FEATURE 9: USE AQUIFERS FOR WATER STORAGE AND RECOVERY

Description

The Groundwater and Drainage Group (D-8550) of the Reclamation Technical Services Center, Denver Federal Center, Denver, Colorado, was asked to evaluate and estimate the potential for artificial recharge of the West Fargo North Aquifer, and to provide an estimate of the costs involved to install a recharge system.

A groundwater model was used to evaluate the potential for the aquifer to accept artificial recharge waters, the type of recharge system that would be most efficient, and the general configuration of the recharge system.

Approach

The approach taken by D-8550 was to construct a simplified 3-D groundwater model and to use the model to evaluate several simplified scenarios of potential recharge system configurations. The goal was to test the aquifer response to recharge of at least 10,000 acre-ft of water. Under current conditions, this is the estimated amount of water that would be required to return the aquifer to artesian conditions. The recharge was assumed to occur within a nine month period using excess 'off-peak' flows which would then be recovered during a three month 'peak demand' period. The recovery period was not modeled as part of this evaluation.

Model Design

The model used was V-MODFLOW, Version 1.5, distributed by Waterloo Hydrogeologic Software, Inc. of Waterloo, Ontario, Canada. Hydrologic parameters required by the model as model inputs were obtained from the USGS Water-Resources Investigations Report 83-4279, "Hydrologic effects of withdrawal of ground water on the West Fargo Aquifer system, Eastern Cass County, North Dakota".

The area modeled was the central part of the West Fargo North Aquifer, comprising an area of 18 square miles (roughly 2 miles wide and 9 miles long). Based on information contained in WRI Report 83-4279, the model area was chosen as being 4 miles wide, 9 miles long, and 125 feet thick. The model grid was selected as consisting of 95 rows, 42 columns, and 2 layers. Each cell was 500 feet by 500 feet. Layer 1, the upper layer, went from elevation 850 feet to the approximate ground surface elevation of 925 feet. Layer 2, the lower layer, went from elevation 800 to 850.

Layer 1 was modeled as the overlying lake deposits as described in WRI 83-4279. They were assigned a hydraulic conductivity (K) of 0.0001 ft/day, a storage coefficient of 0.00005, a specific yield of 0.05, and a porosity of 0.3. Layer 2 was divided into two types of materials, the aquifer itself, and glacial tills adjacent to the aquifer. The glacial tills were located on the margins of the model, between columns 1 to 10, and 32 to 42 - each representing an area approximately 1 mile wide by 9 miles long.

The aquifer occupied the remainder of layer 2, from column 11 to 31 - representing an area approximately 2 miles wide and 9 miles long. The aquifer was modeled as being a rectangular block 50 feet thick, and the transmissivity was set at 10,000 sq.ft/day (K = 200 ft/day), the storage coefficient was 0.07, the specific yield was 0.15, and the porosity was set at 0.3. The values for the till were set at 133 sq.ft/day (K = 2.8 ft/day), 0.0005, 0.15, and 0.25 respectively. Vertical conductivity values were set at 10% of the horizontal values in all cases. Anisotropy ratio was set to 1 for all layers and materials. It should be noted that no porosity values were identified in the WRI report, so the values used as input into the model were obtained by taking the average of several porosity ranges for these types of materials as reported in several textbooks.

Although the lake bed materials were modeled as being 75 feet thick, WRI Report 83-4279 indicates variations from about 53 feet to over 100 feet thick. Also, the aquifer was modeled as being 50 feet thick, although it has been reported to be from less than 5 feet to nearly 120 feet thick. The model placed the top of the aquifer at about 75 feet below ground surface, although WRI Report 83-4279 shows it varying from about 85 feet to over 175 feet deep.

Two general recharge concepts were modeled, conventional vertical wells and horizontal wells. In the conventional vertical well scenario, wells were modeled as fully penetrating and were screened through the entire aquifer material. In the horizontal well scenario, the wells were modeled as river segments with the river bottom being at the target depth for the horizontal well - generally this was set at 2 feet below the top of the aquifer material. In representing the horizontal wells, the river segments were modeled as completely crossing each cell, so the reach through each cell was set at 500 feet, the width of the river was set at 1.5 feet, bed thickness was set at 0.25 foot, and the conductivity of the bed material was set at the aquifer conductivity. River bed conductance in MODFLOW is calculated as the product of the length of river reach within a cell, the width of the river bottom, and the conductivity of the river bed materials. This product is then divided by the thickness of the river bed materials to obtain the calculated river bed conductance. In this model, the conductivity of the material is the same as the aquifer materials (200 ft/day), the horizontal well is assumed to go straight across the cell so its reach would be 500 feet, and the width of the river was modeled as the wetted perimeter of a 12 inch pipe (approximately one-half the total perimeter). The thickness of the river bed materials was taken as the thickness of the disturbed materials surrounding the pipe. These values are based on the fact that the maximum size of pipe that can be placed in a 12" horizontal boring is about 8-3/4" and that there would be 2 - 3 inches of disturbed material surrounding the pipe (Bob Bianchi, 1999, based on phone conversations with contractor capable of installing horizontal wells).

The scenarios under each general concept all had the stated goal of artificially recharging up to 10,000 acre-ft of water over a nine month period. Under the conventional vertical well scenario, it was assumed that the recharge wells would also be used as extraction wells during peak demand times, and as such, would have 1,000 g.p.m. pumps in each well. Recharge studies have indicated that the recharge rates generally are about one-half the extraction rates in dual purpose wells, so a recharge rate of 500 g.p.m. was used in the model scenario. Based on the stated goals, it was calculated that the recharge system would require 18 wells. These wells were placed in the center of each of the 18 sections represented by the model.

Under the horizontal well scenario, it was assumed that the maximum length of well that could be installed using available technology would be about 3,000 feet long (wells up to 4,500 feet in overall length are possible). Initial well design used 3 wells, with each well being 3,000 feet long. Each well was aligned so that they were perpendicular to, and centered on, the long axis of the model. One well was placed in the center of the northern 6 sections, one was placed in the center of the southern 6 sections, and the third was placed in the center of the middle 6 sections of the model area.
The initial heads in the aquifer and the adjacent till materials were set at 841.7 feet. This allowed for 8.3 feet of unsaturated aquifer material available for recharge. This is equivalent to about 28,800 acre-ft of available storage at a porosity of 0.3. The 28,800 acre-ft of available storage is based on the calculated volume of unsaturated aquifer. Although the model represents the unsaturated part of the aquifer as a rectangular block, the actual unsaturated part of the West Fargo North Aquifer resembles more of an inverted pyramid shape tapering from nearly 25 feet thick in the center to zero at the edges.

Results and Discussion

Conventional Vertical Wells

The following table is the final water budget from the MODFLOW run of the conventional vertical well scenario. The run was divided into 9 stress periods of 30 days each. Each stress period is divided into 10 time steps by default, unless specified otherwise in the model inputs. The units of length in the table are feet, the units of time are days. The MODFLOW convention is that water entering the model from some external source, or being mobilized from inside the model is counted as input and is listed in the budget under the "IN:" columns. Water that leaves the model or is taken out of the model as far as being mobilized is concerned, is listed in the "OUT:" columns. In the following table, under the 'Cumulative Volumes' column, 0.46782E+09 cubic feet of water entered the model during the 9 stress periods - some of it came out of storage, but most came from the recharge wells. All of the water that entered the model 'left' the model by being put into storage with the exception of 0.10363E+09 cubic feet (shown as the difference between IN and OUT; IN - OUT = 0.10363E+09). This represents the amount of water that entered the model but did not enter into storage or did not leave the model through some other mechanism. The 'Percent Discrepancy' value is the ratio of the 'Total Out' divided by the 'Total In' expressed as a percentage, and is a measure of the overall balance of the water budget.

Table 9.1
Ending Water Budget, West Fargo North Simulation

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 10 IN STRESS PERIOD 9

CUMULATIVE VOLUMES L**3		RATES FOR THIS TIME STEP L**3/T	
IN:		IN:	
STORAGE =	3.8147	STORAGE =	0.00000E+00
WELLS =	0.46782E+09	WELLS =	0.17327E+07
TOTAL IN =	0.46782E+09	TOTAL IN =	0.17327E+07
OUT:		OUT:	
STORAGE =	0.36419E+09	STORAGE =	0.10289E+07
WELLS =	0.00000E+00	WELLS =	0.00000E+00
TOTAL OUT =	0.36419E+09	TOTAL OUT =	0.10289E+07
IN - OUT =	0.10363E+09	IN - OUT =	0.70378E+06
PERCENT DISCREPANCY =	24.91	PERCENT DISCREPANCY =	50.97

TIME SUMMARY AT END OF TIME STEP 10 IN STRESS PERIOD 8

	SECONDS	MINUTES	HOURS	DAYS	YEARS
TIME STEP LENGTH	515209.	8586.82	143.114	5.96307	0.163260E-01
STRESS PERIOD TIME	0.259200E+07	43200.0	720.000	30.0000	0.821355E-01
TOTAL SIMULATION TIME	0.233280E+08	388800.	6480.00	270.000	0.739220

Figures 1 & 2 are the corresponding potentiometric surface maps for the aquifer at the end of the last stress period. Figure 1 shows the entire modeled area, and Figure 2 shows a close-up of an area around six of the wells.

At the end of 270 days of pumping, with 18 wells constantly recharging at the rate of 500 g.p.m., there was 0.46782E+09 cubic feet (10,740 acre-ft) of water recharged to the aquifer, of which 0.35419E+09 cubic feet (8131 acre-ft) went into storage. This model did not attempt to account for any withdrawals that might be occurring at the same time from domestic, agricultural, industrial, or municipal uses.

Figure 1 shows that as the mounds build up around each recharge well, the 842 foot potentiometric surface contour is pushed out into the adjacent till materials. Originally the 841.7 foot contour was at the boundary of the aquifer and tills. After 270 days, the potentiometric surface along the boundary between the aquifer and tills has risen about 3 to 4 feet.

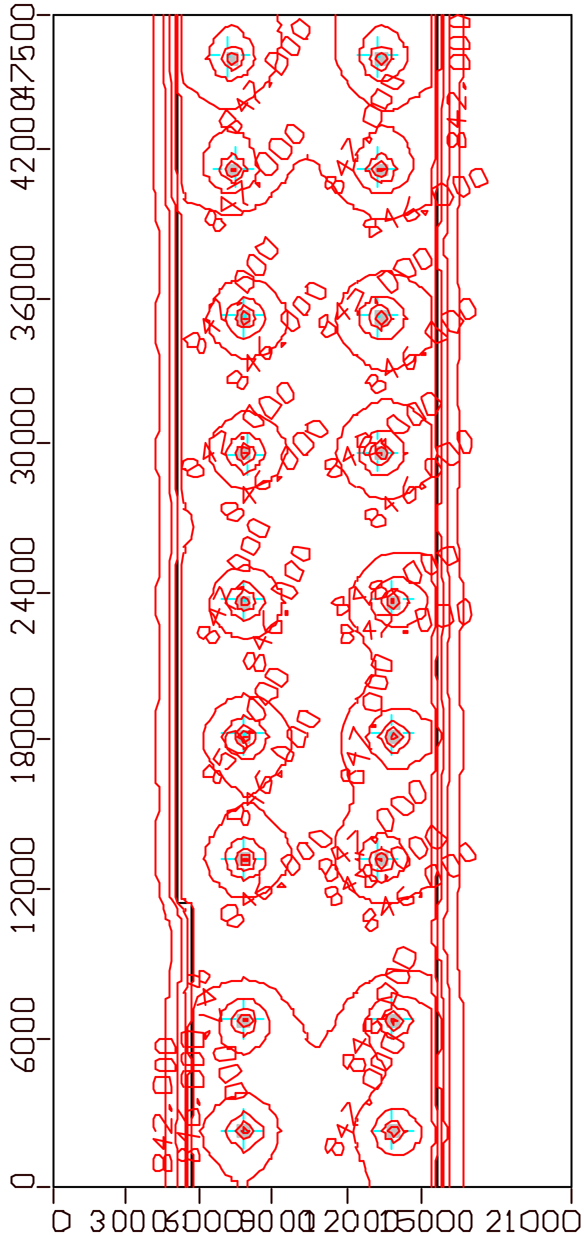

Figure 1. Potentiometric Surface in Aquifer (Layer 2) after 270 days. The potentiometric surface at the boundary between the aquifer and adjacent tills is approximately 845.0 to 846.0 feet

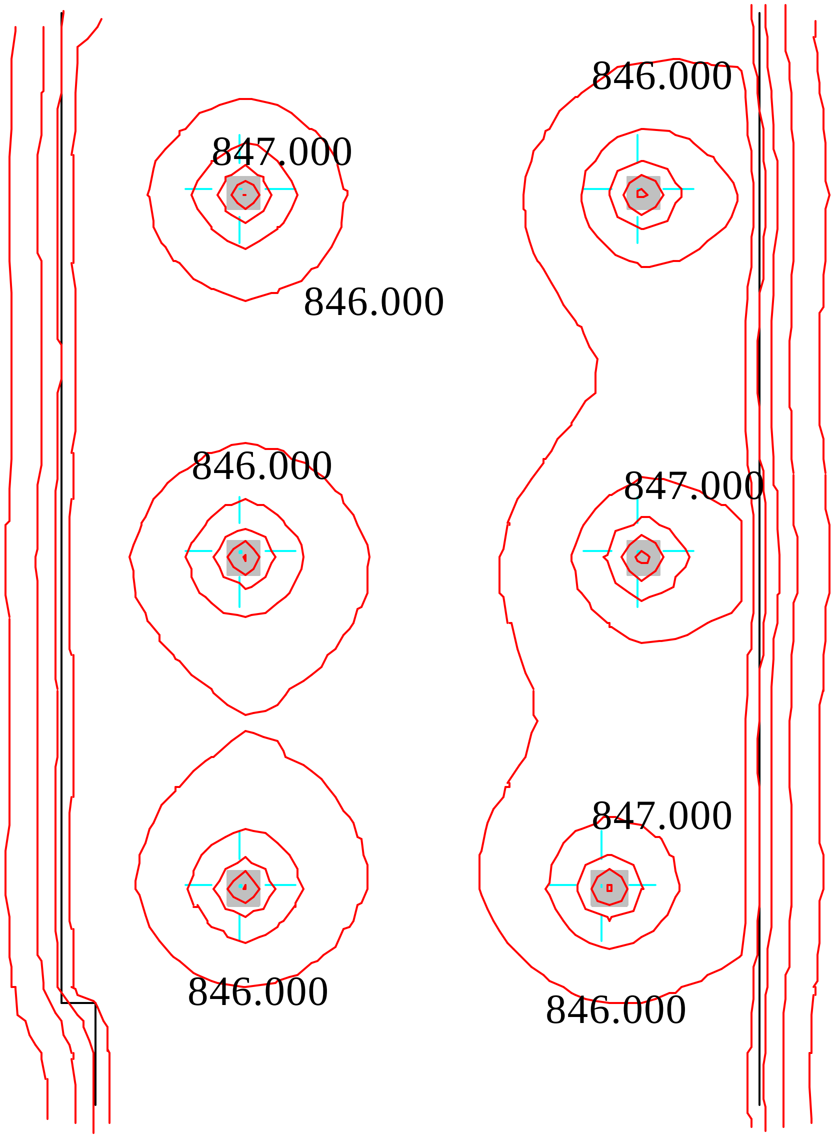

Figure 2. Close-up view of potentiometric surface around six of the wells. Maximum surface contour is 850.0 feet.

The USGS WRI report indicated that under dewatered conditions, the aquifer was probably receiving natural recharge from the tills, the underlying Dakota Aquifer, and to some extent, from the overlying lake bed materials. As the mounds build up, the gradient from the tills towards the aquifer is reduced and eventually reversed so that natural recharge from this source is significantly reduced, and may be stopped altogether. Similarly, as the mounds build up, the recharge from the underlying Dakota Aquifer is probably also reduced. As the aquifer materials are rewetted, and artesian pressures begin to build again, any recharge from the overlying lake bed materials will also probably be reversed.

Figure 2 shows a close-up of the mounds around six of the wells. The level of water in the center of the mounds is about 850.0 feet. The levels at the boundaries of the aquifer with the tills is about 845.0 feet. This indicates a head in the well of about 5 feet, or 8 feet above initial conditions. The heads in the wells after the first 30 days was also about 5 feet (elevation 847.0) indicating that the mounds built rather quickly following start-up of the recharge wells, and afterwards they built out and up at relatively constant rates. Recharge rates of 500 g.p.m. seem to maintain relative heads in the wells of about 5 feet. These mounds are shown with a material porosity of 0.3. If the effective porosity is less than 0.3, then the mounds would probably have similar heads but the perimeters of the mounds would be much broader and adjacent mounds might even begin to coalesce.

Assuming a treatment/distribution facility located near the center of the modeled area, this configuration of wells would require about eight miles of high capacity piping manifolds up the center of the model area, and about nine miles of header piping to attach the 18 wells to the manifold piping. In addition, this configuration would require 18 drill pads and well sites, along with the attendant pumping facilities, pump houses, power drops, and all the associated plumbing and security items.

Additional simulation runs were made to determine if there was an upper limit to the amount of recharge that could be put into aquifer storage. Neither doubling the number of wells, nor increasing the recharge rates to 1000 g.p.m. per well produced unstable conditions within the model, indicating that the aquifer materials, as modeled, were capable of accepting significantly higher recharge rates and significantly greater recharge amounts.

Horizontal Wells

The following table is the water budget after the eighth stress period from the MODFLOW run of the horizontal well scenario. The run was divided into 9 stress periods of 30 days each.

Table 9.2
Stress Period 8 Water Budget, West Fargo North Simulation

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VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 10 IN STRESS PERIOD  8
          ------------------------------------------------------------------------------
CUMULATIVE VOLUMES      L**3                 RATES FOR THIS TIME STEP      L**3/T
     ------------------                           ------------------------
     IN:                                          IN:
     ---                                          ---
     STORAGE =     165.56                         STORAGE =    0.00000E+00
     RIVER LEAKAGE =   0.46580E+09           RIVER LEAKAGE =   0.12304E+07
     TOTAL IN =   0.46580E+09                     TOTAL IN =   0.12304E+07

     OUT:                                         OUT:
     ----                                         ----
     STORAGE =   0.39773E+09                      STORAGE =   0.79383E+06
     RIVER LEAKAGE =   0.00000E+00           RIVER LEAKAGE =   0.00000E+00
     TOTAL OUT =   0.39773E+09                    TOTAL OUT =   0.79383E+06

     IN - OUT =   0.68070E+08                IN - OUT =   0.43656E+06
     PERCENT DISCREPANCY =          15.77         PERCENT DISCREPANCY =           43.13

          TIME SUMMARY AT END OF TIME STEP 10 IN STRESS PERIOD  8
                            SECONDS       MINUTES      HOURS       DAYS         YEARS
                               --------------------------------------------------------------------------
TIME STEP LENGTH             515209.         8586.82    143.114      5.96307    0.163260E-01
STRESS PERIOD TIME           0.259200E+07    43200.0     720.000     30.0000     0.821355E-01
TOTAL SIMULATION TIME        0.207360E+08   345600.     5760.00     240.000      0.657084
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Figures 3 & 4 are the corresponding potentiometric surface maps for the aquifer at the end of the eighth stress period. Figure 3 shows the entire modeled area, and Figure 4 shows a close-up of an area around the central well.

The simulation was run with only 8 feet of head placed on the wells (simulated as a constant stage in the river nodes of 8 feet). After the eighth stress period (or 240 days), the horizontal wells had placed 0.46580E+09 cubic feet (10,693 acre-ft) of water into the model of which 0.39773E+09 cubic feet (9131 acre-ft) went into storage. Again, this model did not attempt to account for any withdrawals that might be occurring at the same time from domestic, agricultural, industrial, or municipal uses.

Figure 3 shows that as the mounds built up around horizontal each recharge well, the 842 foot potentiometric surface contour is pushed out into the adjacent till materials - as was the case under the conventional vertical well scenario. Originally the 842 foot contour was at the boundary of the aquifer and tills. After 240 days, the potentiometric surface along the boundary between the aquifer and tills has risen about 2 feet.

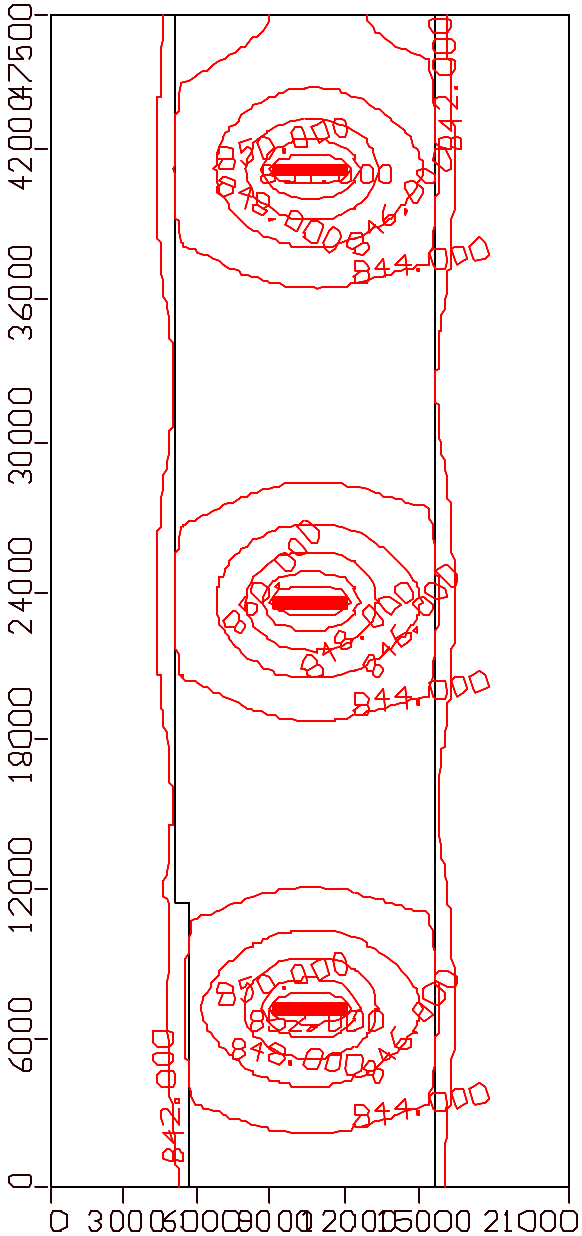

Figure 3. Potentiometric Surface in Aquifer (Layer 2) after 240 days. The potentiometric surface at the boundary between the aquifer and adjacent tills is approximately 844.0 feet

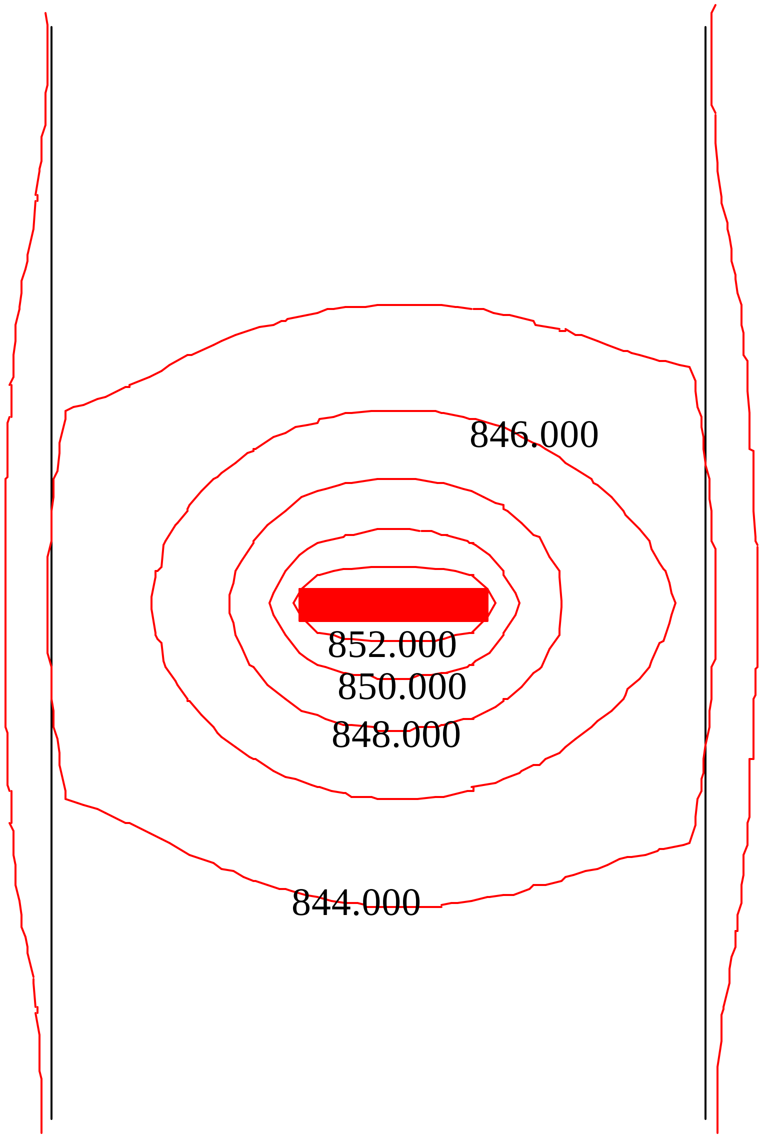

Figure 4. Close-up view of potentiometric surface around six of the wells. Maximum surface contour is about 853.0 feet.

The USGS WRI report indicated that under dewatered conditions, the aquifer was probably receiving natural recharge from the tills, the underlying Dakota Aquifer, and to some extent, from the overlying lake bed materials. As the mounds build up, the gradient from the tills towards the aquifer is reduced and eventually reversed so that natural recharge from this source is significantly reduced, and may be stopped altogether. Similarly, as the mounds build up, the recharge from the underlying Dakota Aquifer is probably also reduced. As the aquifer materials are rewetted, and artesian pressures begin to build again, any recharge from the overlying lake bed materials will also probably be reversed.

Figure 4 shows a close-up of the mounds around the central well. The level of water in the center of the mound is about 853.0 feet. The levels at the boundaries of the aquifer with the tills is about 844.0 feet. This indicates a head in the center of the mound of about 9 feet, or 11 feet above initial conditions. The heads in all three wells after the first 30 days was also about 9 feet (elevation 851.0) indicating that the mounds under this scenario also built rather quickly following start-up of the recharge wells, and afterwards they built out and up at relatively constant rates. These mounds are shown with a material porosity of 0.3. If the effective porosity is less than 0.3, then the mounds would probably have similar heads but the perimeters of the mounds would be much broader, and the contours along the boundary of the aquifer with the tills would become very closely spaced and the mounds would assume a less elliptical shape with the north-south axis being larger relative to the east-west axis..

Since these horizontal wells would be installed near the top of the aquifer materials to maximize the recharge potential while maintaining the minimum heads in the wells, they would not be useable as extraction wells. Conventional vertical wells could be installed within the aquifer to act as extraction wells during peak demand times. Alternatively, horizontal wells installed near the bottom of the aquifer materials could be used as extraction wells.

Assuming a treatment/distribution facility located near the center of the modeled area, this configuration of wells would require about six miles of high capacity piping manifolds up the center of the model area, and a small amount of header piping to attach the 3 wells to the manifold piping. In addition, this configuration would require only 3 drill pads and well sites, along with the attendant pumping facilities, pump houses, power drops, and all the associated plumbing and security items.

Additional simulation runs were made to determine if there was an upper limit to the amount of recharge that could be put into aquifer storage. Neither doubling the number of wells, nor tripling the length of the wells, nor increasing the recharge rates (by increasing the stage in the river nodes to 12 feet) produced unstable conditions within the model, indicating that the aquifer materials, as modeled, were capable of accepting significantly higher recharge rates and significantly greater recharge amounts.

Summary

Based on the information presented in the USGS WRI Report 83-4279, and as it was used as input into the V-MODFLOW model, the aquifer materials appear to be capable of accepting the amounts of recharge waters modeled, at the targeted rates, and within the targeted time frame.

Based on simulation runs that were made separate from the targeted conditions, the limitations to the amount of recharge that can be put into storage in the aquifer do not appear to be related to aquifer properties, but rather to limitations in the number of wells used, the capacities of the wells, site specific aquifer conditions, and other engineering constraints. However, since the model simulated the unsaturated portion of the aquifer as a rectangular block, whereas the actual shape of the unsaturated materials probably more closely resembles an inverted pyramid, there probably are limitations to the amounts of artificial recharge that the aquifer can accept near the boundaries of the aquifer that are controlled by the properties of the aquifer itself.

The use of horizontal wells would require significantly less piping, would have significantly less surface disruption or disturbance, and would appear to be more efficient as far as recharge capacities are concerned as compared to conventional vertical wells.

The results reported from this modeling effort are based on a simplified model using uniform material properties and isotropic mediums. Actual field conditions will vary significantly from location to location, and such variability is not represented in this modeling effort. This modeling effort indicates that the proposed use of the aquifer for storage of artificial recharge waters is feasible and potentially a viable option. Should this option be selected, further detailed investigations will need to be completed to determine the variability of the aquifer properties, the actual extent and degree of unsaturated aquifer materials, the variability in the thickness and lateral extent of the aquifer, the amount of natural recharge from the adjacent materials, etc. All this additional data would be required to properly locate and size the recharge system and system components.

References

Armstrong, C.A., 1985, “Hydrologic effects of withdrawal of ground water on the West Fargo Aquifer system, Eastern Cass County, North Dakota”, Water-Resources Investigations Report 83-4279, 28 pg.

Rec'd 4/23/99

CODE: D-8170

ESTIMATE WORKSHEET

SHEET OF

FEATURE: 23-Apr-99

FEATURE 9
Aquifer Recharge & Recovery
Vertical Well System

PROJECT: Red River Valley Water Supply

DIVISION:

FILE: J:\REDRIVER\RROWELLS.WK4

PLANT ACCT.	PAY ITEM	DESCRIPTION	CODE	QUANTITY	UNIT	UNIT PRICE	AMOUNT	LIFE	Annual Operation	Annual Maintenance	Annual Replacement	Annual Energy	TOTAL ANNUAL
		Drill & install wells with stainless steel casings and screens											
		12-inch dia., 160-feet deep, 30-foot screened (average)		18	EA	$50,000	$900,000.00	50+	$40,000.00	$30,000.00			$70,000.00
		Furnish and install pumps for wells											
		1000 gpm - 200' head		18	EA	$10,000	$180,000.00	15			$19,600.00		$19,600.00
		Furnish and install wellfield control/monitoring equipment		1	LS	$250,000	$250,000.00	10			$17,700.00		$17,700.00
		Furnish and install watertank (200,000 gallon)		1	LS	$200,000	$200,000.00	50+					
		Furnish and install pipe with earthwork & ROW costs											
		21B50	PVC	1.50	miles	$253,000	$379,500.00	50+			$300.00		$300.00
		18B50	PVC	1.00	miles	$230,000	$230,000.00	50+			$200.00		$200.00
		15B50	PVC	6.00	miles	$171,000	$1,026,000.00	50+			$700.00		$700.00
		Air Valve Installations (2 per mile)		17	EA	$5,000	$85,000.00	50+					
		Blowoff Installations (2 per mile)		17	EA	$8,000	$136,000.00	50+					
		Overhead powerlines for wellfield & pumping plant		40	miles	$40,000.00	$1,600,000.00	45			$115,800.00		$115,800.00
		Pumping Plant (50'-20cfs)		1	LS	$510,000	$510,000.00	35+	$40,500.00	$10,200.00		$40,100.00	$90,800.00
		Surge Protection Chamber		1	LS	$150,000	$150,000.00	50+					
		Pipe Jacking (24" carrier pipe X 100')		3	EA	$42,000	$126,000.00	50+					
		Telemetry		1	LS	$150,000.00	$150,000.00	10			$10,600.00		$10,600.00
								Subtotal	$80,500.00	$40,200.00	$164,900.00	$40,100.00	$325,700.00
✓		Mobilization (+/- 5%)					$300,000.00						
✓		SUBTOTAL					$6,222,500.00				Unlisted Items (+/- 20%)		$64,300.00
✓		Unlisted Items (+/- 20%)					$1,277,500.00						
✓		CONTRACT COST					$7,500,000.00				**TOTAL O, M, R, & E**		**$390,000.00**
✓		Contingencies (+/- 25%)					$1,800,000.00						
✓		FIELD COST					$9,300,000.00						
✓		USBR Invest., Mitig., Engr. & Constr. Mgt. (+/- 33%)					$3,200,000.00						
✓		**TOTAL ESTIMATE**					**$12,500,000.00**				**ANNUALIZED CAPITAL COST**		**$890,000.00**
											TOTAL ANNUAL COST		**$1,280,000.00**

QUANTITIES		PRICES	
BY R. Bianchi, J. Baysinger		BY RKC K. Copeland	CHECKED Craig A. Gush 4/23/99
DATE PREPARED	APPROVED	DATE 4/23/99	PRICE LEVEL Appraisal