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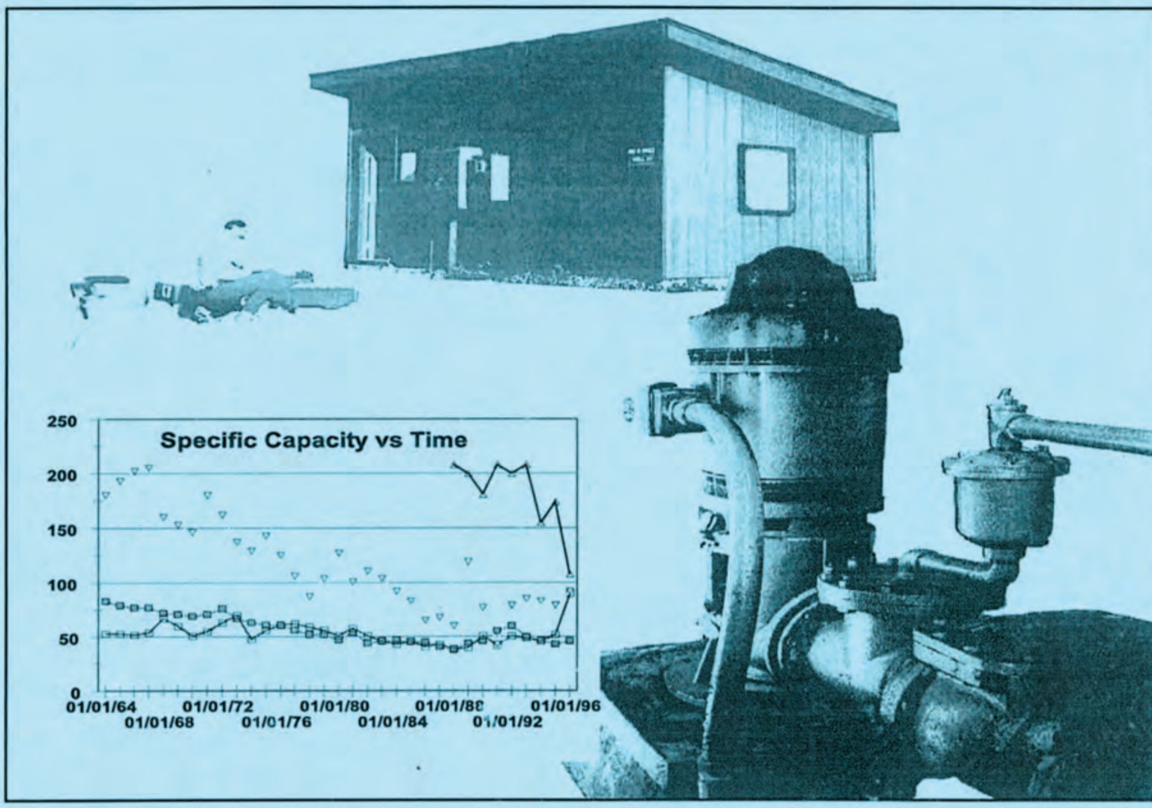
THE ROLE OF HYDRAULIC, CHEMICAL, AND BIOLOGICAL FACTORS IN THE DECLINE OF SPECIFIC CAPACITY IN THE WESTERN CHAMPAIGN WELL FIELD: A PRELIMINARY INVESTIGATION

Edward Mehnert, Keith C. Hackley, David R. Larson, and Samuel V. Panno



Final Report to
Northern Illinois Water Corporation, Champaign, IL

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ILLINOIS STATE GEOLOGICAL SURVEY
William W. Shilts, Chief

Natural Resources Building
615 East Peabody Drive
Champaign, IL 61820-6964

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ABSTRACT

Northern Illinois Water Corporation (NIWC) requested technical assistance from the Illinois State Geological Survey (ISGS) to help determine the cause or causes of the observed decline in specific capacity of wells in its western well field. Specific capacity is a measure of a well's productivity and equals the pumping rate divided by the drawdown in the pumping well.

Through a review of available records and data gathered from limited field and laboratory investigations, we identified hydraulic and geochemical factors as the probable causes for the observed decline in specific capacity, but biological factors do not appear to have a significant role. Hydraulic factors include well interference and entrance velocities exceeding the threshold level of 6 ft/min. The chemical data suggest that carbonate and iron minerals could be precipitating and reducing the porosity and hydraulic conductivity within a 100-foot radius of each affected well. Precipitation of these minerals could be associated with reduced hydrostatic pressure due to drawdown and concomitant degassing of carbon dioxide, which could be exacerbated by the presence of significant amounts of methane.

With the available data, it was not possible to determine whether hydraulic or geochemical factors were the dominant cause in the observed decline in specific capacity. Additional investigations are recommended to provide the data to resolve this problem.

BACKGROUND

Northern Illinois Water Corporation (NIWC) contracted with the Illinois State Geological Survey (ISGS) for technical assistance to help determine the cause or causes of the observed decline in specific capacity of wells in its western well field. The western well field is comprised of 12 high capacity wells with individual pumping capacities ranging from 1.55 to 3.44 million gallons per day (MGD) and is located in and around the northwest part of the City of Champaign (Figure 1). NIWC supplies drinking water to the Cities of Champaign and Urbana, and to surrounding communities.

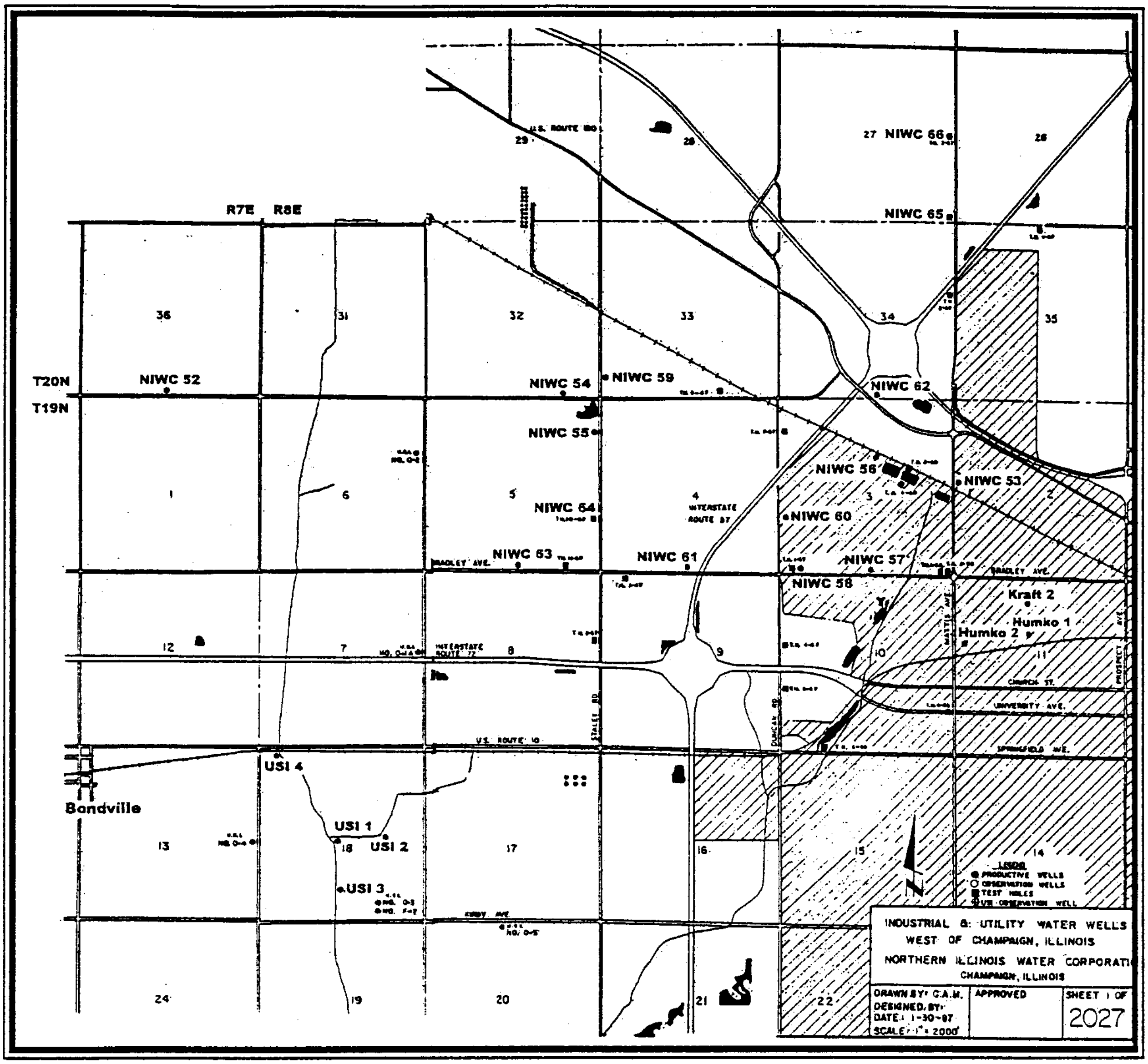

Figure 1. Map of study area showing NIWC, USI, HUMKO and Kraft wells

NIWC has compiled data that documents the loss in specific capacity from 1964 to 1996 (Table 1). Specific capacity is a measure of a well's productivity and equals the pumping rate divided by the drawdown in the pumping well (Freeze and Cherry, 1979). The average annual loss of specific capacity for the western well field was reported to be 1.22%, but the specific capacity data are quite variable from well to well and over time (Figure 2).

Table 1. Specific capacity loss in NIWC's western well field

	Well Number											
	53	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**
Capacity (MGD)	2.55	3.47	1.55	2.43	2.68	3.44	3.07	3.41	3.25	3.54	3.01	2.0
Original SC	106	99.7	57.7	98.7	132	241	164	208	113	144.5	171	84
1996 Average Annual SC	73.8	45.6	89.7	49	32.2	93.8	91.9	69.5	81.4	56	107.9	91
Years in Operation	41	41	39	36	35	33	35	26	22	17	9	2
Delta SC	32.2	54.1	-32	49.7	99.8	147	72.1	139	31.6	88.5	63.1	-7
SC Total Loss (%)	30.38	54.3	-55	50.4	75.6	61.1	44	66.6	28	61.25	36.9	-8
SC Loss per Year	0.79	1.32	-0.82	1.38	2.85	4.46	2.06	5.33	1.44	5.21	7.01	-3.50
%SC Loss per Year	0.74	1.32	-1.42	1.40	2.16	1.85	1.26	2.56	1.27	3.60	4.10	-4.17

Many factors can lead to a loss of capacity in production wells including mechanical problems with the pump and deterioration in the flow capacity near or at the well. We assumed that the pumps are not responsible for the loss in capacity and, instead, investigated possible deterioration in the well screen, gravel pack and the aquifer surrounding the well. Deterioration in the well screen, gravel pack or aquifer can be caused by biological, chemical, and/or physical factors (Borch et al., 1993).

Biological Factors

Iron-oxidizing bacteria are a common problem in production wells and can reduce the hydraulic conductivity around the well screen due to the bacterial biomass or biologically-mediated

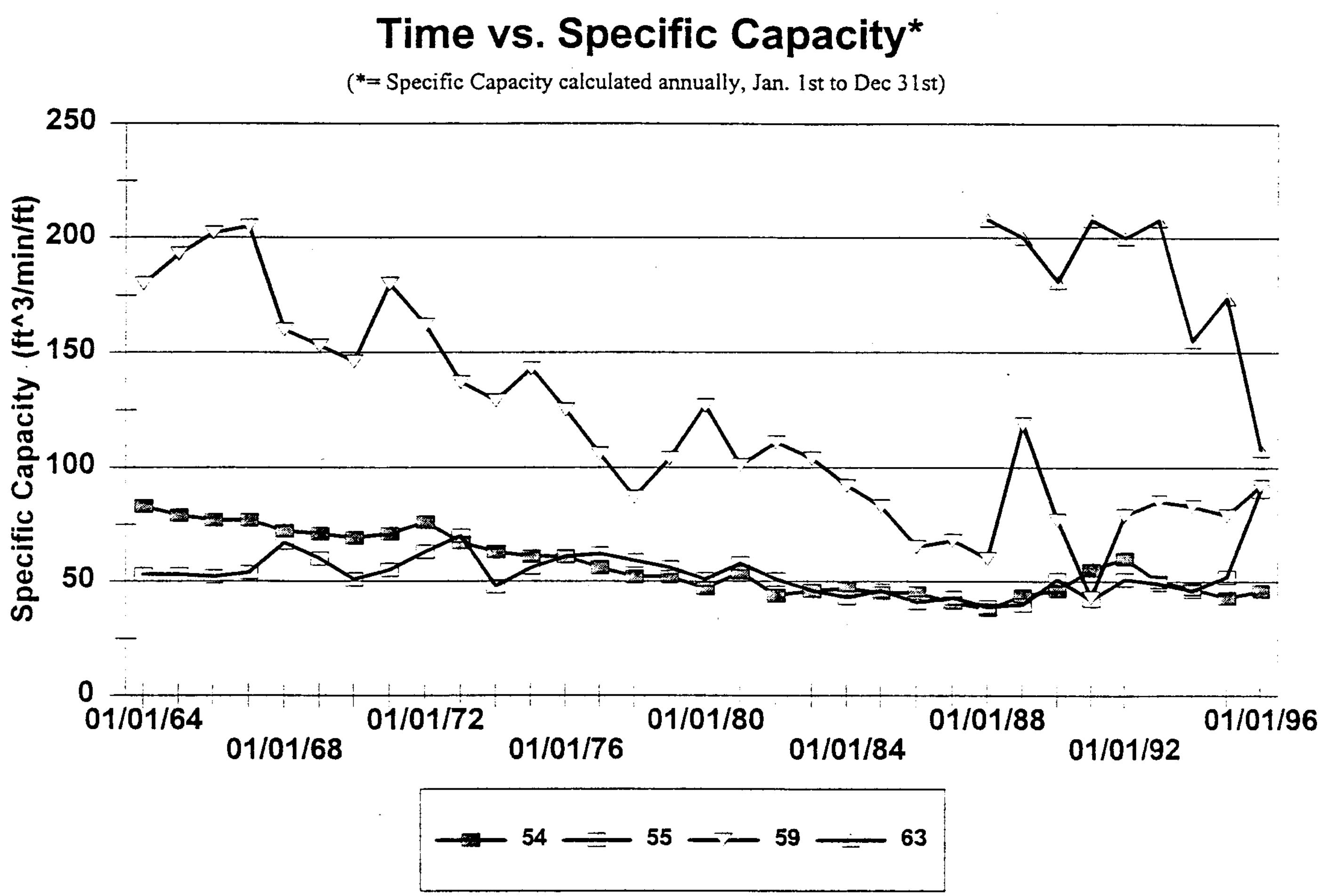

Figure 2. Specific capacity of selected NIWC wells

chemical precipitation. Panno et al. (1994) noted that groundwater in the central part of the Mahomet Sand aquifer contains 0.3 to 15 mg/L of total iron, so iron-oxidizing bacteria may be a problem.

Chemical Factors

An example of a chemical factor that reduces well efficiency is the chemical precipitation of minerals, principally calcium carbonate. The groundwater in the central part of the Mahomet Sand aquifer is known to be very hard and oversaturated with respect to the minerals calcite and dolomite (i.e., calcium carbonate and calcium-magnesium carbonate). Changes in water pressure near the production wells may lead to chemical precipitation, which in turn reduces porosity and hydraulic conductivity of the aquifer near the well or the gravel pack or clogs the screen. Corrosion of well components is another chemical factor that can reduce well efficiency.

Physical Factors

Well efficiency can be decreased by the movement of sand and finer grained materials from the aquifer into the gravel pack or by sand from the aquifer being pumped into the well. The movement of sand and finer grained materials from the aquifer into the gravel pack decreases the hydraulic conductivity of the gravel pack. Sand pumping is the migration of sand into the well and causes wear on the pump parts or fills the well with sand. Clogging of the gravel pack and sand pumping were not investigated in this project.

Hydraulic Factors

Drawdown from other wells in the well field may also cause an apparent decrease in well efficiency via well interference. In other words, sustained drawdown from all wells in the well field may be responsible for the loss in specific capacity. Also, well construction specifications such as screen type and open area can affect the well performance and exacerbate the biological and chemical factors by increasing head loss at the well.

OBJECTIVE

The purpose of this project was to determine, in a preliminary fashion, the significance of hydraulic, chemical, and biological factors that may contribute to the observed decline of specific capacity in NIWC's western well field. Theoretically, this decline may be explained by a combination of these factors or by a single factor.

SUMMARY OF TASKS COMPLETED

Five tasks were planned and completed for this project. A summary of the work completed and results follows.

Task 1: Review of Available Information

Records were copied from NIWC's files by project staff on August 25th through 27th, 1998. Most records in NIWC's files were organized by well. These records were reviewed. Pertinent data were entered into spreadsheets to facilitate analysis. Additional records were obtained from Mark Johnson of NIWC at later dates.

Task 2: Assess Accuracy of Specific Capacity Measurements

Because NIWC 55, NIWC 57, and NIWC 58 were not pumped for 2 to 3 week period, these wells were selected as the wells to be used to assess the accuracy of the specific capacity measurements by comparing water levels measured with an air line and a 200-foot Keck® water level sensor. Of these wells, only NIWC 55 was thought to have an access port that would allow measurement of the water level with the water level sensor.

On October 5, 1998, an attempt was made to measure the static water level in NIWC 55 prior to pumping for sampling. The static water level in the well was measured using a hand operated, bicycle pump hooked up to the air line. The gauge reading was between 20 and 22 psi, which corresponds to water depths between 133.80 feet and 129.18 feet. The length of the air line as of June 18, 1992 is 180 feet.

A threaded plug near the base of the well head on the north side was opened and the sensor lowered its entire length of 200 feet without detecting water. This opening in the wellhead is apparently located over the space between the 14-inch and 24-inch casings. No other openings were found through which the 8-inch long, metal tip of the water level sensor could be passed and lowered into the well. It is not known if the other wells in the western well field have access ports to allow measurement of water levels independent of the air line. This task proved not to be feasible because the water level could not be determined using a water level sensor.

Task 3: Assess the Effect of Pumping Schedules and Aquifer Geometry

A decline in specific capacity can be caused by an increase in the head loss in a pumping well. Head loss in a well is the sum of the head loss within the aquifer and head loss at the well. In this section, head losses within the aquifer are evaluated first, then head losses at the well.

Head Losses within the Aquifer

Interference from other pumping wells and proximity of aquifer boundaries can be factors affecting the head loss within an aquifer. To evaluate the head loss in pumping wells, the geometry and various properties of the aquifer must be known. A literature search and records review were conducted to define the aquifer geometry in the vicinity of NIWC's western well field and to determine certain aquifer parameters. Pumping test data obtained from NIWC were also analyzed to estimate aquifer parameters. These parameters were used to compute steady-state and transient drawdowns in the western well field.

Review of Available Information

Data on the aquifer geometry were obtained from publications and by mapping an area slightly larger than the western well field. This aquifer is comprised of sand and gravel that filled the bedrock valley; thus, the base of the aquifer is defined by the bedrock surface. Using available well logs from the ISGS log library, NIWC files, and the Illinois State Water Survey (ISWS) log library, three maps were prepared for the study area: Elevation of the Bedrock Surface (Figure 3), Elevation of the Top of the Mahomet Sand aquifer (Figure 4), and Thickness of the Mahomet

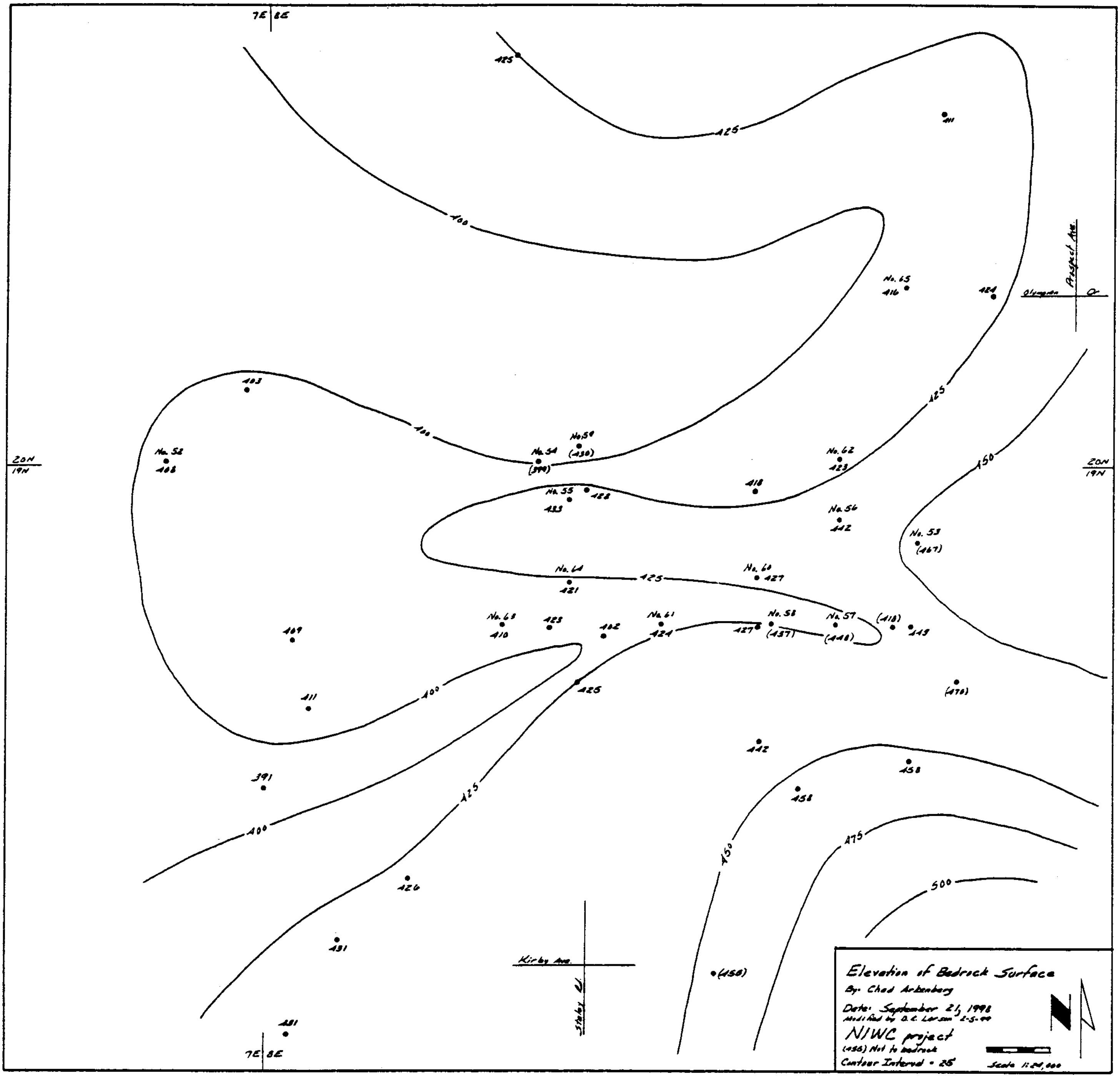

Figure 3. Elevation of the bedrock surface beneath the surface area

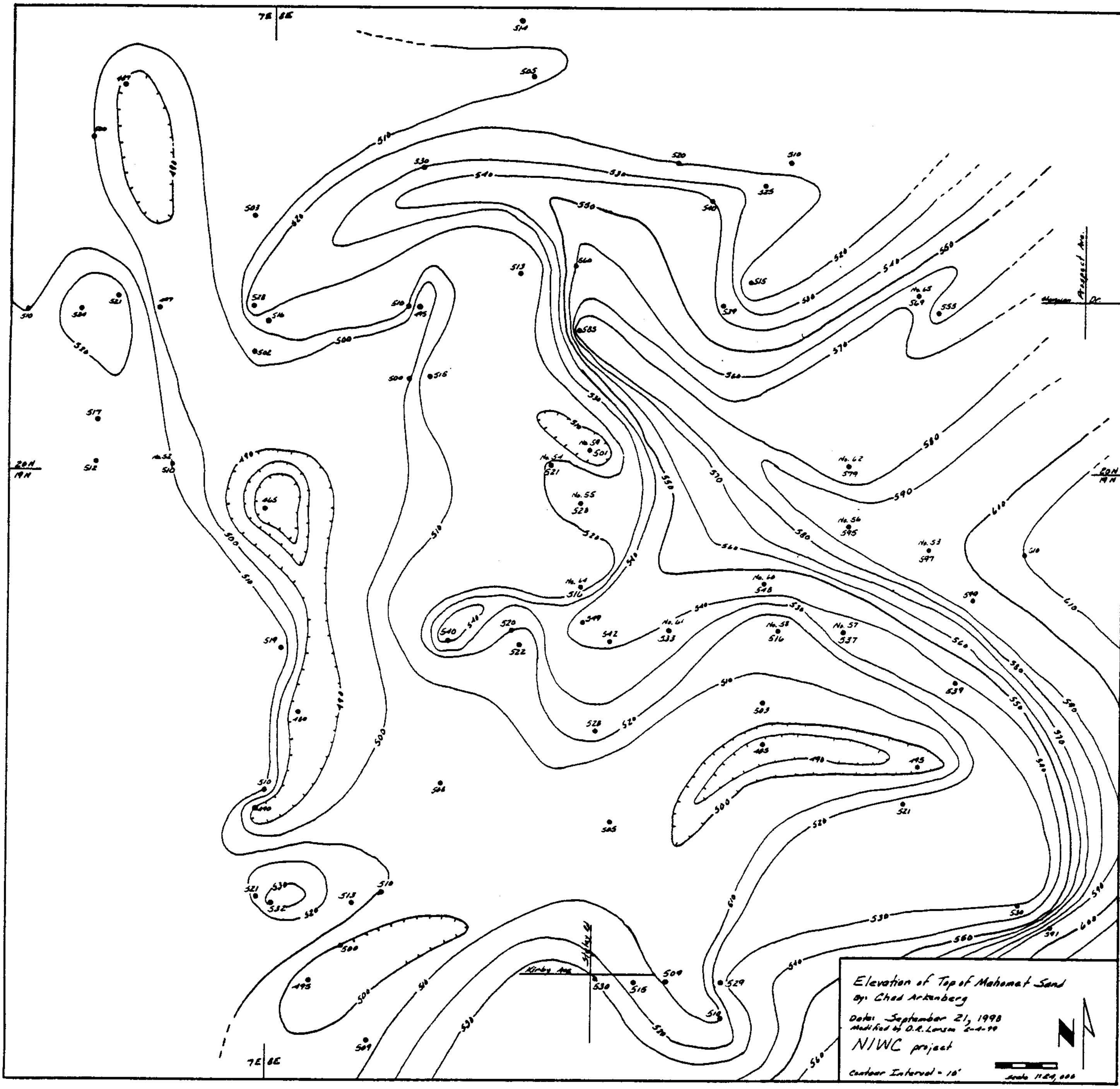

Figure 4. Elevation of the top of the Mahomet Sand aquifer beneath the study area

Sand aquifer (Figure 5).

The bedrock has an irregular surface beneath Champaign County (Figures 3 and 6). Beneath the City of Champaign, the bedrock surface is relatively high and slopes down into the axis of the NE-SW trending bedrock valley northwest of Champaign. This bedrock valley is the principal control on the thickness of the Mahomet Sand aquifer (Figure 5).

The Mahomet Sand aquifer is a confined aquifer. To assess the drawdown from wells completed in a confined aquifer, estimates of aquifer thickness (b), hydraulic conductivity (K) and storativity (S) are needed. The literature was reviewed to obtain estimates of the hydraulic characteristics of the aquifer. Values for hydraulic conductivity (K), transmissivity (T), storativity (S), specific capacity of the aquifer, and leakage for the upper confining layer were obtained from the literature and include data from Champaign County and 16 other counties in central Illinois (Table 2).

Analysis of Pumping Test Data

No estimates of K and S were available in the NIWC records, but pumping test data in those records were analyzed using AQUITEST (Heidari and Moench, 1997) to estimate K and S. The available pumping test data did not always allow S to be estimated, because data from observation wells were not always collected. The quality of the pumping test data were variable, as seen in Figure 7. Better quality data are shown in Figure 7a, while lower quality data are shown in Figure 7b. The latter pumping test (Figure 7b) had a very short duration and the minimum change in head was 0.25 ft. Somewhat surprisingly, the estimates of K (0.37 and 0.70 ft/min) from these two pumping tests are similar.

The following ranges were determined by analyzing 12 pumping tests-- hydraulic conductivity from 0.075 to 3.3 ft/min, and storativity from 2.0×10^{-4} to 6.6×10^{-2}. Aquifer thickness was determined from NIWC's well logs. Aquifer thickness at the NIWC wells ranges from 34 feet at NIWC 57 to 111 feet at NIWC 65 and averages 78 feet (Table 3). In the

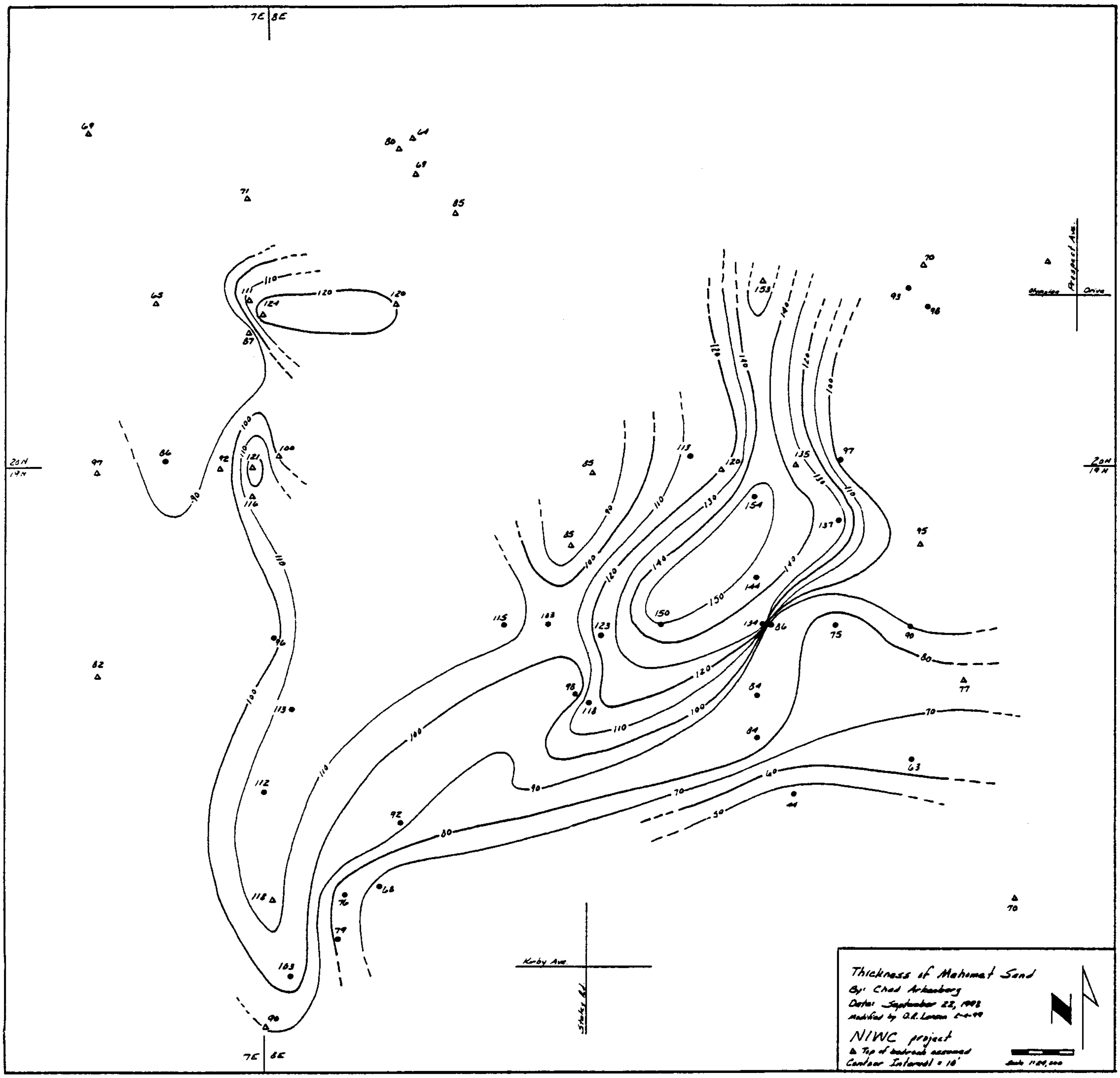

Figure 5. Thickness of the Mahomet Sand aquifer beneath the study area

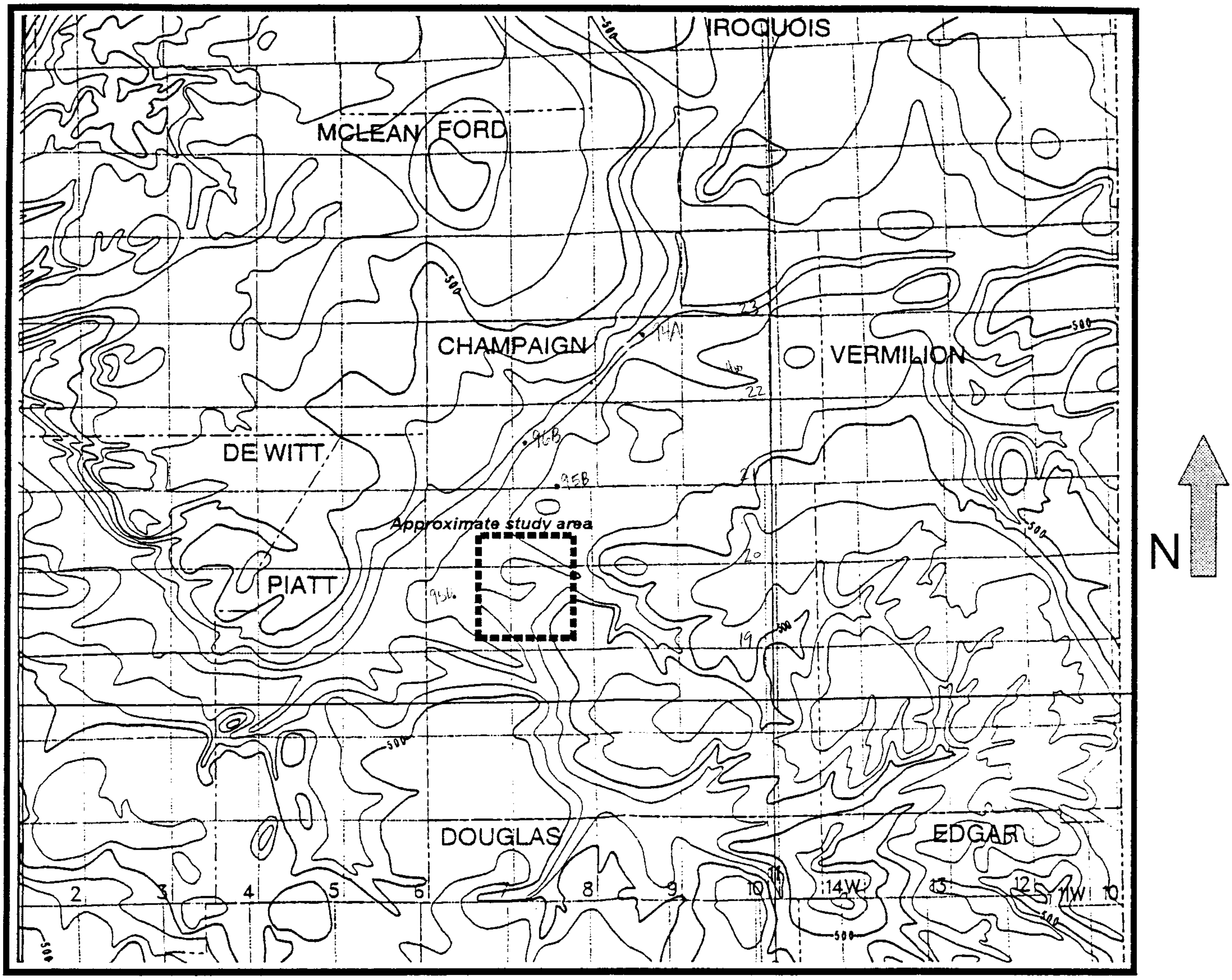

Figure 6. Map of bedrock surface (from Herzog et al., 1994). The contour interval is 50 feet. The original map scale was 1:500,000

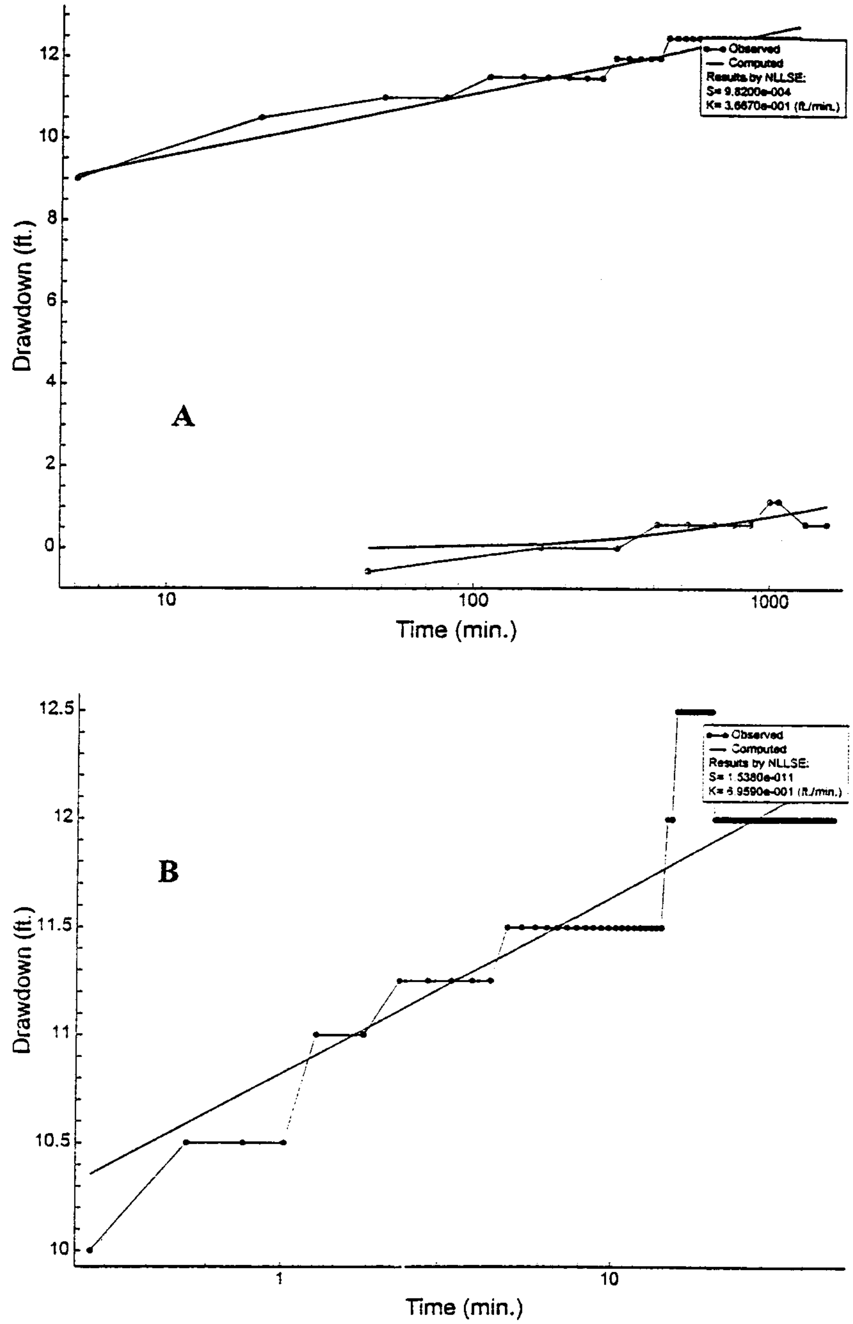

Figure 7. Pumping test analyses for NIWC 53. Figure 7a shows good quality data and 7b shows poor quality data.

Table 2. Summary of aquifer characteristics obtained from published sources

		T (ft^2/min)	K (ft/min) range	K (ft/min) median	S	$K_{vertical}$ (ft/min)	Leakage coeff. (min^{-1})	Unadjusted Cs (ft^2/min)
Source: Cooperative Groundwater Report 8 (Kempton et al., 1982)								
Lithology	Drift, sand and gravel, some clay and silt (Walton, 1965)					9e-05 to 1.5e-04		
	Dirty sand and gravel -Banner Formation*					3.9e-05	1.66	
Aquifer tests	Mahomet Sand	6.57 to 30.2	0.17 to 0.444	0.280	1e-04 to 2.3e-03			
	Other aquifers in the Banner Formation	0.088 to 10.9	0.011 to 0.246	0.084	1.3e-04 to 1.8e-03			
Specific-capacity data	Mahomet Sand	0.436 to 65.9	0.0148 to 0.720	0.281				0.26 to 27.7
	Other aquifers in the Banner Formation	0.028 to 9.10	0.0074 to 0.464	0.045				0.027 to 5.35
Data from Appendix 1 for T19N, R8E	USI 3	19.0	0.189		2.3e-03			
	Wells within the Banner Formation	13.0 to 46.4	0.189 to 0.716	0.305	1.e-04			
	Wells within the Glasford Formation	0.48 to 6.87	0.025 to 0.247	0.175	3.1e-04 to 2.3e-03			
Source: Cooperative Groundwater Report 16 (Wilson et al. [1994])								
Aquifer tests	Aquifer test in Basal Aquifer	0.57 to 47.7	0.057 to 0.382	0.205	1.e-04 to 9.e-02			
7 day calculated values	Sankoty-Mahomet Aquifer	31.8	0.27		5.7e-04	1.2e-04	107.2	
Source: Report of Investigation 62, (see Table 3 T19N, R8E in Visocky and Schicht, 1969)								
Champaign County wells	Sand and gravel, some clay	18.9 to 30.0	0.19 to 0.31	0.281	4.1e-04 to 2.3e-03	1.64e-05 to 3.9e-05	1.01 to 1.21	
All wells	Sand and gravel, some clay to gravel, boulders	5.17 to 30.0	0.029 to 0.368	0.173	2.17e-05 to 2.3e-03	8.4e-07 to 1.13e-03	0.024 to 56.0	

* Results from controlled aquifer tests carried out in wells in T19N, R8E of Champaign County within the Banner Formation. (from Cooperative Report 8, Table 1, Kempton et al. [1982])

Table 3. Aquifer thickness at the NIWC wells

NIWC Well Number	Reported Aquifer Thickness (ft)
53	102
54	>79
55	53
56	55.5
57	76 ~~34~~ X
58	66.5
59	>108
60	93
61	89
62	97
63	51
64	97
65	111

drawdown calculations, the following values were used-- 78 ft for b, 0.50 ft/min for K and 0.001 for S.

Estimation of Drawdown and Well Interference

With the estimated values of b, K, and S, the drawdown in various wells was estimated. Steady-state and transient drawdown were computed for several wells. Steady-state drawdown is the drawdown that occurs some time in the distant future and represents the maximum drawdown. Because continuous and constant pumpage, which was assumed for the steady-state drawdown calculations, is not realistic, transient or time-dependent drawdown was also calculated. NIWC does not continuously pump its wells for extended periods (years at a time), so transient drawdown better represents its operations. The steady-state and transient drawdowns were computed using analytical solutions from Bear (1979).

Well interference is the drawdown imposed on a pumping well from another pumping well and is common in areas with closely spaced wells. To evaluate well interference, drawdown was estimated for two clusters of three wells each. The first cluster is comprised of three wells, NIWC 61, NIWC 63, and NIWC 64, and is referred to as the "tight cluster" because the wells are 2,600 to 4,900 feet apart. The second cluster is comprised of three wells, USI 2, NIWC 61, and NIWC 65, and is referred to as the "distant cluster" because the wells are 12,000 to 25,000 feet apart. The drawdown data were computed with the data in Table 4, assuming all three wells were pumping at a constant rate. The transmissivity value in Table 4 was calculated using an average aquifer thickness of 78 feet and hydraulic conductivity of 0.5 ft/min. In addition, the wells were assumed to fully penetrate the aquifer.

The steady-state drawdown for wells in the tight cluster ranged from 9.6 to 10.6 ft, with the largest drawdown estimated for NIWC 63. The percentage of the total drawdown due to the pumpage from the other two wells ranged from 34 to 47% for wells in the tight cluster and 20 to 46% for wells in the distant cluster. These results show that, for steady-state conditions, well interference is very significant. To understand how long its takes for well interference to become significant, transient analysis was undertaken.

Table 4. Input data used to compute drawdown

Parameter	Units	Value
Transmissivity	ft^2/min	39
Storativity	--	10^{-3}
Pumpage from NIWC 61	gpm	859
Pumpage from NIWC 63	gpm	1034
Pumpage from NIWC 64	gpm	766
Pumpage from NIWC 65	gpm	1378
Pumpage from USI 2	gpm	1767

Well interference at NIWC 61 exceeds 5% of total drawdown after 200 minutes of pumping for the tight cluster and after 2,000 minutes (33 hours) for the distant cluster (Figure 8). Well interference at NIWC 61 exceeds 20% of total drawdown for both clusters after 10,000 minutes (6.9 days). The effects of transmissivity and storativity can also be seen on Figure 8. Lower S and higher T results in significantly greater well interference at NIWC 61 for the distant cluster.

If well interference is a significant cause, then drilling and start-up of a new well in the Mahomet Sand aquifer should affect specific capacity (Figure 9). For example, after NIWC 63 (5,300 feet from NIWC 54 and 4,600 feet from NIWC 55) began operating in July 1988, a significant drop in the specific capacity of NIWC 54 or NIWC 55 would be expected, but it did not occur. In fact, no significant changes in specific capacity could be associated with the start-up of NIWC 63 or any other new well.

These calculations showed that well interference is significant for the given input data, after short periods (hours to days) and over the long run. Well interference or drawdowns imposed by neighboring wells may be interpreted as reductions in specific capacity and may explain the observed decreases in specific capacity. NIWC has increased its pumpage from the Mahomet Sand aquifer by 102% from 1964 to 1996. The production history of high-capacity wells that are not owned by NIWC is unknown, so the effect of these wells on specific capacity can not be evaluated. Increased production from the aquifer supports the argument for well interference as a factor in the overall trend of declining specific capacity. In addition, the minor variations in the specific capacity data may be accounted for by transient pumpage. However, obvious declines in specific capacity do not appear to be related to the presence of new wells in the aquifer.

The analytical solutions used to determine drawdown required the use of constant values of aquifer thickness, hydraulic conductivity, and storativity. For the NIWC wells, the values of aquifer thickness and hydraulic conductivity are known to vary from 34 to 111 feet and 0.075 to

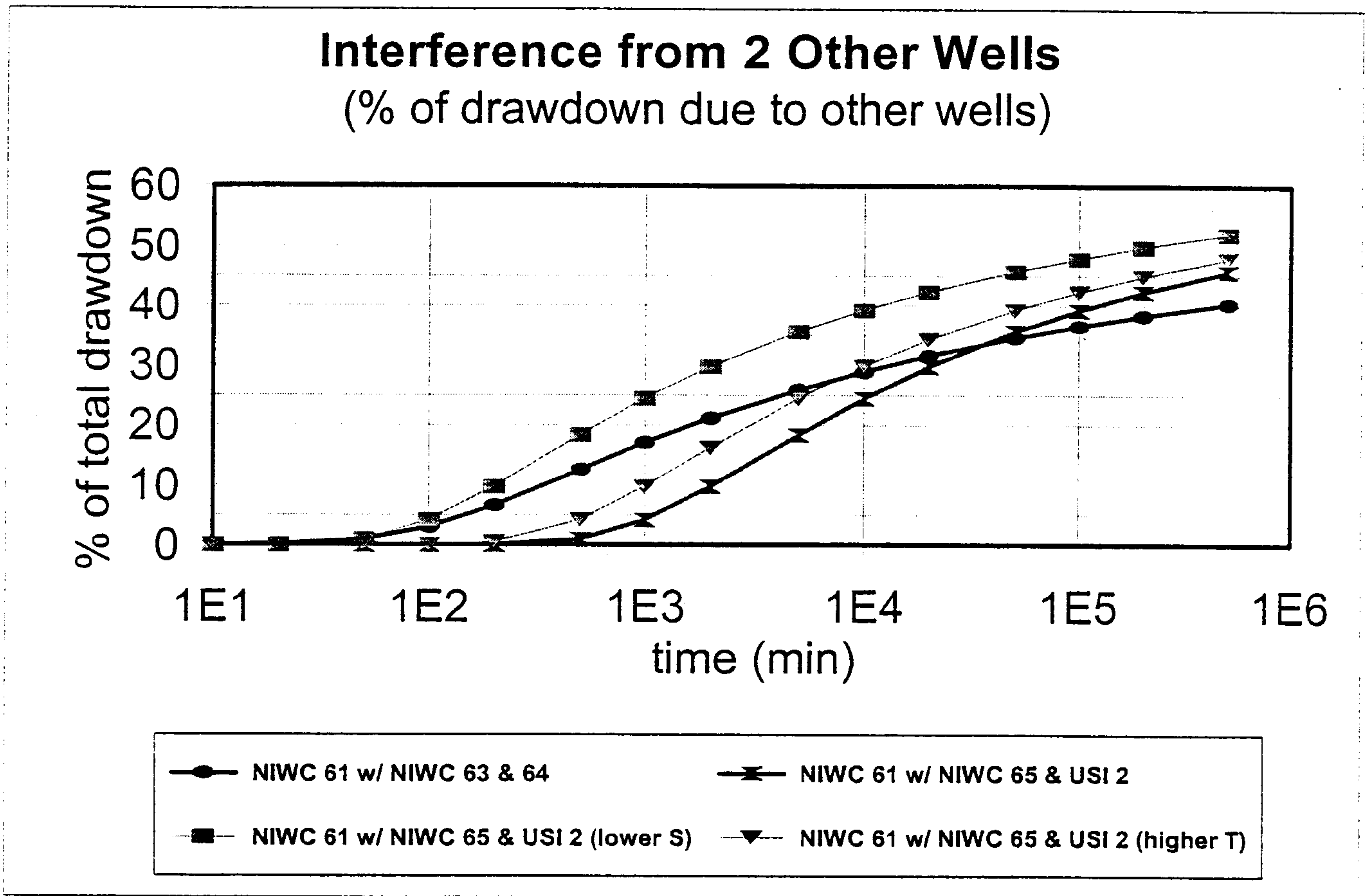

Figure 8. Transient drawdown for the tight and distant cluster

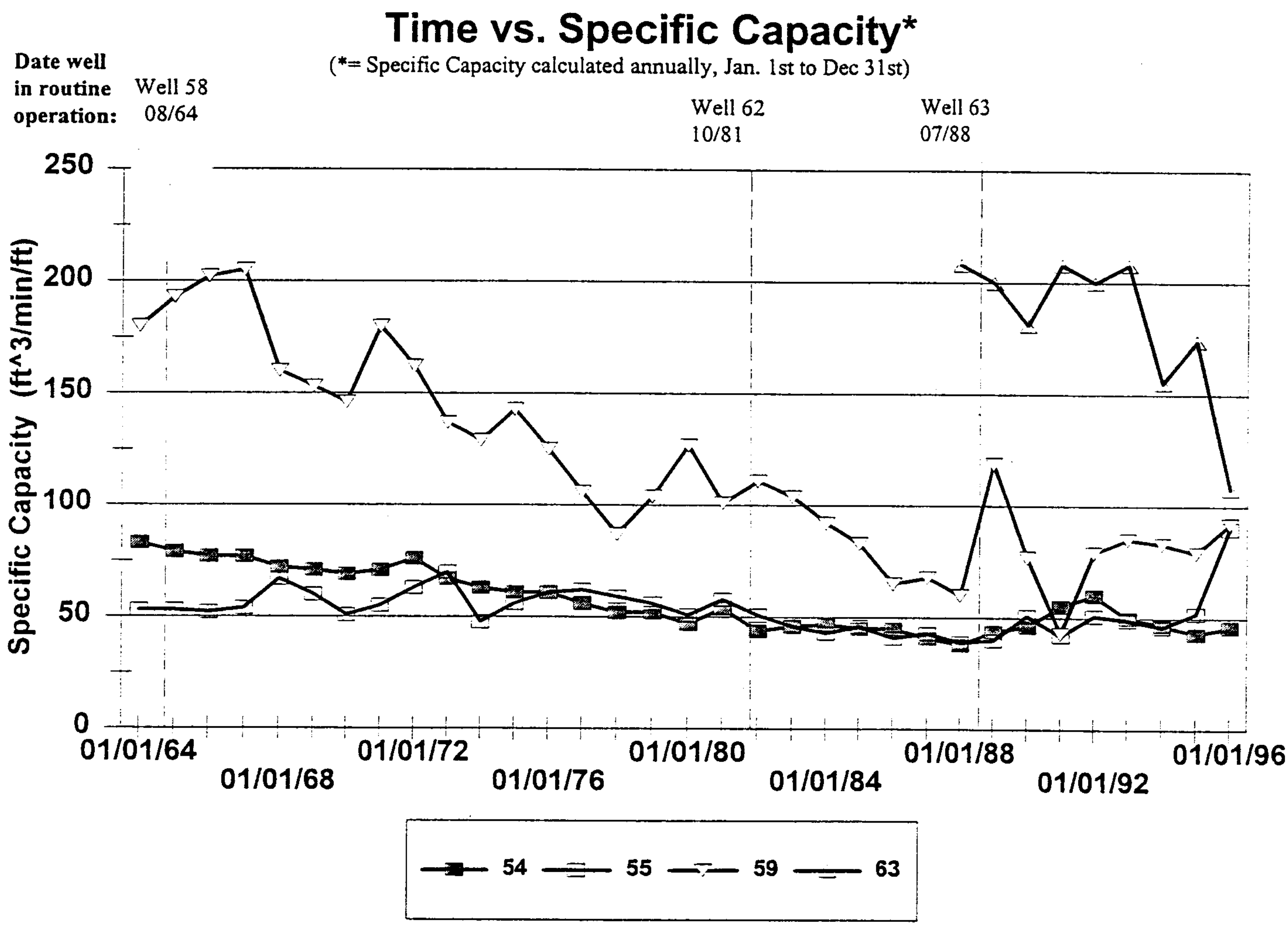

Figure 9. Specific capacity as a function of time and the addition of new wells to the well field

3.3 ft/min, respectively. While the analytical solutions can provide reasonable estimates of drawdown, a groundwater flow model is needed to improve these estimates. Unfortunately, additional geologic and hydrogeologic data are needed before the effort of developing a high quality, groundwater flow model could be justified. Important hydrogeologic data including transmissivity, storativity, leakance, anisotropy, and the effect of aquifer boundaries could be obtained from long-term pumping tests.

Head Losses at the Well

The average entrance velocity of water through the well screen is another factor that affects the specific capacity of a well. Average entrance velocity is calculated by dividing the pumping rate by the open area of the well screen and does not account for well inefficiencies such as the convergence of flow near individual openings of a shutter screen (Driscoll, 1986). Driscoll (1986) notes that well screens designed to have an average entrance velocity of 0.1 ft/sec (6 ft/min) or less will reduce well maintenance over time, create minimal head losses as the water enters the screen, and limit the amount of sand entering the well. Minimizing head losses also reduces the likelihood that the screen openings will be clogged by chemical precipitation, which can be induced by changes in pressure as groundwater flows into the well.

For the well capacities given in Table 1, the average entrance velocities were computed (Table 5). The results do not show a consistent trend between average entrance velocity and specific capacity. Seven wells have average entrance velocities greater than 6 ft/min and show a loss in specific capacity. Four wells have average entrance velocities less than 6 ft/min, and also show a loss in specific capacity. Because the data for some wells show no consistent relationship between entrance velocity and change in specific capacity, other factors, such as well interference, may be contributing to the loss of specific capacity. NIWC 61 has the greatest average entrance velocity, but one of the lower decreases in specific capacity. NIWC 63 has the greatest loss in specific capacity per year, but has one of the lowest average entrance velocities at 2.63 ft/min, well below the recommended 6 ft/min. NIWC 55 has an average entrance velocity of 6.23 ft/min, or slightly greater than the recommended 6 ft/min, but shows a net gain in specific capacity.

Table 5. Entrance velocities for NIWC's western well field

NIWC Well	Well capacity (gpm)	Total Open Area (ft^2)	Entrance velocity (ft/min)	S.C. loss per year	Q at 6 ft/min
53	1770.83	38.3	6.18	0.7854	1718.28
54	2409.72	74.2	4.34	1.3195	3329.77
55	1076.39	23.1	6.23	-0.8210	1036.76
56	1687.50	38.3	5.89	1.3806	1718.28
57	1861.11	38.3	6.50	2.8514	1718.28
58	2388.89	53.9	5.93	4.4606	2419.03
59	2131.94	38.3	7.44	2.0600	1718.28
60	2368.06	40.3	7.86	5.3269	1808.60
61	2256.94	32.2	9.36	1.4364	1446.88
62	2458.33	36.8	8.93	5.2059	1652.18
63	2090.28	106.2	2.63	7.0111	4764.51
64	2090.28	80.8	3.46	-3.500	3625.49
65	1770.83	118.6	2.00	?	5321.02

Task 4: Analyze Groundwater Geochemistry from NIWC Wells

Methods

All water samples were analyzed in the field for temperature, pH, Eh, and specific conductance. Field measurements for pH and specific conductance were made using meters that allowed temperature compensation and were calibrated with appropriate standards at each sampling site. All samples were analyzed for major cations and anions, bacterial species, dissolved organic carbon, and dissolved gases. Selected samples were analyzed for tritium and atrazine.

Groundwater samples were collected in accordance with field techniques described in

Wood (1981). Spigots at the NIWC wells were sterilized with isopropyl alcohol and heated with a propane torch for about 15 seconds prior to sampling. Water was allowed to flow until pH, Eh, temperature, and specific conductance readings stabilized, then water samples were collected.

Samples collected for cations, anions, and alkalinity were filtered through 0.45-μm membranes and stored in polyethylene bottles. Samples analyzed for cations were acidified in the field with ultra-pure nitric acid to a pH of 2.0. Samples collected for pesticides were unfiltered and stored in 60 mL, precleaned amber glass bottles. The samples were transported in ice-filled coolers to the laboratory, and kept refrigerated at approximately 4 ^{o}C until analyses had been completed. Samples collected for pesticide analysis were filtered in the laboratory prior to analysis.

Samples collected for bacterial analysis were stored in sterilized 250 mL bottles and analyzed within 24 hours for total coliform, fecal coliform, and total (other) bacteria using standard techniques (Clesceri et al., 1989). Determination of bacterial species was conducted at the Illinois Department of Agriculture's Animal Disease Laboratory, Centralia, IL using standard methods to isolate and identify bacterial colonies present (Clesceri et al., 1989). All methods used to separate and identify each species are described in Cason et al. (1991). Field blanks included sterilized water (deionized water boiled for 30 minutes) that was poured into sample bottles in the field and poured through sampling spigots in the laboratory. The sampling manifold was soaked in isopropyl alcohol for at least four hours and dried in an oven at 60 ^{0}C overnight prior to sampling the NIWC wells.

Water samples were analyzed for atrazine using enzyme-linked immunosorbent assays (ELISA) following manufacturer's instructions. The ELISA technique has been found to yield data that correlate well with samples analyzed using gas chromatography/mass spectrometry techniques (Thurman et al., 1990).

Concentrations of cations were analyzed using a Model 1100 Thermo-Jarrell Ash

Inductively Coupled Argon Plasma Spectrometer (ICAP). Instrument control, automatic background correction, and spectral interference corrections were performed using a DEC Micro PDP 11/23 computer. Solution concentrations of anions were determined using a Dionex 211i ion chromatograph, following U.S. EPA Method 300 (O'Dell et al., 1984). All water samples had charge balance errors of less than 5%.

The dissolved gases were sampled from water taken at the well head through a spigot connected to the main water lines for the NIWC wells and through a Y connection attached to the pumping hose at the ISWS wells. The sample containers were collapsible, plastic, one gallon containers which were evacuated with a vacuum pump prior to water sampling. The containers were brought back to the laboratory, weighed, and the gases extracted that same day using a syringe. The gases were stored in pre-evacuated glass vials fitted with a septum and analyzed by a commercial lab for methane (CH_4) and carbon dioxide (CO_2) by gas chromatography. The analyses were performed using a gas chromatograph equipped with both a thermal-conductivity detector and a flame ionization detector. Helium was used as the carrier gas. The component peak areas were quantified by comparing them to previously run standards. The percentage of CH_4 and CO_2 were converted to concentration of dissolved gas per liter using Henry's Law.

Water samples for tritium analyses were collected in one liter HDPE containers. The tritium analyses were determined on 200 mL of water using the enrichment technique described by Ostlund and Dorsey (1977). The tritium enriched samples were purified by vacuum distillation, mixed with a scintillation cocktail and counted in a low-level scintillation counter (Packard 2000 CA/LL). The tritium results are reported in tritium units (TU), which is defined as one tritium atom per 10^{18} hydrogen atoms.

Groundwater Chemistry

Three NIWC wells (NIWC 55, 57, and 58) were sampled in September 1998 in the middle of their pumping cycle. The same three wells were sampled in October 1998 following a two to three week idle period. Each well was sampled sequentially from 30 seconds to 600 seconds after start up. In addition, six wells drilled and maintained by the ISWS that lie along the thalweg of the Mahomet Sand aquifer (MSA) and between the thalweg and NIWC's western well field were sampled (Figure 10). A "thalweg" is the line of maximum depth in a stream channel, and is used herein to refer to that feature in the Mahomet Bedrock Valley.

Groundwater from the Mahomet Sand aquifer in the study area is a relatively dilute, mixed cation-HCO_3^- type water (Panno et al., 1994). Relatively low Eh values, low concentrations of sulfate and nitrate, and the presence of relatively high concentrations of ammonia, iron, manganese, and methane (Table 6) all are consistent with reducing conditions and isolation from the atmosphere. Additional data that support the idea that the MSA is isolated from the atmosphere include the tritium and atrazine concentrations, which were all below detection limits (Table 6). The chemical composition of groundwater in the study area (Table 6) reflects the composition of the Mahomet sands, which consists primarily of quartz, feldspar, and carbonate minerals (calcite and dolomite) (Willman and Frye, 1970).

Analysis of water chemistry data, using the chemical reaction model NETPATH (Plummer et al., 1994), showed that almost all groundwater samples were saturated to oversaturated with respect to a variety of carbonate, silica, and iron-bearing minerals (Table 6). These minerals include calcite, aragonite, dolomite, siderite, quartz, chalcedony, hematite, goethite, and $Fe(OH)_3$ (iron oxyhydroxide). A trend that consistently appeared in the data was that groundwater from the western well field had a significantly higher degree of saturation with these minerals than did any groundwater sample from other parts of the MSA. Groundwater from the NIWC's western well field also had lower partial pressures of CO_2 (pCO_2) and lower total dissolved solids (TDS) than the other samples farther away from the well field (Figure 11). These data suggest that the groundwater in the western well field is undergoing degassing possibly as a result of lowering of the hydraulic head in the vicinity of the wells. As stated by Henry's Law, the amount of dissolved gas in a liquid is proportional to the partial pressure of the gas in contact with the liquid. The equilibrium expression for the solubility of a gas in water is:

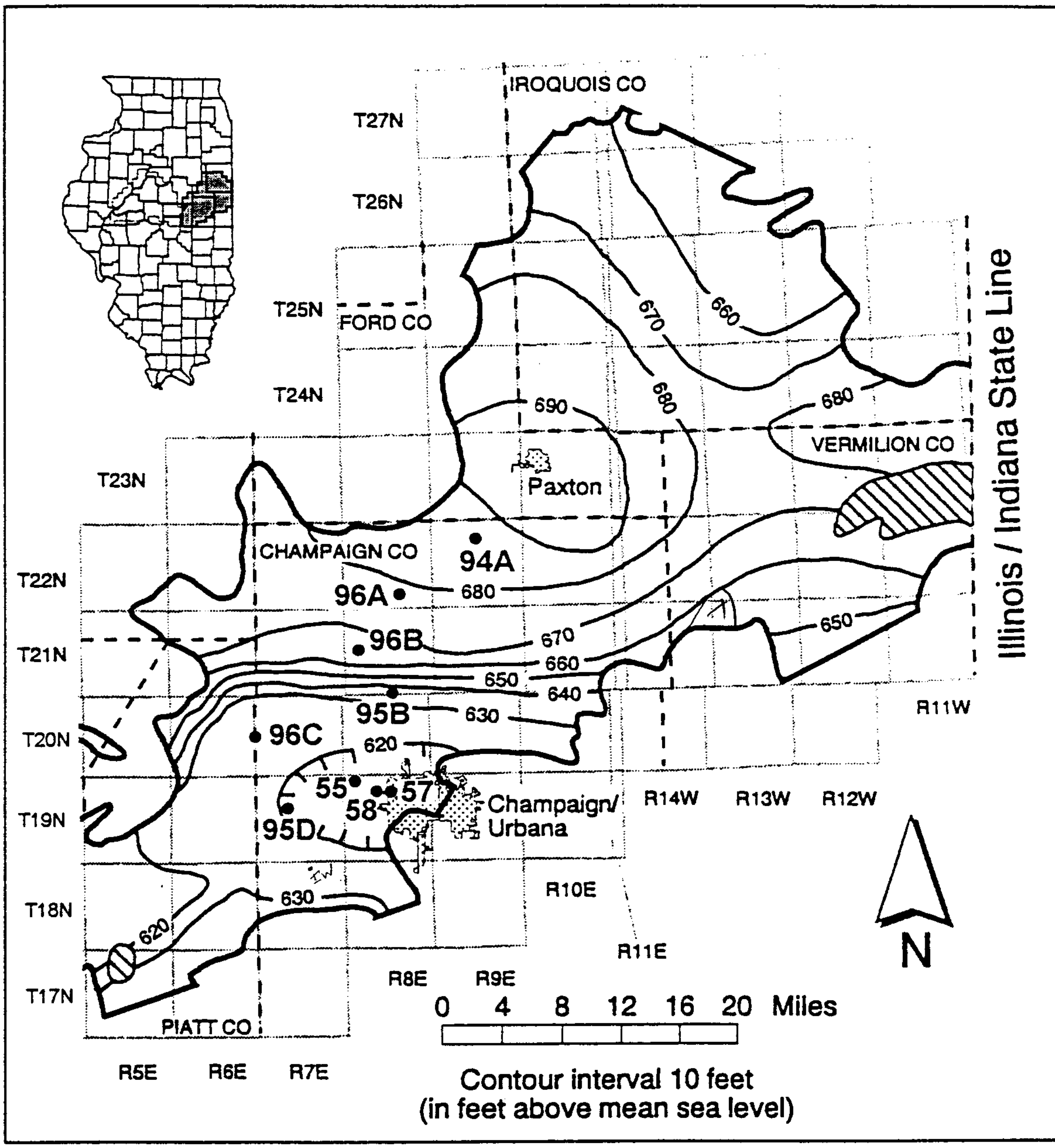

Figure 10. Map showing the location of NIWC and ISWS wells used for groundwater geochemistry sampling (modified from Wilson et al., 1998). The contours of the potentiometric surface of the Mahomet Sand aquifer are also shown.

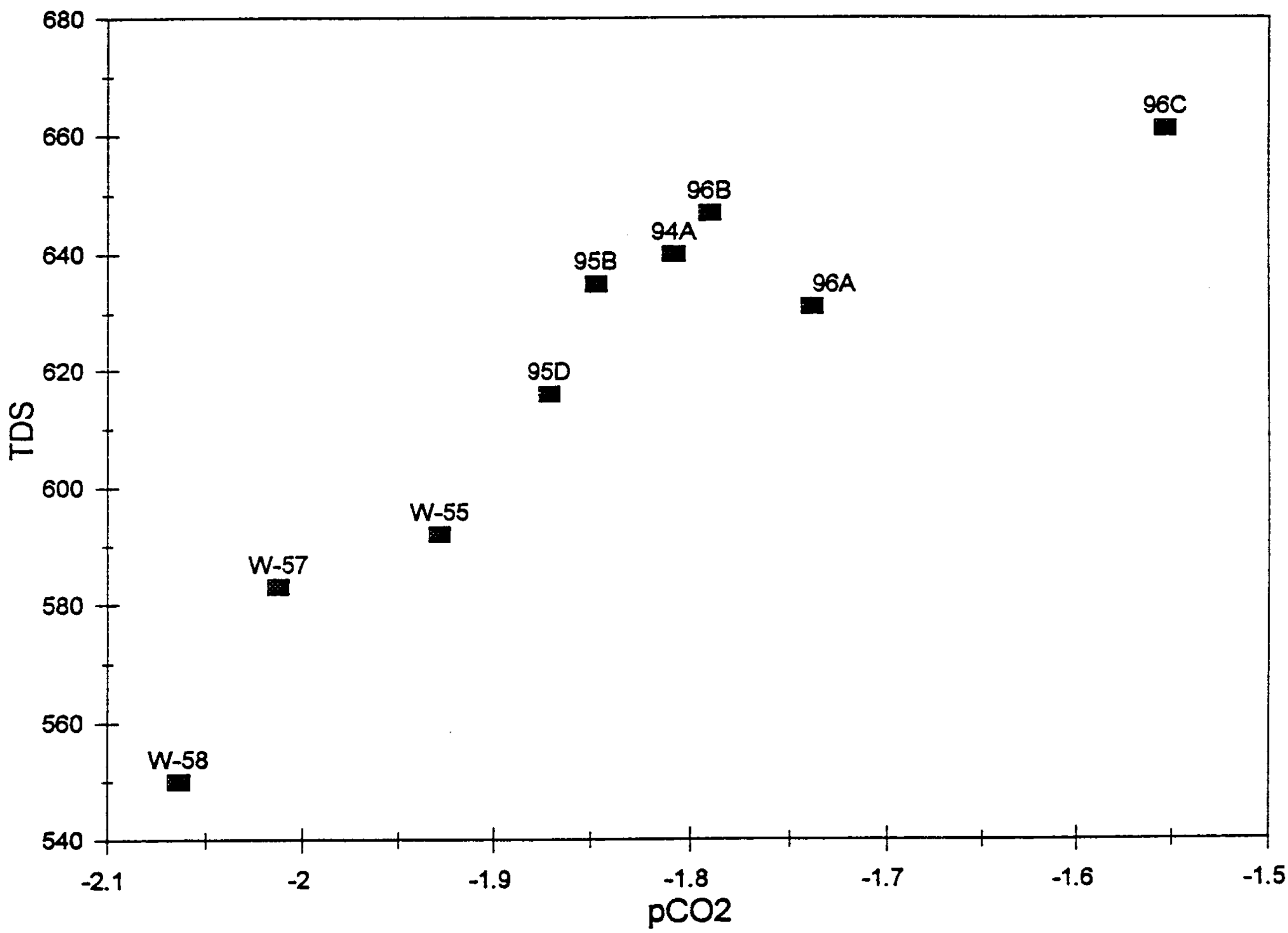

Figure 11. Comparison of total dissolved solids (TDS) and the partial pressure of CO_2 (pCO_2) in groundwater samples from NIWC and ISWS wells.

Table 6. Geochemical and isotopic data for wells screened in the Mahomet Sand aquifer. All ionic data are reported in mg /L.

Sample #	Date Sampled	Owner	Well Screen Depth (m)	Elevation (m)	Pumping Rate (L/s)	Temp. (°C)	pH	Eh (mV)	Sp. Cond. (μS/cm)	Tot. Alk. as $CaCO_3$ (mg/L)	Na^+	K^+	Ca^{2+}	Mg^{2+}	SiO_2	HCO^-_3	NO^-_3	NH^+_3	SO^{2-}_4	Cl^-
CHM94A	10/26/98	ISWS	117	250	0.24	14.1	7.4	71	664	374	48.9	2	72.6	28.3	19.1	456	<1.6	ND	8.7	0.8
CHM95B	10/27/98	ISWS	85.3	239	0.21	13.8	7.4	40	665	379	36.1	2	71.2	36.1	18.5	462	<1.6	ND	6.0	1.0
CHM95D	10/27/98	ISWS	86.2	213	0.27	14.0	7.4	-28	645	372	35.9	2	69.1	33.9	16.9	454	<1.6	ND	<0.3	1.7
CHM96A	10/26/98	ISWS	94.5	220	0.34	13.8	7.3	107	670	342	32.8	1	82.8	31.6	19.8	417	<1.6	ND	42.9	0.6
CHM96B	10/26/98	ISWS	89.9	215	0.31	13.9	7.3	92	676	349	29.1	2	84.8	33.3	20.5	426	<1.6	ND	42.8	0.9
CHM96C	10/27/98	ISWS	88.4	213	0.28	13.8	7.1	76	699	372	26.9	<1	88.4	34.7	22.7	454	<1.6	ND	31.4	1.0
55-98	9/10/98	NIWC	91.4	224	63	13.0	7.6	49	637	360	34.4	3	61.3	34.5	13.1	439	<0.8	0.71	0.21	1.8
57-98	9/10/98	NIWC	92.6	229	100	13.2	7.6	37	603	356	47.3	<1	52.0	29.9	13.5	434	<0.8	1.53	<0.3	1.5
58-98	9/10/98	NIWC	99.4	234	150	13.1	7.5	56	648	335	39.4	<1	52.2	29.9	13.3	408	0.01	1.34	0.22	2.1
Detection limits											1.34	0.629	0.004	0.003	0.024		0.005	0.010	0.010	0.010
Sample #	Fe	Mn	Log pCO_2 (atm) (calc.)	TDS (mg/L) (calc.)	SI_{CAL}	SI_{ARAG}	SI_{DOLO}	SI_{SID}	SI_{HEM}	SI_{GOET}	$SI_{Fe(OH)3}$	Total Colif. (cfu)	Fecal Colif. (cfu)	Fecal Strep. (cfu)	Total Aerobic (cfu)	NVOC (mg/L)	CH_4 (mmol/L)	CO_2 (mmol/L)	Tritium (TU)	
CHM94A	1.43	0.07	-1.808	640	0.240	0.088	0.264	0.644	13.5	6.16	0.272	0	0	0	10	2.1	4.64×10^{-3}	1.47×10^{-1}	<0.40	
CHM95B	0.89	0.05	-1.847	635	0.283	0.131	0.459	0.485	12.2	5.55	-0.340	0	0	0	207	2.0	2.98×10^{-2}	1.08×10^{-1}	ND	
CHM95D	1.87	0.03	-1.871	616	0.280	0.128	0.442	0.817	10.6	4.72	-1.173	0	0	0	108	2.2	2.81×10^{-1}	2.17×10^{-1}	ND	
CHM96A	0.68	0.24	-1.739	631	0.135	-0.170	0.041	0.179	13.4	6.15	0.255	0	0	0	88	2.4	1.21×10^{-3}	2.07×10^{-1}	<0.66	
CHM96B	0.84	0.13	-1.791	647	0.211	0.059	0.207	0.332	13.4	6.15	0.257	0	0	0	10	1.4	1.12×10^{-3}	1.62×10^{-1}	ND	
CHM96C	1.73	0.13	-1.554	661	0.048	-0.104	-0.122	0.465	12.2	5.55	-0.338	0	0	0	90	2.2	5.19×10^{-3}	5.96×10^{-1}	ND	
55-98	0.91	0.05	-1.929	592	0.245	0.092	0.417	0.522	12.8	5.86	-0.028	0	0	0	8	2.0	1.76×10^{-1}	3.51×10^{-1}	<0.42	
57-98	1.31	0.02	-2.013	583	0.252	0.100	0.440	0.753	13.6	6.26	0.366	ND	ND	ND	10	3.5	4.90×10^{-1}	3.62×10^{-1}	<0.52	
58-98	1.11	0.02	-2.064	550	0.261	0.108	0.459	0.692	13.2	6.06	0.172	0	0	0	130	2.7	3.42×10^{-1}	3.22×10^{-1}	ND	
Detection limits	0.009	0.009										1	1	1	1					

ND = Not determined; NC = Not calculated; BDL = Below detection limits; cfu = Colony forming units/100 mL water; SI = Saturation index; NVOC = Nonvolatile organic carbon; TU = Tritium unit

$$[G_{(aq)}] = K_H \times P_{(g)}$$

Where $[G_{(aq)}]$ is the concentration of dissolved gas, K_H is Henry's constant for a specific gas at a certain temperature and $P_{(g)}$ is the partial pressure of the specific gas. Thus, a liquid can hold more dissolved gas at higher pressure. As the pressure decreases, the dissolved gas escapes from the liquid in order to restore equilibrium with the changing system. This relationship is shown in Figure 12 for water in equilibrium with CO_2 and CH_4 at concentrations similar to those observed in the NIWC wells.

The major dissolved constituents in a confined aquifer, such as the Mahomet Sand aquifer, are typically considered to be in chemical equilibrium with the minerals that make up the aquifer material. Changes exerted on the system, such as large scale pumping, upset this equilibrium. Thus, a drop in pressure due to large scale pumping may decrease the amount of dissolved CO_2 in the water through degassing, which in turn will affect the equilibrium of the carbonate geochemistry of the groundwater, typically resulting in the precipitation of carbonate minerals within the aquifer, the gravel pack, or the well screen (e.g., Driscoll, 1986). The relationship between dissolved CO_2 and calcite ($CaCO_3$) precipitation is shown more clearly in the following chemical reaction:

$$CaCO_3 + H_2O + CO_2 \rightleftharpoons Ca^{2+} + 2HCO_3^-$$

If CO_2 is released from water, the chemical reaction will be driven to the left, decreasing dissolved solids (Ca^{2+} and $2HCO_3^-$) and precipitating $CaCO_3$.

Field parameters, TDS and the log pCO_2 are good indicators of changes in groundwater chemistry resulting from the rate at which a well is pumped. Values of pH in the ISWS wells (mean = 7.31) are consistently lower than those within the western well field (mean = 7.57). "Mean" in this case is arithmetic mean calculated by first converting pH values to hydrogen ion concentrations. The difference in pH is reflected in chemical changes in groundwater that are proportional to the rate of pumping. Specifically, the log pCO_2 (Figure 13) and TDS (Figure 14) show a linear decrease with

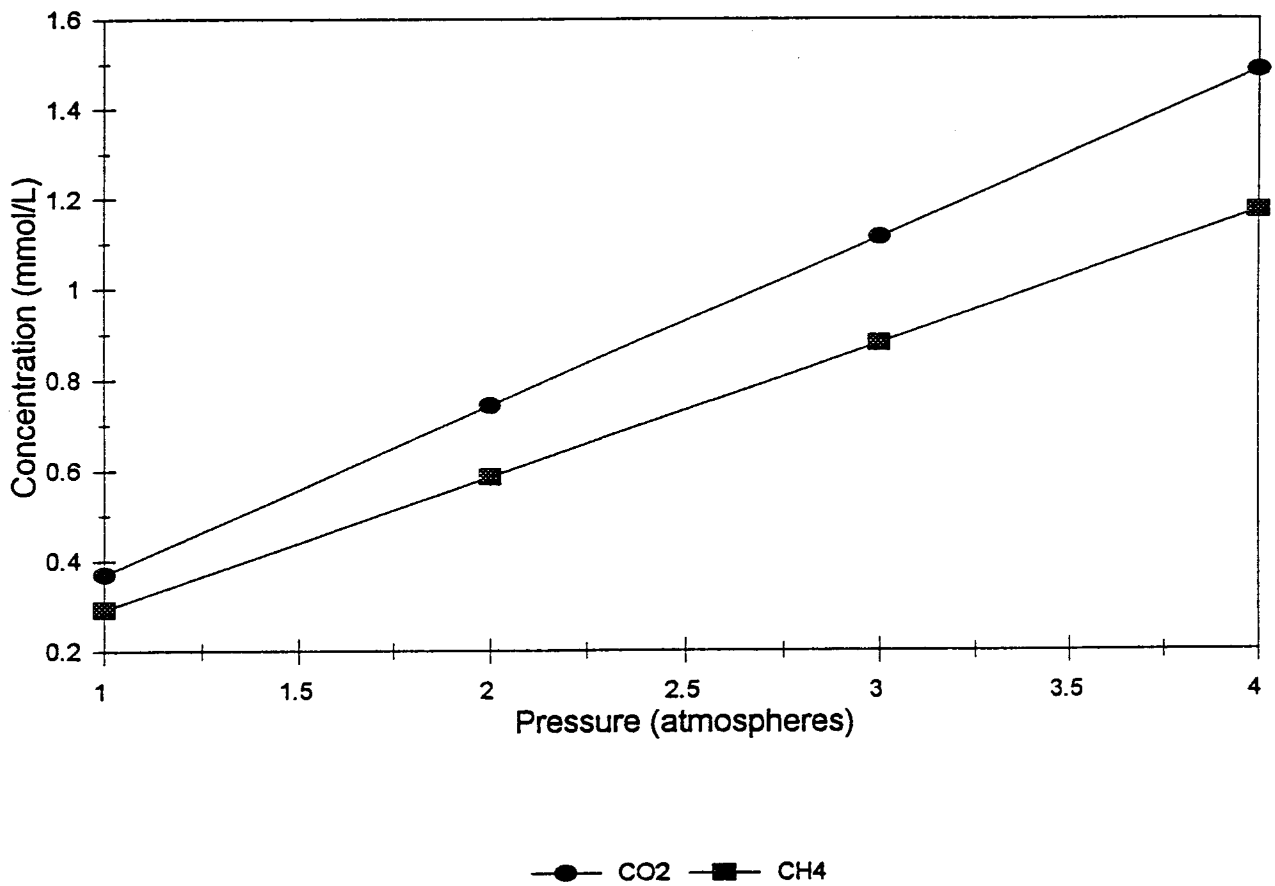

Figure 12. Changes in dissolved carbon dioxide and methane concentrations resulting from changes in pressure at 25 °C, based on Henry's Law.

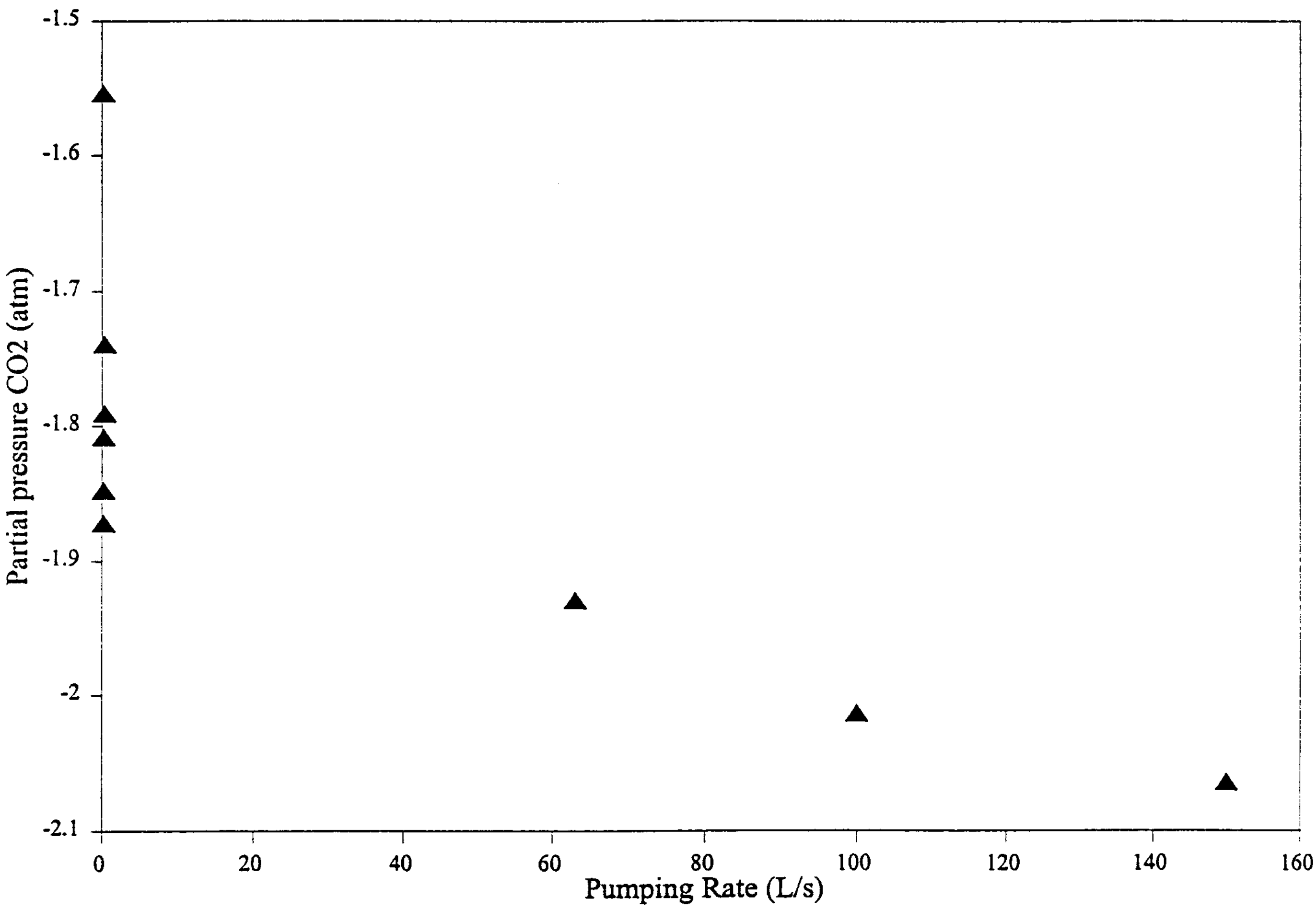

Figure 13. The loss of pCO_2 with increased pumping rate yields a mechanism for the precipitation of carbonate minerals within the aquifer near NIWC's wells.

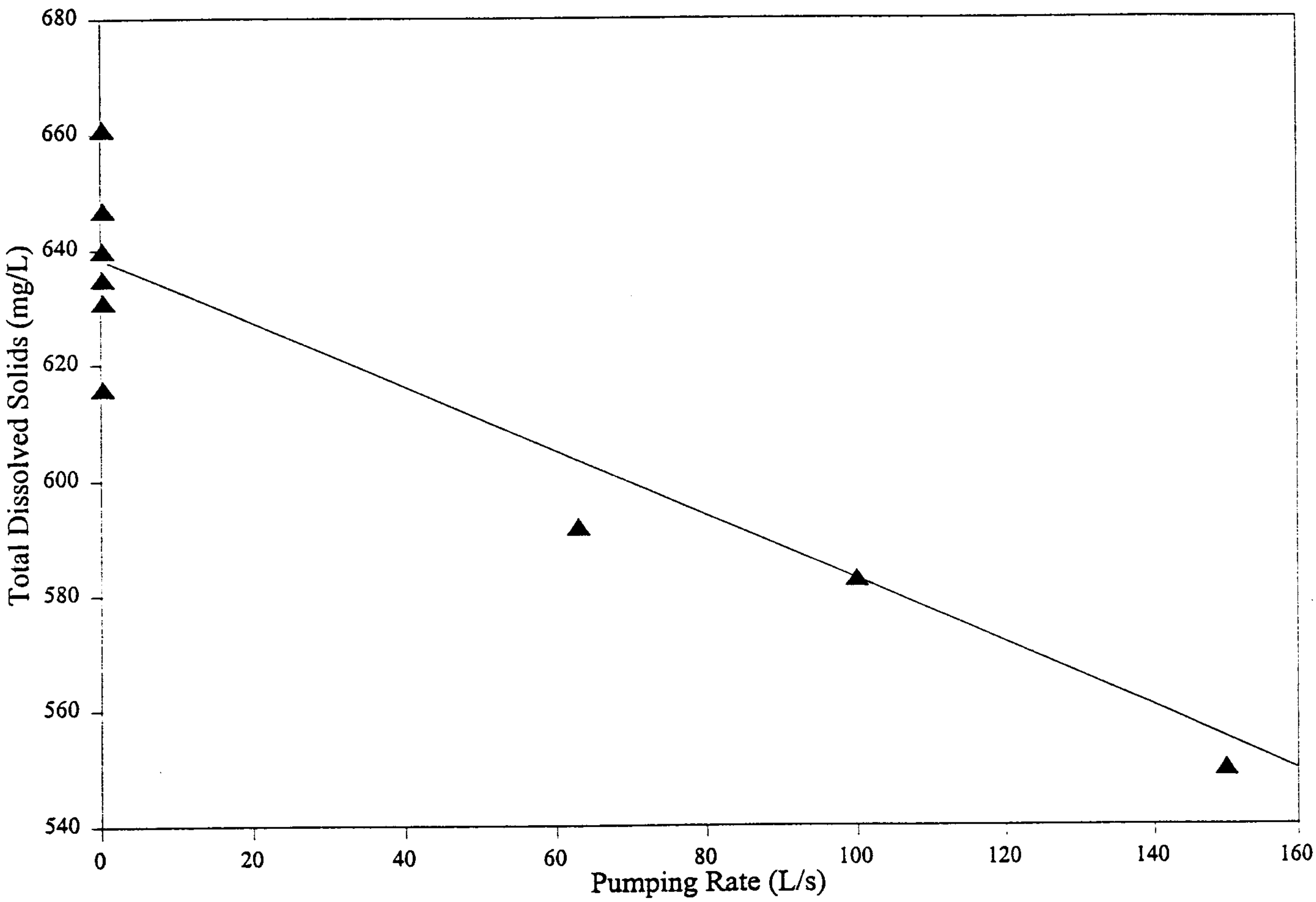

Figure 14. A linear relationship between pumping rate and total dissolved solids (TDS) is believed to reflect the loss of TDS due to precipitation of carbonate minerals within the aquifer surrounding NIWC's wells.

the pumping rate. That is, as the pumping rate from wells in the Mahomet Sand aquifer increases, the TDS and pCO_2 decrease. The loss of TDS relative to pumping rate may be calculated from the least squares equation:

$$Y = -0.59X + 638$$

where Y = TDS and X = pumping rate in liters/second ($r^2 = 0.88$ for the mean TDS of the ISWS wells and three NIWC wells). The average loss in TDS in the NIWC western wells, relative to wells to the north and west, is about 63 mg/L. This change in TDS represents a significant mass of dissolved solids that could be precipitating near the NIWC wells, especially when one considers the volume of water pumped by each well in the western well field. The precipitation of these minerals could eventually reduce the porosity and hydraulic conductivity of the aquifer around the well and could be responsible for the loss of specific capacity. The following example demonstrates the effect precipitation can have on a well:

> Assume that calcite precipitates in the pore spaces of the Mahomet Sand aquifer within a 100-foot radius of a production well, and that the aquifer is 50 feet thick. Also assume that a well is pumped at 1500 gpm for one year, so the total volume of water pumped is 7.9×10^8 gallons. The amount of calcite (density = 2.71 g/cm^3) precipitating from this water is 1.93×10^8 g or 7.1×10^7 cm^3. Assuming a porosity between 25 and 50% for a sand and gravel aquifer (Freeze and Cherry, 1979), and using mean porosity of 38% (a very conservative estimate given the probable compaction within this aquifer), the total void space in the cylindrical aquifer segment is 1.7×10^{10} cm^3. Thus, 0.42% of the void spaces per year or 4.2% in 10 years would be filled by calcite. The percent loss of porosity depends on the actual size of the zone of cementation; as the volume of the area of precipitation decreases, the percent loss of porosity increases asymptotically (Figure 15).

This scenario is consistent with the results of 1995 acidification of NIWC 57. Acidification of the well resulted in a significant increase of specific capacity that steadily declined to its previous level over the course of about one year. If the remediation was effective only in close proximity to the well and along preferred pathways from the well, then the groundwater flow along these flowpaths would improve specific capacity. However, the specific capacity would only be maintained until the porosity of the newly cleared, although smaller flowpaths, was reduced to

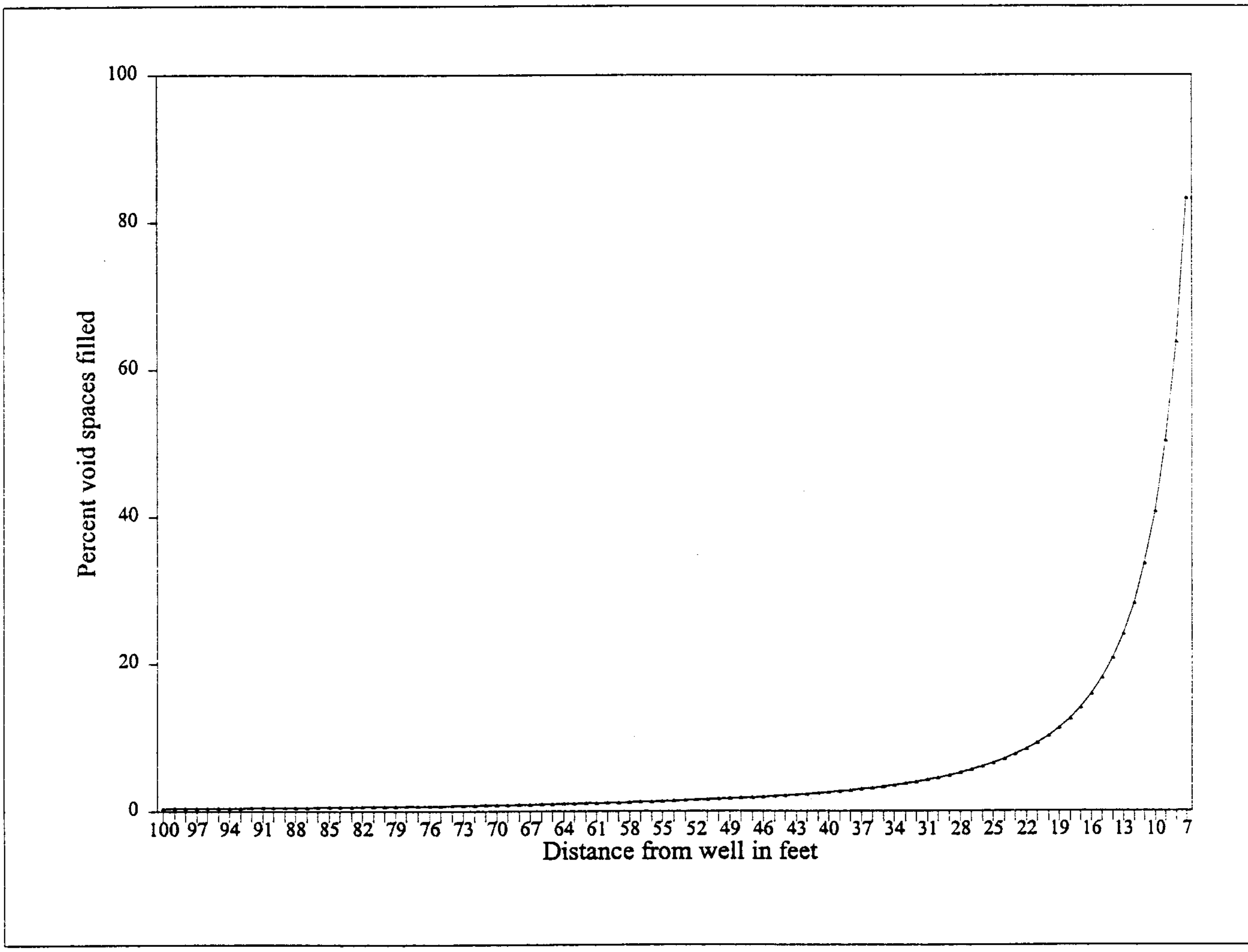

Figure 15. The percent of void spaces in Mahomet Sand aquifer that could be filled after one year of pumping a well at a rate of 1500 gallons per minute relative to distance from the well where precipitation begins. For example, about 41% of the voids are filled if precipitation begins at 10 feet from the well.

previous levels. Loss of specific capacity, in this case, would take less time than if groundwater were allowed to flow through a larger volume of aquifer.

An increase in chloride and decrease in silica in the proximity of the western well field (Figures 16 and 17) was also observed. The increase in chloride suggests that pumping within the well field is drawing groundwater with higher concentrations of chloride from a source other than the MSA. It cannot be determined from available data whether the source of this groundwater is from older adjacent bedrock or younger beds overlying the Mahomet Sand aquifer. Panno et al. (1994) showed that groundwater in the underlying bedrock is a Na^{+}-Cl^{-} type groundwater and would be a likely candidate. Concentrations of SiO_2 in groundwater from the bedrock range from 6.0 to 12.4 mg/L (based on limited data), whereas the groundwater from the MSA and overlying Glasford sands range from 16.3 to 24.6 mg/L (Panno et al, 1994). Assuming that silicate minerals are not precipitating within the aquifer, the lower SiO_2 concentrations at and near the NIWC wells (Figure 17) are consistent with the influx of groundwater from the bedrock.

Bacteria

The bacterial composition of the water from ISWS wells provided background information about the type of bacteria that might be present in the aquifer. *Bacillus subtilis*, *Pseudomonas* spp., and to a lesser extent *Staphylococcus saprophyticus* were consistently observed in water samples from the ISWS wells (Table 7). These genera and species are typical soil bacteria and could have been introduced into the well or materials around the well during drilling. Alternatively, because the concentrations are so low and of the same magnitude, they could be incidental bacteria present (e.g., as a biofilm) in the 60 meters of plastic tubing of our pump. No Fe- or S-oxidizing bacteria were found in the isolates. The aerobic bacteria in the ISWS wells were found at levels that ranged from 8 to 207 colony forming units/100 mL (cfu). Low bacterial counts, 10 cfu or less, could be due to airborne bacteria incorporated during sampling (E.C. Storment, Department of Agriculture, personal communications, 1998). For example, one of four sterilized field blanks contained 2 cfu of *Bacillus subtilis*.

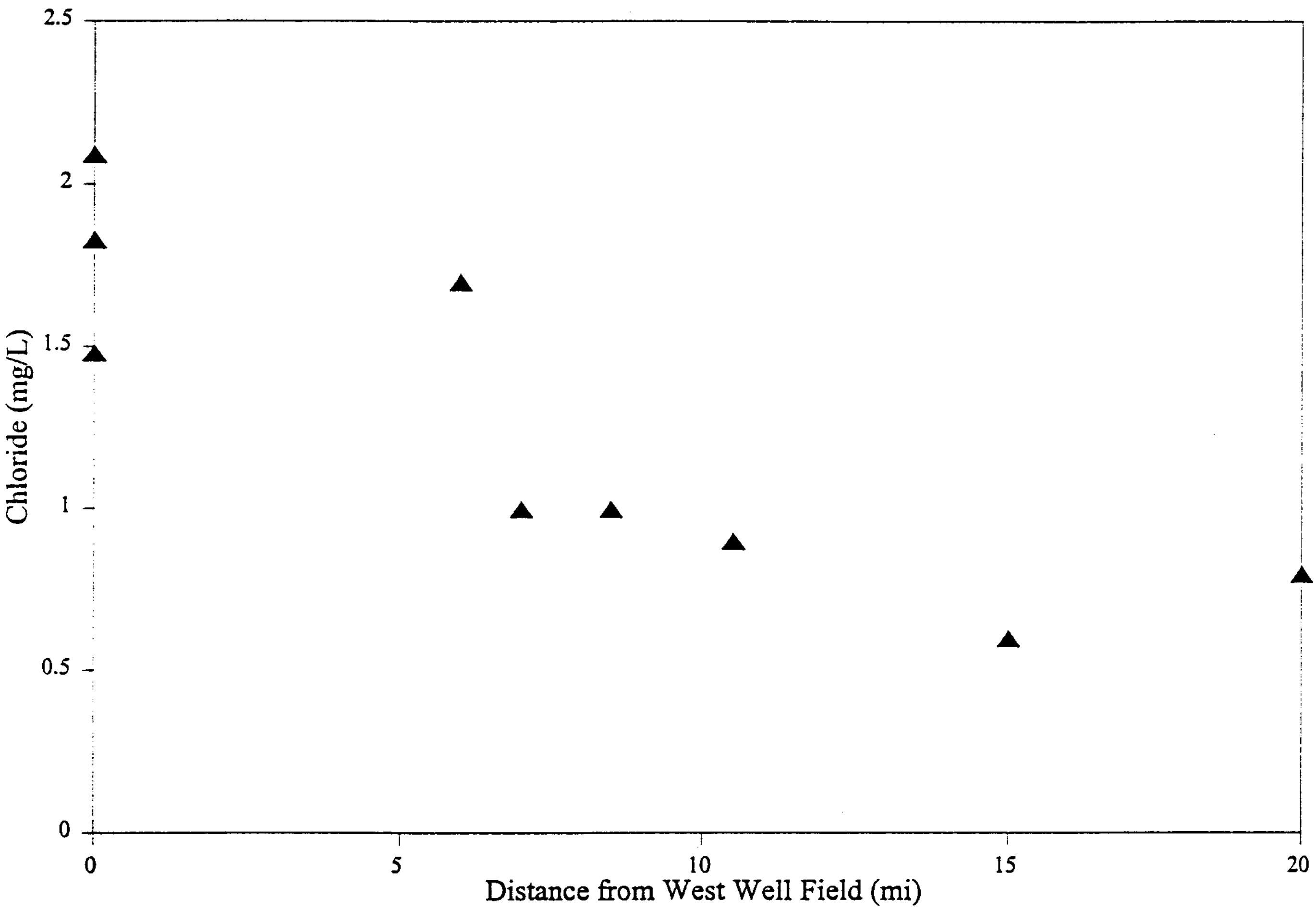

Figure 16. Chloride increases with proximity to the western well field supporting the hypothesis that pumpage is attracting groundwater from an adjacent source (in this case, with a higher chloride concentration).

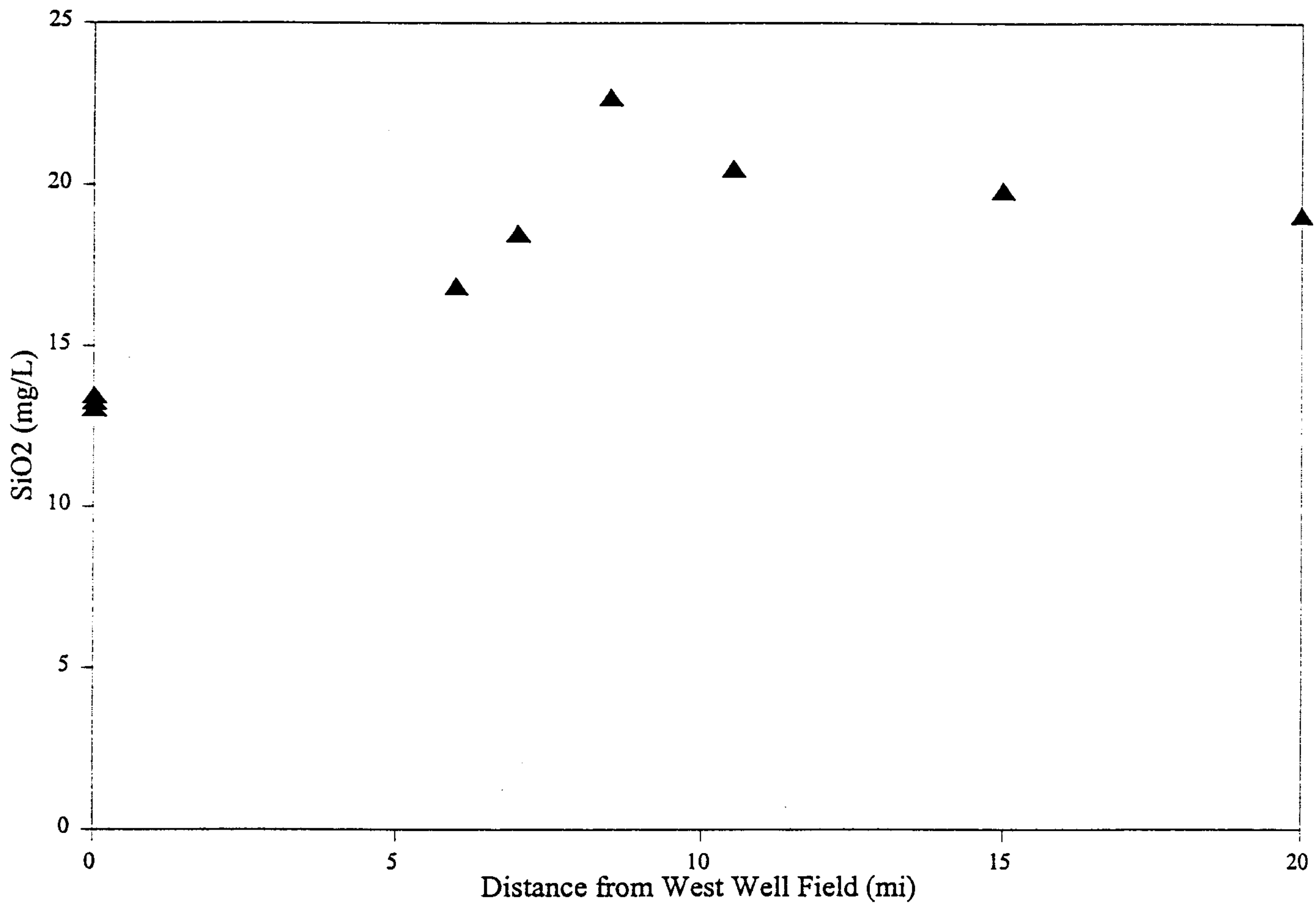

Figure 17. Silica decreases with proximity to the western well field suggesting the possible influx of groundwater from a bedrock source.

Table 7. Bacterial genera and species isolated from groundwater samples from ISWS and NIWC wells in the Mahomet sands. NIWC samples were collected during normal pumping operations (cfu = colony forming units/100 mL water).

Well No.	Total Aerobic Bacteria (cfu)	Bacterial Isolates
ISWS 94A	10	*Bacillus subtilis* *Pseudomonas* spp.
ISWS 95B	207	*Bacillus subtilis* *Pseudomonas* spp.
ISWS 95D	108	*Bacillus subtilis* *Pseudomonas* spp. *Staphylococcus saprophyticus*
ISWS 96A	88	*Bacillus subtilis* *Pseudomonas* spp.
ISWS 96B	10	*Bacillus subtilis* *Pseudomonas* spp.
ISWS 96C	90	*Bacillus subtilis* *Pseudomonas* spp. *Staphylococcus saprophyticus*
NIWC 55	8	*Enterobacter agglomerans* *Pseudomonas* spp. *Staphylococcus xylosus*
NIWC 57	10	*Enterobacter agglomerans* *Pseudomonas* spp. *Staphylococcus xylosus*
NIWC 58	130	*Micrococcus* spp. *Bacillus* spp.

Bacterial analysis of groundwater collected from NIWC wells during operation revealed the presence of genera and species slightly different from those of the ISWS wells (Table 7). Isolates from these samples showed the presence of *Enterobacter agglomerans*, *Pseudomonas* spp., *Staphylococcus xylosus* in NIWC 55 and NIWC 57, and *Micrococcus* spp. and *Bacillus* spp. in NIWC 58. These bacteria were probably not introduced during the sampling of the NIWC wells because the water samples were collected directly from the well through a cleaned spigot (rinsed with alcohol and flamed). For these wells, the sampling pump, suspected of contaminating samples collected from the ISWS wells, was not used.

Species of *Enterobacteriaceae* are often dominant in pipe sediment biofilms and is one of two strains of coliforms most often involved with noncompliance problems with public water systems. In addition, *Enterobacter*, *Pseudomonas*, and *Micrococcus* species are known to form and/or colonize biofilms (Geldreich, 1996). *Staphylococcus xylosus*, as with all strains of *Staphylococcus*, are not known to be naturally-occurring in groundwater systems, but are normal inhabitants of the human skin (Chapelle, 1992; Geldreich, 1996) and, to a lesser extent, fecal matter (Antai, 1987) and soils (Alexander, 1977). Their presence may indicate contamination of the water samples or sample bottles due to handling (Chapelle, 1992) or may indicate the introduction and colonization of this bacteria genera into the wells or associated distribution system during construction and maintenance (LeChevallier and Seidler, 1980; Geldreich, 1996). No Fe- or S-oxidizing bacteria were detected in any of the samples, nor were there any indication (e.g., staining of filters) of the presence of these bacteria during analysis of the samples.

Surging of the NIWC wells resulted in little change in the groundwater chemistry of the wells, but did reveal a surprising number of colonies of aerobic bacteria for NIWC 58. The number of colonies decreased from greater than 600 cfu at 30 and 90 seconds to 155 after 300 seconds and to 106 cfu after 600 seconds (Table 8). This pattern would be expected if surging dislodged part of a biofilm. Whether the biofilm is present in the aquifer materials, gravel pack, or well materials is not known; however, Geldreich (1996) points out that in distribution systems, biofilms initially form in slow-flow areas. In addition, the highest counts of total aerobic bacteria from water samples, collected while the three wells were in full operation, were found in NIWC 58. The sample from NIWC 58 had 130 cfu, whereas samples from NIWC 55 and NIWC 57 had only 8 and 10 cfu, respectively, during the same period. In general, groundwater samples from NIWC 55 (a well with little change in specific capacity) and NIWC 58 (a well with a significant loss in specific capacity) showed little difference in the cfu and species. This suggests that any biofilms present are having little effect on specific capacity.

Table 8. Bacterial genera and species isolated from groundwater samples during "surging" of NIWC wells following a two-week or more "idle period" for the wells.

Well No.	Time Since Well Start Up	Total Aerobic Bacteria (cfu)	Bacterial Isolates
NIWC 55	30 s	142	*Staphylococcus aureus* *Acinetobacter baumannii*
NIWC 55	90 s	42	*Staphylococcus aureus* *Acinetobacter lwoffii*
NIWC 55	300 s	8	*Staphylococcus aureus*
NIWC 55	600 s	196	*Bacillus cereus* *Staphylococcus aureus* *Acinetobacter lwoffii*
NIWC 57	0 s	208	*Staphylococcus intermedius* *Enterobacter* spp. *Pseudomonas* spp.
NIWC 57	30 s	44	*Acinetobacter lwoffii* *Micrococcus* spp. *Pseudomonas* spp. *Bacillus subtilis*
NIWC 57	90 s	72	*Pseudomonas aeruginosa* *Bacillus subtilis* *Staphylococcus epidermidis*
NIWC 57	300 s	52	*Bacillus cereus* *Enterobacter agglomerans*
NIWC 57	600 s	100	*Pseudomonas aeruginosa* *Staphylococcus epidermidis*
NIWC 57	900 s	80	*Pseudomonas aeruginosa* *Staphylococcus aureus*
NIWC 58	30 s	>600	*Bacillus cereus* *Staphylococcus aureus* *Enterobacter agglomerans*
NIWC 58	90 s	>600	*Bacillus cereus* *Staphylococcus xylosus* *Enterobacter cloacae*
NIWC 58	300 s	155	*Bacillus cereus* *Staphylococcus aureus* *Escherichia coli*
NIWC 58	600 s	106	*Bacillus* spp. *Acinetobacter baumannii* *Staphylococcus intermedius*

Dissolved Gases

Dissolved gas analyses indicated that there were significant differences between groundwater sampled from the NIWC wells in the western well field and most groundwater sampled from ISWS wells west and north of the well field. The NIWC wells contained significantly greater amounts of CH_4 than most of the ISWS wells (Figure 18). The one ISWS well (ISWS 95D) that contained a significant amount of CH_4 is located just west of NIWC's western well field.

The concentrations of dissolved CO_2 measured from water samples was compared to the partial pressure of CO_2 (pCO_2) calculated from the chemistry of the water using a geochemical equilibrium model. We expected a positive correlation between these two data sets. However, a positive correlation for the CO_2 results was only observed for the five ISWS wells located to the north and west of the western well field. The measured CO_2 values in the three NIWC wells and ISWS 95D were significantly greater than what would be expected when compared to the calculated pCO_2 data (Figure 19). Possible explanations for this observation include the rapid CO_2 degassing and chemical disequilibrium caused by a significant hydraulic pressure drop, and, to a lesser degree, the entrapment of CO_2 with the degassing of less soluble compounds, such as methane.

The principle reason for the irregular correlation between the dissolved CO_2 values and the calculated pCO_2 for some of the wells is most probably the rapid exsolution of CO_2 due to the pressure drop within the cone of depression around the western well field. The wells with the higher than expected dissolved CO_2 are all within, or very near, the main cone of depression for the NIWC western well field. Near the well field, there is an increased gradient of hydrostatic pressure drop which would cause more rapid degassing of CO_2 from the groundwater. Because the rate of CO_2 exsolving from water is much faster than the rate of precipitation of carbonate minerals from solution, we would expect that the chemical constituents dissolved in the groundwater in the vicinity of the high capacity wells to be out of chemical equilibrium with the surrounding minerals. Thus, if the system is out of equilibrium we would not expect the values

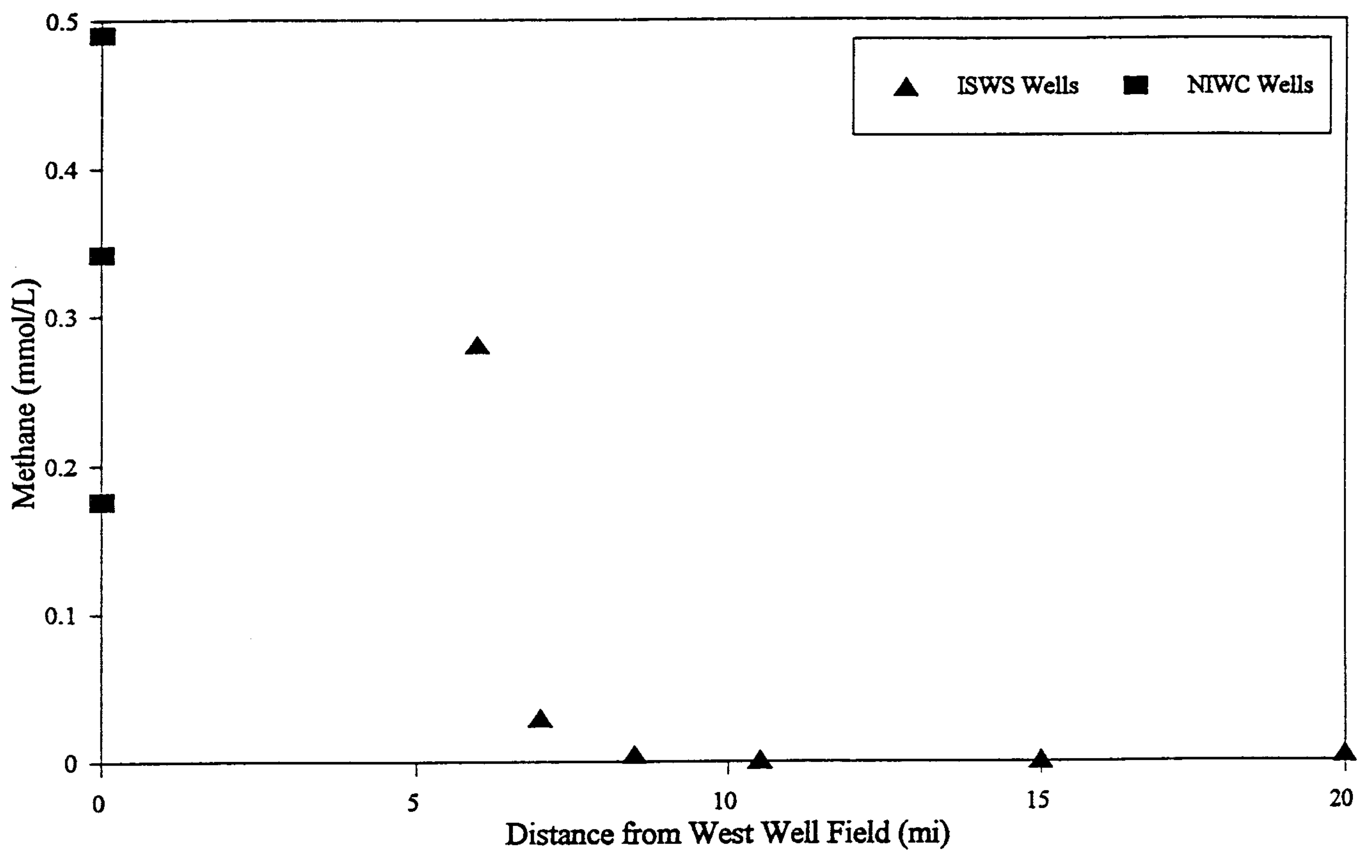

Figure 18. Dissolved methane increases with proximity to the western well field suggesting that pumpage is attracting groundwater with a higher concentration of methane from an adjacent source (bedrock perhaps).

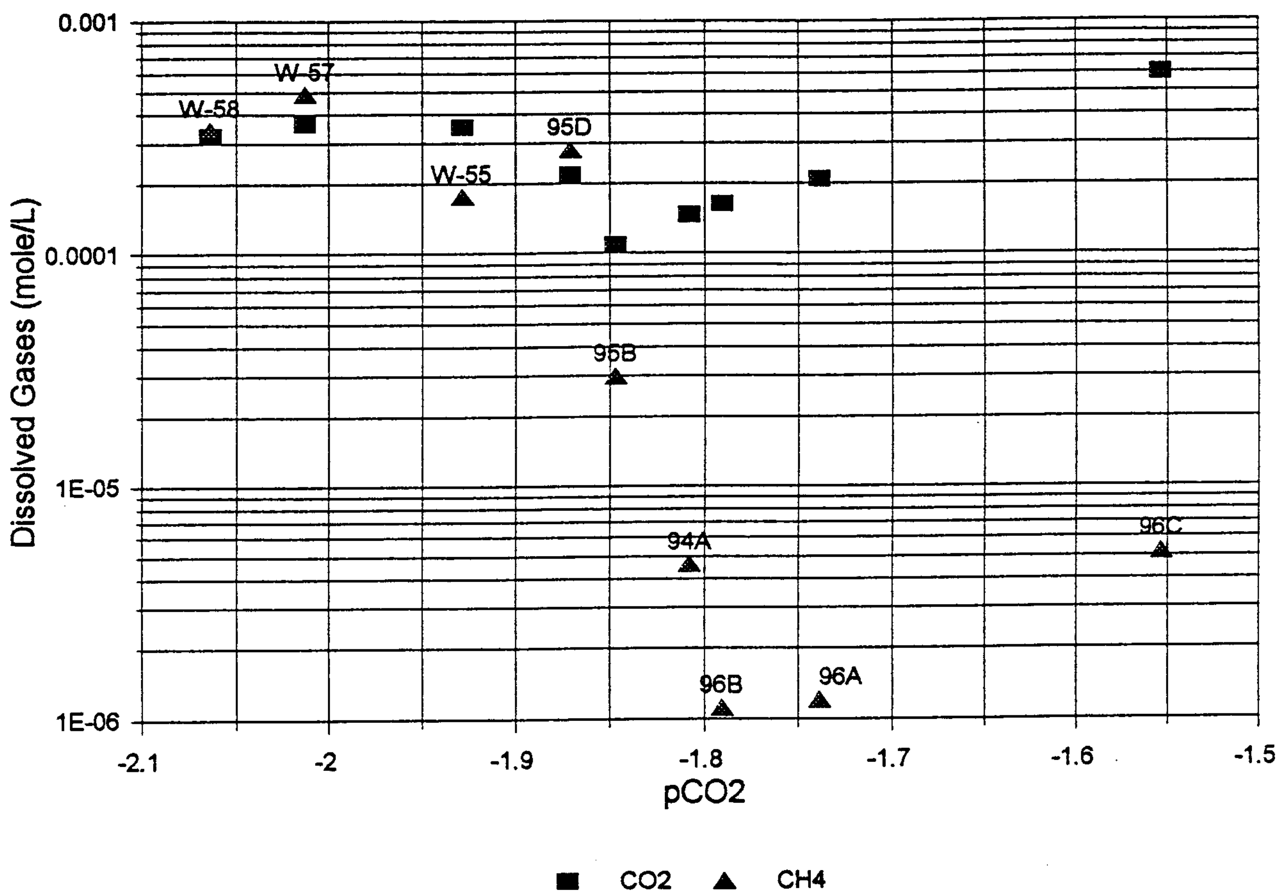

Figure 19. Comparison of the concentration of dissolved gases with the calculated pCO_2 values for six ISWS wells and three NIWC wells (NIWC 55, NIWC 57 and NIWC 58). Also shown are measured CH_4 concentrations which are highest in the vicinity of the well field and may be responsible for exacerbating the loss of CO_2 from groundwater by acting as a carrier gas to sweep CO_2 from the system during pumping.

of the dissolved CO_2 measured from the water samples to correlate with the calculated values of pCO_2, which were computed with an equilibrium model. This would explain the irregular trends observed for the CO_2 data on Figure 19 for the samples taken near the western well field.

The other possible mechanism which may have some contribution to the higher dissolved CO_2 values measured from the NIWC wells and ISWS 95D well is the entrapment of CO_2 with the degassing of CH_4. The concentration of dissolved CH_4 in these wells is relatively high, similar to the values obtained for dissolved CO_2. In contrast, the rest of the wells sampled in the thalweg of the MSA have very low CH_4 concentrations. As the groundwater is pumped, the less soluble gases, such as CH_4, will degas and partially strip out other gases, including CO_2, from the water. The mechanism described here may be comparable to the process known as "air stripping", where compressed air is bubbled through a container of water to remove other volatile compounds (Nyer, 1985). Degassing of groundwater due to the presence of CH_4 has been reported for the Milk River Aquifer in Canada in relation to a noble gas study by Andrews et al. (1991). Thus, perhaps the degassing of CH_4 from the groundwater at the NIWC wells has increased the amount of dissolved CO_2 which would normally be released from the groundwater due to the loss of hydrostatic pressure around the wells. As previously mentioned, the loss of CO_2 will cause precipitation of minerals, thus decreasing the porosity and hydraulic conductivity around the wells and eventually lowering the specific capacity. Our limited number of gas analyses indicates that some NIWC wells contain greater amounts of CH_4 than others, which may help to explain why some wells show greater specific capacity loss relative to others. For example, NIWC 55 contains the least CH_4 of the three NIWC wells sampled and has no loss in specific capacity; conversely, NIWC 57 has the greatest CH_4 concentration and also has the highest total loss in specific capacity. These observations are based on a rather small set of samples and further investigation is required to determine whether the geochemical trends observed for the wells sampled thus far holds for other wells in the MVA and the western well field.

Pesticides

Atrazine was not detected in any water samples. Because pesticides are measured in the parts per billion range and are applied to agricultural fields which overlie much of NIWC's western well field, these data suggest that shallow groundwater does not rapidly recharge the Mahomet Sand aquifer. In addition, no tritium was detected in the NIWC groundwater samples, which supports the idea that shallow groundwater does not rapidly recharge the Mahomet Sand aquifer.

SUMMARY

Several factors were identified that may cause the overall decline in specific capacity in the NIWC western well field. Through a review of available records (NIWC, ISGS, and ISWS records and ISGS and ISWS publications) and data gathered from limited field and laboratory investigations, we identified hydraulic and geochemical factors as the probable causes for the observed decline in specific capacity, but biological factors do not appear to be significant.

The hydraulic factors include well interference and entrance velocities exceeding the threshold level of 6 ft/min. Well interference may explain some of the decline in specific capacity because it increases the drawdown at a pumping well. For the well clusters studied, a minimum of 20% of the total, steady-state drawdown was due to pumpage of other wells, which includes NIWC and non-NIWC wells. Likewise, entrance velocities that exceed 6 ft/min can lower specific capacity by causing additional head loss at the well or increasing the drawdown at the well.

The chemical composition and gas content of groundwater samples from the western well field, when compared to groundwater samples from other parts of the MSA suggest that carbonate and iron minerals could be precipitating within a 100-foot radius of each affected well. Precipitation of these minerals could be caused by reduced hydrostatic pressure due to drawdown and concomitant degassing of CO_2. According to the data collected during this investigation, additional CO_2 could be extracted by degassing of significant amounts of methane. Bacterial analysis of groundwater samples suggests that biofilms may be present in all NIWC wells, gravel pack or adjacent sediments. However, there was little difference in the cfu and species between groundwater samples from NIWC 55 and NIWC 57, suggesting that biofilms present are having little effect on specific capacity.

With the available data, it was not possible to determine whether hydraulic or geochemical factors were the dominant cause in the observed decline in specific capacity. Additional investigations, such as those outlined below, are needed to provide the data to resolve this problem.

RECOMMENDATIONS

1) ***Experiment with pumpage rates*** Conduct experiments with wells to develop relationships between specific capacity and pumpage. The pumpage rates should be converted to average entrance velocities, which will allow one to study the effect of entrance velocity on specific capacity. Certain wells may be more susceptible to head losses from entrance velocities that exceed the threshold level due to well design, mineral precipitation, or variability in geologic materials.

2) ***Collect high quality hydraulic data*** Additional data are needed to characterize the aquifer. The data needed include hydraulic conductivity, anisotropy, storativity, leakance, aquifer thickness, aquifer geometry, porosity, and pumpage. These data are needed before a high-quality groundwater flow model can be constructed and used to improve the management of the aquifer. A high-quality flow model can be used to better understand the aquifer dynamics, which are complex because of the presence of multiple, high-capacity users. Some of these data can be obtained by conducting pumping tests of sufficient duration (4 to 28 days).

3) ***Collect additional geochemical data*** We suggest collecting single groundwater samples from four additional wells in the western well field and six additional wells from outside the well field (including production wells from another well field not in the Champaign-Urbana area) for further comparison of dissolved methane and its relationship to dissolved CO_2, specific capacity, and other chemicals and biological parameters. These comparisons would indicate whether our observations are the result of a local phenomenon.

A core of geological materials, collected from the aquifer near the screen of NIWC 57, would yield information on the presence of and type of precipitated minerals and/or biofilms. We recommend that the core be collected at three distances from NIWC 57, possibly at ≤5 feet, 15 feet, and 25 feet. In addition, we suggest that the unconsolidated geologic materials be cored using a rotasonic drill rig to minimize the amount of physical and chemical disturbance of the core.

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