | 2-1 | #4561 | 1 | | | 2-1 | 6 | 4 |
| | | 2-2 | #4561 | 1 | | | 2-2 | #4561 | 2 |
| | | 2-3 | #4980 | 1 | | | 2-3 | #4561 | 2 |
| | | 2-4 | #4980 | 1 | | | 2-4 | #4980 | 1 |

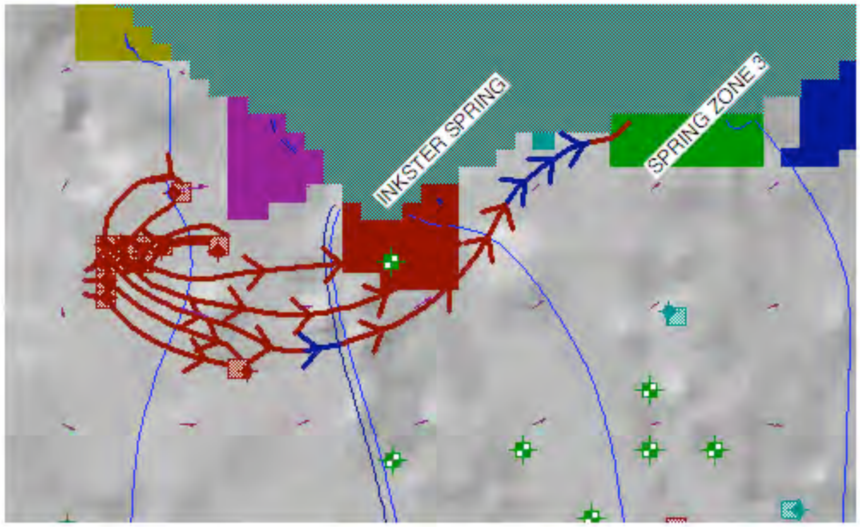


Figure 23(a). Particle track for ARR recharge of 514 AF/y and 80% (412 AF/y) recovery through local pumping.

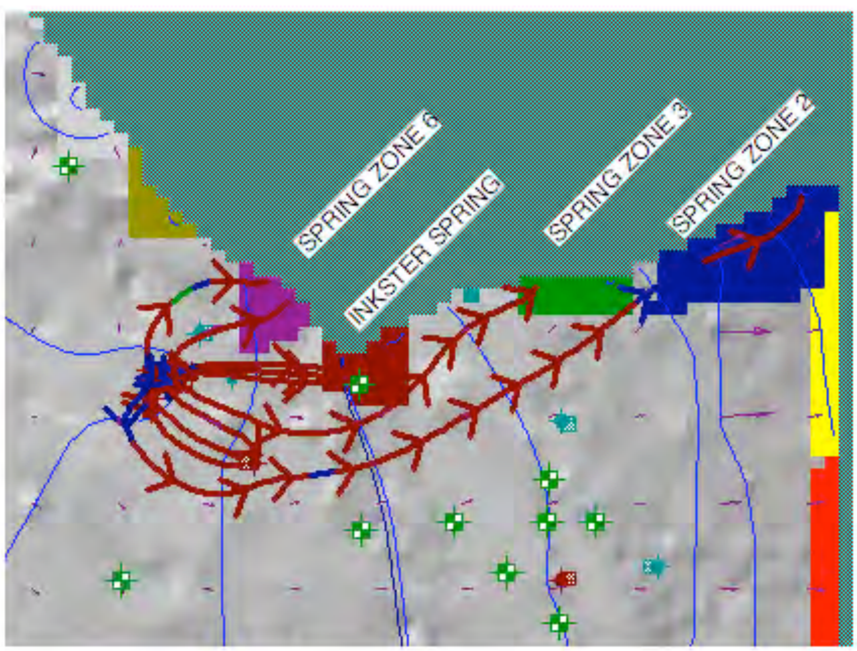


Figure 23(b). Particle track for ARR recharge of 514 AF/y and 40% (206 AF/y) recovery through local pumping.

**<u>Summary of Particle-Tracking Analysis:</u>** Particle tracking indicates the direct movement of water molecules from the basin toward discharge zones. Recharged waters tend to be retained for an average of two to three years before being discharged through springs, and as many as six years before being discharged from distant ET discharge zones near the northeast boundary of the model. A significant portion of waters not recovered through local pumpage associated with the project are recovered through irrigation well field #1877A southeast of the basin complex. With no local pumpage recovery, the maximum direct loss through springs and ET is estimated at about 26% for approx. 1,000 AF/y recharge, and about 20% for approx. 500 AF/y recharge. The rest of the waters (74% and 80% respectively) are lost through more ET, drain, and spring discharge sinks through indirect hydraulic effects of basin operations: i.e., through elevated water tables caused by upgradient impedance, or downgradient enhancement of aquifer heads which drive flow and discharge. The effects of basin operation on spring discharges along the Forest River would be prolonged enhanced flows caused by increased water levels near the spring from basin operation.

## TRANSIENT-FLOW MODEL OF THE INKSTER AQUIFER

The transient model was constructed using the same boundaries, grid, properties and parameters as the steady-state model. Final head values for the steady-state model were used for initial heads in the transient-flow model. Recharge and discharge scenarios were the same as the steady-state model so that climatic effect was invariant. Although pumping from some additional water permits was initiated in the early 1990s, the wells used in the model were the same as for the steady-state model, including points of diversion for Water Permits #1840, #1877, #3830 and #3892. Actual reported annual pumpage for each well was used and applied at a steady rate over 105 days. An exception was #1840 (the Agassiz Rural Water supply well field) which was applied at a constant rate over the full year.

### Transient Simulations of the ARR Basin

The spatial representation of natural recharge was the same as in the steady-state model. However, the infiltration rate was calculated for each year according to the following constraints. Initial infiltration rate (i) and cumulative infiltration (I) measurements for the first (south triangular) basin were described as:

$$I = 5.37t^{0.76} \qquad (2)$$

and

$$i = 4.08t^{-0.24} \qquad (3)$$

In this equation, the coefficient value (4.08 ft./d) approximates the initial unclogged hydraulic conductivity and was retained as a local basin operational property. The time period (t) was constrained by reported initial and final pumping dates for each year, and applied with the actual total reported basin infiltration (I, acre-feet) to recalculate an annual exponent.

$$I_{year} = 5.37t^{k} \qquad (4)$$

and

$$i_{year} = k5.37t^{k-1} \qquad (5)$$

The calculated rate was distributed over the nine injection well cells representing the full basin in the approximate order of wetting, beginning in the east and filling toward the west (Schuh, Patch and Maendel, 2009). With the initiation of the second (north rectangular) basin in 1994, the north basin was also activated in staggered increments from east to west. In summary, the order of filling was (Figure 14): Basin 1 (the triangular basin) fill east to west [cell order 1-5, 1-4, 1-1, 1-2, 1-3]; followed by: Basin 2 (the rectangular basin) fill east to west [cell order 2-4, 2-3, 2-2, 2-1]. The infiltration rates were averaged and applied as seven discrete time increments.

Extraction wells dedicated to the basin waters (Figures 13 and 14) are the points of diversion for Water Permits #4561 (north of basin 2) and #4980 (east of the center line between the two basins). Operational times for wells #4561 and #4980 were 105 days, beginning on May 15th of each year. Pumpage for individual wells was not reported by the FRC, and was, rather, "distributed" over wells in the vicinity of the basin. Our simulations indicated that the two dedicated wells could not be pumped at the reported rates in large application years without drying by the end of the summer. This likely occurs because basin waters are spreading in all directions and some move westward beyond the immediate influence of the wells, and cannot be locally extracted in late summer. The transient model was modified by increasing the K in a northwest to southeast oriented channel near the basin. This is justified by evidence of a deeper and coarser channel oriented northwest to southeast, that is indicated by aerial infrared photography for the extent of the modified area (Figure 7 in Schuh, Patch and Maendel, 2009), by the orientation of the well field southeast of the basin (Figure 6 in Schuh, Patch and Maendel, 2009), and by lithologic logs for the irrigation wells which indicate the presence of deeper gravelly strata (see logs 154-055-14CBB and 154-055-14DCC in Appendix 2). Four local K zones are shown on Figure 24. The inner zone near the basin was assigned a local K of 150 ft./d, while the three outer zones had an identical local K of 90 ft./d. This compares with K of 55 ft./d for the entire aquifer, derived from calibration of the steady-state model.

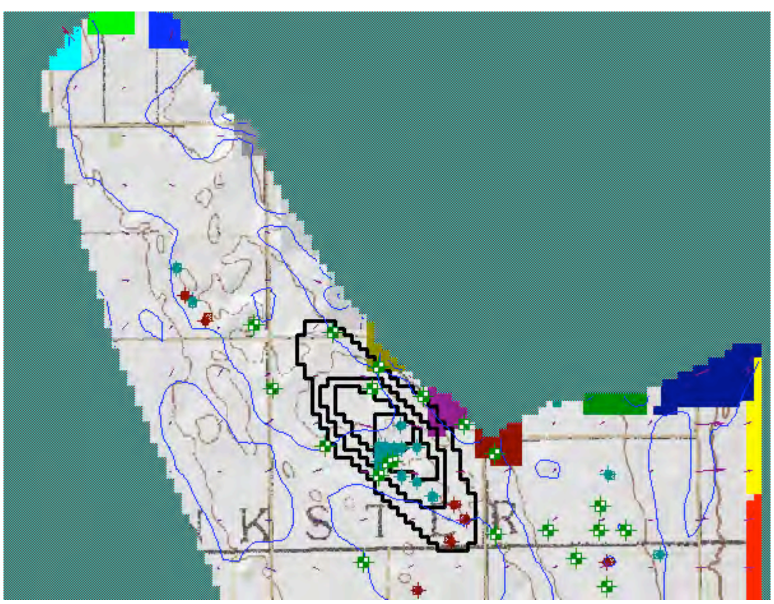

Figure 24. Hydraulic conductivity zone boundaries (black lines).

In addition, recovery of recharged waters was shared with three additional wells (IRR5, IRR4, and IRR2) previously allocated to well field #1877A, and located between 400 and 1400 feet of the basin in the southeast direction. All pumpage for well field #1877A, which preceded the basin operation, was then confined to points of diversion at IRR1, IRR1A, and IRR2A in the southeast corner of Section 15 (Figure 2).

Because the purpose of the simulations is to evaluate potential losses of basin recharge water, and ARR waters are small in relation to overall recharge and discharge for the aquifer, a low mass balance discrepancy was required. Mass balance discrepancies were below 0.02 and 0.01%. This amounted to a difference of about 8.4 acre-feet for the simulated time.

**Model Verification:** Nine monitoring wells (B2, B3, B8, B9, B10, B11, B12, B13 and SWC6) were placed near, and at distances up to a quarter-mile from the basin (Figure 2). These wells were used for verification of the transient model. Of the wells, only one (SWC6) had been installed before initiation of recharge operations, and therefore only one of the wells had been used for calibration of the steady-state model.

A 15-year (1992 to 2007) transient simulation was run using reported annual recharge and pumping scenarios. In general, temporal correspondence of simulated and measured heads was good. The amplitudes of measured peaks and valleys were generally larger than the simulated, which would be expected when the water table is approaching land surface where vadose response amplification occurs (Gillham, 1984). MODFLOW parameters do not simulate the near-surface head amplification, which is dependent on non-linear vadose-zone hydrologic processes.

The initial vertical correspondence was poorest near the river, indicating that the initial water tables were substantially lower than estimated in the steady-state model. This is not surprising for two reasons. First, there were few control elevations measured near the river for use in steady-state calibration. The only well available for calibration was SWC6, located near Inkster Spring, and simulated water levels at this location were initially within three feet of the measured elevations (Figure 25) and were even closer after six years. This is a key position for simulation of Inkster Spring discharge. Second, the steady-state calibration was based on "characteristic" water-level elevations in the mid-to late 1980s. However, the period from 1988 through 1992 was dry, which would have enhanced drawdown near the river through seepage. Initial dry conditions followed by very wet conditions in 1993, and a wetter climatic pattern in the mid-to late 1990s likely explain the pattern of increasing measured ground-water levels during the first six years of simulation.

Increasing natural water levels are illustrated for monitoring well sites B8 (Figure 26), B9 (Figure 27), and B10 (Figure 28). For all three well sites the simulated water-level elevations are substantially higher (5 feet for B9, about 15 feet for B8 and B10) than the measured, indicating more initial drawdown along the river than simulated in the steady-state model. However, after scaling, all three exhibit similar relative recharge and discharge patterns, with reasonably good time correspondence for peaks. Simulated data were "scaled" to observed data by calculating the difference between simulated and observed after an initial equilibration time (generally one year was used) and adding the difference to all simulated values. Well B9, particularly, has a good correspondence for scaled amplitude as well as timing of peaks. A similar pattern is seen for Well B11, located a quarter mile north of the basin, approaching Spring Zone 6 (Figure 29).

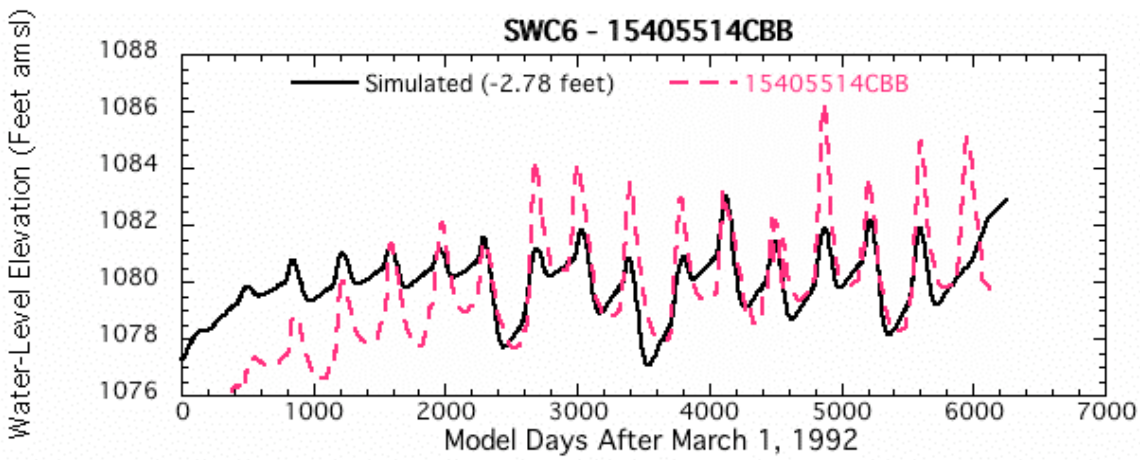


Figure 25. Simulated (black) and measured (red) water-level elevations for the monitoring well nearest Inkster Spring (154-055-14CBB).

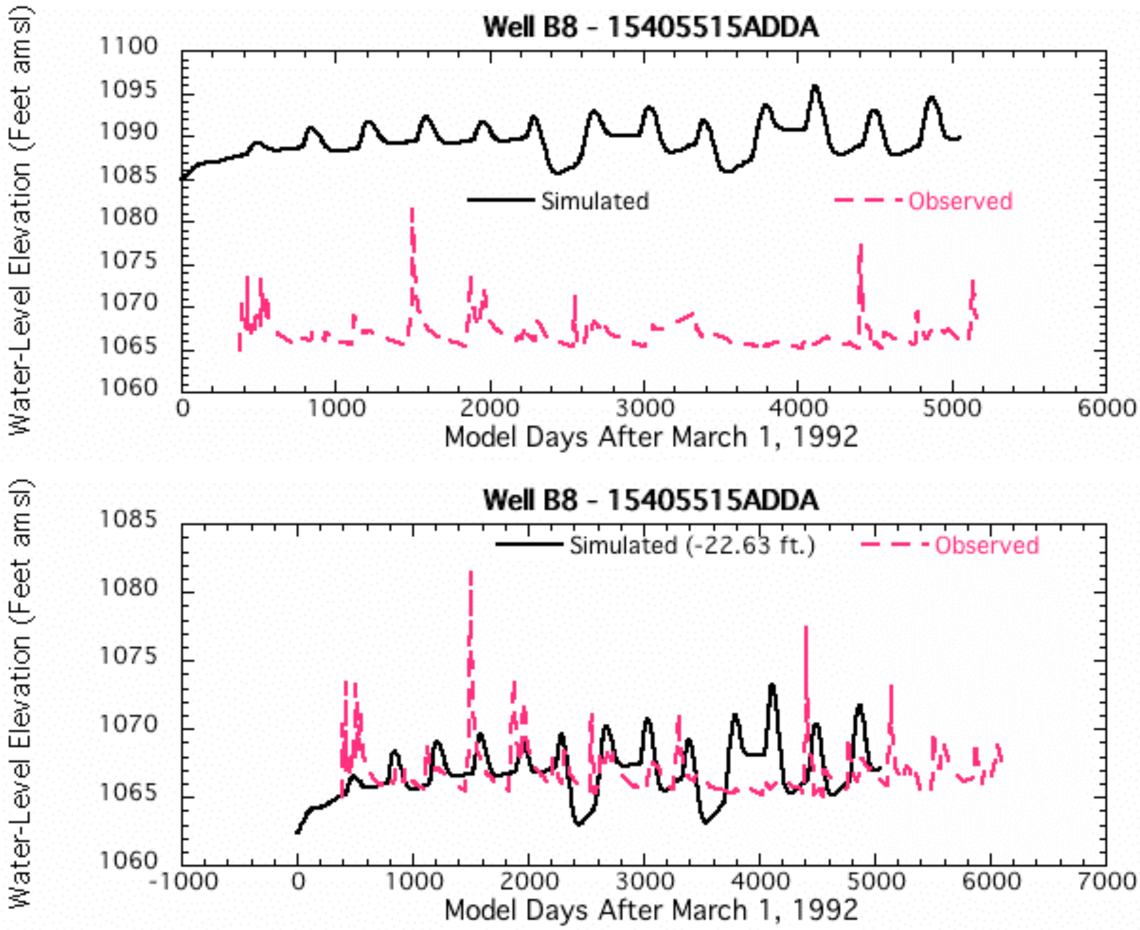


Figure 26. Simulated (black) and measured (red) water-level elevations for the monitoring well located northeast of Inkster Spring (154-055-15ADDA) (top), and scaled (March 1, 1993) simulated values (black) and measured (red) water levels (bottom).

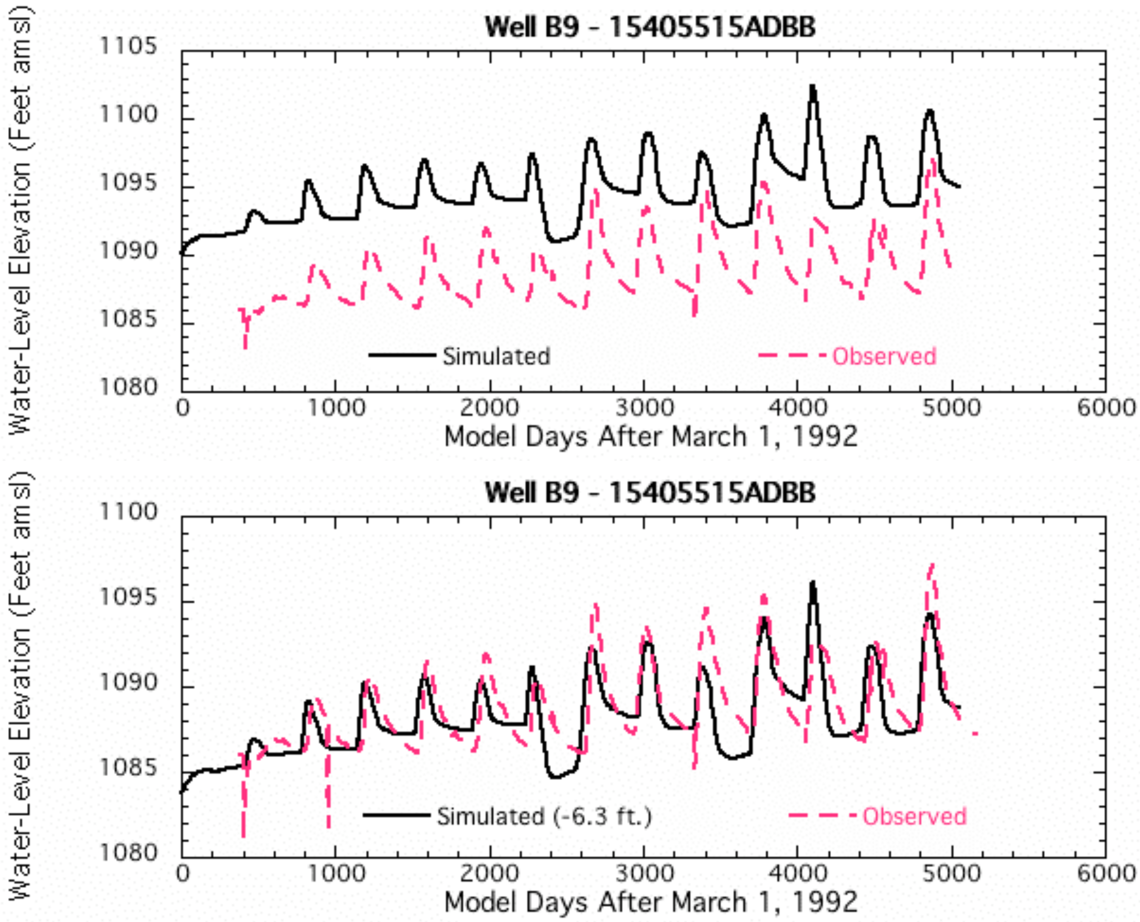


Figure 27. Simulated (black) and measured (red) water-level elevations for the monitoring well located near southeast of Spring Zone 6 (154-055-15ADBB) (top), and scaled (March 1, 1993) simulated values (black) and measured (red) water levels (bottom).

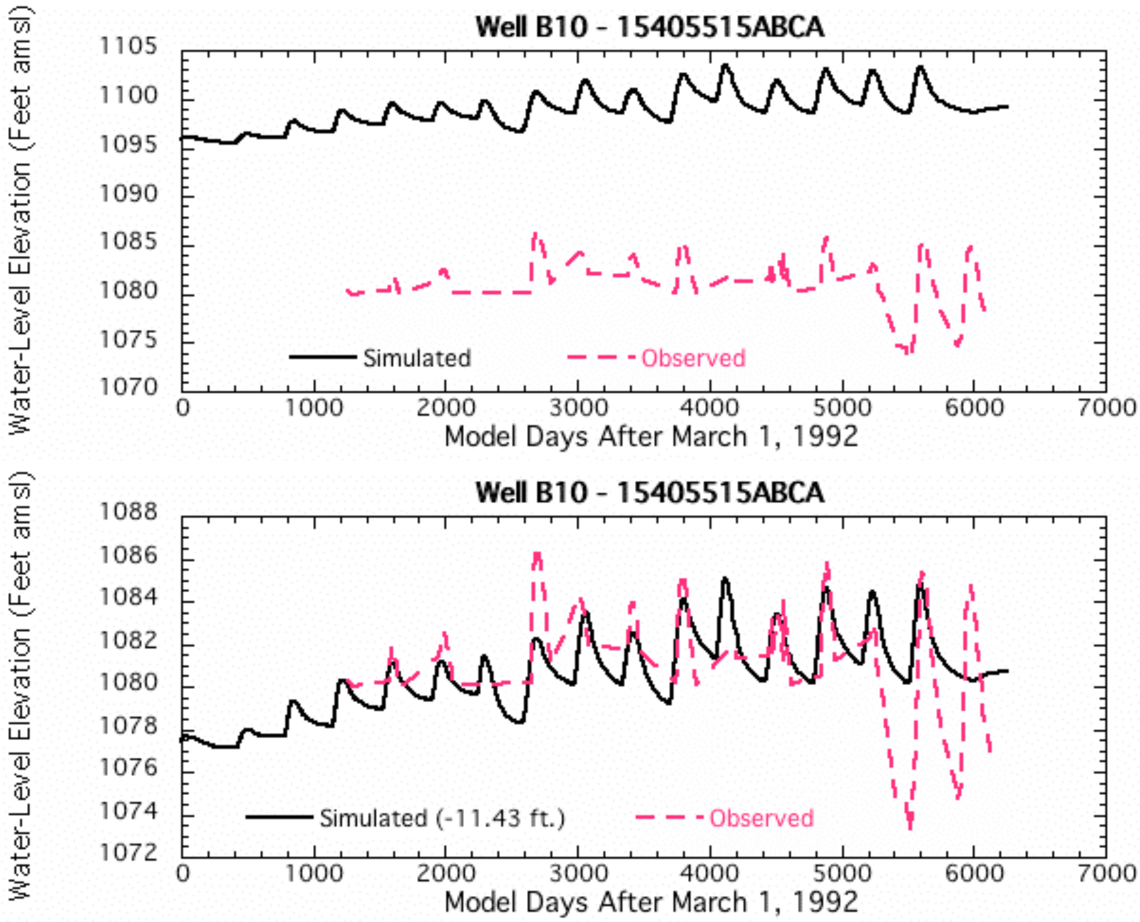


Figure 28. Simulated (black) and measured (red) water-level elevations for the monitoring well located near due south of Spring Zone 6 (154-055-15ABCA) (top), and scaled (March 1, 1993) simulated values (black) and measured (red) water levels (bottom).

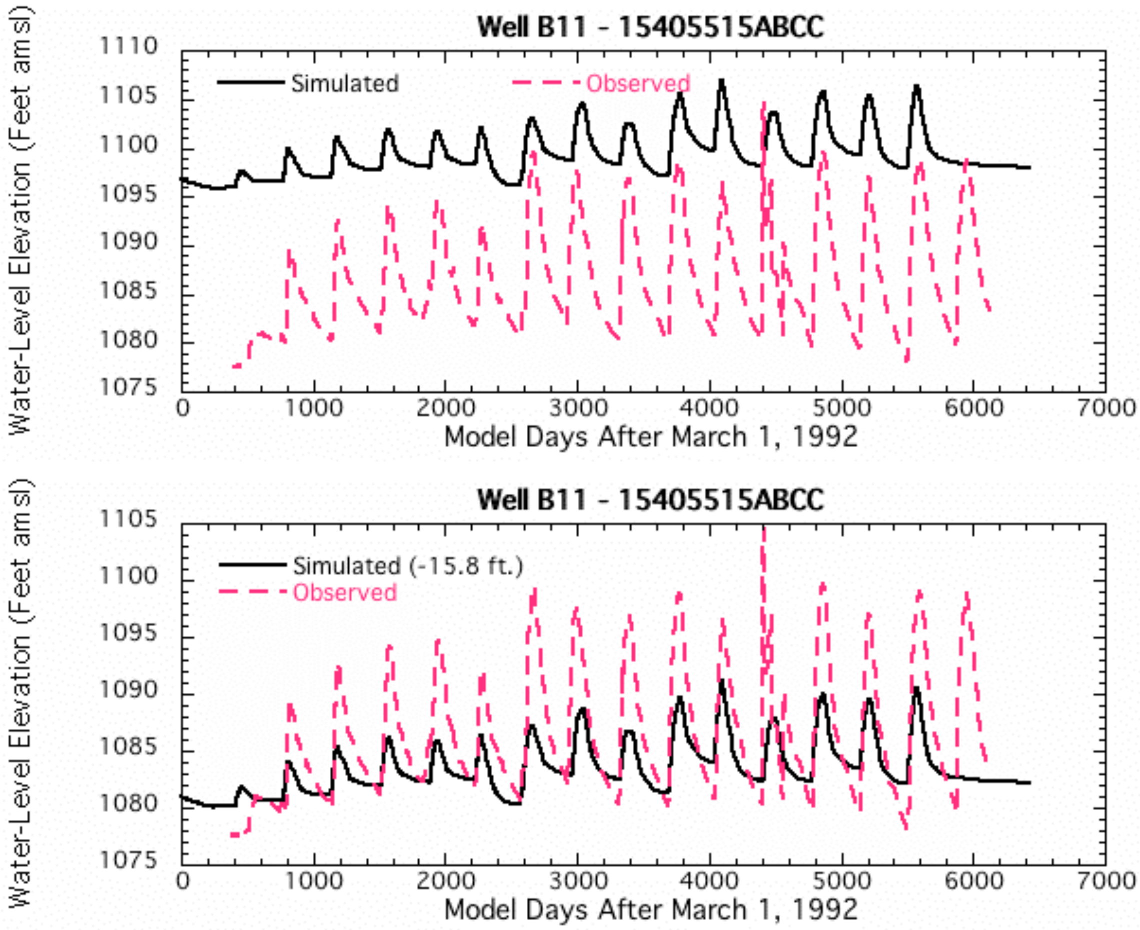


Figure 29. Simulated (black) and measured (red) water-level elevations for the monitoring well located ¼ mile north of the ARR basin (154-055-15ABCC) (top), and scaled (March 1, 1993) simulated values (black) and measured (red) water levels (bottom).

Near the basin, and south (landward) of the basin (Site B12, Figure 30) initial correspondences of simulated and measured water levels are reasonably good at all times, with slightly lower water elevations than simulated at the beginning. Peaks and valleys are nearly exact, and scaled amplitudes are very close. The same is true a quarter-mile west and landward of the basin (Site B13, Figure 31). Both time correspondences and scaled amplitudes are nearly exact.

Simulated water levels for sites B2 and B3 (Figure 32), southeast of the basin and approaching the #1870A well field, were initially high, likely due to the fact that simulated pumping for #1870A in the steady-state model was only applied to Well IRR1 in the southeast corner of Section 15, whereas actual pumping was applied over five wells, including IRR2, IRR4, and IRR5 nearer the basin. These may have caused the larger than expected initial drawdown. The simulated recharge peaks and discharge valleys corresponded reasonably well with measured elevations. However, unlike other sites where measured fluctuations in amplitude were larger than the simulated elevation changes, the amplitude fluctuations were larger for the simulated sites. This was likely related to the distribution of pumping applied over the five wells nearest the basin for the simulation. Overall, simulated and measured time correspondences were reasonably close. Scaled differences of amplitude also corresponded reasonably well for many sites.

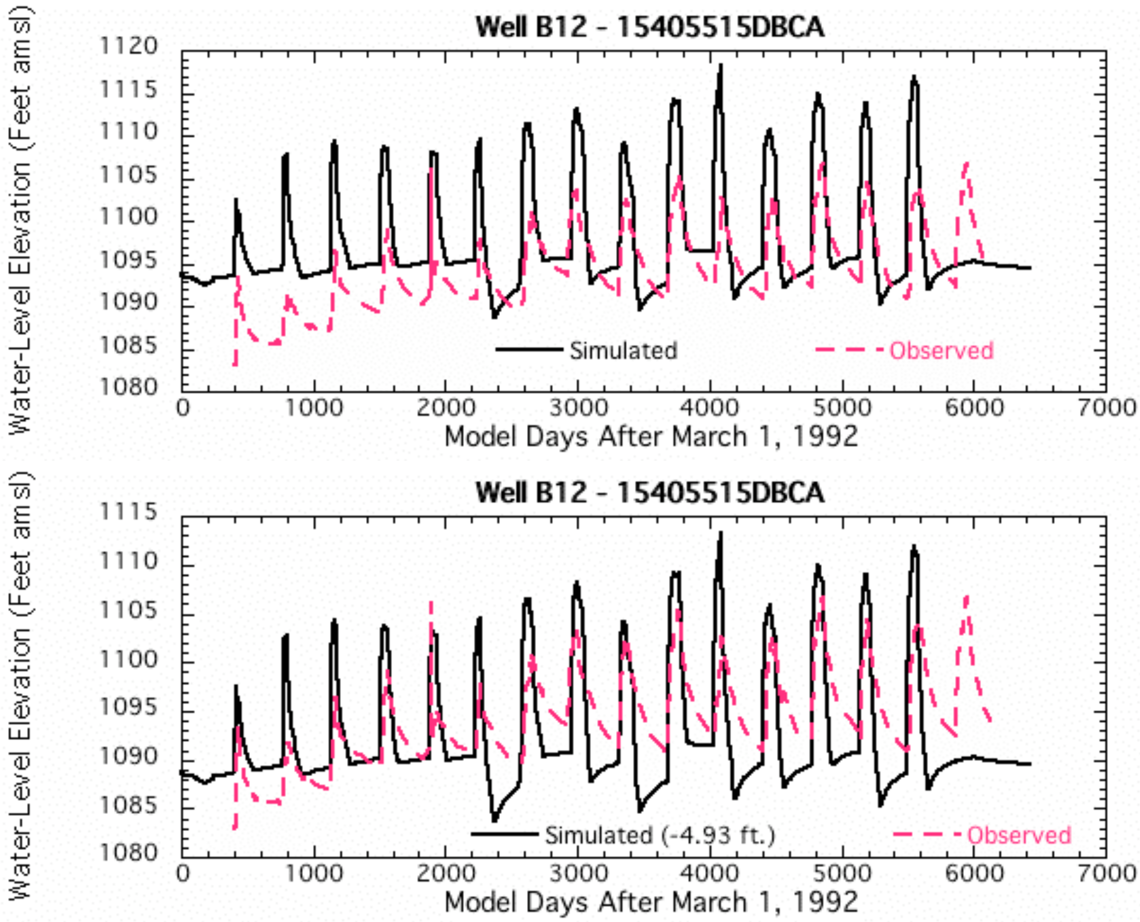


Figure 30. Simulated (black) and measured (red) water-level elevations for the monitoring well located near and south of the ARR basin (154-055-15DBCA) (top), and scaled (March 1, 1993) simulated values (black) and measured (red) water levels (bottom).

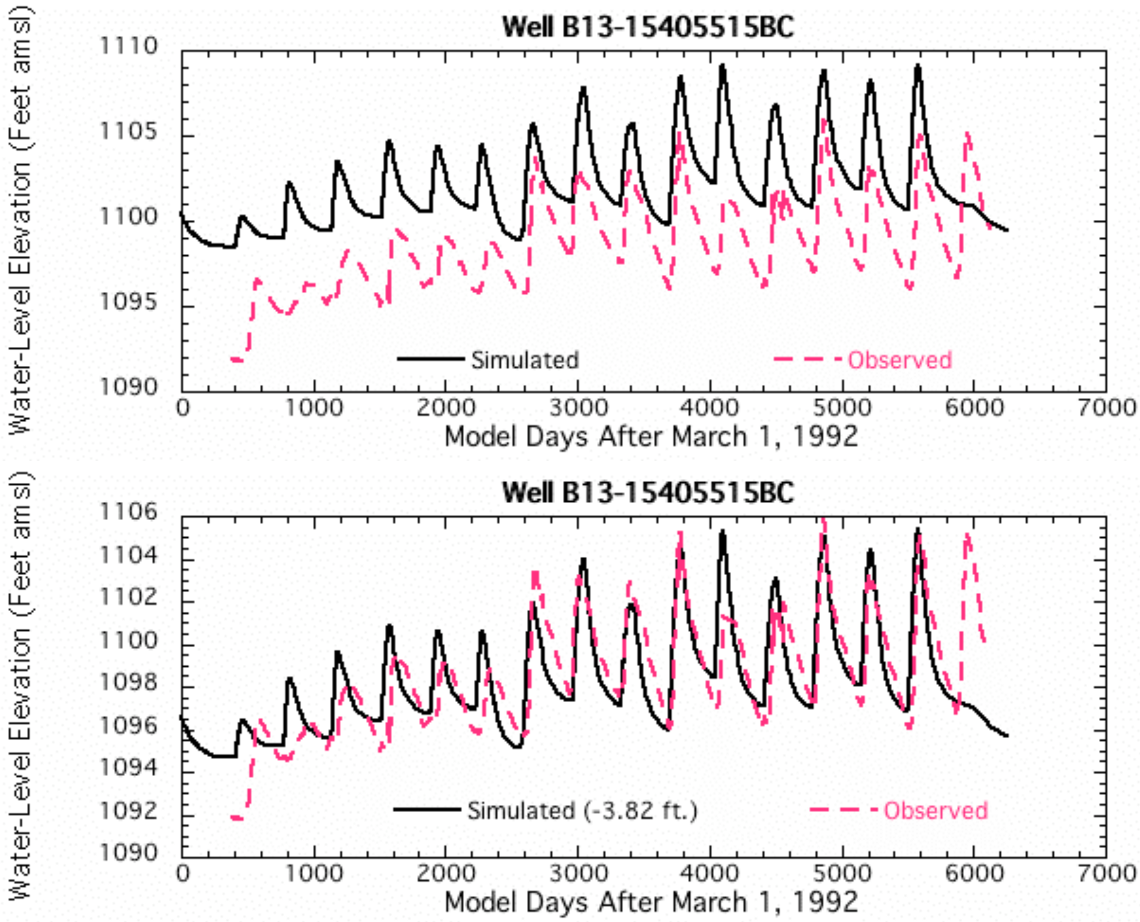


Figure 31. Simulated (black) and measured (red) water-level elevations for the monitoring well located ¼ mile west of the ARR basin (154-055-15BC) (top), and scaled (March 1, 1993) simulated values (black) and measured (red) water levels (bottom).

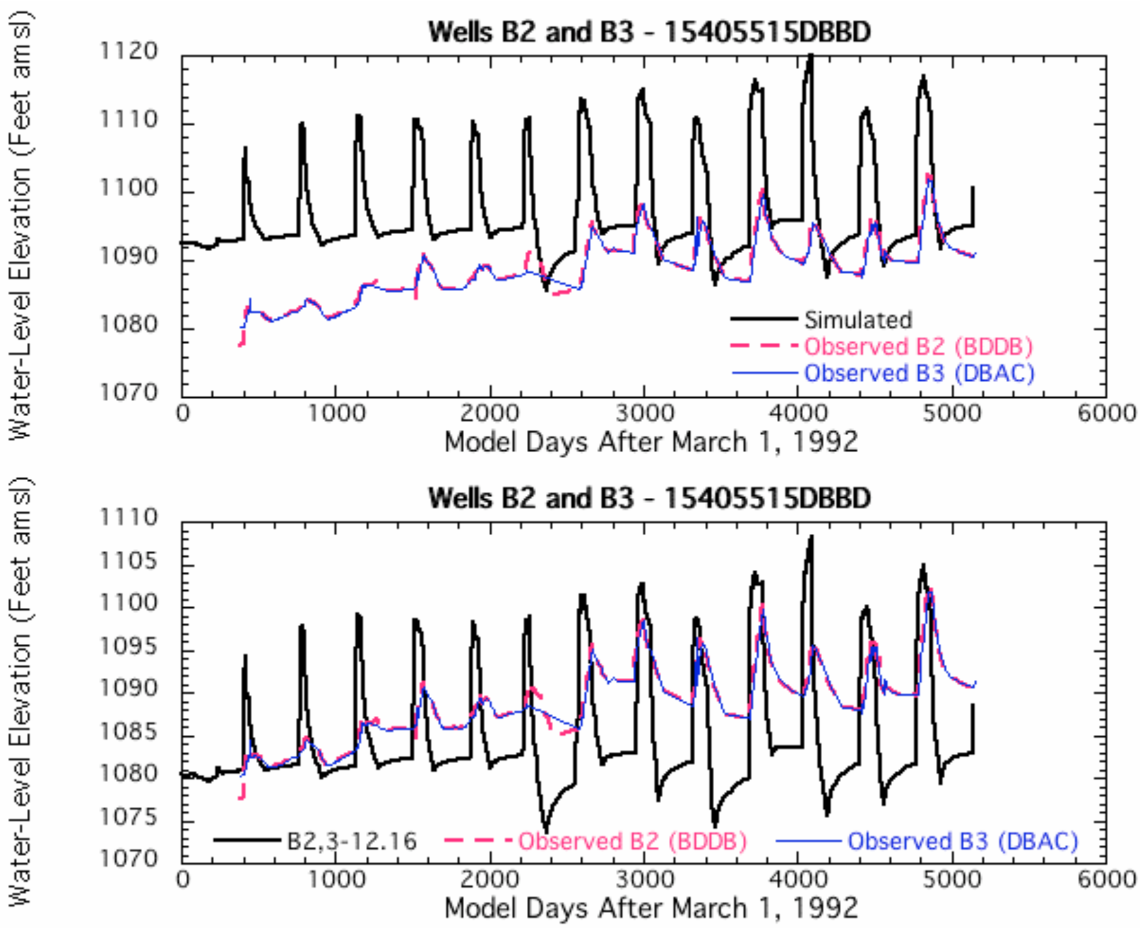


Figure 32. Simulated (black) and measured (red) water-level elevations for the monitoring wells located approx. 200 feet (B2-154-055-15DBBD) and 500 feet (B3 - 154-055-15DBAC) southeast of the ARR basin (top), and scaled (March 1, 1993) simulated values (black) and measured (red) water levels (bottom).

**ARR Simulations:** Several different scenarios were simulated for the Forest River Colony ARR facility:

(1) the actual sequence of recharge and recovery provided in annual reports by the Forest River Community were simulated from the first pilot year in 1992 through 2007;
(2) the actual sequence of recharge was simulated with scenarios of 80%, 90% and 100% pumping recovery;
(3) the actual sequence of recharge was simulated with scenarios of 90% recovery using different well placement scenarios; and
(4) a single recharge application was simulated for 12 years with pumping scenarios of (a) no pumping, and (b) pumping of half of the recharged waters after 1, 3, 5 and 7 year hiatus.

**Simulation of the Actual Operational Scenario**: During the fall of 1992 an initial 6 acre-feet recharge test was conducted. Thereafter, recharge and recovery were conducted for 16 years, of which 15 (through 2007) were simulated in sequence. Recharge and recovery scenarios were conducted as described under the model description above, applying the stresses listed in Table 6.

Because the aquifer, apart from ARR operation, was adjusting to new stress distributions in the transient model, a "No-ARR" case was first simulated to provide a "natural" baseline. The results of ARR stress scenarios were then analyzed as relative changes in discharge through various sinks, accomplished by the subtraction of operational discharge for each sink from the No-ARR case. Simulations for four of the springs found to be most active for ET [Inkster Spring (5), Spring Zone 6, Spring Zone 7 and Spring Zone 8], for losses through drainageways two miles south of the basin, and for losses through ET and seepage through the shallow sandy soils east of the aquifer boundaries are shown on Figure 33. The first year of ARR operation was 1993. The first separation of ARR discharge from background discharge occurred in the first operational year for Springs 6 and 7, and the following year for Inkster Spring (5) and Spring 8. Discharge through local ET, through drains located in Sections 26 and 35 two to four miles south of the basin, and through seepage and ET beyond the eastern boundary about two miles east of the basin (Figure 34) began to occur about three years after initiation of the basin operation. The delay of ET loss until 1996 likely occurred because 1996 was the first year of large recharge (greater than 500 AF/y).

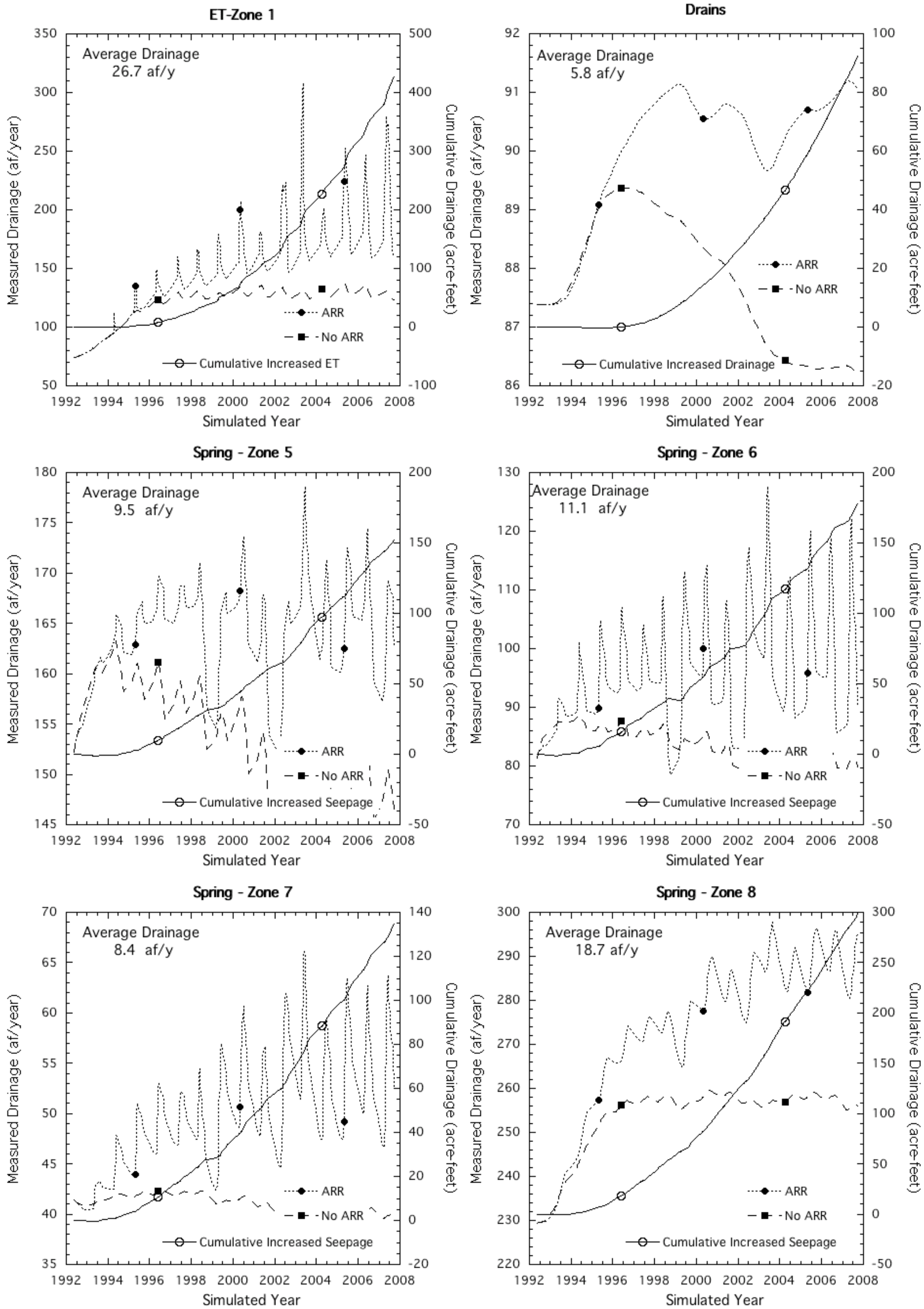


Figure 33. Simulated discharge of recharge waters through ET and drainage through south drains (Sections 26 and 35), and through Spring Zones 5, 6, 7 and 8.

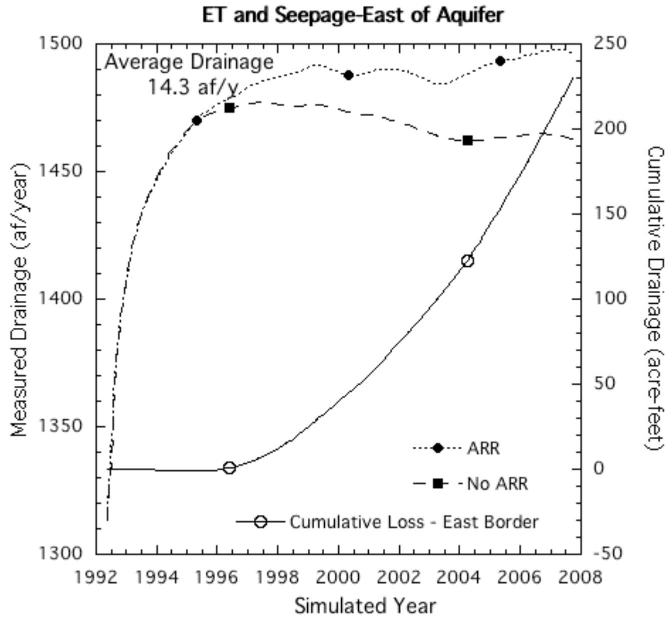


Figure 34. Simulated discharge of recharge waters through ET seepage east of the aquifer boundary.

The simulated distribution of total natural discharge over the time sequence of 1992 through 2007 operational scenario is presented on Table 2. Natural discharge is simulated for three different pumping recovery intensities, including pumping of 100%, 90% and 80% of the recharged water each year. The 80% scenario is derived from the actual pumping schedule implemented by the Community. Other scenarios were implemented by scaling pumping rates upward proportionately for each well. Three different pumping scenarios were simulated for the 90% rate to investigate the differences in retention efficiencies with different possible well placements. These will be discussed in more detail later.

Results indicated that the largest natural discharge (about half of the total loss) occurred through combined Spring Zones 5 (Inkster Spring) through 8. Spring discharge losses varied from 4% of the recharged water for the 100% pumping recovery scenario, to as high as 7.2% of the recharged water for the 80% pumping recovery scenario. Next largest natural discharge losses occurred through combined ET, varying from 3% for the 100% pumping recovery scenario to 4.4 for 80% recovery. Combined ET and seepage losses through evaporative soils and seeps east of the aquifer boundary (approx. 2 miles east of the basin) were 1.5 to 1.9% of total ARR recharge; and drainage losses (approx. 2.5 to 4 miles south of the basin) were 0.5 to 0.9%.

Table 2. Summary of the distribution of total natural discharge after simulated operation of the ARR facility using 1992 through 2007 recharge and pumpage. Total simulated recharge was 10,597 acre-feet.

| % of Recharge Pumped -> | 100% acre-feet | 90%-1 acre-feet | 90%-2 acre-feet | 90%-3 acre-feet | 90%-4 acre-feet | 80% acre-feet |
|---|---|---|---|---|---|---|
| Drain | 68.12 | 81.21 | 78.37 | 69.38 | 57.19 | 92.42 |
| Spring Zone 2 | 24.01 | 29.43 | 28.19 | 22.06 | 25.84 | 34.08 |
| Spring Zone 3 | 21.99 | 27.34 | 26.11 | 20.33 | 24.04 | 31.99 |
| Spring Zone 4 | 3.13 | 3.92 | 3.74 | 2.91 | 3.49 | 4.60 |
| Inkster Spring | 103.08 | 129.36 | 123.66 | 95.26 | 119.42 | 152.26 |
| Spring Zone 6 | 119.93 | 151.44 | 144.29 | 146.79 | 157.41 | 177.61 |
| Spring Zone 7 | 70.81 | 105.18 | 103.64 | 122.50 | 125.69 | 134.83 |
| Spring Zone 8 | 109.70 | 198.53 | 229.65 | 272.46 | 279.28 | 298.67 |
| Spring Zone 9 | 3.47 | 5.67 | 6.40 | -7.47 | 8.77 | 8.12 |
| Spring Zone 10 | 2.09 | 3.29 | 3.70 | 4.29 | 4.40 | 4.63 |
| Spring Zone 11 | 1.46 | 2.30 | 1.87 | 2.28 | 2.36 | 3.23 |
| Spring Zone 12 | 2.98 | 4.70 | 5.27 | 6.12 | 6.28 | 6.61 |
| | | | | | | |
| ET Zone 1 | 224.68 | 315.12 | 325.82 | 353.81 | 359.23 | 426.35 |
| ET Zone 3 | 6.20 | 7.97 | 7.54 | 5.66 | 6.84 | |
| ET Zone 5 | - | - | 0.01 | | 0.01 | |
| ET Zone 6 | 8.16 | | 11.64 | 0.00 | 13.01 | |
| ET Zone 7 | 15.13 | 19.80 | 21.47 | 25.61 | 26.32 | |
| ET Zone 8 | 1.05 | 2.19 | 2.72 | 3.62 | 3.74 | |
| ET Zone 9 | 2.22 | 3.69 | 4.16 | 4.88 | 5.00 | 65.03* |
| ET Zone 13 | 21.63 | 26.48 | 25.37 | 20.30 | 22.31 | - |
| ET Zone 14 | 4.44 | 5.40 | 5.19 | 4.42 | 3.97 | - |
| ET Zone 15 | 19.00 | 23.41 | 22.37 | 17.50 | 20.23 | |
| ET Zone 16 | 0.97 | 1.11 | 1.07 | 0.54 | 0.79 | 102.19* |
| | | | | | | |
| E. Bnd. Zone 13 | 51.81 | 63.29 | 60.69 | 48.76 | 53.24 | |
| E. Bnd. Zone 14 | 84.37 | 102.25 | 98.21 | 81.84 | 80.49 | |
| E. Bnd. Zone 15 | 26.84 | 32.81 | 31.44 | 24.75 | 28.65 | |
| E. Bnd. Zone 16 | 26.84 | 0.13 | 4.16 | 0.11 | 0.10 | 229.92* |
| | | | | | | |
| Total Natural Discharge | 1,024.10 | 1,346.01 | 1,376.74 | 1,348.68 | 1,438.08 | 1772.53 |
| Discharge fraction of Recharge | 0.10 | 0.13 | 0.13 | 0.13 | 0.14 | 0.17 |

* Combined (ET Zone 3-9, ET Zone 13-16, East Boundary Flux)

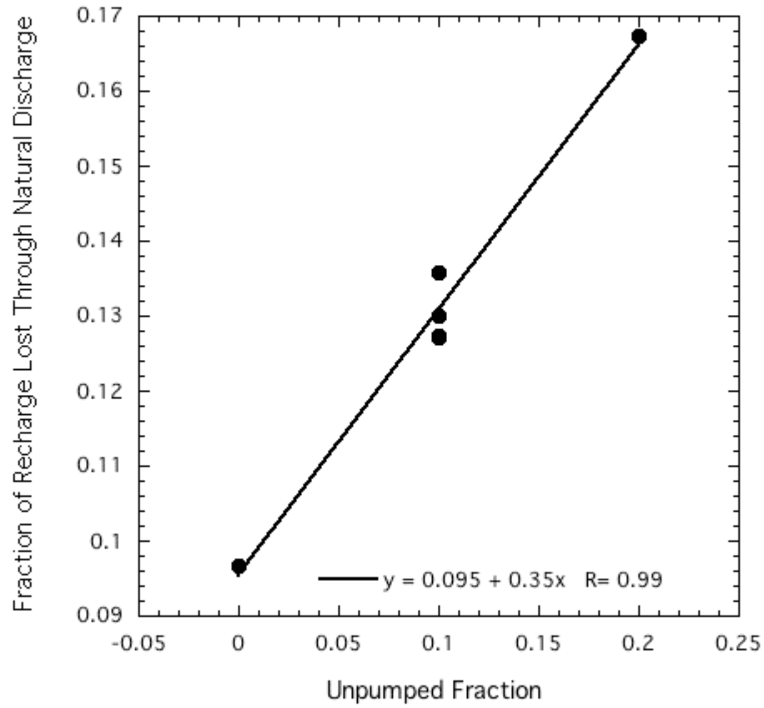


Figure 35. Simulated total natural discharge or ARR water through springs, ET, seepage east of the aquifer boundary and drainage.

The fraction of total loss through natural discharge over the full simulated 15 years for each annual unpumped fraction (the fraction of annual ARR recharge left unrecovered in the aquifer) is summarized on Figure 35. About 10% is lost regardless of pumping recovery. The "lost" fraction increases by 35% for each incremental increase in annual unpumped water. This somewhat complex relationship can be explained in practical terms as follows: If 1,000 acre-feet are recharged and 1,000 acre-feet are recovered, 95 acre-feet [(0.35 x 0 + 0.095) x 1,000 acre-feet], where 0 is the unpumped fraction, will eventually be lost through natural discharge. This will result in an overdraft from the aquifer of 95 acre-feet. If only 80% of recharged waters are pumped in each year, about 165 acre-feet [(0.35 x 0.2 + 0.095) x 1,000 acre-feet], where 0.2 is the unpumped fraction, will be lost. Because 200 acre-feet have been left in the aquifer, a surplus of 35 acre-feet will be left in the aquifer. According to Figure 35, retained water and lost waters balance, with between 15% and 16% of recharged waters left in the aquifer. Leaving a small buffer for the limitations of model simulations, the current overall retention rate of about 20% of total recharged water seems reasonable.

**Basin Effects on Inkster Aquifer Hydrology:** Effects of ARR operation on Inkster aquifer equipotential lines (purple – 2 ft. contours) and flow lines (red arrows) are shown on Figure 36. The two-page figure compares flow system effects for a high-volume recharge (2002 scenario, 1,029 acre-feet) during early (April 21) and late (June 1) recharge, mid- and late-season pumping after recharge (July 5 and August 28), and March 1 of the following year (2003), after aquifer redistribution, with initial conditions (March 1, 1992) before operation of the basin. The full intervening recharge and discharge regime, beginning in 1992, and continuing through 2003, was included in the simulation. Flow lines are predominantly eastward, except for the northwest portion of the aquifer for which flow is toward the river where it discharges through springs. Equipotential lines bend toward the drainageways in the south-central portion of the aquifer.

The simulated hydraulic mound formed by the recharge basin is most strongly evident on April 21, and begins to dissipate somewhat by June 1 because of decreased infiltration caused by clogging of the basin with sediment. Pumping extraction begins on May 15, but the simulated basin mound remains distinct through early July (July 5). Steeper gradients remain near the basin on August 25, but by March 1 of 2003 simulated equipotential lines are generically similar to the 1992 pre-operational scenario, although equipotential lines are elevated about two feet. Well effects can be seen on June 1, and throughout the mid-to late operational period.

The main effect of ARR operation is the early radial proliferation of the ground-water mound, which affects Spring Zone 6 almost immediately, and Spring Zones 5 and 7 by July. A strong flow component toward Spring Zone 8 is also clearly evident. Northwest of Spring Zone 8, Spring Zones 9 through 12; and northeast of Inkster Spring (Spring Zones 2, 3, 4) little effect is observed. Figure 37 shows the simulated effect of the basin operation on water level elevations for a north-south transect through Spring Zone 8, about three-quarter miles northwest of the basin on July 5, 2002, compared with March 1, 1993 before the beginning of basin operation. The well drawdown effects of pumping from wells of Water Permit #1877 are also shown.

**March 1, 1992** **April 21, 2002** **June 1, 2002**

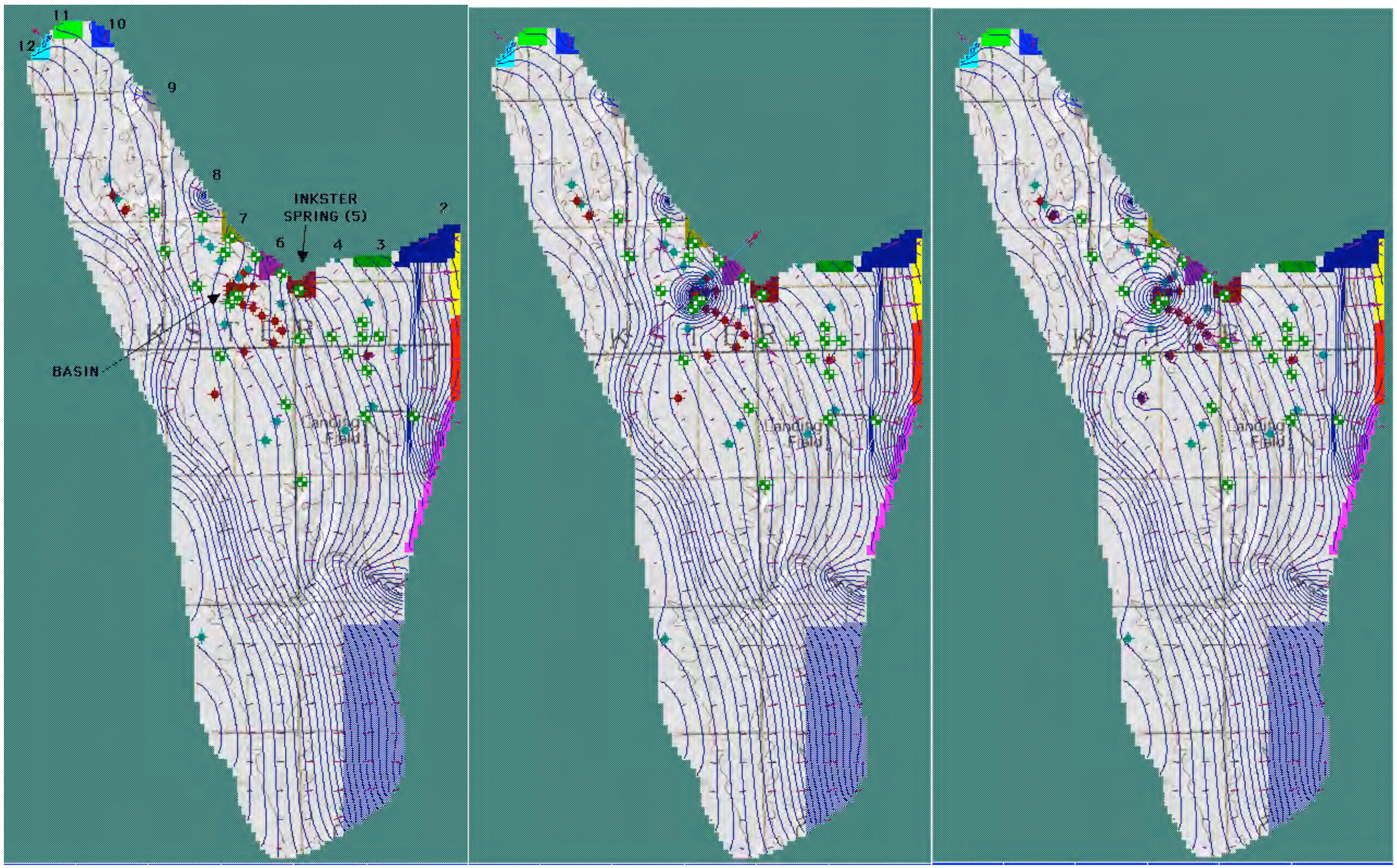


Figure 36. Simulated head equipotentials and flow lines (red arrows) for the Inkster aquifer (2 ft. intervals) before, during and following 1,085 acre-feet of ARR infiltration and recovery (continued on next page).

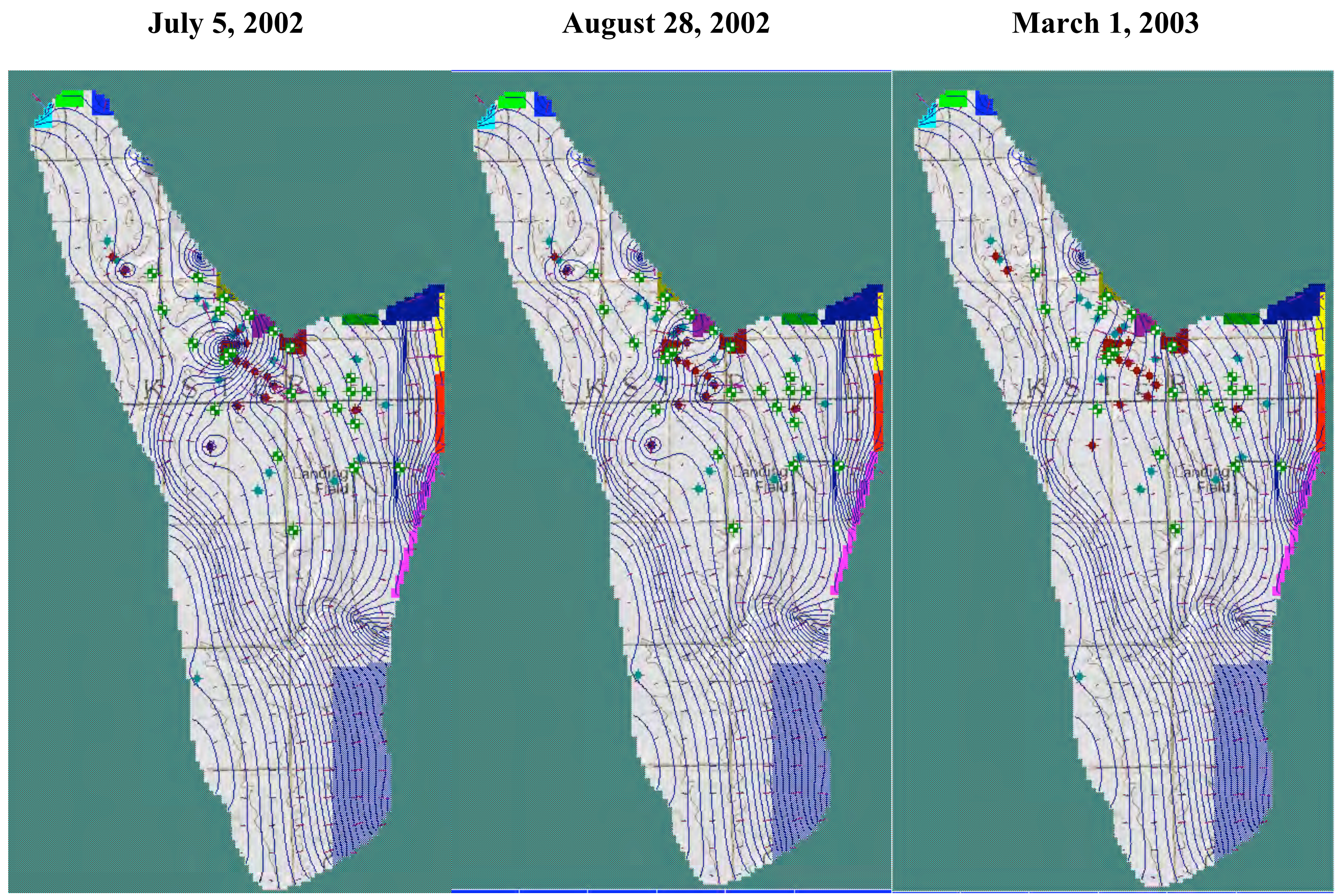


Figure 36. (Continued from previous page) Simulated head equipotentials and flow lines (red arrows) for the Inkster aquifer (2 ft. intervals) before, during and following 1,085 acre-feet of ARR infiltration and recovery.

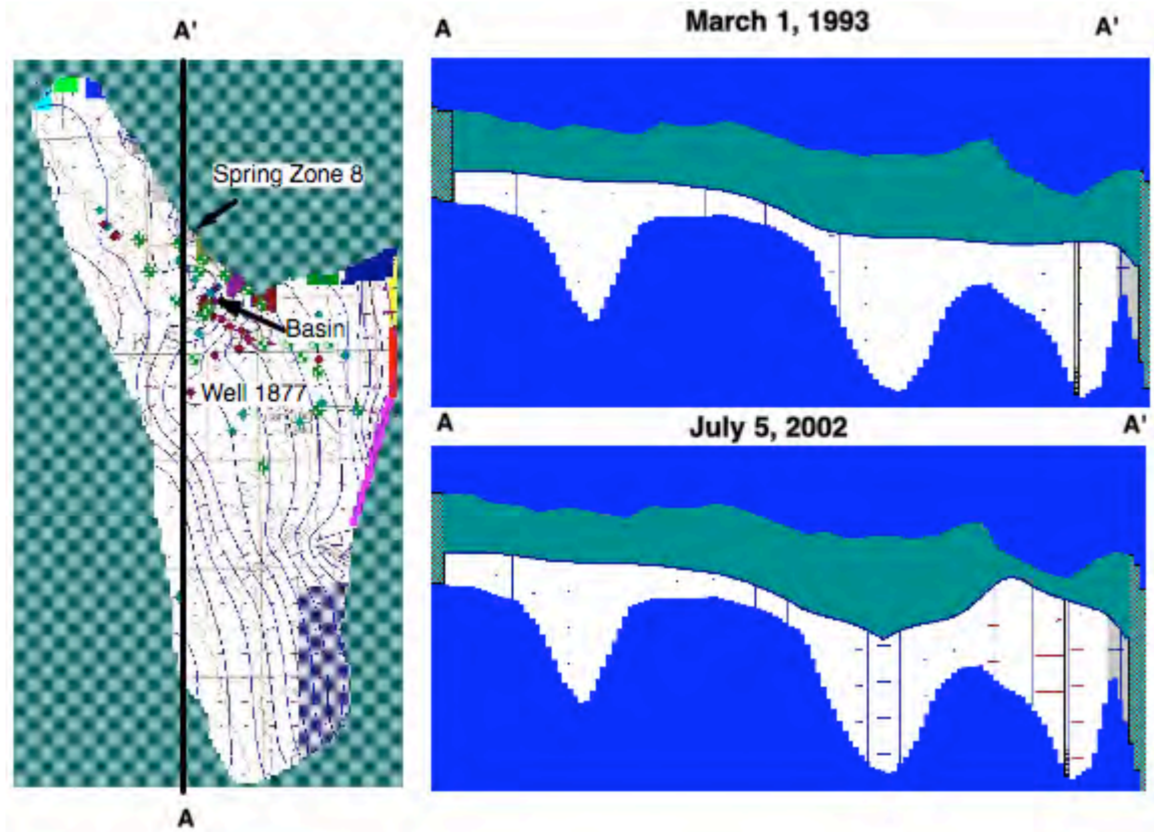


Figure 37. Comparison of simulated water level elevations (vertical exaggeration x 100) for a north (A') – south (A) transect of the Inkster aquifer, intersecting Spring Zone 8, for March 1, 1993 (before basin operation) and July 5, 2002 (after nine years of operation and one month following the completion of the infiltration of 1,085 acre-feet of water at the basin site).

**Discharge Sinks - Time and Magnitude of Natural Discharge:** A model scenario consisting of one large recharge basin operation (2002, 1,085 acre-feet), with no pump recovery, was conducted to examine the discharge distribution times for different discharge sinks. The simulation included one pre-operational year (1992) and 14 years of post-operational redistribution.

Scaled temporal discharge responses for each discharge sink were calculated as a fraction of the maximum simulated discharge for each sink. The scaled discharge response curve for ET, and for discharge through the south drains (> 2.5 miles south of the basin) and the east boundary (approx. 2 miles east of the basin) are shown on Figure 38. The ET response was immediate, but quickly declined. The ET response indicates that much of the early increased ET resulted from mound elevation and proliferation which placed the local ground water closer to land surface. ET, therefore, declined as the mound dissipated. This means that long-term sustained ET losses indicated in the previously discussed long-term annual operational scenarios were likely dependent on annual peaks, which were dependent on each operational period, and would not be sustained without ongoing annual applications. Discharge through the drains (Sections 26 and 35) began about 1.5 years after infiltration at the basin, peaked about four to five years after the infiltration event, and slowly reduced to about 20% of its maximum rate by the end of the simulated period. Discharge through soils and seeps east of the aquifer began after one year, peaked at about 2 years after the infiltration event, and decreased to a relative loss rate of about 30% of the maximum east boundary discharge at the end of the 15-year post event redistribution period.

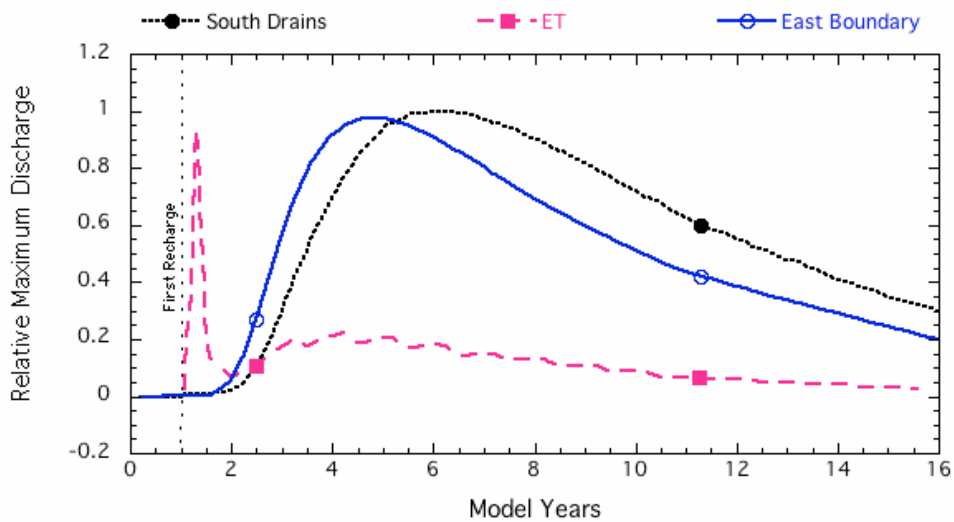


Figure 38. Relative (scaled) discharge loss of ARR waters through natural drainageways, ET, and seepage and ET beyond the eastern boundary.

The simulated time distribution of scaled individual spring losses is shown on Figure 39. Increased discharge through Zones 4, 5, 6, 7 and 8 began within the operational year, and peaked first at Zones 6 and 7 (within the first year), followed by peaks at Zones 5 (Inkster Spring) and 8 near the completion of the operational year (March 1 of 1994). Their losses were nearly complete by the end of the 15-year post operational period. Zone 3 discharge peaked about two years after the infiltration event. Zones 2 (downgradient) and 9 (upgradient) began to discharge after about a year, with peak discharge about three years after the recharge event. Spring Zones 10, 11, and 12, located in the far northwestern corner of the aquifer, began elevated discharge after about two years, and peak discharge occurred about six to nine years after the recharge event. After 15-years, discharge was still occurring at 40% of the scaled maximum discharge rate for Spring Zones 10, 11, and 12. These springs were affected by the "backup of the flow system" caused by recharge waters, illustrated on Figure 37.

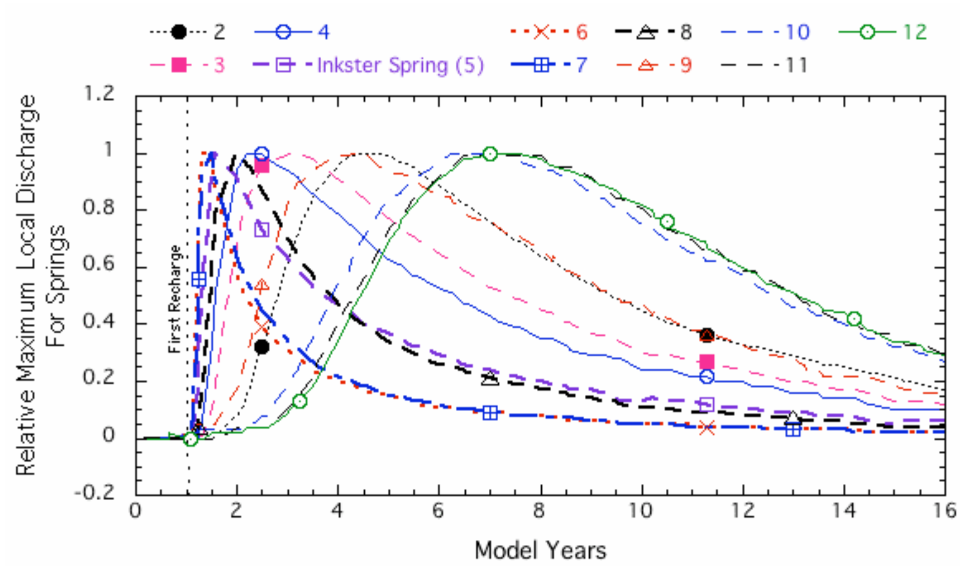


Figure 39. Relative (scaled) discharge loss of ARR waters through natural springs along the Forest River.

The relative contribution of different discharge sinks to total discharge is shown on Figure 40. Figure 40A shows the discharge distribution by major components, in which all spring discharge is presented as a lump total. Figure 40B further distributes the spring losses by individual zones. Fourteen years after the recharge event, most (44%) of the water has been discharged through springs, 27% has been discharged through ET, 20% has been discharged as ET and seepage east of the aquifer, and 9% has been lost through natural drainageways. Thus, springs constitute the largest natural loss.

Of the springs, about 13% of the total ARR recharge is discharged through Spring Zone 8, about 9% through Inkster Spring Zone 5, about 8% through Spring Zone 6, and about 5% through Spring Zone 7. About 35% out of the simulated total (44%) spring discharge occurred through the four spring zones nearest the basin.

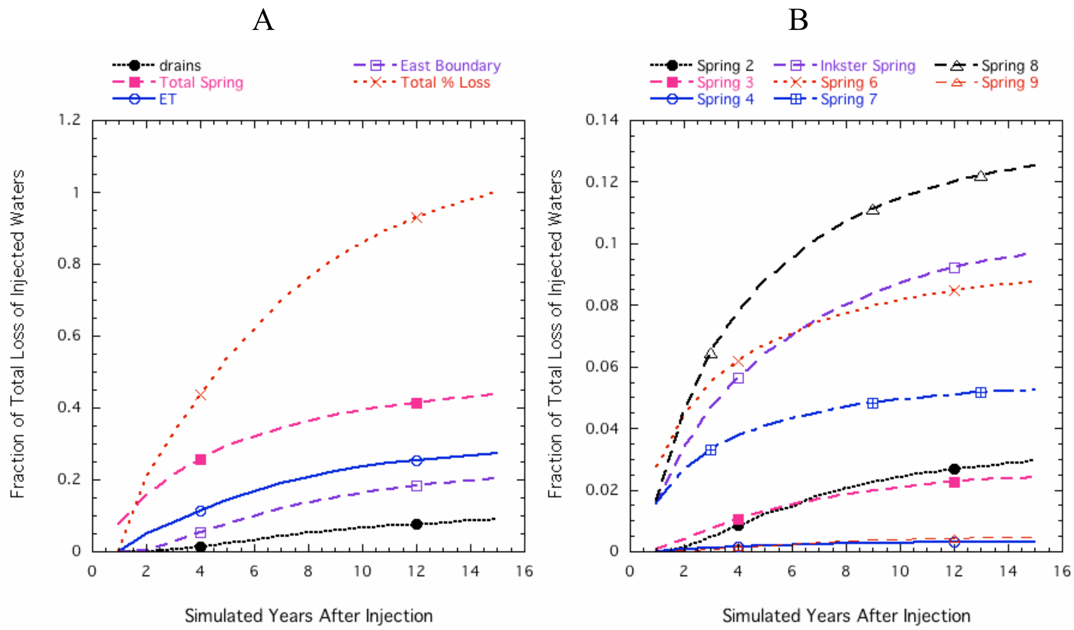


Figure 40. The simulated relative fraction of discharge through major natural discharge sinks (A), and the fraction of total discharge through individual spring zones (B).

**Effects of Delayed Pumping:** With a single recharge event and no recovery, simulated initial natural discharge loss rates were about 12% per year, and gradually decline after about five years. After 15 years of redistribution, about 10% of the recharged waters is indicated to remain in the aquifer (Figure 41).

If half of the recharged water is recovered by pumping in the second year (the year after the recharge event), about 30% of the recharged water is lost by year five, with 20% retained in the aquifer. After 15 years about 40% has been discharged, with about 10% of the recharged waters retained (Figure 41).

If half of the recharged water is recovered in year four, 40% of the total has already been lost, with 10% remaining after pumping. By interpolation between the year 4 and year 6 scenarios, it is evident that all of the remaining unpumped recharge water has been naturally discharged by year five. However, for all scenarios of pumping recovery later than year two (possibly year three by interpolation), final natural discharge exceeds the non-recovered recharge waters. Loss effects from delayed pumping are shown by line trends above the horizontal dashed line on Figure 41, which indicate the proportion of retained water after pumping. Proportional discharge trends above the retention (50%) line indicate that more than half of the recharge waters will eventually be lost, and that pumping recovery exceeds the long-term amount of water retained in the delay before pumping. It means that by waiting for the third year to pump, excessive water will be transported to areas beyond the zone of effective well recovery. The operators will, therefore, have lost more water to natural discharge than the aquifer has retained for pumping recovery at the 50% rate. The aquifer is, therefore, being mined.

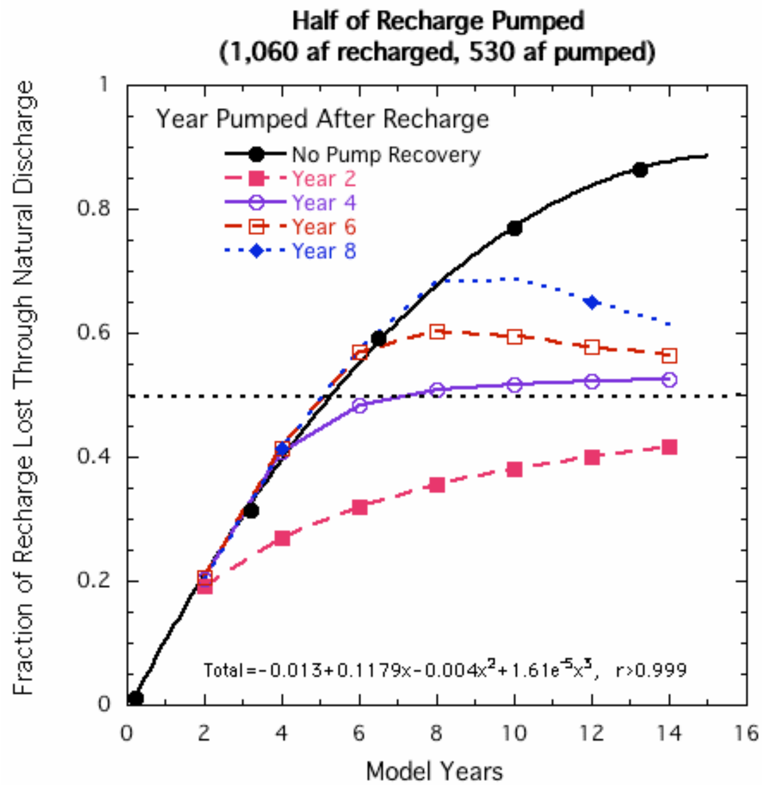


Figure 41. Relative loss through natural discharge with: (1) no pumping of recharged water, and pumping recovery of half of the recharged water after (2) two years, (3) four years, (4) six years and (5) eight years.

**Summary:** Simulations indicate that if no pumping recovery is undertaken for a single recharge year, the aquifer will initially lose recharge water at a rate of about 12% per year, and will gradually decrease in the loss rate until about 90% of the recharge water has been lost through natural discharge in the 15th year. If pumping is delayed until the second year, about 20% will be lost by the second year, and about 4% per year of the remaining water will be lost through natural discharge for the next 14 years. If pumping is delayed until the third year after recharge, insufficient water will remain in the aquifer in the long term to support pumping of one-half of the recharged quantity. By the fourth year after pumping, combined natural discharge losses, and waters moved beyond the zone of recovery which will eventually be lost to pumping recovery, and cannot support pumping at one-half the rate of recharge. A one-year delay in pumping limits recovery. If pumping is delayed beyond two years, the water is virtually non-recoverable in the near-basin well field. It is possible that other wells downgradient of the recharge basins, particularly in the direction of the springs, could intercept some of these waters before discharge. But the complexity of such a management scenario would be beyond reasonable limits of simulation and administration. While the results would vary with different pumping rates, the rule of thumb is that after the second year the water is gone.

**Transient Simulation of a Proposed New ARR Basin**

The Forest River Community has applied for an additional permit (#5931) to withdraw an additional 900 acre-feet per year from the Forest River during spring elevated flows for implementation of ARR in a basin in the center of Section 22, 1 mile south of the original ARR facility. The proposed basin is more distant from discharge effects of the Forest River springs, but is closer to the natural drain complex in Sections 26, 27 and 35, and is directly upgradient of boundary discharge Zones 13 and 15 (Figure 42).

A hypothetical basin of 6.78 acres was simulated at the proposed location using eight 192x192 feet cells oriented north-to-south in a 2:1 length-to-width ratio. Total simulated recharge was 978 acre-feet per year, beginning on simulated day 45 after March 1 (April 15), and ending on simulated day 92 after March 1 (June 1). Recharge rates were fitted as a declining power function of time using Equation 5.

Recharge stresses were applied as injection wells (Figure 43). Well recovery was distributed evenly between three wells. Simulations indicated that one or two simulated wells alone were incapable of fully extracting the water without drying the cells. Combinations of three extraction wells were selected from four simulated well locations: (1) Well EXP-1 located about 400 feet north of the basin; (2) Well EXP-2 located 200 feet south of the basin; (3) Well EXP-3, located 1,440 feet north-northeast of the basin; and (4) Well EXP-3(4) located 1,793 feet directly south of the basin. Wells EXP-1 and EXP-2 were placed to optimally recover waters directly within the recharge mound; Well EXP-3 was placed to intercept waters beyond the immediate recharge mound and moving toward the eastern boundary discharge areas; and Well EXP-3(4) was placed to recover waters beyond the immediate recharge mound and moving toward the natural drainageways south of the recharge zone. All well recovery simulations included Wells EXP-1 and EXP-2 nearest the basin. Wells EXP-1 and EXP-2 were placed for most efficient early recovery and for minimization of local ET losses through depression of the local mound.

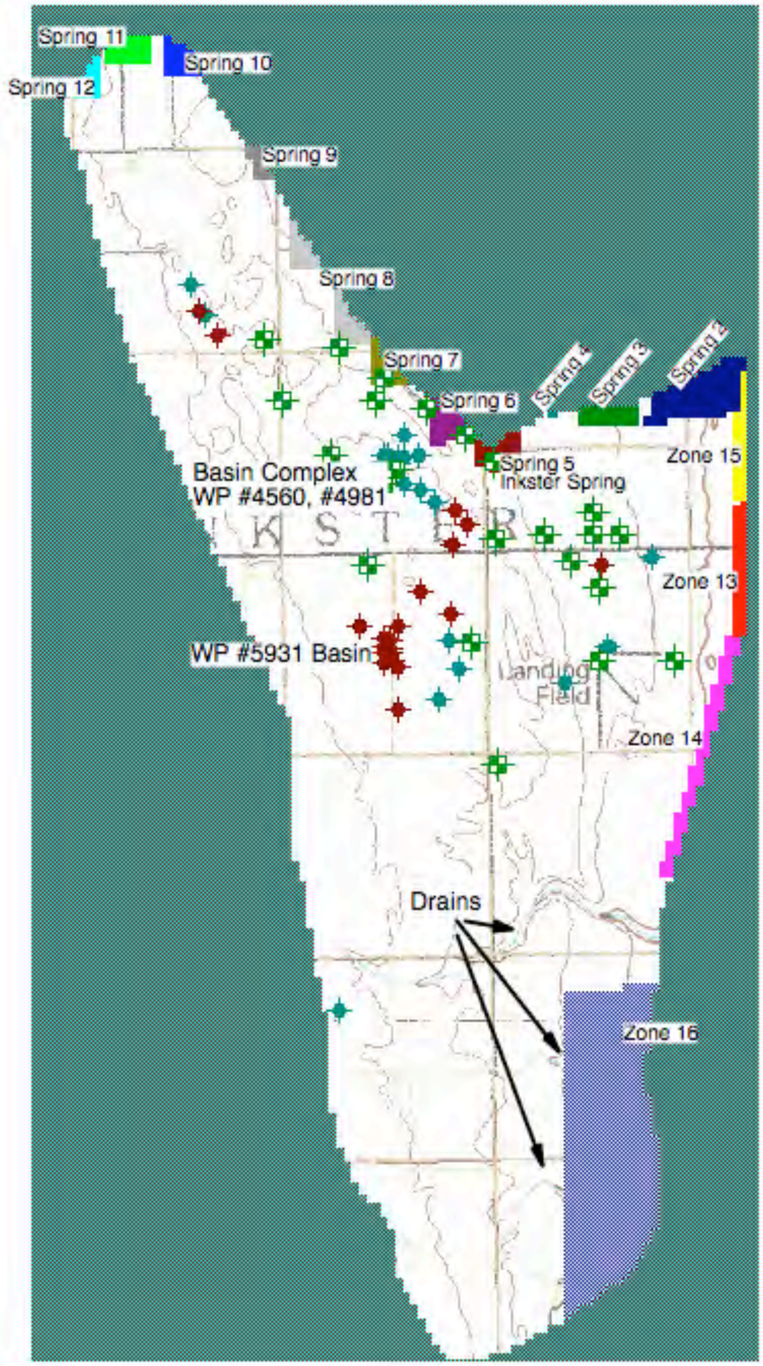


Figure 42. Proposed location for a south recharge facility (WP #5931 Basin) in relation to natural discharge sinks.

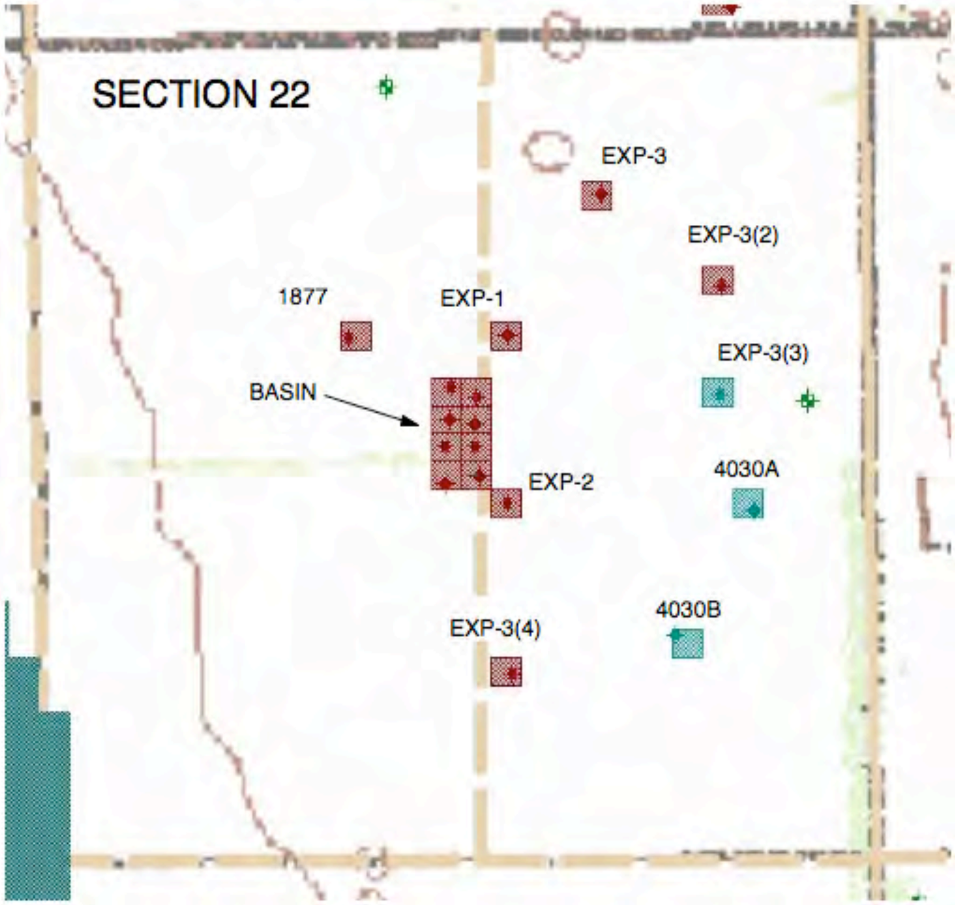


Figure 43. Relative locations of the recharge basin and potential extraction well options [EXP-1, EXP-2, EXP-3, EXP-3(2), EXP-3(3), EXP-3(4)].

Simulated scenarios are shown on Table 3. Well extraction options using the south well [EXP-3(4)] resulted in substantially less losses through Spring Zone 6 and through the drains, but resulted in more losses through Inkster Spring. Losses through the eastern boundaries were similar. Fractional losses were slightly less for the EXP-3(4) well option, but differences were not substantial [10% for EXP-3(4) and 11% for EXP-3], and insignificant within the limitations of the model.

Simulated operations for the two facilities (north and proposed south) combined, with serial applications of 978 AF/y in the proposed south basin and 1,030 AF/y in the north basin resulted in estimated natural discharge losses of about 20% over 12 years (Table 3). Thus, combined operations resulted in an increased loss of about 47% over single-operation simulated losses. Simulated single-operation losses are 0.11 (south basin) and 0.16 (north basin) compared with 0.2, which might be expected from the combined influence of both basins on heads driving discharge zones.

Table 3. Summary of the simulated distribution of total natural discharge after simulated operation of the proposed south ARR facility using 978 acre-feet per year of discharge; and simulated discharge for operation of two basins (north and south) simultaneously at 978 acre-feet per year, and 1,030 acre-feet per year respectively.

| % of Recharge Pumped -> | 0% (no recovery) acre-feet | 73% [Wells EXP-1,2,3] acre-feet | 80%-1 [Wells EXP-1,2,3] acre-feet | 80%-2 [Wells EXP-1,2,3(4)] acre-feet | 80% (both basins) acre-feet |
|---|---|---|---|---|---|
| Drain | 1,419 | 500 | 304 | 264 | 455 |
| Spring Zone 2 | 94 | 24 | 11 | 14 | 63 |
| Spring Zone 3 | 90 | 22 | 11 | 13 | 61 |
| Spring Zone 4 | 13 | 3 | 1 | 2 | 9 |
| Inkster Spring | 350 | 86 | 43 | 52 | 286 |
| Spring Zone 6 | 226 | 62 | 81 | 38 | 332 |
| Spring Zone 7 | 115 | 32 | 18 | 20 | 227 |
| Spring Zone 8 | 243 | 67 | 38 | 42 | 502 |
| Spring Zone 9 | 6 | 2 | 1 | 1 | 14 |
| Spring Zone 10 | 3 | 1 | 1 | 1 | 8 |
| Spring Zone 11 | 2 | 1 | 0 | 0 | 6 |
| Spring Zone 12 | 4 | 0 | 1 | 1 | 11 |
| | | | | | |
| ET Zone 1 | 2,551 | 591 | 505 | 499 | 2,056 |
| ET Zone 3 | 39 | 7 | 3 | 4 | 22 |
| ET Zone 5 | 0 | - | - | - | 2 |
| ET Zone 6 | 20 | - | - | - | 23 |
| ET Zone 7 | 25 | 6 | 2 | 3 | 54 |
| ET Zone 8 | 4 | 1 | 0 | 0 | 9 |
| ET Zone 9 | 4 | 1 | 1 | 1 | 9 |
| ET Zone 13 | 112 | 31 | 15 | 18 | 62 |
| ET Zone 14 | 59 | 21 | 12 | 12 | 22 |
| ET Zone 15 | 88 | 21 | 10 | 12 | 55 |
| ET Zone 16 | 20 | 8 | 5 | 5 | 7 |
| E. Bnd. Zone 13 | 259 | 77 | 38 | 46 | 146 |
| E. Bnd. Zone 14 | 703 | 243 | 132 | 140 | 307 |
| E. Bnd. Zone 15 | 105 | 28 | 13 | 17 | 70 |
| E. Bnd. Zone 16 | 2 | 1 | 1 | 1 | 1 |
| Drain (Zone 16) | 7 | 3 | 2 | 2 | 2 |
| Total Recharge | 11,741 | 11,741 | 11,741 | 11,741 | 24,105 |
| Total Natural Discharge | 6,563 | 1,837 | 1,250 | 1,206 | 4,821 |
| Discharge fraction Of Recharge | 0.56 | 0.16 | 0.11 | 0.10 | 0.20 |

The magnitude and relative proportion of simulated natural discharge losses of recharged waters are shown on Figure 44. First losses are detectable during the second year, and losses begin to accelerate during the third and fourth years after first operation of the basin. After three years, fractional losses are 5%, after six years they are 10%, and after 10 years they are about 50%. Largest losses are through ET, and second losses are through natural drainage, followed by losses through the eastern boundary and Spring Zones 5 through 8 in the north. Total spring losses never reach 10% during the simulation period.

A B

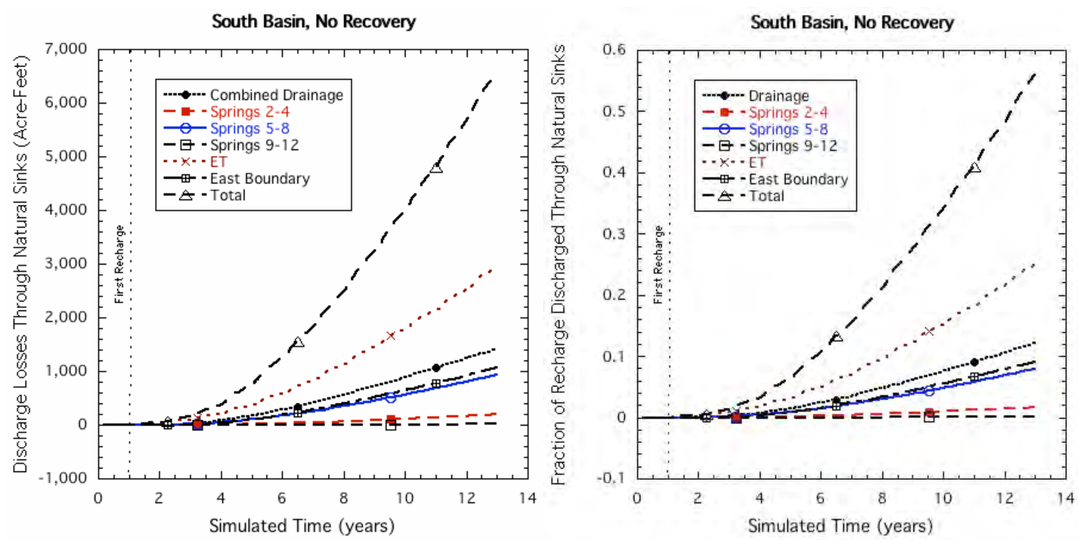


Figure 44. Loss of ARR waters through natural discharge (A), and natural discharge loss as a fraction of total recharge (B) for simulations of the proposed south basin.

**<u>Discharge Sinks - Time and Magnitude of Natural Discharge:</u>** The redistribution and discharge of water following a single recharge event was simulated using the same procedure as described for the north basin. Recharge was 978 acre-feet, and redistribution and discharge were simulated for 12 years following the recharge event.

Simulated discharge through ET increased slightly in the first year of the recharge event, but the main increase in ET occurred beginning a year after the event (Figure 45). Discharge through ET peaked about three to five years after the event, and remained high (up to 60% of the maximum) for the entire 11 years. The initial small relative increase was caused by the mound near the basin. But the delayed and sustained ET indicated that the main cause was the migration of water to shallow water table areas, which are more prevalent in the south Inkster aquifer than in the north. Increased drainage began within the first year of recharge, peaked about two years after the event, and gradually declined to about 30% of the maximum discharge after 12 years of redistribution.

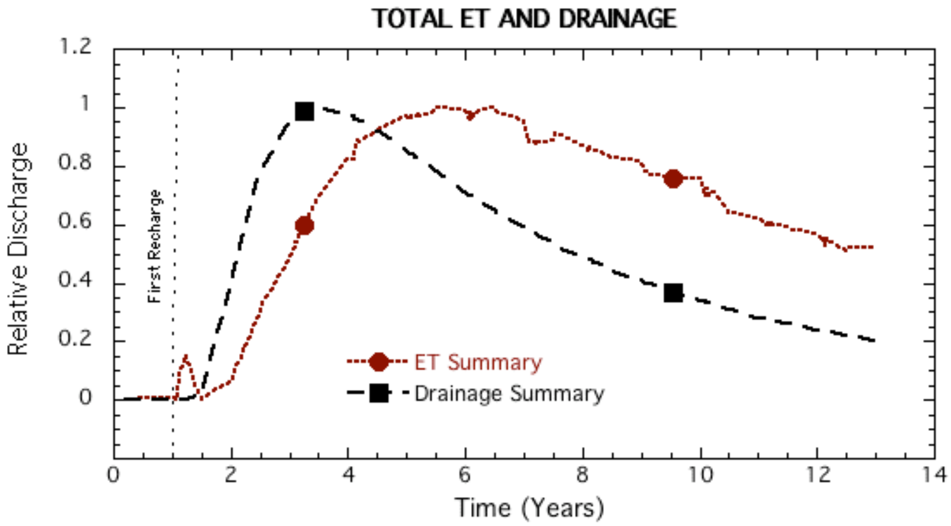


Figure 45. Simulated fraction of maximum discharge through ET and drainage for the proposed south basin.

Discharge through eastern boundaries, which physically occurred as ET and seepage beyond the boundaries, began about a year after recharge, and peaked for Zone 14 after three years, Zones 13 and 15 after four years, and Zone 16 after six years (Figure 46). East boundary losses were significant, but small, accounting for less than 10% of recharged waters.

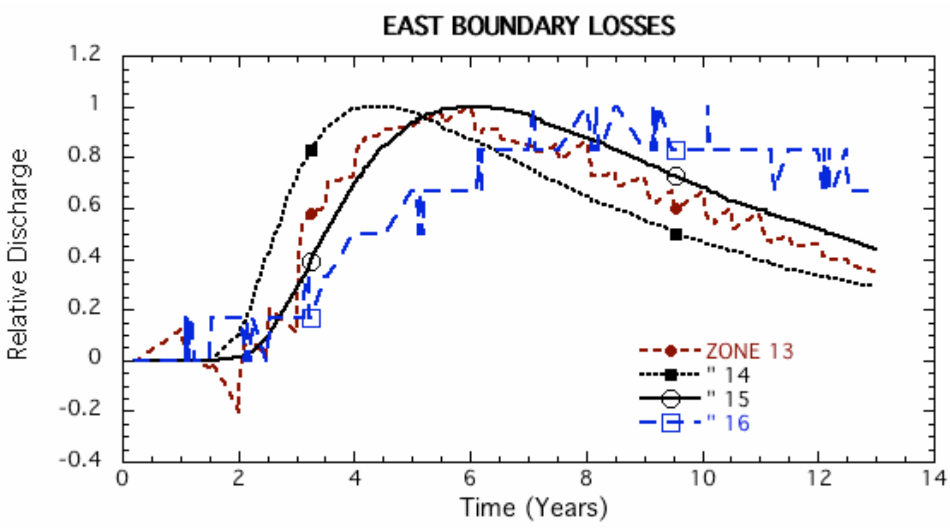


Figure 46. Simulated fraction of maximum discharge through the east aquifer boundaries for the proposed south basin.

Simulated discharges through Spring Zones 5 (Inkster Spring), 6, 7 and 8 are shown on Figure 47. Discharge began within the first year in Zones 5 and 6, peaked about one and a half years after the event, and then gradually declined to about 30% of the maximum discharge rate. Zones 7 and 8 began to discharge about a year after the recharge event, peaked about two years after the event, and then gradually declined to about 30% of the maximum. Discharge through Springs 5 through 8 were significant, similar to eastern boundary losses, but account for less than 10% of recharge waters.

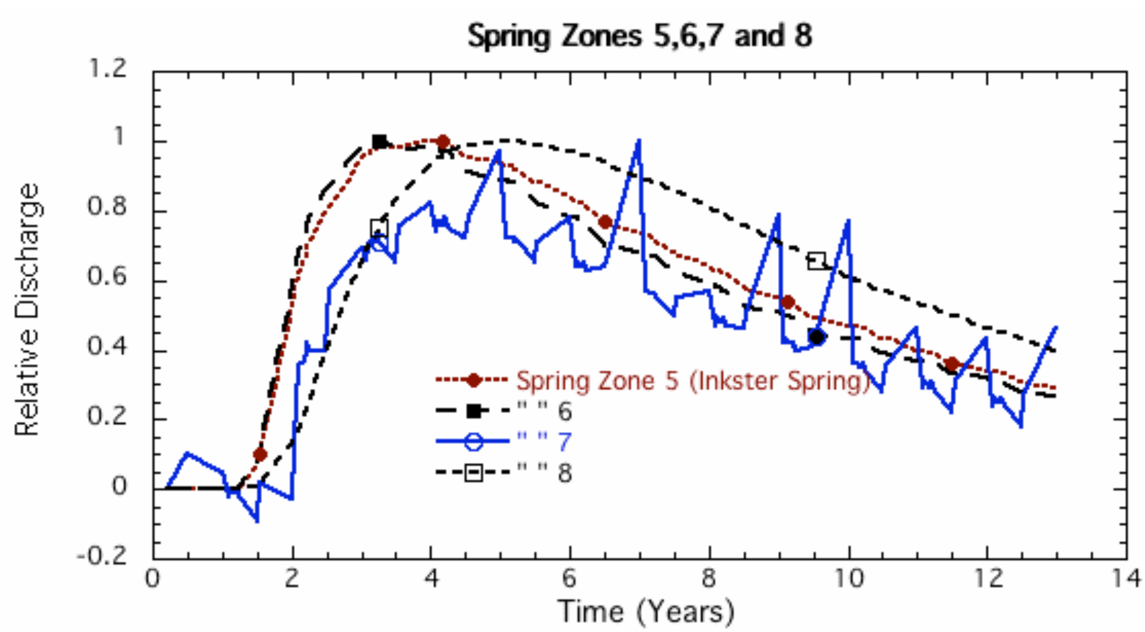


Figure 47. Simulated fraction of maximum local discharge through Spring Zones 5, 6, 7 and 8 following recharge through the south basin.

Simulated discharges through Spring Zones 2 and 3 began in the same year as the recharge event (Figure 48), peaked about three years after the event, and declined to about 40% of maximum after 12 years. Spring Zone 9 began to discharge ARR waters about two years after the recharge event, peaked after about seven years, and gradually decreased to about 75% of maximum discharge after 12 years. Discharge through Spring Zones 9, 10, 11 and 12 began after three years, peaked about eight years after recharge, and remained at full discharge through the remaining simulated 12-year period. While there were discernible discharge responses for these springs, they were quantitatively insignificant.

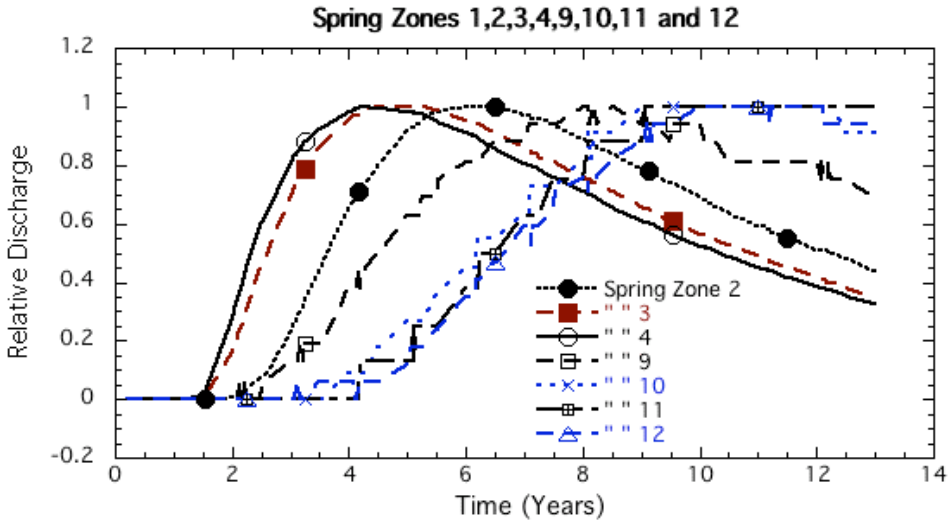


Figure 48. Simulated fraction of maximum discharge through Spring Zones 2, 3, 4, 9, 10, 11 and 12 following recharge through the south basin.

**South Basin Projected Operational Requirements:** Simulations of the proposed south basin indicate that losses are through ET, followed by drainage. This compares with the north basin for which main losses are through springs seeping to the Forest River. Compared with the north basin, losses are similar, ranging from 10 to 20%. However, the distribution of loss differs, with no immediate loss, and a larger proportion of loss for the unpumped fraction (57%) at the end of the operational year (Figure 49). Main losses begin in the second year, and peak at the end of two to five years following the recharge event. Simulated combined operation of the north and (proposed) south basins resulted in great water loss, about 20% of the total recharged water, than did single operation of either the north or south basin.

The simulations indicated that there may be some limitations on aquifer holding capacity and well recovery capacity for the proposed south basin. Simulations indicate that at least three wells may be needed for full recovery of the south basin recharge waters. Two wells will likely be needed very near the basin, located within a few hundred feet north and south of the basin. More distant supplemental wells located a quarter-mile northeast or south of the basin will also likely be useful. At least one well south of the basin is important to intercept waters that would move toward the south drain. The simulated optimal pumping recovery for the south basin would be at about 98% (unpumped fraction of approx. 0.018, from 0.573 x 0.018 – 0.0105, from Figure 49).

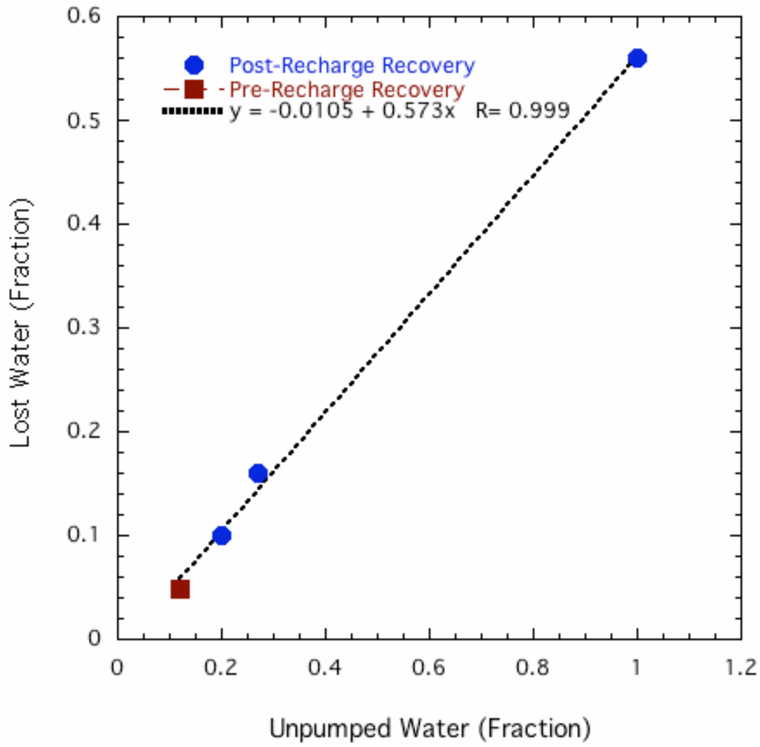


Figure 49. Fraction of unpumped water that is simulated as lost through ET, drainage, springs and boundary losses.

It must be understood that stratigraphic data and monitoring wells for verification are limited in the south basin area, and that south simulations may be subject to substantial error. It should be understood, further, that waters simulated as lost through ET are not necessarily fully lost to beneficial use, because wells placed in evaporative zones would likely be able to recover some of the water. However, recoverable amounts are uncertain, and their recovery should not be included as a part of the water budget for planning purposes.

# CONCLUSION

Approximately 80% of waters recharged through the FRC ARR basin facility were pumped from the aquifer. Transient model simulations of the FRC ARR effect on the Inkster aquifer indicated that about 17% of recharged water would have been lost to natural discharge. Simulated losses were thus close to preliminary management estimates. The optimal efficiency was found to be 90% pumping recovery, which would result in a 13% loss through natural discharge. While most efficient, however, this would constitute deficit pumping of 3% and would be unacceptable from the standpoint of water appropriation management.

Natural losses of recharged waters were distributed as 10% initial loss regardless of pumping scenario, and 35% annual loss of unpumped water at the end of the year. Largest natural discharge under the 1993-2007 operational scenario occurred through spring loss at four spring complexes [Inkster Spring (Zone 5), Spring Zone 6, Spring Zone 7 and Spring Zone 8] within a mile of the basin. Simulated natural losses through ET from the aquifer were 31%. Discharge through ET and seepage beyond the eastern boundary of the aquifer were estimated at 12%. The remaining 10% was discharged through more distant springs and drains in the southern portion of the aquifer.

Both spring and ET losses were strongly influenced by the hydraulic mound formed and propagated during and following the basin operation, and the effect of that mound on the aquifer flow system. Simulation of the hydraulic pulse caused by a single year of recharge indicated that most ET occurred within the first year, and was related to the shallower local water table caused by the mound. Losses of recharge water through seepage and ET beyond the eastern boundary of the aquifer began about a year after the recharge event, peaked at about three and a half years after the event, and continued at a substantial (>20% of the maximum) rate for 15 years. Losses through the south drain began about a year and half after the recharge event, peaked at five years, and continued at a substantial (>20%) rate for the entire simulated 15-year period. Spring losses through the nearest four (Zones 5, 6, 7, 8) spring complexes began within the operational year and peaked within a year of the recharge event. They then gradually declined to less than 20% of maximum natural discharge within six years of the recharge event. The more distant springs, which represented minimal discharge losses, peaked as late as seven years after the recharge event.

Simulation of an operational scenario in which no pumping recovery occurred for varying periods after a single recharge event indicated that if pumping is delayed beyond two years, the recharged water is effectively non-recoverable in the near basin well field. Some of the water may be recoverable elsewhere, but incorporation of that possibility within a reasonable management scenario would not be feasible.

Steady-state particle-path analysis indicated that the destination of water and solute particles recharged through the basin was strongly dependent on location of recharge within the basin.

Transient simulations of a proposed second basin a mile south of the first basin indicated that principal losses would be through ET (40% of natural discharge), about 25% through surface drains south of the proposed basin, and about 18% each through springs along the river and through ET and seepage beyond the eastern aquifer boundary. Simulated ET losses peak about three years after a recharge event, indicating that most losses would plausibly occur through shallow water-table areas more distant from the basin. Simulated drain losses begin within the operational year and peak about two years after the recharge event. Simulated losses through the eastern aquifer boundary begin about two years after the recharge event, and peak at three to eight years after the event. Simulated spring losses for Spring Zones 5 through 8 begin about a year after the recharge event and peak about two to four years after the event.

Simulated "first-year" natural losses of recharge water through the south basin are negligible (0%) compared with about 10% for the north basin. However, losses of unpumped water after the first year are greater at 57%, compared with 35% for the north basin. Overall estimated long-term (12-year) losses for 80% pumping recovery in the first year for each recharge event were about 10% compared with 17% for the north basin.

Water-level and lithologic information for the proposed south basin is sparse, and there is no operational verification for simulated results, as there is for the north basin. Model results are thus speculative. Preliminary results indicate, however, that at least three wells may be needed for recovery of recharge water at the south location.

Simulated combined long-term natural discharge losses for operation of both north and south basins with 80% pumping recovery during the year of the recharge event were greater (approx. 20%) than either of the individual basins (17% and 11%).

In general, simulations for operation of the north ARR facility indicate that actual losses of recharge water are likely close to the 20% residual non-recovered water that has resulted from 14 years of operation under the preliminary management scheme. Some minor modifications may be considered in the future.

The principal finding of the model is that ARR storage in the Inkster aquifer is short-term storage. It must be applied principally from year to year. The Inkster aquifer has a relatively deep water table (mostly deeper than 20 feet). Such deeper water tables in North Dakota's shallow unconfined systems are usually found only where streams or drainageways intersect the aquifer. This implies high risk of seepage and spring losses. Conversely, aquifers having shallower water tables would likely be unable to store sufficient recharge water without first being evacuated through pumpage. Discharge losses through such shallow water-table systems would likely be primarily through ET near the basin. Management of such a system may require a program of deficit replacement, that is, pumpage and use followed by replacement. This was proposed by Shaver (1990) as a procedural plan for operation of an ARR facility in the Oakes aquifer in southeastern Dickey County, ND, but was never implemented. Simulation of such a system may be a worthwhile objective for future investigations of potential ARR use in North Dakota.

In most cases, use of ARR in shallow unconfined aquifers must be viewed as a means for transferring unused surface waters to a ground-water reservoir for beneficial use within a relatively short period of time, optimally within a year, of the time of capture. ARR in shallow unconfined aquifers is usually not an appropriate means for providing long-term supplemental storage.

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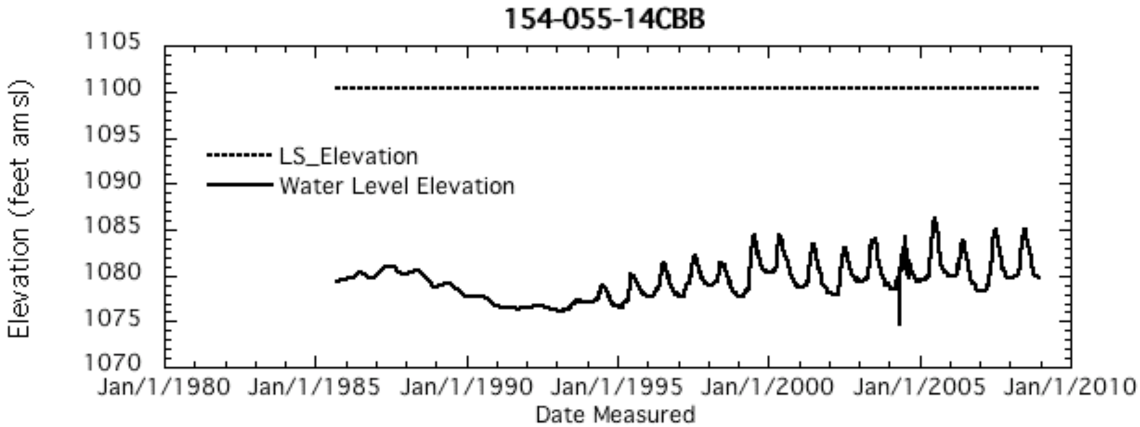
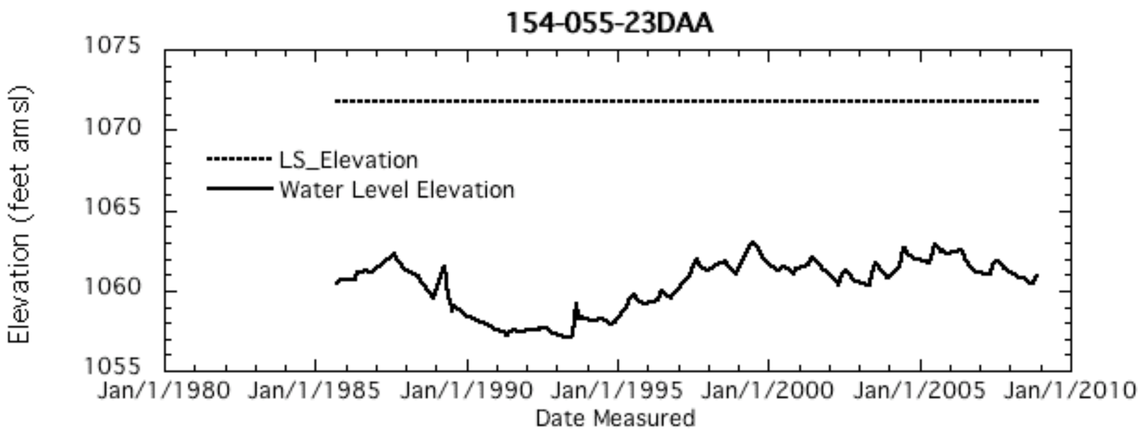
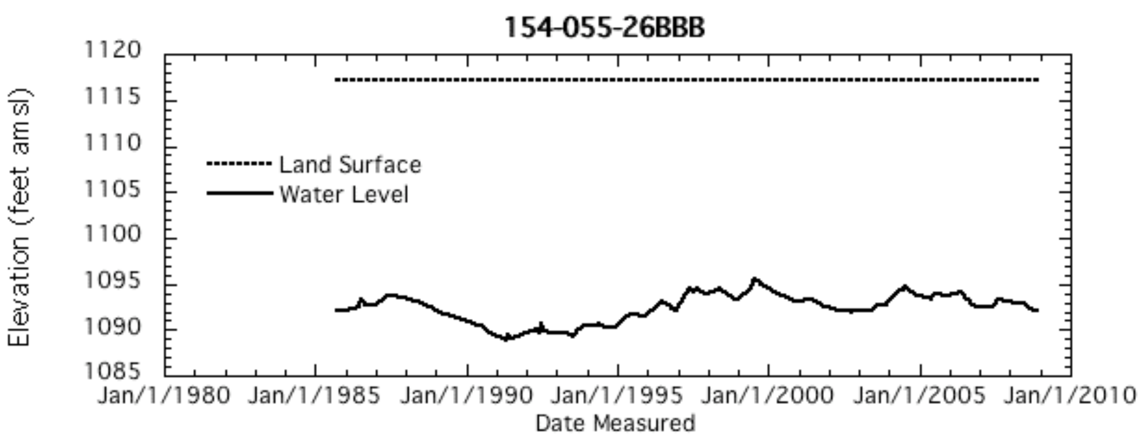
# APPENDIX A: SAMPLE HYDROGRAPHS FOR THE INKSTER AQUIFER


154-055-14CBB
1105
1100
1095
1090
1085
1080
1075
1070
Elevation (feet amsl)
LS_Elevation
Water Level Elevation
Jan/1/1980 Jan/1/1985 Jan/1/1990 Jan/1/1995 Jan/1/2000 Jan/1/2005 Jan/1/2010
Date Measured


154-055-23DAA
1075
1070
1065
1060
1055
Elevation (feet amsl)
LS_Elevation
Water Level Elevation
Jan/1/1980 Jan/1/1985 Jan/1/1990 Jan/1/1995 Jan/1/2000 Jan/1/2005 Jan/1/2010
Date Measured


154-055-26BBB
1120
1115
1110
1105
1100
1095
1090
1085
Elevation (feet amsl)
Land Surface
Water Level
Jan/1/1980 Jan/1/1985 Jan/1/1990 Jan/1/1995 Jan/1/2000 Jan/1/2005 Jan/1/2010
Date Measured

## APPENDIX B: LITHOLOGIC LOGS FOR WELL AND TEST HOLE SITES IN THE INKSTER AQUIFER

**153-055-14DCC**
NDSWC 12370

| | | | |
|---|---|---|---|
| Date Completed: | 09/12/1989 | Purpose: | Observation Well |
| L.S. Elevation (ft): | 1121.6 | Well Type: | 2 in. - PVC |
| Depth Drilled (ft): | 100 | Aquifer: | Inkster |
| Screen Int. (ft.): | 75-80 | Data Source: | |

Completion Info:

Remarks:

## Lithologic Log

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-5 | CLAY, SILT, SAND | loose, oxidized, (alluvium?) |
| 5-7 | SAND | fine to very coarse, mainly coarse, oxidized |
| 7-11 | CLAY | silty, sandy, pebbly inclusions, light brown to slightly reddish, oxidized, (TILL) |
| 11-73 | CLAY | silty, sandy, pebbly inclusions, medium gray, moderately firm, unoxidized, (TILL); interbedded medium to coarse sand and gravel 56-60 ft and 66-73 ft |
| 73-80 | SAND & GRAVEL | medium sand to 3 mm gravel, mainly coarse to very coarse sand, angular gravel to rounded sand, quartz, shale, carbonates, rock fragments |
| 80-100 | CLAY | (TILL), as above; interbedded sand lenses 80-82 ft |

**154-055-09BDD**
NDSWC 11627

| | | | |
|---|---|---|---|
| Date Completed: | 08/20/1985 | Purpose: | Observation |
| Well | | | |
| L.S. Elevation (ft): | 1127 | Well Type: | 1.25 in. - |
| Depth Drilled (ft): | 60 | Aquifer: | Inkster |
| Screen Int. (ft.): | 28-32 | Data Source: | |

Completion Info:

Remarks: Well abandoned because dry.

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | SOIL | brownish black, sandy |
| 1-13 | SAND | fine to coarse, oxidized, yellowish brown, predominantly quartzose, predominantly medium in grain size, subrounded |
| 13-26 | SILT & SAND | silt and very fine sand; very fine silt to very fine sand, predominantly very fine sand, yellowish brown, oxidized |
| 26-41 | SAND | medium to coarse gravel (3/4 inch), predominantly fine gravel (1/8 inch), unoxidized, olive gray appearance, gravels composed of igneous fragments predominantly, subangular, interbedded with clay lenses (drilled tight) |
| 41-60 | TILL | olive gray, shale detrital clay matrix |

**154-055-09DDD**
NDSWC 11626

Date Completed: 08/20/1985 Purpose: Observation
Well
L.S. Elevation (ft): 1108.8 Well Type: 1.25 in. -
PVC
Depth Drilled (ft): 45 Aquifer: Inkster
Screen Int. (ft.): 31-36 Data Source:

Completion Info:

Remarks:

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-2 | SOIL | blackish brown, sandy, gravel |
| 2-23 | GRAVEL | fine to coarse, maximum 1/2-3/4 inch, poorly sorted, subangular to subrounded, predominantly subrounded, predominantly igneous and metamorphic fragments, size predominantly medium gravel 1/8 inch, oxidized to 19 ft |
| 23-36 | SAND | medium, well sorted, subrounded, very shaley 80% |
| 36-45 | TILL | oxidized, olive gray, mainly shale detrital with clay matrix |

**154-055-10CDCDC**
NDSWC 12764

Date Completed: 06/18/1991 Purpose: Observation Well
L.S. Elevation (ft): 1115.74 Well Type: 1.25 in. - PVC
Depth Drilled (ft): 60 Aquifer: Inkster
Screen Int. (ft.): 45-50 Data Source:

Completion Info:

Remarks:

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-3 | TOPSOIL | |
| 3-8 | SAND | very fine to coarse, predominantly medium, moderate sorting, oxidized rusty brown, mostly shale |
| 8-16 | CLAY | silty, very sandy, pebbly inclusions, moderately firm, oxidized, (TILL) |
| 16-23 | SAND | very fine to very coarse, mainly medium, oxidized, as above |
| 23-36 | SAND & GRAVEL | as above with up to 5 mm gravels, mainly very coarse sand, subrounded to subangular, oxidized |
| 36-43 | SAND & GRAVEL | unoxidized, as above |
| 43-50 | SAND | very fine to very coarse, mainly medium, moderate sorting, mostly rounded shale |
| 50-60 | CLAY | silty, sandy, pebbly, medium gray, moderately firm, inclusions, (TILL) |

**154-055-14CBB**
NDSWC 11624

Date Completed: 08/20/1985 Purpose: Observation Well
L.S. Elevation (ft): 1100.4 Well Type: 1.25 in. - PVC
Depth Drilled (ft): 70 Aquifer: Inkster
Screen Int. (ft.): 47-52 Data Source:

Completion Info:

Remarks:

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | SOIL | blackish brown, sandy |
| 1-3 | SAND | medium |
| 3-26 | SAND & GRAVEL | coarse to 1/2-3/4 inch size gravel, predominantly 1/8-1/4 inch gravel, oxidized, yellowish brown, mainly igneous fragments, subrounded to subangular, predominantly subrounded, unoxidized at 26 ft |
| 26-44 | SAND | medium to coarse sand, predominantly coarse sand, unoxidized, moderate sorting, olive gray |
| 44-53 | SAND | medium to coarse sand, mainly detrital shale particles, subrounded to subangular |
| 53-70 | TILL | olive gray, shale particles in clay matrix |

**154-055-14CCC**
NDSWC 2426

| | | | |
|---|---|---|---|
| Date Completed: | 09/02/1965 | Purpose: | Observation |
| Well - Plugged | | | |
| L.S. Elevation (ft): | 1115.6 | Well Type: | 1 in. - ABS |
| Depth Drilled (ft): | 94 | Aquifer: | Inkster |
| Screen Int. (ft.): | 58-61 | Data Source: | |

Completion Info:

Remarks:

## Lithologic Log

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | dark brown, sandy |
| 1-5 | SAND | medium brown, subangular to rounded, predominantly shale and rounded quartz fragments, moderate to good sorting, medium grained |
| 5-15 | SAND | mottled brown, same as above, sorting poor to moderate, medium grained |
| 15-25 | SAND | medium brown, subangular to subrounded, predominantly coarse shale fragments, fine rounded quartz grains, fine to medium grained |
| 25-35 | SAND | mottled brown, subangular to subrounded, predominantly shale fragments and quartz grains, large number of limestone fragments, medium to coarse grained |
| 35-63 | SAND | same as above, fewer limestone fragments, quartz well rounded, medium grained |
| 63-73 | SAND | gray, subrounded to rounded, predominantly quartz, fine to medium grained |
| 73-94 | TILL | olive gray, clay, few rock fragments |

**154-055-14CDC1**
NDSWC 11623

Date Completed: 08/20/1985 Purpose: Observation Well
L.S. Elevation (ft): 1094.8 Well Type: 1.25 in. - PVC
Depth Drilled (ft): 60 Aquifer: Inkster
Screen Int. (ft.): 46-51 Data Source:

Completion Info:

Remarks: WEST WELL
WL adjust 4/1/92 from survey data. Records checked in 1993, they indicate this well has never been sampled. Attemp to sample in 93.

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | SOIL | blackish brown, sandy |
| 1-6 | SAND | medium to fine gravel, yellowish brown, predominantly coarse sand, oxidized, moderately sorted, subangular to subrounded, quartzose |
| 6-31 | SAND & GRAVEL | medium sand to fine gravel, predominantly fine gravel, quartzose, subrounded, interbedded coarser gravel lenses with gravel up to 3/8 inch, out of oxidized at 19-22 ft |
| 31-41 | SAND | very fine silt, oxidized, olive gray |
| 41-54 | SAND | fine to medium, predominantly medium, some silt |
| 54-60 | TILL | detrital shale particles in clay matrix |

**154-055-14CDD**

NDSWC 2515

| | | | |
|---|---|---|---|
| Date Completed: | 05/25/1966 | Purpose: | Observation Well |
| L.S. Elevation (ft): | 1097 | Well Type: | 1.25 in. - |
| Depth Drilled (ft): | 63 | Aquifer: | Inkster |
| Screen Int. (ft.): | 41-61 | Data Source: | |

Completion Info:

Remarks: Groth Bros. pbs well #3 200' NW of prod. well.

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-9 | SAND | fine to coarse, subrounded, quartzose, oxidized |
| 9-13 | SAND | medium to coarse, subrounded to rounded, quartzose, oxidized |
| 13-20 | SAND | as above, unoxidized, gravely |
| 20-40 | SAND | fine to medium, subrounded, quartzose, shale fragments common |
| 40-56 | SAND | fine, subrounded to rounded, quartzose, limestone fragments predominantly |

**154-055-14DCB**
NDSWC 12374

| | | | |
|---|---|---|---|
| Date Completed: | 09/13/1989 | Purpose: | Observation Well |
| L.S. Elevation (ft): | 1092.13 | Well Type: | 2 in. - PVC |
| Depth Drilled (ft): | 25 | Aquifer: | Inkster |
| Screen Int. (ft.): | 6-21 | Data Source: | |

Completion Info:

Remarks: 1000 ft NORTH OF HIGHWAY

## Lithologic Log

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-12 | SAND & GRAVEL | very fine to 2 mm, poorly sorted, mainly medium, oxidized |
| 12-25 | SAND | very fine to very coarse, moderately sort, mainly medium, unoxidized, 50% shale, slightly rounded to moderately rounded, 40% quartz rounded, 10% subrounded other |

**154-055-14DCC**
NDSWC 2516

Date Completed: 05/25/1966 Purpose: Observation Well
L.S. Elevation (ft): 1090.6 Well Type: 1.25 in. - PVC
Depth Drilled (ft): 84 Aquifer: Inkster
Screen Int. (ft.): 48-68 Data Source:

Completion Info:

Remarks:
Groth Bros. obs well #4

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-13 | SAND | very fine to fine, subangular to subrounded, quartzose, oxidized |
| 13-20 | SAND | fine to medium, subangular to subrounded, quartzose, unoxidized; abundant shale fragments |
| 20-32 | SAND | fine, well sorted, subangular to subrounded, abundant shale and limestone fragments |
| 32-40 | SAND | fine to coarse, subangular to subrounded, quartzose, abundant shale fragments |
| 40-70 | SAND | fine to medium, subangular to subrounded, quartzose, limestone fragments abundant |
| 70-74 | SAND | fine, well sorted, subrounded, quartzose, abundant shale fragments, limestone absent |
| 74-84 | SILT | medium dark gray to olive gray |

**154-055-14DCC1**
NDSWC 12372A

| | | | |
|---|---|---|---|
| Date Completed: | 09/12/1989 | Purpose: | Observation Well |
| L.S. Elevation (ft): | 1090.23 | Well Type: | 4 in. - PVC |
| Depth Drilled (ft): | 18 | Aquifer: | Inkster |
| Screen Int. (ft.): | 7-17 | Data Source: | |

Completion Info:

Remarks: EAST WELL
WL adjust 4/1/92 from survey data

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-3 | SAND | oxidized, fine |
| 3-4 | CLAY | oxidized, yellow |
| 4-10 | SAND | oxidized, fine |
| 10-14 | SAND | fine, gray |
| 14-18 | SAND | fine, and silt clay |

**154-055-14DCC2**

NDSWC 12372

Date Completed: 09/12/1989 Purpose: Observation Well

L.S. Elevation (ft): 1090.39 Well Type: 1.25 in. - PVC

Depth Drilled (ft): 80 Aquifer: Inkster

Screen Int. (ft.): 38-42 Data Source:

Completion Info:

Remarks: WEST WELL

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-10 | SAND | very fine to very coarse, moderate sorting, mainly fine to medium, oxidized, reddish brown |
| 10-63 | SAND & GRAVEL | very fine to 5 mm gravel, poorly sorted, mainly fine to medium sand, unoxidized, medium gray, 50% shale, 30% quartz, 20% carbonates and rock fragments; silty form 10-14 ft; slightly coarser from 18-32 ft; interbedded from 32-40 ft with silt lenses |
| 63-80 | CLAY | silty, sandy, pebbly inclusions, moderately firm, (TILL) |

**154-055-14DCD1**
NDSWC 12373A

| | | | |
|---|---|---|---|
| Date Completed: | 09/13/1989 | Purpose: | Observation |
| Well | | | |
| L.S. Elevation (ft): | 1084.27 | Well Type: | 2 in. - PVC |
| Depth Drilled (ft): | 25 | Aquifer: | Inkster |
| Screen Int. (ft.): | 6-21 | Data Source: | |

Completion Info:

Remarks: EAST WELL MAP ON BACK
WL adjust 4/1/92 from survey data.

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-10 | SAND | oxidized, fine |
| 10-25 | SAND | fine |

**154-055-14DCD2**

NDSWC 12373

Date Completed: 09/13/1989 Purpose: Observation
Well
L.S. Elevation (ft): 1084.44 Well Type: 1.25 in. -
PVC
Depth Drilled (ft): 80 Aquifer: Inkster
Screen Int. (ft.): 38-43 Data Source:

Completion Info:

Remarks: WEST WELL
WL adjust 4/1/92 from survey data

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-10 | SAND | very fine to medium, mainly fine, oxidized |
| 10-57 | SAND & GRAVEL | very fine to 2 mm gravel, poorly sorted, mainly medium sand, unoxidized 40-60% shale, 30-40% quartz, 20% other |
| 57-80 | CLAY | silty, sandy, pebbly inclusions, medium gray, moderately firm, (TILL) |

**154-055-15BCBBB**
NDSWC 12770

Date Completed: 06/18/1991 Purpose: Observation
Well
L.S. Elevation (ft): 1119.2 Well Type: 1.25 in. -
PVC
Depth Drilled (ft): 60 Aquifer: Inkster
Screen Int. (ft.): 33-38 Data Source:

Completion Info:

Remarks:

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-29 | SAND & GRAVEL | medium sand to 25+ mm gravel, coarser with depth, poorly sorted, mainly 3-6 mm gravel, angular to subrounded, predominantly subrounded, 40% rock fragments, 30-40% shale, 30% carbonates, oxidized |
| 29-30 | CLAY | slow drilling, poor sample recovery |
| 30-38 | SAND & GRAVEL | fine sand to 3-5 mm gravel, poorly sorted, mainly very coarse sand, more shale than above |
| 38-43 | CLAY & SILT | moderately firm, no inclusions |
| 43-60 | CLAY | silty, sandy, pebbly; inclusions, medium gray, (TILL) |

**154-055-15CCC**
NDSWC 2425

| | | | |
|---|---|---|---|
| Date Completed: | 09/02/1965 | Purpose: | Observation |
| Well - Destroyed | | | |
| L.S. Elevation (ft): | 1126 | Well Type: | 14 in. - none |
| Depth Drilled (ft): | 60 | Aquifer: | Inkster |
| Screen Int. (ft.): | 0-42 | Data Source: | |

Completion Info:

Remarks: the well is no longer here. It has apparently been destroyed -- JCP.

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-10 | GRAVEL | sandy, very poorly sorted, angular to rounded, shale, quartz, dolomite, limestone, igneous crystalline, lignite, great variations in fragment size |
| 10-24 | SAND | poorly sorted, angular to rounded, shale, quartz, dolomite, limestone, igneous crystalline, lignite, gravely, average size about 1 1/2 mm, get coarser downward (about 21 ft), and average size becomes about 2 mm, oxidized |
| 24-42 | TILL | very silty, olive gray with a shade of dark greenish gray, moderately soft, cohesive, mostly dolomite, shale, great variation in size, some quartz, calcareous, unoxidized |

**154-055-15DBA**
Test Hole

| | | | |
|---|---|---|---|
| Date Completed: | 05/23/1994 | Purpose: | Test Hole |
| L.S. Elevation (ft): | N/A | | |
| Depth Drilled (ft): | 0 | | |
| | | Data Source: | |

Completion Info:

Remarks: Owner is Forest River Community

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-18 | SAND | silty sand |
| 18-37 | GRAVEL | coarse gravel |
| 37-44 | SAND | medium to coarse sand |
| 44-60 | CLAY | blue clay |

**154-055-15DBC**

Other

| | | | |
|---|---|---|---|
| Date Completed: | 06/09/1989 | Purpose: | Test Hole |
| L.S. Elevation (ft): | N/A | | |
| Depth Drilled (ft): | 0 | | |
| | | Data Source: | |

Completion Info:

Remarks: Owned by Forest River Community

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-35 | GRAVEL | medium to coarse gravel, brown |
| 35-67 | GRAVEL | medium to coarse gravel, about 70% gray shale |
| 67-80 | TILL | gray till |

**154-055-22ADD**
NDSWC 12376

Date Completed: 09/13/1989 Purpose: Observation Well
L.S. Elevation (ft): 1120.66 Well Type: 2 in. - PVC
Depth Drilled (ft): 80 Aquifer: Inkster
Screen Int. (ft.): 48-53 Data Source:

Completion Info:

Remarks:

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-5 | CLAY & SILT | oxidized |
| 5-21 | SAND & GRAVEL | very fine to 3 mm, oxidized and poorly sorted |
| 21-55 | SAND & GRAVEL | very fine to 5 mm gravel, poorly sorted, mainly medium to coarse sand, 40% shale, 40% quartz, some carbonates and rock fragments; very silty form 39-46 ft |
| 55-80 | CLAY | silty, sandy, pebbly inclusions, medium gray, moderately firm, (TILL) |

**154-055-22BAA**
NDSWC 11943

Date Completed: 10/31/1986 Purpose: Observation Well
L.S. Elevation (ft): 1125.9 Well Type: 1.25 in. - PVC
Depth Drilled (ft): 80 Aquifer: Inkster
Screen Int. (ft.): 45-50 Data Source:

Completion Info:

Remarks: SOUTH WELL
Data base has 22baa -baa1 & baa2 with water levels.

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-12 | SAND | fine to fine pebbles, predominantly very coarse sand, angular to rounded, predominantly subangular, 30% carbonates, 30% igneous, 40% quartz, oxidized silt line at 7 and 12 ft |
| 12-44 | GRAVEL | coarse sand to gravel 1/2 inch diameter, predominantly fine gravel 1/8 inch diameter, angular to rounded, predominantly subrounded to rounded, 1/3 quartz, 1/3 carbonates, 1/3 igneous, some coarser gravel up to 1 inch diameter to 36 ft, oxidized to 29 ft, |
| 44-50 | CLAY | olive gray, very sandy |
| 50-51 | GRAVEL | coarse gravel or cobbles at 50-51 ft |
| 51-80 | TILL | olive gray, silty, slightly pebbly, soft, slightly plastic, 55-60 ft many interbedded gravel lenses |

**154-055-22BAA1**
NDSWC 11619

| | | | |
|---|---|---|---|
| Date Completed: | 8/1985 | Purpose: | Observation |
| Well - Plugged | | | |
| L.S. Elevation (ft): | N/A | Well Type: | 1.25 in. - |
| PVC | | | |
| Depth Drilled (ft): | 80 | Aquifer: | Inkster |
| Screen Int. (ft.): | 39-44 | Data Source: | |

Completion Info:

Remarks: replaced by 154-055-22BAA

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-12 | SAND | fine to fine pebble-predominantly very coarse sand, angular to rounded-predominantly subangular 30% carbonates, 30% igneous, 40% quartz, oxidized silt lens 7 ft. and 12 ft. |
| 12-44 | GRAVEL | coarse sand to gravel 1/2 in. diameter-predominantly fine gravel 1/8 in. diameter, angular to rounded-predominantly subrounded to rounded, 1/3 quartz, 1/3 carbonates, 1/3 igneous, some coarser gravel up to 1 in. diameter to 36 ft., oxidized to 29 ft.-belo |
| 44-50 | CLAY | olive gray, very sandy |
| 50-51 | GRAVEL | coarse or cobbles, 50 to 51 ft. |
| 51-80 | TILL | olive gray-silty, slightly pebbly, soft, slightly plastic; 55 to 60 ft., many interbedded gravel lenses |

**154-055-23ABC**
NDSWC 12375

| | | | |
|---|---|---|---|
| Date Completed: | 09/15/1989 | Purpose: | Observation Well |
| L.S. Elevation (ft): | 1094.79 | Well Type: | 2 in. - PVC |
| Depth Drilled (ft): | 32 | Aquifer: | Inkster |
| Screen Int. (ft.): | 10-25 | Data Source: | |

Completion Info:

Remarks: SOUTH OF WATER RESERVOIR 1200 ft

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-14 | SAND | very fine to very coarse, oxidized |
| 14-32 | SAND | very fine to very coarse, unoxidized, poorly sorted shale and quartz, mainly fine to medium |

**154-055-23BAA2**
NDSWC 2512

Date Completed: 05/25/1966 Purpose: Observation Well
L.S. Elevation (ft): 1095.5 Well Type: 1.25 in. -
Depth Drilled (ft): 63 Aquifer: Inkster
Screen Int. (ft.): 42-57 Data Source:

Completion Info:

Remarks:
tbm lower 15' hacksaw slotted

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-5 | SAND | fine to coarse, subangular to subrounded, quartzose, abundant shale fragments, very coarse to pebbles, oxidized |
| 5-15 | SAND | medium to coarse, subangular, quartzose, limestone and shale fragments abundant, oxidized |
| 15-20 | SAND | medium, subangular, quartzose, scattered fragments limestone and shale, well rounded, unoxidized |
| 20-25 | SAND | fine to medium, subangular to rounded, quartzose, gray color due to unoxidized shale fragments |
| 25-57 | SAND | medium, subangular, quartzose, abundant, subrounded, coarse, limestone and shale fragments, shale increases with depth |
| 57-63 | TILL | olive gray |

**154-055-23BAA3**
NDSWC 2513

Date Completed: 05/25/1966 Purpose: Observation Well
L.S. Elevation (ft): 1096.7 Well Type: 1.25 in. -
Depth Drilled (ft): 74 Aquifer: Inkster
Screen Int. (ft.): 36-56 Data Source:

Completion Info:

Remarks:
tbm lower 12' hacksaw slotted

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | SOIL | brownish gray, sandy |
| 1-7 | SAND | fine to medium, subrounded to rounded, oxidized, predominantly shale fragments, minor amounts, fine, subangular quartz |
| 7-18 | SAND | fine to coarse, subangular to subrounded, quartzose, shale and limestone fragments abundant, minor amounts shale gravel, oxidized |
| 18-23 | SAND | unoxidized, as above |
| 23-30 | SAND | coarse, gravely, subrounded to subangular, predominantly shale fragments, gravel predominantly very light gray to buff limestone |
| 30-56 | SAND | medium to coarse, subangular to subrounded, quartzose, abundant limestone and shale fragments |
| 56-63 | SAND | fine to medium, subangular to subrounded, quartzose, abundant shale fragments |
| 63-68 | SAND | medium (poorly sorted), subangular to subrounded, quartzose, minor amounts shale fragments |
| 68-74 | TILL | olive gray, clayey |

**154-055-23BAA4**
NDSWC 2581

| | | | |
|---|---|---|---|
| Date Completed: | 08/16/1966 | Purpose: | Observation |
| Well | | | |
| L.S. Elevation (ft): | 1097 | Well Type: | 1.25 in. - |
| Depth Drilled (ft): | 73.5 | Aquifer: | Inkster |
| Screen Int. (ft.): | 0-60 | Data Source: | |

Completion Info:

Remarks:
pipe with sandpoint.

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-11 | SAND | medium 60%; fine 30%, coarse 10%; dusky brown; well sorted; subangular to subrounded; 40% shale, 45% quartz; drills fast |
| 11-21 | SAND | medium 50%; fine 20%; coarse 20%, fine to medium gravel 10%; dusky yellow, moderately well sorted; subangular to subrounded, 30% shale, 55% quartz, drills fast |
| 21-56 | SAND | medium to coarse, olive gray; well sorted, subangular to subrounded, 40% shale, 50% quartz, drills fast |
| 56-63 | SAND | coarse sand 55%, fine gravel 35%, fine to medium sand 15%, moderate sorting, subangular to subrounded; 55% shale, 35% quartz, drills fast |
| 63-73.5 | CLAY | silty, olive gray; good coherence and plasticity, very calcareous, drills smooth (lake sediment) |

**154-055-23BAB**
NDSWC 2514

Date Completed: 05/25/1966 Purpose: Observation Well
L.S. Elevation (ft): 1091.5 Well Type: 1.25 in. - PVC
Depth Drilled (ft): 73 Aquifer: Inkster
Screen Int. (ft.): 40-60 Data Source:

Completion Info:

Remarks: TBM

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-3 | SILT | moderate brown, clayey, scattered sand grains, cohesive, very calcareous |
| 3-14 | SAND | poorly sorted, fine to very coarse, subangular to subrounded, quartzose, oxidized |
| 14-17 | SAND | as above, unoxidized |
| 17-33 | SAND | poorly sorted, medium to very coarse, subrounded to subangular, quartzose, gravely, more shale fragments than above, poorly sorted, medium to very very coarse, subrounded, gravely |
| 33-67 | SAND | fine to medium, subrounded, quartzose, abundant shale fragments |
| 67-73 | TILL | olive gray; poor samples, cut by sand |

**154-055-23DAA**
NDSWC 11622

| | | | |
|---|---|---|---|
| Date Completed: | 08/20/1985 | Purpose: | Observation Well |
| L.S. Elevation (ft): | 1071.8 | Well Type: | 1.25 in. - PVC |
| Depth Drilled (ft): | 60 | Aquifer: | Inkster |
| Screen Int. (ft.): | 27-33 | Data Source: | |

Completion Info:

Remarks: 15 ft SOUTH NEAR BENCH MARK

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | SOIL | blackish brown, sandy |
| 1-23 | SAND & GRAVEL | fine to fine gravel, poorly sorted, predominantly coarse sand, oxidized to 13 ft, oxidized yellowish brown, unoxidized olive gray, predominantly quartz, some igneous particles |
| 23-31 | SAND | medium to coarse, moderate sorting, predominantly medium, olive gray |
| 31-56 | silt | to very fine sand, 50-50 silt to sand |
| 56-60 | TILL | olive gray |

**154-055-23DBB1**
NDSWC 12053

| | | | |
|---|---|---|---|
| Date Completed: | 09/30/1987 | Purpose: | Observation Well |
| L.S. Elevation (ft): | 1097.1 | Well Type: | 2 in. - PVC |
| Depth Drilled (ft): | 80 | Aquifer: | Inkster |
| Screen Int. (ft.): | 50-55 | Data Source: | |

Completion Info:

Remarks: NORTH WELL

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | black |
| 1-56 | SAND & GRAVEL | very fine sand to 3 mm gravel, poorly sorted, generally medium sand, oxidized upper 20 ft, 50-60% shale, 25-30% carbonates, 20-25% quartz |
| 56-69 | CLAY | silty, medium gray, soft, no inclusions, (lacustrine) |
| 69-80 | CLAY | silty, sandy, pebbly, moderately firm, medium gray, (TILL) |

**154-055-23DBB2**
NDSWC 12054

| | | | |
|---|---|---|---|
| Date Completed: | 09/30/1987 | Purpose: | Observation Well |
| L.S. Elevation (ft): | 1096.9 | Well Type: | 2 in. - PVC |
| Depth Drilled (ft): | 40 | Aquifer: | Inkster |
| Screen Int. (ft.): | 33-38 | Data Source: | |

Completion Info:

Remarks: MIDDLE WELL

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-2 | TOPSOIL | |
| 2-11 | SAND | oxidized fine sand |
| 11-23 | SAND | fine to coarse sand |
| 23-40 | SAND | coarse shale sand |

**154-055-23DBB3**

NDSWC 12055

| | | | |
|---|---|---|---|
| Date Completed: | 09/30/1987 | Purpose: | Observation |

Well

| | | | |
|---|---|---|---|
| L.S. Elevation (ft): | 1096.6 | Well Type: | 2 in. - PVC |
| Depth Drilled (ft): | 20 | Aquifer: | Inkster |
| Screen Int. (ft.): | 12-17 | Data Source: | |

Completion Info:

Remarks: SOUTH WELL.
This well is dry. Keep this well, it may come back someday.

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-11 | SAND | fine |
| 11-18 | SAND | fine to coarse sand |

**154-055-26BBB**
NDSWC 11621

| | | | |
|---|---|---|---|
| Date Completed: | 09/19/1985 | Purpose: | Observation Well |
| L.S. Elevation (ft): | 1117.2 | Well Type: | 1.25 in. - PVC |
| Depth Drilled (ft): | 60 | Aquifer: | Inkster |
| Screen Int. (ft.): | 38-42 | Data Source: | |

Completion Info:

Remarks: EAST OF TREE GROVE

## Lithologic Log

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | SOIL | blackish, sandy |
| 1-15 | SAND | very fine to medium, quartzose |
| 15-26 | SILT | yellowish brown, oxidized, subangular to subrounded |
| 26-48 | SAND | fine to fine gravel, predominantly coarse, oxidized to 36 ft, dark material; shale detrital |
| 48-60 | TILL | olive gray, sandy |

**154-055-28DDD**
NDSWC 12554

| | | | |
|---|---|---|---|
| Date Completed: | 05/23/1990 | Purpose: | Observation Well |
| L.S. Elevation (ft): | 1147.45 | Well Type: | 2 in. - PVC |
| Depth Drilled (ft): | 120 | Aquifer: | Inkster |
| Screen Int. (ft.): | 45-50 | Data Source: | |

Completion Info:

Remarks:

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-3 | TOPSOIL & SUBSOIL | |
| 3-10 | GRAVEL & SAND | up to 15-25 mm, poorly sorted, oxidized, mostly igneous rock fragments and quartzose |
| 10-25 | CLAY & SILT | slightly sandy, oxidized to 12 ft, unoxidized, medium gray below 12 ft, smooth (offshore lake) |
| 25-52 | SAND | very fine to fine, silty, slightly clayey, mostly very fine, dark, quartz and shale |
| 52-102 | SILT & CLAY | mostly silt, drills fast, smooth; sandy from 52-84 ft, silty clay from 84-102 ft |
| 102-120 | CLAY | silty, sandy, pebbly, inclusions, moderately firm, (TILL) |

**154-055-34ABB**
NDSWC 12369

Date Completed: 09/08/1989 Purpose: Observation
Well
L.S. Elevation (ft): 1129.85 Well Type: 2 in. - PVC
Depth Drilled (ft): 310 Aquifer: Inkster
Screen Int. (ft.): 6-21 Data Source:

Completion Info:

Remarks: #12369-310' & #12369A-25' west 10'

**Lithologic Log**

| Depth (ft) | Unit | Description |
|---|---|---|
| 0-1 | TOPSOIL | |
| 1-13 | SAND | fine to coarse, mainly medium, oxidized; interbedded clay at 6-7 ft |
| 13-22 | SAND | fine to very coarse, mainly medium to coarse, moderate sorting, unoxidized, quartzose with some shale carbonates and other |
| 22-62 | CLAY | medium gray, moderately firm, silty, sandy, and pebbly, inclusions, (TILL) |
| 62-89 | CLAY & SILT | medium gray, moderately plastic, smooth (lacustrine) |
| 89-148 | CLAY | (TILL), as above; rock at 115-116 |
| 148-161 | CLAY & SILT | some sand grain inclusions, smooth, slightly laminated, with gray and white streaks, sticky, soft (lacustrine origin) (TILL?) |
| 161-300 | CLAY | (TILL as above); rocky throughout |
| 300-310 | CLAY & SILT | slightly shalified, moderately well indurated, micaceous, brownish gray (Niobrara?) |