
Kansas Geological Survey

Elevation and Variability of the Freshwater Interface in the Great Bend Prairie Aquifer, South-Central Kansas

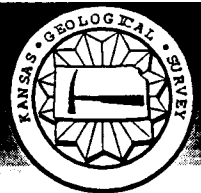
by

D. P. Young, G. W. Garneau,
R. W. Buddemeier, D. Zehr,
and J. Lanterman

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GEOHYDROLOGY



The University of Kansas, Lawrence, KS 66047 Tel. (913) 864-3965

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I. Introduction

The Mineral Intrusion Project is a research effort to understand the hydrologic, water-quality, and water-resource management implications of natural saltwater intrusion into the freshwater Great Bend Prairie aquifer in the eastern portion of Groundwater Management District No. 5 (GMD5). It is funded by the Kansas Water Office (KWO) and is being carried out by the Kansas Geological Survey (KGS), in collaboration with GMD5.

The region of the study is shown in figure 1. In much of this area a bedrock aquifer of Permian age is in direct hydraulic connection with the base of the Great Bend Prairie (alluvial) aquifer. This connection, which elsewhere is commonly blocked by intervening confining layers of low permeability, permits the brines that occur naturally in the Permian bedrock to contaminate the fresh water of the overlying alluvial aquifer. The nature and extent of the connection is illustrated by the map and vertical section shown in figure 2.

Groundwater use in eastern GMD5 is limited by actual and potential water-quality problems, many of which result from contamination of the fresh water by Permian saltwater discharge. In order to support efficient use and management of water resources in the area, the objectives of the Mineral Intrusion Project include: understanding the regional controls on the interface between freshwater and saltwater (also referred to as the "transition zone") and interface responses to groundwater withdrawal and recharge; determining local effects of high-volume pumping on the depth and characteristics of the saltwater interface; and developing data and interpretations that will be useful for water-resource management.

A detailed statement of the problem, including a description of study objectives and experimental approaches, has been prepared by Buddemeier et al. (1992). Young (1992) compiled and reviewed the available information on the geology and hydrology of the Permian bedrock units. Whittemore (1993) collected and discussed the available information on water quality in the study area derived from a network of monitoring wells installed and operated cooperatively by KGS and GMD5.

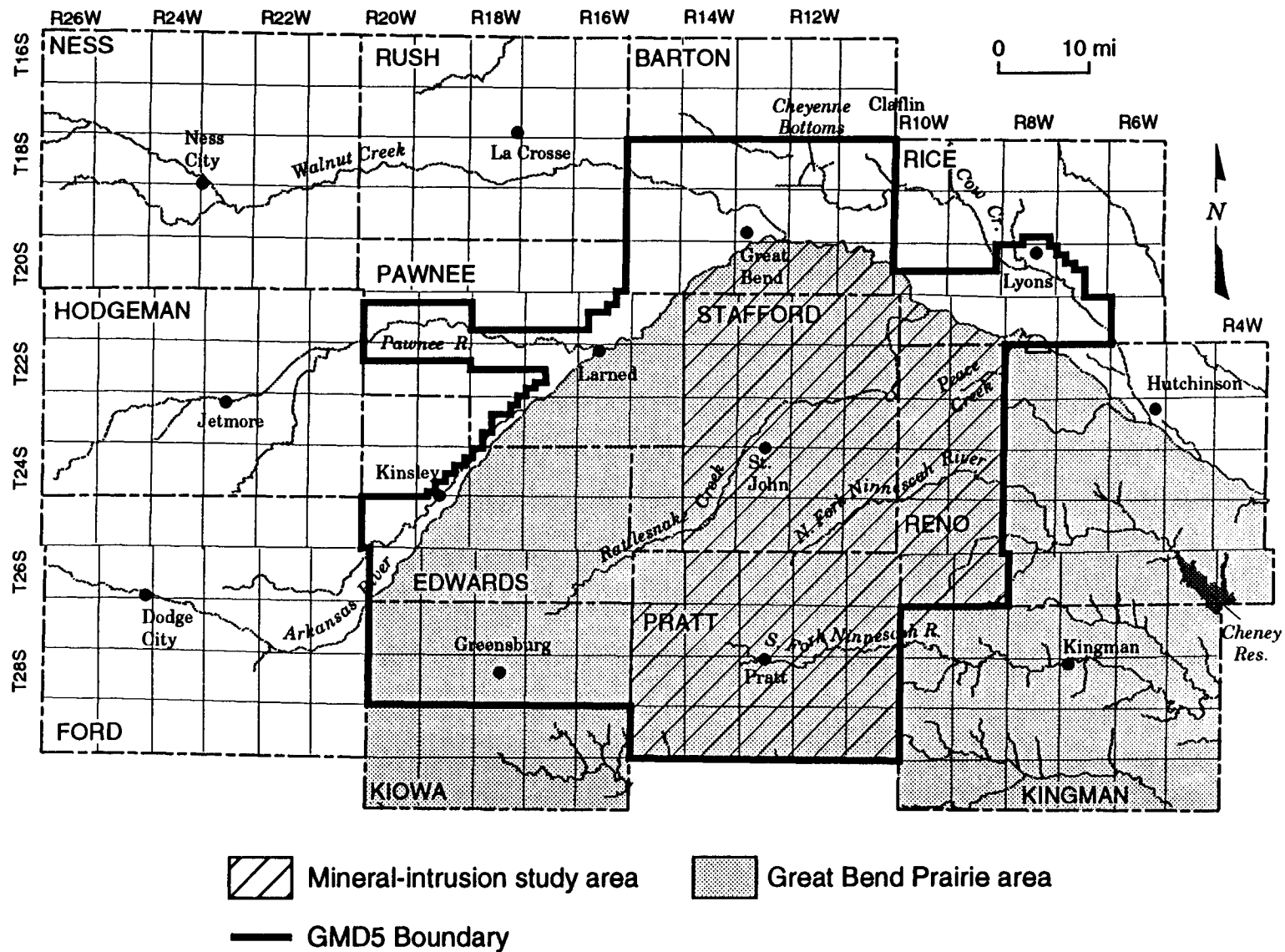


Figure 1. Major features in the region of Big Bend Groundwater Management District (GMD5) and location of the Mineral Intrusion study area.

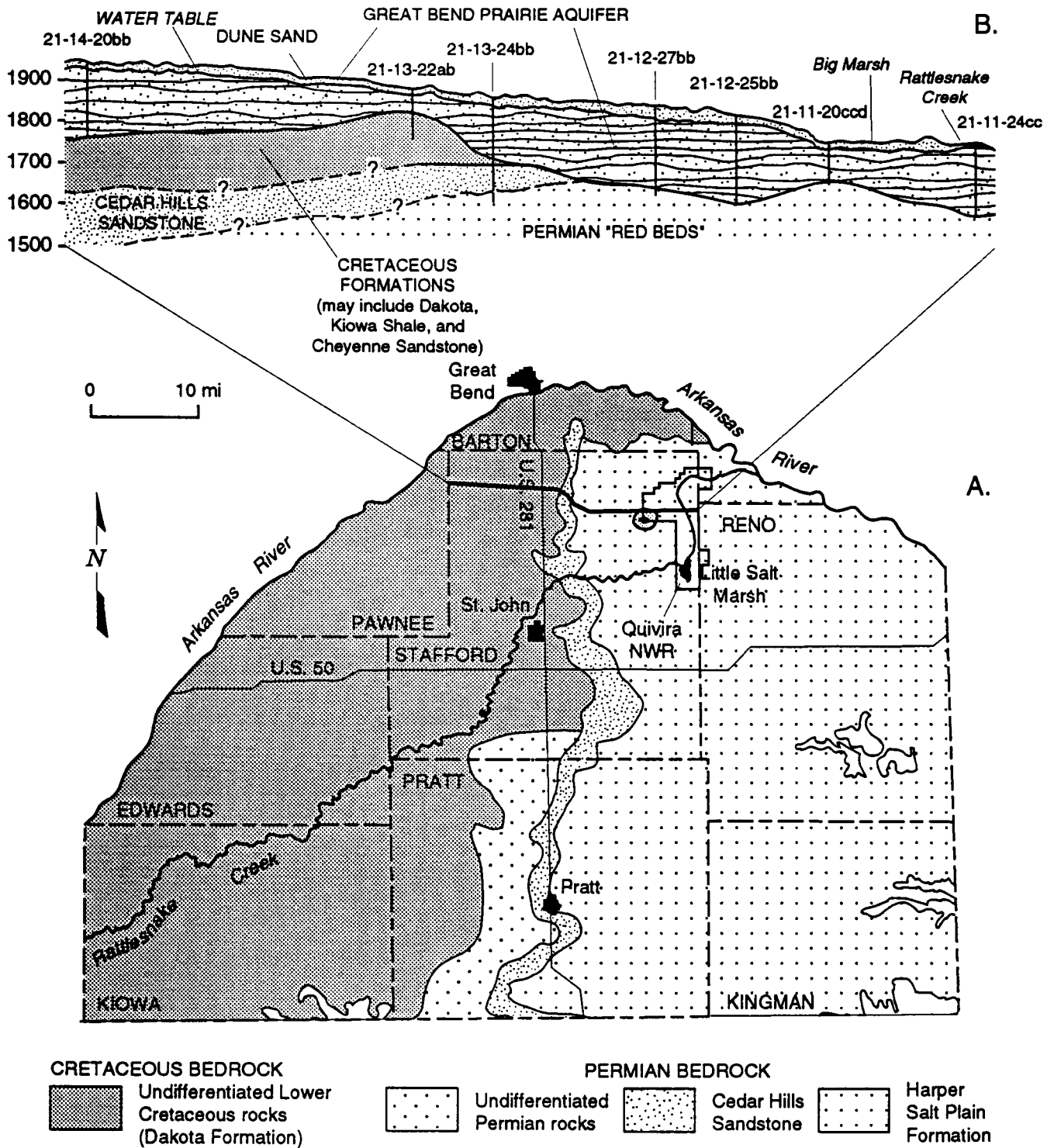


Figure 2. A. Bedrock geology underlying the Great Bend Prairie aquifer and areas in which the Permian bedrock has the potential to contribute saltwater to the overlying aquifer (adapted from Fader and Stullken, 1978). B. Vertical section from west to east across the region, showing the relation of the alluvial Great Bend Prairie aquifer to the underlying Cretaceous and Permian strata (adapted from Latta, 1950).

Buddemeier et al. (1993) reported on progress during fiscal year 1993. That report presented information on monitoring-well installations and field measurements, water chemistry, core and drill log analyses, log interpretation, saltwater distribution, and model development. Notably, it described the development and verification of down-hole geophysical logging techniques that permit identification of the depth and characteristics of the saltwater interface or transition zone in the aquifer formations surrounding the wells of the monitoring network.

During 1993, the KGS/GMD5 monitoring-well sites (figure 3) were all logged for natural gamma activity and formation conductivity as determined by electromagnetic (EM) induction. In addition, an intensive study site [the Siefkes site; see Buddemeier et al. (1993) for detailed description] was established, and a transect corridor across the region of greatest saltwater intrusion (approximately Townships 21 and 22 South; see figure 3) was identified. The wells in these areas were subject to repeated logging throughout the year. This report is based on the results of those logging activities, and focuses on the elevation and variability of the freshwater-saltwater interface or transition zone. It includes refinements and modifications to the methods of freshwater-saltwater interface and transition zone characterization presented by Buddemeier et al. (1993). Section II describes the methods currently used to describe and quantify the characteristics of the transition zone. Section III contains the results of logging surveys to date: baseline data on the monitoring sites (such as elevations of land surface, water table, and bedrock at monitoring-well sites); values derived from well logs (such as transition zone characteristics and freshwater and saltwater saturated thicknesses); and changes in the transition zone characteristics with time. Distribution of the saltwater and possible controls on the interface characteristics are discussed in section IV.

II. Interpretation and Calibration of Conductivity Logs

A. Background and Objectives

Previous water-quality studies of the GMD5 monitoring-well network (summarized by Whittemore, 1993) have determined the areal distribution and a very general depth

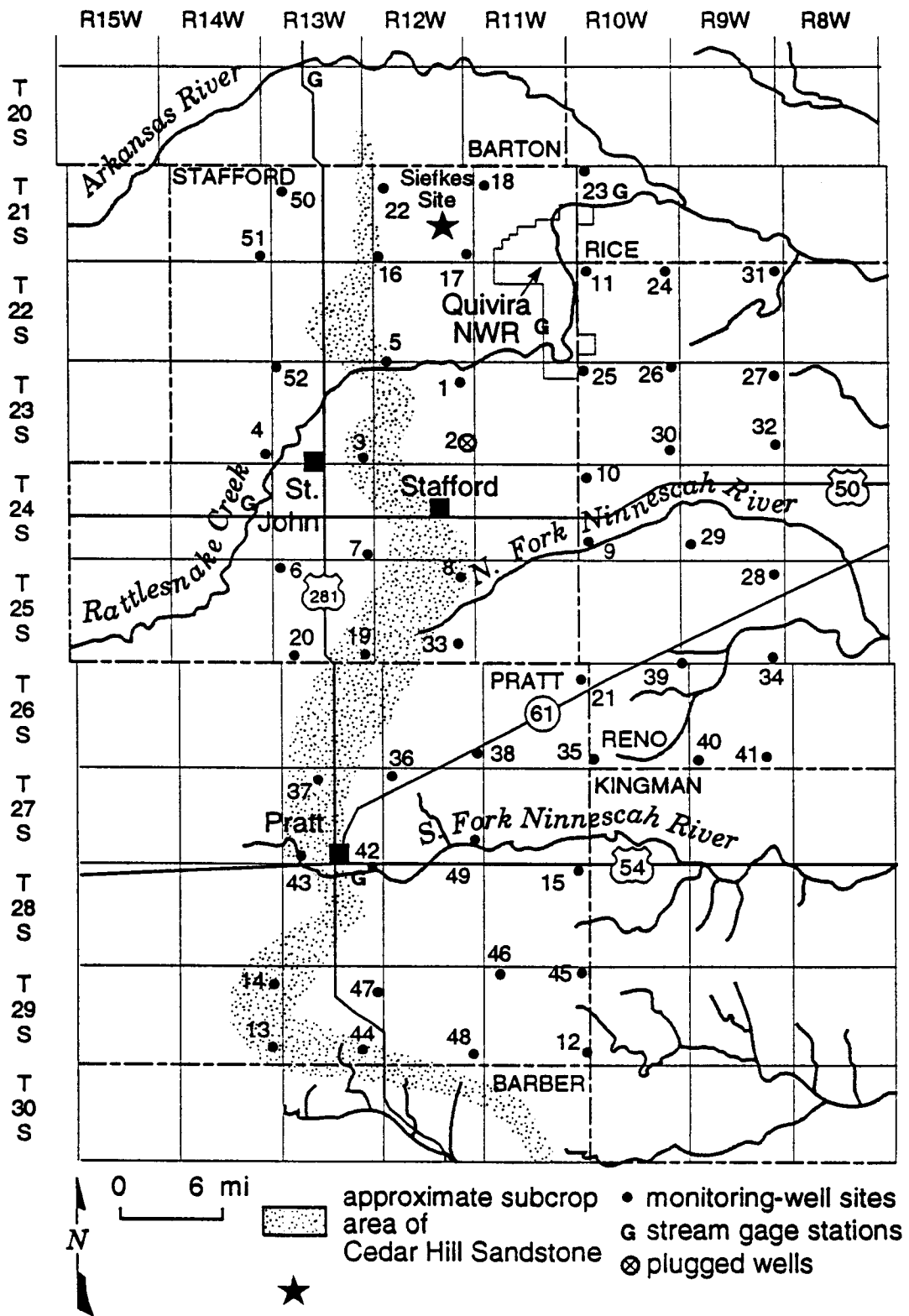


Figure 3. Observation wells and other physical features in the area of the KGS/GMD5 monitoring-well network.

characterization of saltwater. The studies could not develop a precise picture of the depth of the freshwater-saltwater interface or variability in the characteristics of the transition zone because sampling and analysis were limited to the screened intervals of the monitoring wells.

The present study uses a focused-induction electromagnetic logging system (Century Geophysics UL-1000 data logger, portable draw-works, and a model 9510 combination gamma-EM tool) that senses the formation conductivity outside of the well borehole, and can thus obtain essentially continuous conductivity profiles independent of the screened interval of the well. Studies reported earlier (Buddemeier et al., 1993) showed that measurements of the EM profiles are stable and highly reproducible over short time periods. The EM signal is controlled in large part by the salinity of the ground water, and therefore can provide a basis for characterizing the saltwater transition zone. However, there are a number of further requirements that must be fulfilled to meet the objectives of the study:

- o EM records need to be calibrated or very stable over time so that slow or subtle changes in the saltwater transition zone can be measured.
- o To the extent possible, the confounding effects of lithologic variations on formation conductivity should be removed from the records so that the measured signal depends primarily on the pore water salinity.
- o Standard, quantitative measures of transition-zone characteristics must be developed that are appropriate to the physical and chemical processes that form the transition zone, that are useful to both researchers and managers, and that permit regionalization of local observations and comparisons over both space and time. This is a challenging requirement because of spatial variations in the nature of the transition zone and in the depth to which the various monitoring wells penetrate the saltwater zone.
- o Uncertainties associated with either the measurement or the calculation techniques must be determined in order to provide guidance for scientific interpretation and management applications.

B. Basic Principles

The conductance of a material is a measure of its ability to transmit an electrical current, and is normally determined by the concentration and mobility of charged particles such as ions or electrons. Specific conductance is a technical term that defines the electrical conductivity of a material of standard dimensions, so that different materials can be compared independent of their geometry. Resistivity is the inverse of conductivity, and measures the resistance of a material to the passage of electrical current. The electrical unit of resistance is the "ohm," named after G. S. Ohm. In a bit of scientific wit, its inverse, the unit of conductance, was originally defined as the "mho." More recently, the unit of conductivity has been renamed (based on the International System of Units) the "siemens," which is numerically the same as the mho. These units are rather large compared to the conductivity of most natural materials, so the units commonly used for measurement of conductance are millisiemens per meter (mS/m) or microsiemens per centimeter ($\mu\text{S}/\text{cm}$). The equivalent older units are millimhos per meter (mmho/m) and micromhos per centimeter ($\mu\text{mho}/\text{cm}$). One mS/m = ten $\mu\text{S}/\text{cm}$; this report uses mS/m.

In the case of water, conductance is dependent on its dissolved ionic content, and increases rapidly with increasing salt concentration. However, the exact relationship between the salt content of water (also referred to as salinity, and closely related to total dissolved solids or TDS) and its conductance depends on the relative concentrations and electrical characteristics of the dissolved ions. In natural environments the chemical composition of salty water is usually complex, but if the relative proportions of the different ions are reasonably constant then the electrical properties can be calibrated in terms of salt concentration and conductivity can be used as an approximate measure of concentration. In the Mineral Intrusion study area, the composition of the Permian brine varies over relatively narrow limits, allowing estimation of chloride using a plot of conductance vs. chloride ion concentration (fig. 4) similar to that constructed by D. Whittemore (personal communication). Chloride ion concentration is a good indicator of salinity because concentration ratios of the various ions in solution are relatively constant for a given salinity in the study area.

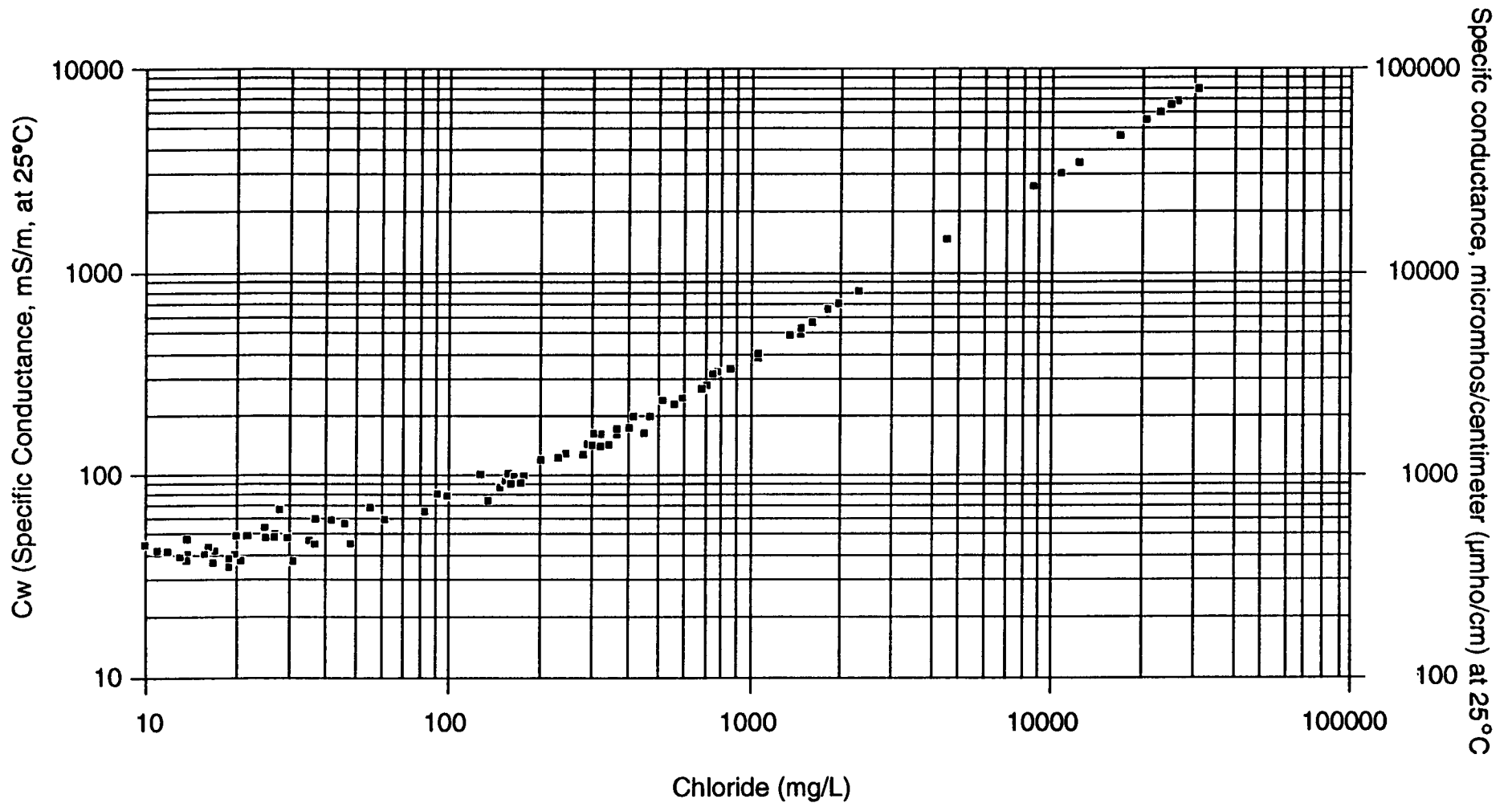


Figure 4. Specific conductance (Cw) vs. chloride concentration of water samples from observation wells in the Great Bend Prairie aquifer.

Figure 4 is plotted using logarithmic axes because the ranges of concentrations and conductivities of interest are large. The relationship is not linear over the entire range, which further complicates the use of conductivity measurements for direct field estimation of salt content. However, over the range from moderately fresh to moderately salty, a plot of conductivity vs. chloride on linear axes can be treated as a straight line with acceptable accuracy. Figure 5 shows a limited range of data from figure 4, replotted on a linear graph and with key water-quality thresholds indicated. The water-quality thresholds for irrigation and livestock (fig. 5) are not absolute, but are listed to serve as guidelines. For irrigation, permissible chloride concentrations depend on type of crop, environmental conditions, and management practices, and a single value can not be given (Committee on Water Quality Criteria, 1972). Similarly, suitability of water for livestock depends on age, sex, species, and physiological state of the animals.

When we apply electrical techniques to characterize ground water in the subsurface, we are measuring the combined characteristics of the water and the geologic framework. Unfortunately, the combined characteristics are not simply the sum of the separate characteristics. However, the groundwater conductance can be estimated using approximations for the range of interest. The conductivities of dry aquifer materials (sands and gravels) and of fresh water are both low, so moist soils and saturated freshwater aquifers have conductivities measured in tens of mS/m. As the groundwater becomes saltier, its conductivity signal becomes more dominant. However, the water occurs only in the pore space of the aquifer, so in effect the salt water is "diluted" by the less conductive rock. If we assume that (1) pores are straight channels and (2) the measured conductance C_m of a saturated formation with porosity n is simply the sum of the separate formation and water conductivities, C_f and C_w , then

$$C_m = (1 - n)C_f + (n)C_w. \quad (1)$$

If the total conductivity of the saturated aquifer is great enough so that we can neglect the contribution of the mineral formation (equal to or greater than hundreds of mS/m compared to a few tens for the dry formation), then as a first approximation we can estimate that:

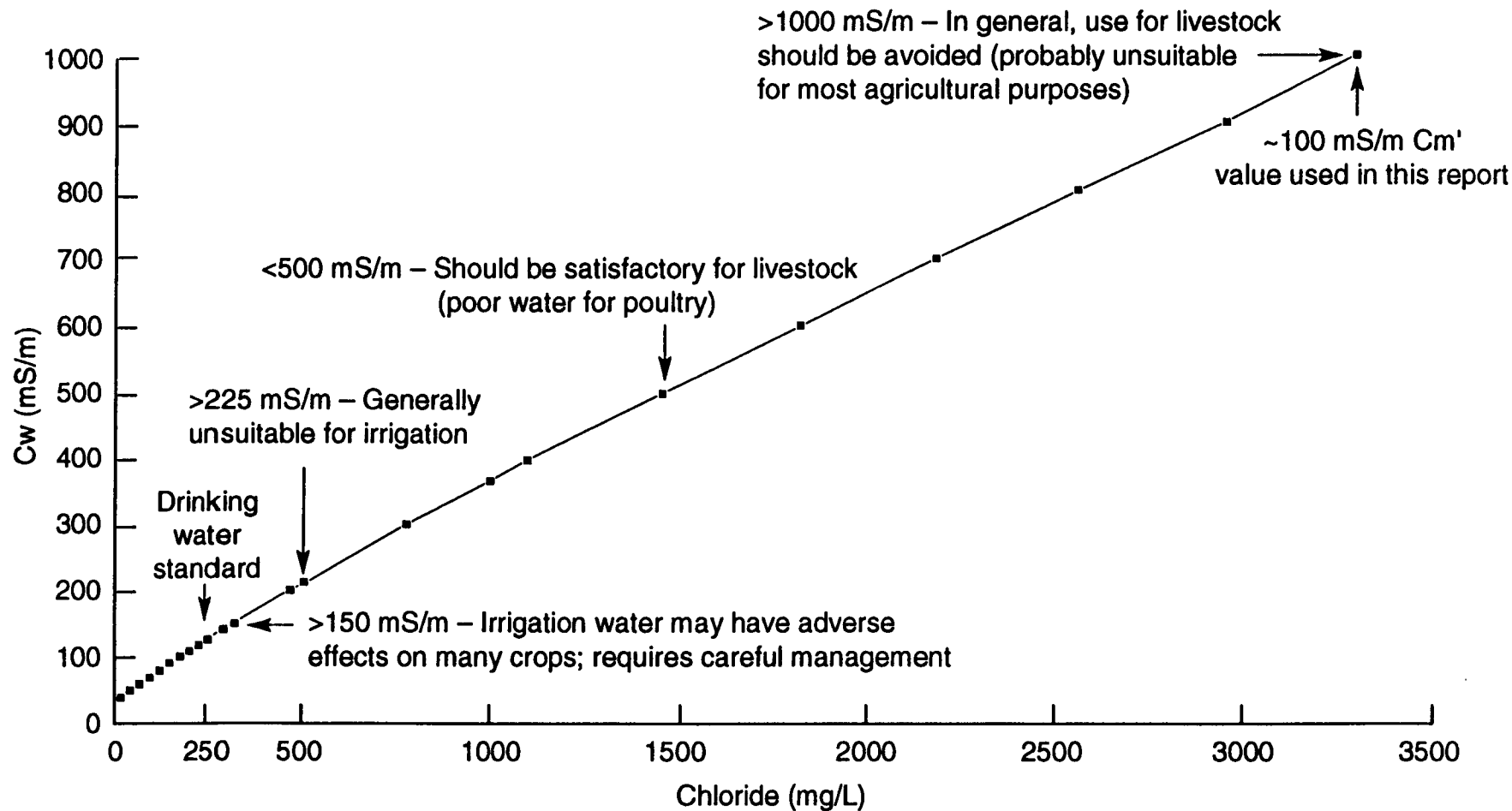


Figure 5. Lower range of data from figure 4, with key water quality thresholds indicated (see text). Points are from a curve hand-fitted to the data in figure 4.

$$C_m = (n)C_w$$

or

$$C_w/C_m = 1/n. \quad (2)$$

This approximation is a simplification of the well known empirical relation derived by Archie (1942), which may be written:

$$C_w/C_m = 1/n^m, \quad (3)$$

where m is a cementation or shape factor, ranging from about 1.3 to 2 for unconsolidated to partly consolidated sands. In theory, m has the lowest value ($m = 1$) for straight tubes, in which case equation 3 reduces to equation 2. In reality, pores in aquifers are not straight tubes, but rather a complex branching network of void spaces connected by pore throats; higher values of m reflect increasing tortuosity, which lengthens current pathways (Doveton, 1986) and lowers formation conductance C_m .

While the relationship presented in equation 3 (the Archie equation) is an approximation, it illustrates that the relation between water conductivity and saturated formation conductivity depends to a great extent on porosity, and is influenced by the tortuosity of the matrix. The relationship is useful because it allows interpretation of trends and major differences with confidence, helps determine what variables affect or control the results, and provides an avenue for estimation of the limitations and uncertainties of the results.

C. Applications

The results discussed in this report are based on logs collected by the Mineral Intrusion Project during 1993. Logging procedures followed the manufacturer's recommendations for an electronic depth profile of data points collected at 0.1 foot intervals.

Instrument Drift Calibration

Comparison of logs taken weeks or months apart showed evidence of a systematic linear offset in conductivity values, independent of depth or conductivity. Calibration of the EM logs prior to the lithologic correction (described below) was necessary to compensate for this apparent baseline drift. Such a drift might be caused by temperature changes or by changes in the instrument electronics. Because the instrument was allowed to equilibrate with the temperature of the borehole fluid for at least 30 minutes before each logging run (according to manufacturer's recommendations) and because the temperature of the borehole fluid is expected to remain comparatively constant relative to the atmosphere, the drift is most likely the result of electronic changes. The instrument was obtained new in 1993, so the changes may be the result of time required for instrument "burn-in." The instrument drift is illustrated in figure 6, which shows the general increase in average EM response with time, compared to the gamma-log values that show only minor random fluctuations. The apparent tendency of the EM response to level off near the end of the record is also consistent with the instrument "burn-in" hypothesis. The drift rate between April and July averaged 0.176 mS/m per day; although negligible on the time scale of a single logging expedition, the accumulated bias would be significant over a comparison period of many months to years. The manufacturer of the probe has developed improved stability circuitry, and the system will be overhauled and upgraded during 1994.

April 1993 measurements from site 50 (figure 3) were chosen as a reference for both tracking and correction of EM log stability (drift), and as a basis for variable background correction for the lithologic signal (discussed below). The depth interval analyzed for the drift and lithologic corrections (50 to 185.6 ft below land surface) was kept below the observed fluctuations in water level over the course of the study to eliminate possible effects of changing saturation levels. The EM logs from the other sites are corrected for the conductivity drift by subtracting from each value the difference between the average value for the April 1993 site 50 EM log and the average value of the site 50 log recorded at approximately the same time as the log being corrected. Because of the lack of a corresponding site 50 log in May 1993, logs

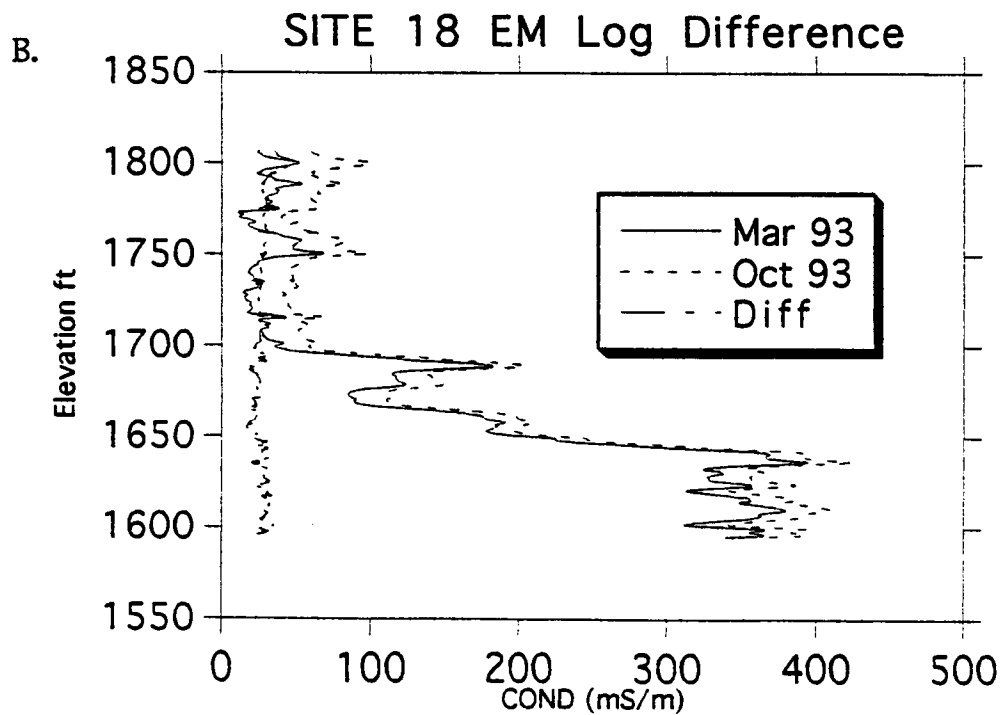
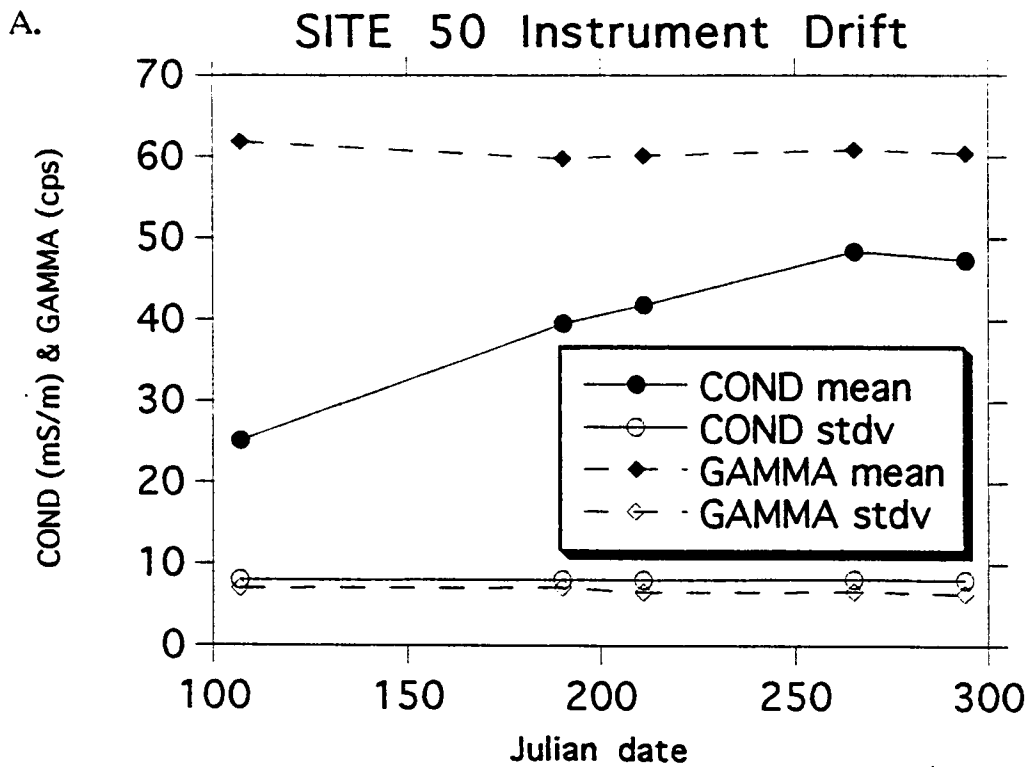


Figure 6. (A) EM logging instrument drift resulting in general increase of average conductivity with time. (B) No significant variation of drift offset with signal strength for a well having a distinct transition zone.

collected in May were corrected by interpolation of the offset correction between April and July; comparison of data from wells logged at all three times indicates that this procedure is justified.

The drift correction is assumed to be a constant regardless of the strength of the EM response because the absolute difference in conductivity between successive logs from sites with strong transition zones remains constant throughout the profile (fig. 6B). As an example of the magnitude of the change produced by this correction, the drift correction of approximately -22 mS/m between March and October results in a 1.2 ft offset (decrease) in the apparent October elevation of the 100 mS/m level in the transition zone at the site 22 Permian well. Uncertainties introduced by the correction procedure are certainly smaller than the bias removed, and are estimated to be less than 10% of the average correction, or 1-2 mS/m.

Lithologic Contributions to Conductivity

The Great Bend Prairie aquifer consists of unconsolidated deposits of gravel, sand, silt and clay. Because clay minerals possess high cation-exchange capacities, the response of EM logs to a clay will be greater than to a quartz arkosic sand if both are saturated with a fluid of low ionic strength. In the Great Bend Prairie aquifer, clay layers generally correspond to increases in both the logged gamma activity and conductivity, particularly at the lower range of observed groundwater salinities (see Buddemeier et al., 1993). However, as groundwater salinities increase, the effects of clay layers on the EM log tend to become relatively less significant because the pore water conductivity is so much greater than the lithologic component. The gamma-EM relation is further complicated because the formation conductivity is also dependent on other factors such as porosity and tortuosity of the matrix—factors about which we have little information for the study area. To reduce the effects of matrix (particularly clay) conductivity on the groundwater salinity signal, especially in the upper part of the zone of transition from fresh water to salt water, a lithologic correction has been developed and applied to the EM logs.

Logs from monitoring site 50 (figure 3) were used as a reference for both variable background lithologic signal reduction as well as for tracking and correction of EM log stability

(drift, as discussed above). This particular site overlies the saltwater-confining Cretaceous bedrock west of the region most strongly affected by mineral intrusion, and the alluvial aquifer has not shown any historic degradation of water quality. Averages and standard deviations were determined for both EM and gamma-ray data points over the same depth interval in the deepest monitoring well at site 50. The depth interval analyzed for the alluvial lithologic correction (50 to 185.6 ft below land surface) was the interval of overlapping gamma-ray and EM records (below fluctuations in the water table).

If amplitude peaks due to higher gamma-ray activity and cation-exchange capacity of clay minerals (saturated with water of a constant conductance) both result from the same clay content, there will be the cross-correlation between the gamma-ray and EM log types. The positive cross-correlation between the gamma-ray and EM signals in logs from site 50 was demonstrated and used by Buddemeier et al. (1993) to reduce the variable background lithologic signal from the EM logs. The cross-correlation indicates that values from the two types of logs can be statistically matched so that both have the same mean and standard deviation and therefore have comparable amplitude values. With the logs statistically matched, one log can be subtracted from the other and thus "corrected" for the amplitude variations caused by the clay minerals. In this report the corrected conductance at a given depth, C_m' , will be termed the "aquifer conductance." This corrected conductance is calculated by the equation

$$C_m' = (C_m - C_d) - C_g' + [C_g' / (C_m - C_d)] \quad 18 \quad (4)$$

where:

C_m = measured conductance at the specified depth in the sample log;

C_d = instrument drift correction (see above);

C_g' = gamma log conductivity correction, defined as:

$$C_g' = [(G_s - G_{ave}) / G_{std}] C_{std} + C_{ave} \quad (5)$$

where:

G_s = smoothed (35-sample moving average filter) sample gamma log value at the specified depth;

G_{ave} = average smoothed gamma count over the standard interval of the April 1993 site 50 log;

G_{std} = standard deviation of G_{ave} ;

C_{ave} = average measured conductivity over the standard interval of the April 1993 site 50 log;

C_{std} = standard deviation of C_{ave} .

The value C_g' in equations 4 and 5 represents the gamma-ray log value matched to the amplitude of the corresponding EM conductivity log on the basis of the log statistics from site 50. Matching of log statistics is accomplished in equation 5 through standardization (subtraction of the average standard value and division by the standard deviation of the gamma-ray log resulting in a zero mean and standard deviation of one) and normalization (multiplication and addition of the EM log standard deviation and average, respectively).

The subtraction of C_g' from the measured formation conductance C_m should result in a log having a zero mean over the depth range where the pore water conductance is the same as the fresh water of site 50. To restore a representative positive baseline level characteristic of clean sand saturated with fresh water to the corrected aquifer conductance value, the ratio of the gamma-ray conductance C_g' and measured formation conductance C_m is multiplied by the baseline level (18) and added back to the subtracted value. This baseline level was determined from the regions of minimum gamma-ray and EM activity on the site 50 logs. Thus, the correction (equation 4) reduces the confounding lithologic contributions to the formation conductivity particularly at the lower levels of water conductance while maintaining the baseline relationship between water conductance and aquifer conductance.

The 35-sample smoothing filter was adopted after trials with a range of filter values showed that this produced the best match of amplitude (and therefore also standard deviation) between the two types of logs.

This approach to lithologic correction differs from the method described by Buddemeier et al. (1993) in the use of subtraction (rather than division) to relate the conductivity-scaled gamma values to the direct conductivity measurements. Thus, all units are maintained in mS/m, and the method produces a quantitative result by keeping the processed log values as conductivity units (mS/m) rather than as a unitless index. Maintaining the corrected logs in the original units allows direct comparisons of the effectiveness of the applied corrections, and facilitates conversion of the corrected log into other units (such as chloride concentrations).

The effectiveness of the process is illustrated in figure 7B–C which shows an example of the alluvial lithologic correction. In this example log, a relatively large EM amplitude high, representing a clay lens centered at about the 1710 ft elevation level, is attenuated from an apparent conductivity of nearly 150 mS/m to about 60 mS/m by the lithologic and drift correction combined. Note that the drift corrections accounted for 23 mS/m of the change in this example log collected on September 18, 1993.

The lithologic correction described above applies only to the alluvial section of the log profiles, and typically represents no more than a 60–70 mS/m shift (decrease) from the raw EM values in clay-rich intervals. For a clean sand and gravel section, the lithologic correction results in no change between the raw and corrected value on average across the section. Abrupt changes in the EM logs due to hydrostratigraphic (porosity and permeability) discontinuities at the alluvium-bedrock contact are obvious from logs of wells that fully penetrate both the alluvial section and the bedrock contact. The amplitude changes in the EM logs from the Permian bedrock section are apparently caused primarily by the fact that these alternating layers of siltstones and sandy siltstones have porosities much lower than the overlying alluvium. The empirical relation between porosity and formation conductivity was presented in equation 3. In the Permian bedrock section, relationships between gamma activity and conductivity do not conform to the same patterns as in the alluvium (see log examples in Buddemeier et al., 1993). Because of the marked discontinuity in hydrostratigraphic characteristics between the alluvium

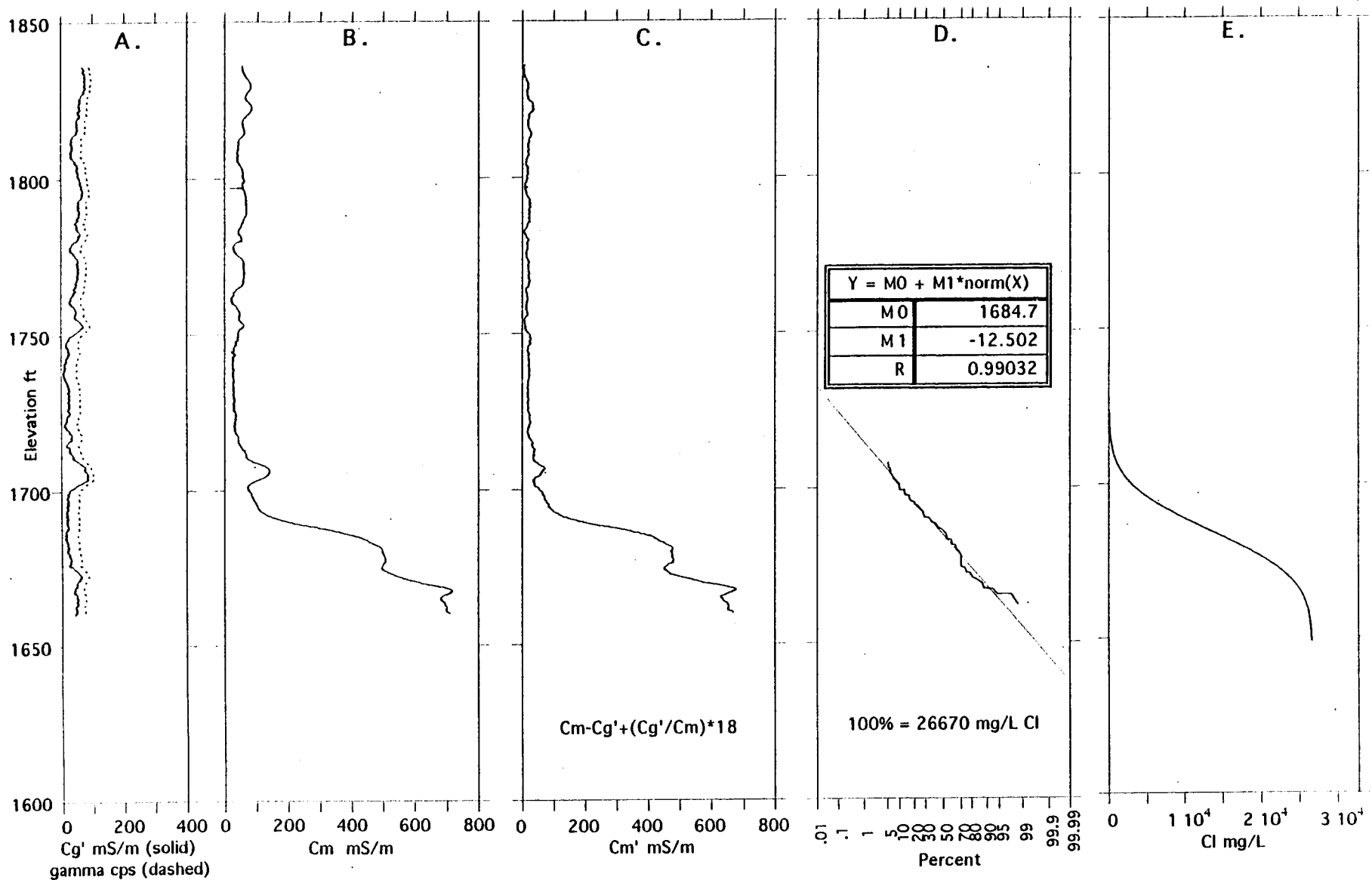


Figure 7. Gamma-ray and EM logs for Siefkes site bedrock well (MI-SS-P). (A.) Filtered raw and EM-log matched gamma-ray log (Cg'). (B.) Raw EM log. (C.) Corrected EM log. Parts D and E are discussed in section on work in progress. (D.) Transition zone of corrected EM log converted to chloride concentration, by correlation of Fig. 9, in terms of percent based on groundwater sample concentration (Whittemore, 1993) and plotted on normal probability axis. Inset shows equation of least-squares fitted line to transition zone. (E.) Least-squares line of part D converted to chloride concentration (mg/L) representing a cumulative normal distribution transition zone profile.

and the bedrock and since many sites lack log data from the bedrock section, only the corrected alluvial section is used for characterizing the transition zone in this report.

Pore water Conductivity Contributions (Aquifer Conductance vs. Water Conductance)

A significant goal was to define a relation between formation conductance (the conductivity of a specific volume of saturated formation as determined from EM logs) and water conductance (as determined from well-water samples) for the Great Bend Prairie aquifer. One such relation is illustrated in figure 8, which plots the aquifer conductance (C_m) from the corrected EM logs across the screened intervals of the monitoring wells versus well-water conductance (C_w) from Whittemore (1993). The water samples were collected and analyzed prior to 1987. However, since groundwater samples collected from four of the same monitoring sites in 1993 showed specific conductance changes no greater than $\pm 5\%$ from the earlier values, we have used the complete set of earlier values for the comparison. Figure 8 illustrates the excellent correlation between aquifer conductance and water conductance in the Great Bend Prairie aquifer.

The relationship calculated from the correlation in figure 8 shows that the slope is 0.092. Using this value for C_w/C_m and an m value ($m = 1.3$) representative of unconsolidated sands (Archie, 1942), and solving for n , equation 3 yields a porosity of 16%, a reasonable estimate of porosity. This is within the common range of effective porosity estimates (10–20%) for the aquifer (Bayne and Ward, 1969). The conductivity intercept, 9.1 mS/m, can be interpreted as the average residual formation conductivity not removed by the lithologic correction. In other words, the clean sand contribution to aquifer conductance is approximately half of the baseline combined clean sand plus freshwater conductance of 18 mS/m (C_m). This suggests that the correction is generally effective, but the uncertainty in its application to individual values is reflected in the scatter of the data points around the fitted line.

The 100 mS/m level of aquifer conductance (C_m) has been selected as the minimum conductivity that presently can be reliably and easily tracked over time and correlated in space

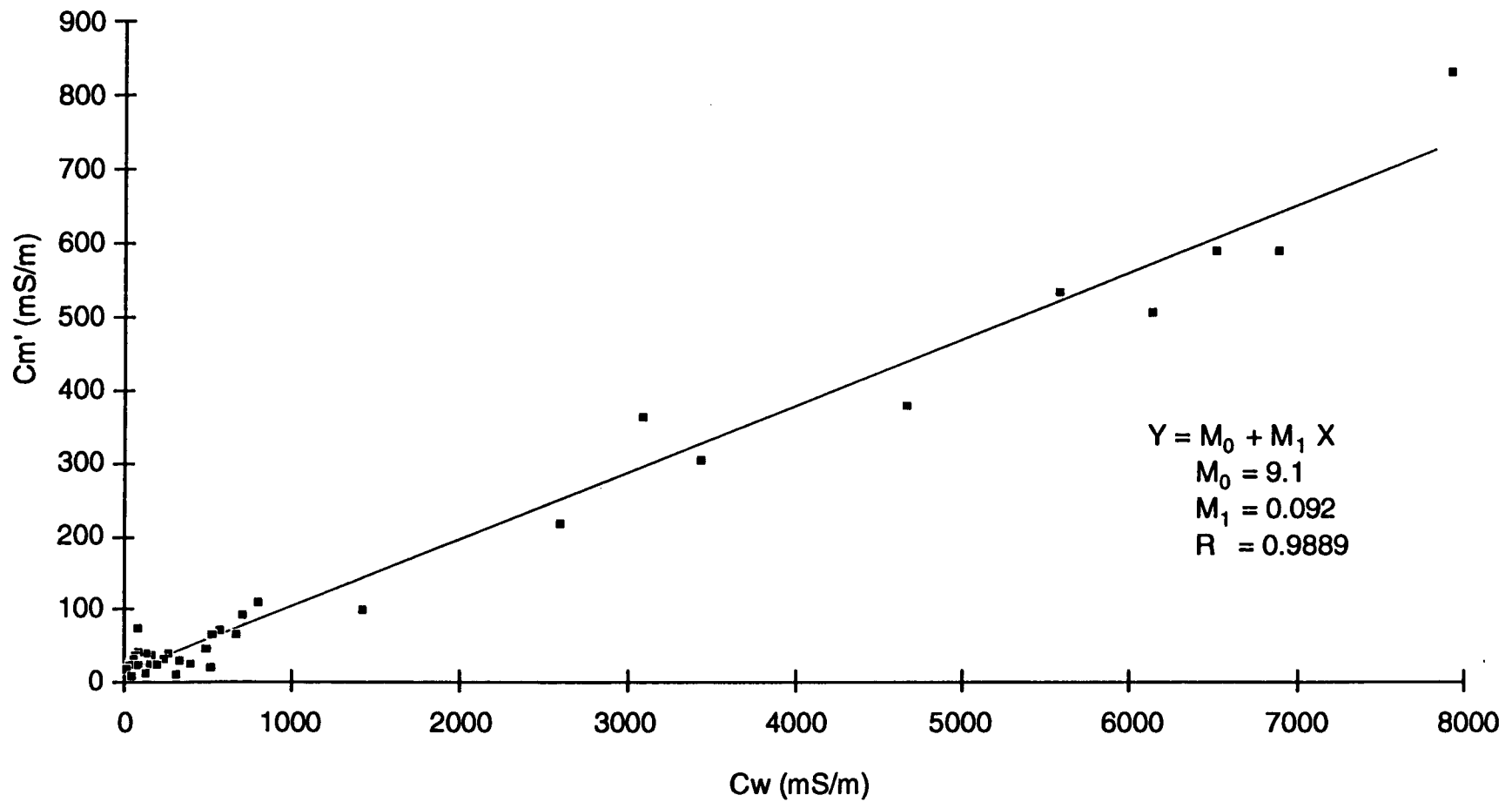


Figure 8. Aquifer conductance (Cm') vs. specific conductance of water samples (Cw) from screened intervals of observation wells in the Great Bend Prairie aquifer. Cw values are from Whittemore (1993).

(see discussion of accuracy and precision below). It is important to note that the 100 mS/m C_m' level used to characterize the transition zone in this report represents a porewater or groundwater conductivity (C_w) of roughly 1000 mS/m, a quality of water that is unusable for most agricultural purposes. Figure 5 shows a chloride equivalent of about 3300 mg/L; the recommended drinking water standard for chloride is 250 mg/L. We expect to develop improved characterization of lower sensitivities on the basis of work now in progress.

We ultimately wish to predict chloride concentration (or some other salinity indicator) from EM logs. Because of the correlations between 1) measured chloride concentration and specific conductance of water samples, and 2) aquifer conductance and specific conductance of water samples, we also examined the direct relation between aquifer conductance and chloride concentration from the same data set. We found an excellent linear correlation, which is illustrated in figure 9. As a result, we can now estimate chloride concentrations from lithologic-corrected EM logs. We can also use aquifer conductance as a proxy for salinity expressed as total dissolved solids because the ionic ratios of the Permian brine are reasonably constant for given salinities. This is useful not only for different types of measurements and standards, but also allows interpretation of the conductivity observations in terms of physical principles applicable to the distribution of chemical properties.

Measurement Precision and Accuracy

As noted above, the logging equipment records data at 0.1 ft intervals. It is normally possible to index the depth meter to the casing datum to within much less than 0.1 ft, thus the relative depth measurement uncertainty (between successive measurements in the same well) should be within ± 0.1 ft. Uncertainties in absolute depths or elevations, or in relative comparisons between wells, depend on the accuracy with which absolute or relative casing elevations are known, and must be evaluated according to site-specific conditions. Repeat measurements and logging runs at slower speeds were used to test reproducibility of readings and to improve statistical confidence in gamma counts. The accuracy of the EM tool is indicated by

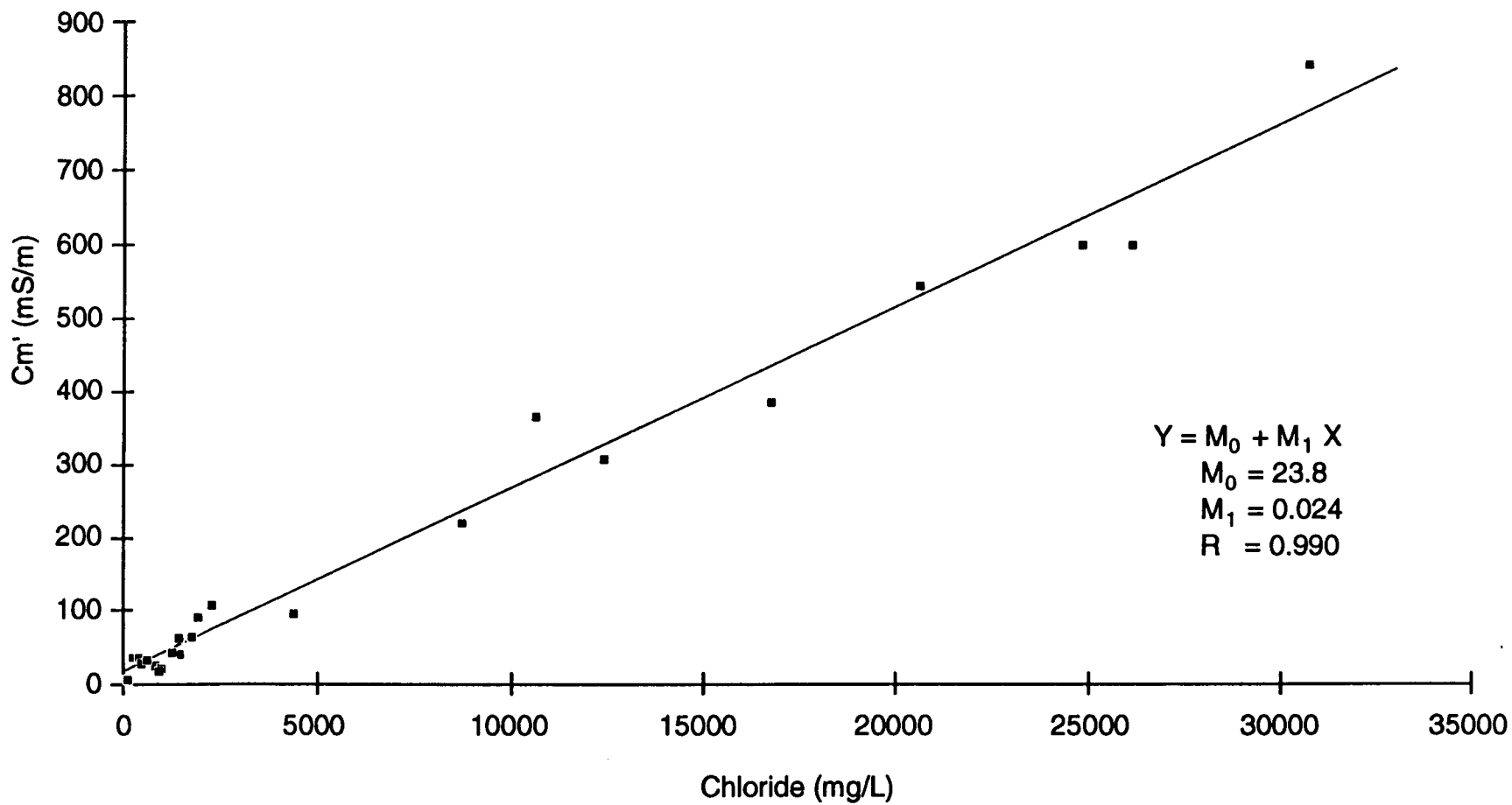


Figure 9. Aquifer conductance (Cm') vs. chloride concentration of water samples from screened intervals of observation wells in the Great Bend Prairie aquifer. Chloride values are from Whittemore (1993).

the manufacturer to be in the range of ± 10 mS/m; short-term precision, as determined by reproducibility of repeated log runs, is at least that good. These values represent uncertainties in the basic measurement, but the corrections and assumptions involved in interpretation introduce further uncertainty even as they improve the overall utility of the results.

A primary source of additional uncertainty is the lithologic correction. Although it is useful and reasonably accurate on average (see discussion of fig. 8), the accuracy of its application in any specific situation is affected by a number of sources of natural variability. These include variations in the gamma activity, specific conductivity, and porosity of various minerals and strata, and on the statistical nature of radioactivity (gamma ray) measurements.

Variations in the gamma ray-EM log cross correlation can be caused by the presence of volcanic ash, the chemical and electrical characteristics of different clay minerals and the nature of their interactions with salt water, differences in bulk formation conductivity due to porosity and tortuosity changes, and the inherent uncertainty in gamma-ray measurements. Volcanic ash, with generally higher concentrations of uranium and thorium, will give a higher gamma-ray response as compared to the typical background alluvium radiation represented by site 50. Ash deposits from Pleistocene eruptions in Wyoming, California, and New Mexico have been identified in the Great Bend Prairie region. However, they are apparently not very extensive, indicating significant reworking by the stream and aeolian processes that deposited the alluvium (Ward et al., 1993). Thus, any perturbations of the lithologic correction due to volcanic ash should be minor and local.

The interaction between the matrix and the ground water determines the strength of the combined conductivity signal. Therefore the relative conductance contribution, as compared to the groundwater contribution, can vary depending on the groundwater salinity. The lithologic correction described above compensates for the signal contribution of a clay lens saturated with fresh water, since it is based on the cross correlation at site 50, a freshwater location. This approach is taken because at higher salinities the EM signal derived from the porewater can

overwhelm the lithologic component, and a correction is most important in the lower range of observed groundwater salinities.

The measured conductivity depends on both the intrinsic electrical characteristics of the formation minerals, and their amounts and physical arrangements (shape, orientation, and porosity). Different clay minerals possess varying cation-exchange capacities: less than 40 meq/100 g for kaolinites, illites, and chlorites; greater than 80 meq/100 g for vermiculites and montmorillonites (Domenico and Schwartz, 1990). Since we have no quantitative information on the clay mineralogy or on the composition of various admixtures of aquifer constituents, we can only develop an empirical relationship between the EM and gamma-ray log responses based on statistics to derive the correction.

Just as variation in mineral type may alter formation electrical properties (and radioactivity, as discussed above), variations in porosity introduce uncertainty into the application of average correction values to individual points because of the relationship between porosity and measured conductivity (see equation 3). Porosity variations up to 50% are possible within a class of deposits (sands, clays, etc.) and porosities of clays may differ from sands by factors of two to three, but large differences between classes of materials can be treated by the empirical relationships developed by Archie (1942) and described by Doveton (1986).

The statistics of gamma-ray counting also contribute to the uncertainty of the lithologic correction due to the random nature of gamma decay. The count rates observed under normal logging procedures (0.1 ft measurement interval, 30 ft/min logging speed) may have standard deviations ranging from 25 to 50% based on the statistics of radioactive decay. Some of this is compensated for in the filtering (smoothing) process, but like the mineralogical and porosity variations discussed above, the resulting uncertainty in the correction is a few tens of percent. Unlike the other uncertainties, that due to gamma counting statistics can be reduced by collecting more data in the form of repeated logs or slower logging rates. This has not been done for the results reported here because it is a relatively minor factor and only one component of the overall

uncertainty, but it could be useful in specific cases where the highest possible resolution of the upper limit of the transition zone is important.

The variable background lithologic correction can be considered quantitative over an interval of approximately 5 feet (typical screened interval of monitoring wells) because of the highly significant relationship between the median corrected value of C_m' and the groundwater sample chloride concentration (fig. 9). In view of the various sources of uncertainty discussed above, the uncertainty in the value of an individual point on the corrected log will be on the order of 25–50% of the difference between corrected and uncorrected value at low conductivities (<100 mS/m). This level of uncertainty translates to an approximate value of up to 35 mS/m for the typical maximum correction of 60–70 mS/m stated earlier. An approach to dealing with the point-to-point variability on the corrected EM logs by profile curve fitting procedures is discussed in the work-in-progress section following.

Considering all factors influencing the detection and measurement of the transition zone characteristics discussed in this report, our present estimate of the overall uncertainty in the depth of specific porewater conductivity levels based on processed (corrected) logs is from ± 0.5 to ± 1.0 ft. This range in uncertainty is related to the relative salinity change of the transition zone, such that the stronger the conductivity contrast, the more accurate the depth determination. Part of the uncertainty range (0.1–0.2 ft) comes from the inherent precision of the logging method, but a larger proportion is due to uncertainties in the lithologic correction. As discussed above, the short-term precision of differences or measurements within a single well is better than the estimated total uncertainty, while uncertainties in between-well comparisons are dominated by uncertainties in absolute ground or casing elevations at the individual sites, and may be considerably greater. The selection of $C_m' = 100$ mS/m (discussed above) as an interim index of the transition zone elevation reflects these considerations. This value is high enough to be relatively unaffected by point-to-point correction uncertainties, and can be readily identified within the depth uncertainty range of 0.5–1.0 ft.

Work in Progress: Conductivity Profile Characterization

The corrected conductivity profiles from different sites are individually reproducible, have a generally similar form, and reflect primarily the salinity of the ground water. However, the natural variability of the geohydrologic environment is reflected in the detailed variations in individual log profile structures—variations which complicate decisions about how to compare profiles in a consistent and generalizable fashion. One approach to developing the needed comparisons is to fit the field data to a mathematical model that is physically reasonable and provides a "cleaned up" version of the natural phenomenon for ease of calculation, manipulation, and comparison. The basic approach to the work in progress is presented below.

We have approached the problem of standardized comparisons by adopting a paradigm which is known to accurately represent physical phenomena such as dispersion of a solute within a porous medium (Domenico and Schwartz, 1990) and for which an equation can be fit to the depth profile of corrected conductivity with a good correlation. The paradigm selected is the normal distribution; in effect, we approximate the vertical conductivity profile within the transition zone as the cumulative distribution function of the Gaussian "bell-shaped curve." The normal cumulative distribution profile represents the characteristic probability distribution of a sampled variable that exhibits a symmetric frequency distribution about its mean value. Cumulative normal distributions have been used successfully to characterize the freshwater-saltwater transition zone profile in an unconsolidated coastal aquifer (Schmorak and Mercado, 1969). In this earlier study, significant deviations from the normal distribution profile were found to be directly related to nonsteady-state conditions caused by pumping above the transition zone that resulted in the upward movement of the interface as defined by the 50% concentration level in the transition zone.

Since the equations fitted to the various profiles produce idealized curves of exactly the same form, the fitted profiles can be rigorously compared in a quantitative fashion. An additional advantage is that the equation provides a consistent picture of that part of the curve

that is of greatest interest but most subject to uncertainty and distortion—the upper limit of the transition zone where deteriorating water quality begins to affect possible uses.

The simplest approach to fitting the corrected EM logs to normal distributions is to convert the conductivities into chloride concentrations using the linear relationship demonstrated earlier, and to rescale the concentrations into percentages of the maximum chloride. For the example illustrated here we have used the chloride concentration of the water sample from Siefkes Permian well (reported by Buddemeier et al., 1993) as the maximum concentration upon which percentages are based. The rescaled transition zone profile, when plotted on elevation-probability axes (fig. 7D), can then be fitted with a least-squares line. The equation for the fitted line is shown in the inset table of fig. 7D. The term M_0 in the figure inset is the elevation of the 50% level, the slope (in normal probability space) is given by M_1 , and the correlation coefficient, R , indicates the goodness-of-fit. A straight line in normal probability space represents the cumulative distribution function of a normal distribution. Using the line equation, a normally-distributed cumulative transition zone profile can be generated back into chloride concentration (fig. 7E). The slope of the fitted line (M_1) now represents the rate of change, still in percentage, at the 50% level (inflection point) on the normal distribution curve. Because the equation of the curve is fixed, the curve-fitting process can also be adapted to the characterization of the complete transition zone by extension of the fitted line for wells having logs that only partially penetrate the transition zone.

The slopes, elevations, and correlation coefficients generated by the curve-fitting process represent parameters that characterize the transition zone, along with the actual conductivity values at selected points in the curve. Systematic changes in these parameters represent detectable changes in the freshwater-saltwater transition zone profile. The curve-fitting process allows the elevation of points near the upper and lower extremes of the transition zone to be estimated in order to determine the apparent thickness of the transition zone in spite of the high-frequency amplitude fluctuations that persist on the corrected EM logs. We are developing an approach that uses the elevation of the curve-fitted 10% and 90% levels, rounded-off to the

nearest 0.1 ft, to delimit the thickness of the transition zone. The 50% level will be used as an indicator of the interface elevation, as it is easily determined mathematically and can also be estimated with reasonable accuracy from the raw conductivity logs in most cases. As discussed above, the 100 mS/m value is used as a direct, independent estimate of the transition zone location.

We emphasize that the use of standardized, fitted conductivity curves is an empirical approach that supports research purposes and comparisons over time and space. The standardized salinity curves can also be used for salt-budget calculations. However, this approach is not essential to a basic description and understanding of saltwater distribution, and it can not replace interpretation of actual log measurements and chemical analyses in cases of site-specific management and assessment, where the details of the local context will be important. A full report on the development and applications of the curve-fitting analysis will be issued later.

III. Results of Surveys

A. Experimental Design

The original study design called for:

1. Annual measurement of at least the deepest well at all monitoring sites, if possible before the beginning of the irrigation season.
2. Periodic remeasurement of those wells with well-developed transition zones within the alluvial deposits of the Great Bend Prairie aquifer, and/or those believed likely to undergo change.
3. Frequent measurement (weekly to bi-weekly) throughout the irrigation season of a network of wells near an irrigation well with a history of deteriorating water quality (the Siefkes intensive study site).
4. Additional measurements (either as part of the study or by collaborating agencies) as time and resources permit in order to further develop methods, to improve time resolution, and to investigate short-range variability by comparing multiple wells at the same site.

The study design was substantially achieved, although some modifications were required—or made possible—by the unusually high rainfall that occurred through mid-1993. One or more wells at each of the 51 sites in the KGS/GMD5 monitoring-well network (fig. 3) and all accessible wells in the vicinity of the intensive study site were logged for natural gamma activity and formation conductivity as determined by electromagnetic (EM) induction (see Section II and previous reports for details of methods). Most sites were logged prior to the onset of irrigation pumping, although site accessibility and well obstructions caused a delay in a few cases.

To monitor possible changes in the transition zone with time, a number of wells were relogged. Permian wells at sites 11, 16, 17, 18, 22, and 25 were logged approximately monthly, as were the newly installed Permian and deep aquifer monitoring wells at the Siefkes Intensive Study Area (see Buddemeier et al., 1993 and discussion below) and site 50, which served as a field standard (see Section II). These wells are located in the northern part of the study area (the transect area), where salt water is known to underlie fresh water in the alluvial aquifer, and conductivity logs from most of these wells exhibit distinct transition zones. At all sites, water levels were measured prior to logging and intermittently as opportunities arose. At the Siefkes site water levels in the monitoring wells and in a number of oil-field supply and other wells were monitored frequently.

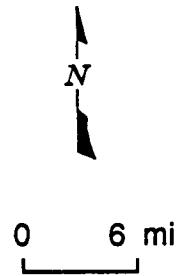
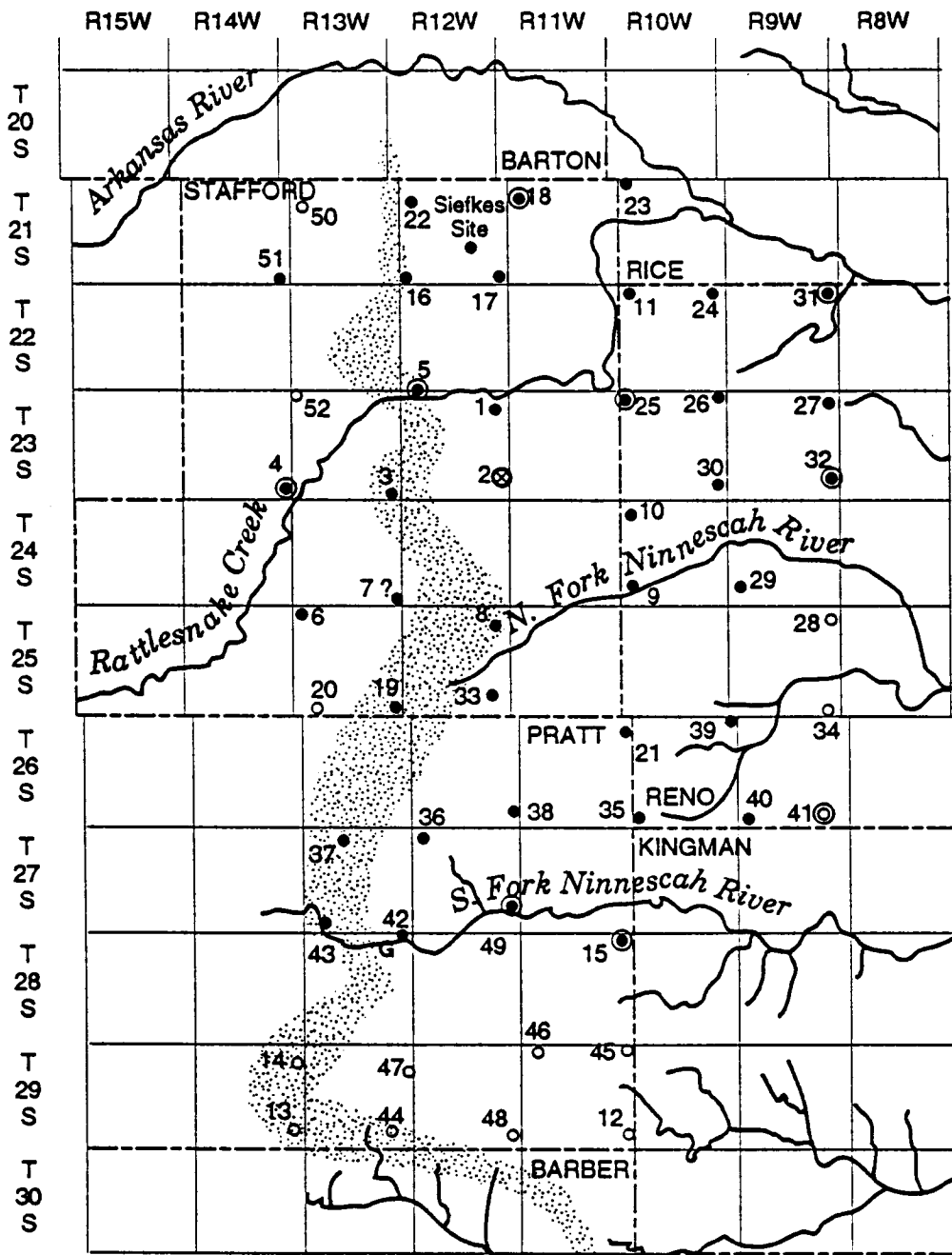
Because of high rains and recharge, irrigation was late and much smaller in total volume pumped than in a normal year, but regional and local recharge was unusually high. The original design was therefore modified so that the repeat measurements were taken somewhat more frequently than had been envisioned for the wells in category 2 above, but less frequently than had been planned to track the effects of a normal irrigation season. This adjustment was considered appropriate to get the maximum information from the unusual opportunity to observe the effects of abnormally high recharge.

B. Transition Zone Elevation and Characteristics

By processing and analyzing data from the logs and other available information (especially Whittemore, 1993), it was possible to identify and characterize the sites that exhibit elevated salinity (a chloride concentration greater than 250 mg/L) and/or a freshwater-saltwater interface or transition zone above the bedrock. We refer to such sites as saline transition zone sites; they are identified in figure 10. At sites 4, 6, 7, 50, 51, and 52, the alluvial aquifer presumably is separated from Permian strata by Cretaceous bedrock (Fader and Stullken, 1978), which can act to confine saltwater below the Great Bend Prairie aquifer. However, chloride concentrations greater than 250 mg/L have been observed in the alluvial aquifer at sites 4, 6, and 51 (Whittemore, 1993). Although it is not certain that salt water occurs above bedrock at site 7 (it was not possible to log to bedrock), site 7 was included as a saline transition zone site because of very saline water in the bedrock well. Figures showing the corrected EM logs and water-quality data from earlier measurements are contained in Appendix A.

Baseline data for each of the saline transition zone sites are listed in tables 1A and 1B. These data include land surface elevations, elevations of and depths to water and bedrock, and the C_w and chloride values of water samples from the Permian wells. Table 1A presents data for those sites at which the 100 mS/m C_m' level can be estimated from lithologic-corrected EM logs from the first logging date. The 100 mS/m C_m' level refers to an aquifer conductance equivalent to a chloride concentration of roughly 3300 mg/L (figs. 8 and 9). Baseline data for the new wells at the Siefkes site were taken from the September 1993 logs because these wells showed evidence of continued recovery following installation in April 1993. The wells were drilled with low-conductance drilling fluids, and although they were developed after installation, the steady rise in conductivity during the 5 months following installation indicates that the ambient ground water was gradually flushing away residual drilling fluid.

Sites listed in table 1B are known to be salty (e.g., Whittemore 1993) and/or have evident transition zones, but the elevation of the 100 mS/m level (above bedrock) could not be estimated from lithologic-corrected EM logs from these sites. At some of the sites, the water salinity (or



- Monitoring well sites
- ⊗ Plugged well site
- ⊙ Sites where the average Permian head is above the average deep aquifer head
- Saline/transition zone sites
- ⊙ Saline/transition zone sites where the average Permian head is above the average deep aquifer head
- ▨ approximate subcrop area Cedar Hills Sandstone

Figure 10. Monitoring well sites and site numbers, indicating the saline transition zone sites and sites where the average Permian head is above the average deep aquifer head.

Table 1A. Baseline data for saline transition zone sites at which the 100 mS/m Cm' level could be determined.

Site	Location	Land Elev	Date	DTW	Depth to 100 mS/m Cm'	Depth to BR	WL elev	100 mS/m Cm' elev	BR elev	Cond. (mS/m)	Cl (mg/l)
1	23-12-12BAA	1827	3/26/93	5.3	111.7	146	1821.7	1715.3	1681	3690	13200
5	23-12-06BBB	1855	9/17/93	1.8	79.6	181	1853.2	1775.3	1674	8550	41200
9	24-10-31CBC	1755	4/25/93	9.0	76.5	87	1746.0	1678.4	1668	1070	3280
11	22-10-06CBB	1763	3/27/93	13.5	146.4	208	1749.5	1616.7	1555	6690	25000
16	21-12-31CCC	1872	3/25/93	12.0	146.7	220	1860.0	1725.2	1652	8850	34800
17	21-12-36DDC	1804	3/25/93	11.6	84.0	114	1792.4	1719.9	1690	2890	9880
18	21-11-07BBB	1810	3/25/93	19.0	143.9	214	1791.0	1666.0	1596	3520	12200
21	26-11-01DDD	1801	5/20/93	21.6	112.4	137	1779.4	1688.0	1664	3510	11700
22	21-12-06CCB	1855	3/25/93	16.1	175.7	215	1838.9	1679.4	1640	8260	32500
25	23-10-06BBA	1780	3/28/93	6.3	25.0	98	1773.7	1754.8	1682	4100	17400
26	23-10-01AAA	1738	4/20/93	6.8	80.7	177	1731.2	1657.1	1561	3710	13470
36	27-12-06BAA	1892	4/21/93	28.0	164.0	195	1864.0	1727.8	1697	5680	21800
42	28-13-01CBA	1829	4/22/93	13.1	139.9	160	1815.9	1689.1	1669	1550	4900
SP	21-12-27DACC	1840	9/18/93	9.0	147.2	186	1831.0	1692.7	1654	7080	26670
SDA	21-12-27DADD	1840	9/18/93		145.7			1694.3		3840	13940

DTW- Depth to water (feet below land surface) in shallow wells. Some values estimated.

COND- Specific conductance of water from Permian wells and Siefkes deep aquifer well.

Cl- Chloride concentration of water from Permian wells and Siefkes deep aquifer well.

Water levels in all wells are listed in Appendix B.

Table 1B. Baseline data for saline transition zone sites at which the 100 mS/m Cm' level could not be determined.

Site	Location	Land elev	Date	DTW	Depth to 100 mS/m Cm'	Depth to BR	WL elev	100 mS/m Cm' elev	BR elev	Cond. (mS/m)	Cl (mg/L)
3	23-13-36DCC	1898	5/19/93	22.0	-	130	1876.0	-	1768	ND	ND
4	23-14-36DDC	1912	4/22/93	8.7	-	129	1903.3	-	1783	7760	31000
6	25-13-06BCB	1950	4/19/93	19.3	-	148	1930.7	-	1802	10200	42640
7	24-13-36DDD	1906	4/18/93	21.0	-	150	1885.0	-	1756	7590	34200
8	25-12-11AAA	1848	4/21/93	8.8	-	117	1839.2	-	1731	10600	43800
10	24-10-06DCC	1790	4/25/93	18.3	-	156	1771.7	-	1634	623	1710
15	28-11-01AAA	1725	4/22/93	29.7	-	128	1695.3	-	1597	213	466
19	25-13-36DCC	1901	4/19/93	11.7	-	163	1889.3	-	1738	99	192
23	21-10-06AAD	1743	4/20/93	22.4	-	94	1720.6	-	1649	2130	6480
24	22-10-01ADB	1743	4/20/93	27.3	-	123	1715.7	-	1620	631	1820
27	23-09-01ADA	1685	4/20/93	9.9	-	104	1675.1	-	1581	651	1841
29	24-10-36AAA	1732	4/25/93	38.6	-	151	1693.4	-	1581	6000	22000
30	23-10-36DAA	1750	4/25/93	13.1	-	138	1736.9	-	1612	652	2410
31	22-09-01ADA	1664	4/20/93	13.4	-	93	1650.6	-	1571	652	1771
32	23-09-25DDD	1689	4/24/93	2.5	-	172	1686.5	-	1517	715	1864
33	25-12-36CBB	1872	5/20/93	33.9	-	141	1838.1	-	1731	425	1160
35	26-10-31CCC	1760	4/21/93	19.0	-	153	1741.0	-	1607	2140	6750
37	27-13-05CAB	1971	4/21/93	58.7	-	240	1912.3	-	1731	770	2310
38	26-12-36ADD	1844	4/21/93	26.0	-	189	1818.0	-	1655	691	1908
39	26-10-01AAA	1679	10/22/93	3.2	-	55	1675.8	-	1624	3630	12300
40	26-09-31DCC	1735	4/22/93	56.2	-	158	1678.8	-	1577	272	663
43	27-13-31DDD	1872	4/22/93	5.0	-	65	1867.0	-	1807	750	2198
49	27-12-35AAA	1737	7/7/93	-1.3	-	105	1738.3	-	1632	8480	32700
51	21-14-36DDD	1916	3/26/93	17.3	-	200	1898.7	-	1716	ND	ND

DTW- Depth to water (feet below land surface) in shallow wells. Some values estimated.

COND- Specific conductance of water from Permian wells.

Cl- Chloride concentration of water from Permian wells.

Water levels in all wells are listed in Appendix B.

conductivity) simply never reached that equivalent level (~ 1000 mS/m C_w); at some it was not possible to log to bedrock because of obstructions; and logs from a few sites were faulty or questionable. Wells with obstructions are being investigated and will be repaired if possible.

Since the total saturated thickness of the alluvial aquifer (difference in elevation between bedrock and water table) is known at each site, it is possible to calculate the proportion of saturated thickness above and below the 100 mS/m C_m' elevation for each of the sites listed in table 1A. For all practical purposes, ground water below this elevation can be considered unusable. It is important to realize that water above the 100 mS/m C_m' elevation ranges from fresh and usable to salty and virtually unusable. This separation is much more realistic than assuming the freshwater saturated thickness extends to bedrock; however, it is still a significant overestimate of the freshwater resources available.

The saturated thickness values and the percent of water below the 100 mS/m C_m' elevation are tabulated in table 2. The percent of the total alluvial-aquifer saturated thickness that is below the 100 mS/m C_m' elevation ranges from 0 to 81 percent at these sites. The spatial pattern of this unusable saltwater saturated thickness in the alluvial aquifer is shown in figure 11. It seems clear that saltwater intrusion is a regional phenomenon in the vicinity of the study transect in northern Stafford County, and we have contoured the percent of saturated thickness occupied by high-salinity water in that area. We have used 20% of total saturation occupied by salt water as the cutoff for contouring; elsewhere, the salt-affected sites are indicated by symbols and individual percentages. Based on a larger set of chemical data with less precise interface elevation control, Whittemore (1993) contoured the area in northeastern Pratt Co. and along the Stafford-Reno county line as a region of consistent deep aquifer salinity. The logging data presently available seem to support that interpretation, but do not provide enough data to demonstrate regional connections, or to make a regional estimate of transition zone elevation or saltwater saturated thickness.

Research is in progress on estimating a lower conductivity (or salinity) level from the EM logs, closer to the range of generally usable water. This would be a salinity some ten times less

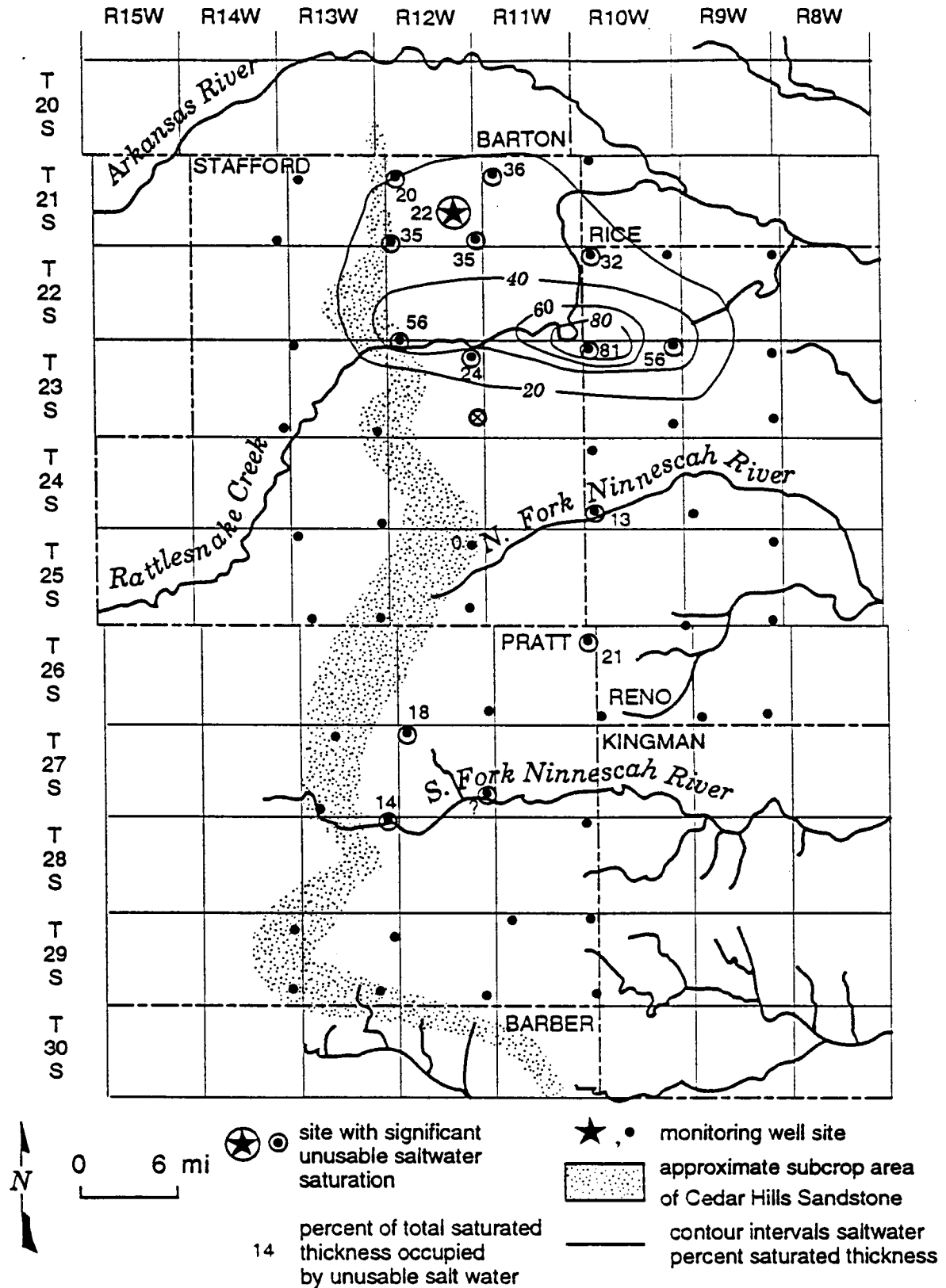


Figure 11. Percent of saturated thickness occupied by unusable salt water in the Great Bend Prairie aquifer.

Table 2. Saturated thicknesses above and below the 100 mS/m Cm' elevation.

Site	Sat. thick above	Sat. thick. below	Total sat. thick.	Percent below
1	106.4	34.3	140.7	24
5	77.9	101.3	179.2	56
9	67.6	10.4	78.0	13
11	132.8	61.7	194.5	32
16	134.8	72.2	207.0	35
17	72.5	38.9	111.4	35
18	125.0	70.0	195.0	36
21	91.4	24.0	115.4	21
22	159.5	39.4	198.9	20
25	18.9	81.8	100.7	81
26	74.1	96.1	170.2	56
36	136.2	30.8	167.0	18
42	126.8	20.1	146.9	14
SP	138.3	38.7	177.0	22

than the present characterization level (refer to fig. 5 for key water-quality thresholds). This will enable us to construct a more detailed estimate of actual freshwater and saltwater saturated thicknesses in the Great Bend Prairie aquifer.

C. Water Levels and Salinity

Historic Water Levels

A summary table of water levels from the KGS/GMD5 monitoring-well network is contained in Appendix B. This table lists all 1993 water-level measurements from the study wells and calculated hydraulic-head differences between the various wells at each site. Included for comparison are the averages and standard deviations of the heads and head differences for 1993 and for the period 1987 through 1993. The heads discussed are based on water level elevations only and are not corrected for the varying densities of water with different salt contents. This is discussed in more detail below.

At most of the monitoring well sites, Permian heads (or water levels) are lower than alluvial aquifer heads. At some sites (1, 6, 9, 10, 19, 20, 23, 28, 31, 40, 44, and 45) Permian heads are very close to (average within 0.5 ft) or occasionally above deep aquifer heads. And at

some sites (4, 5, 15, 18, 25, 31, 32, 41, and 49) the average Permian head is higher than the average deep aquifer head, a condition that favors upward migration of Permian waters. Permian heads are commonly higher than the water-table elevation at sites 4, 5, 9, 15, 31, 41, 44, and 49, and have been observed higher than land surface elevation at sites 4, 5, 41, and 49.

Figure 10 maps the distribution of sites where the Permian head is higher than the deep aquifer head for both saline transition zone and freshwater sites. A Permian head higher than the head near the base of the alluvial aquifer (head reversal) at a site implies a potential for upward flow of saltwater. Of the nine sites where the average bedrock head is above the deep aquifer head, eight of these (4, 5, 15, 18, 25, 31, 32 and 49) are saline transition zone sites. However, most saline transition zone sites exhibit a downward head gradient, and one of those with an upward gradient (site 41) is not a transition zone site.

Determining groundwater potentials and flow directions in the study area is complicated because of the variable densities of fresh and salt waters. Hydrologists have commonly tried to account for the effects of variable density by converting saltwater heads to equivalent freshwater heads. For example, two columns of water of the same height and referred to the same base elevation will exert pressures on the base level that are proportional to the density of the solutions. Permian brine may be up to 3–5% more dense than fresh water, which could mean several feet of difference in equivalent freshwater head over a saturated aquifer thickness of a hundred feet or more. If these corrections were made to the existing data, it would give an even greater indication of upward flow from the Permian in the study area. However, this technique (and other methods of determining flow directions in variable-density fluids) can lead to erroneous interpretation of groundwater flow (Jorgensen et al., 1982; Davies, 1987). Further, most of the methods apply only to wells in the same aquifer and/or make other assumptions that are not met in the study area. For these reasons, hydraulic heads are not adjusted for density in this report. Hydraulic heads (or water levels or fluid levels) listed and discussed in this report are the actual levels measured in wells. Density effects will be considered in more detail in future modeling studies.

1993 Water Levels

As a result of the unusually high precipitation, water levels rose in virtually every well in the monitoring well network during the first half of 1993, and most remained above January 1993 levels at the time of last observation (see Appendix B). Hydrographs illustrating 1993 water-level fluctuations in all wells at the saline transition zone sites are contained in Appendix C. The reader is cautioned that the lines connecting data points do not necessarily represent the behavior of the water levels, but are merely for convenience in showing trends.

Maximum observed head rises in the shallow aquifer and Permian monitoring wells are shown in figure 12. Water-level rises were greatest in the northern part of the study area. South of the North Fork of the Ninescah River and the Stafford/Pratt county line, water levels in shallow monitoring wells generally rose approximately four feet or less, and north of the county line they generally rose four feet or more. Many of the largest water-level rises were observed in the transect area. At site 18, for example, the head in the shallow well rose more than 14 feet and the Permian head rose about 8 feet from January to early August.

Observed Permian head rises were less than or approximately equal to water-table rises at most sites (figure 12). The Permian head remained above the deep aquifer head at sites 5 and 25. The Permian head at site 5, normally above the deep and shallow aquifer heads, has risen above land surface this year (1993). At sites 6 and 18, the deep aquifer head dropped below the Permian head in August, possibly due to nearby pumping (see well hydrographs in Appendix C).

A primary objective of the logging efforts in 1993, particularly at the Siefkes intensive study site (figure 13 and table 3), was to monitor the effects of (irrigation) pumping on the fresh water-saltwater interface or transition zone. Because of extraordinary amounts of precipitation (and subsequent recharge and ponding) in the spring and summer, pumping was minimal. However, enough irrigation occurred late in the season to provide some observations on responses to the start and stop of pumping. Fluid levels at the Siefkes site are presented in table 4 (which also indicates the dates on which irrigation was occurring) and illustrated in figures 14-16.

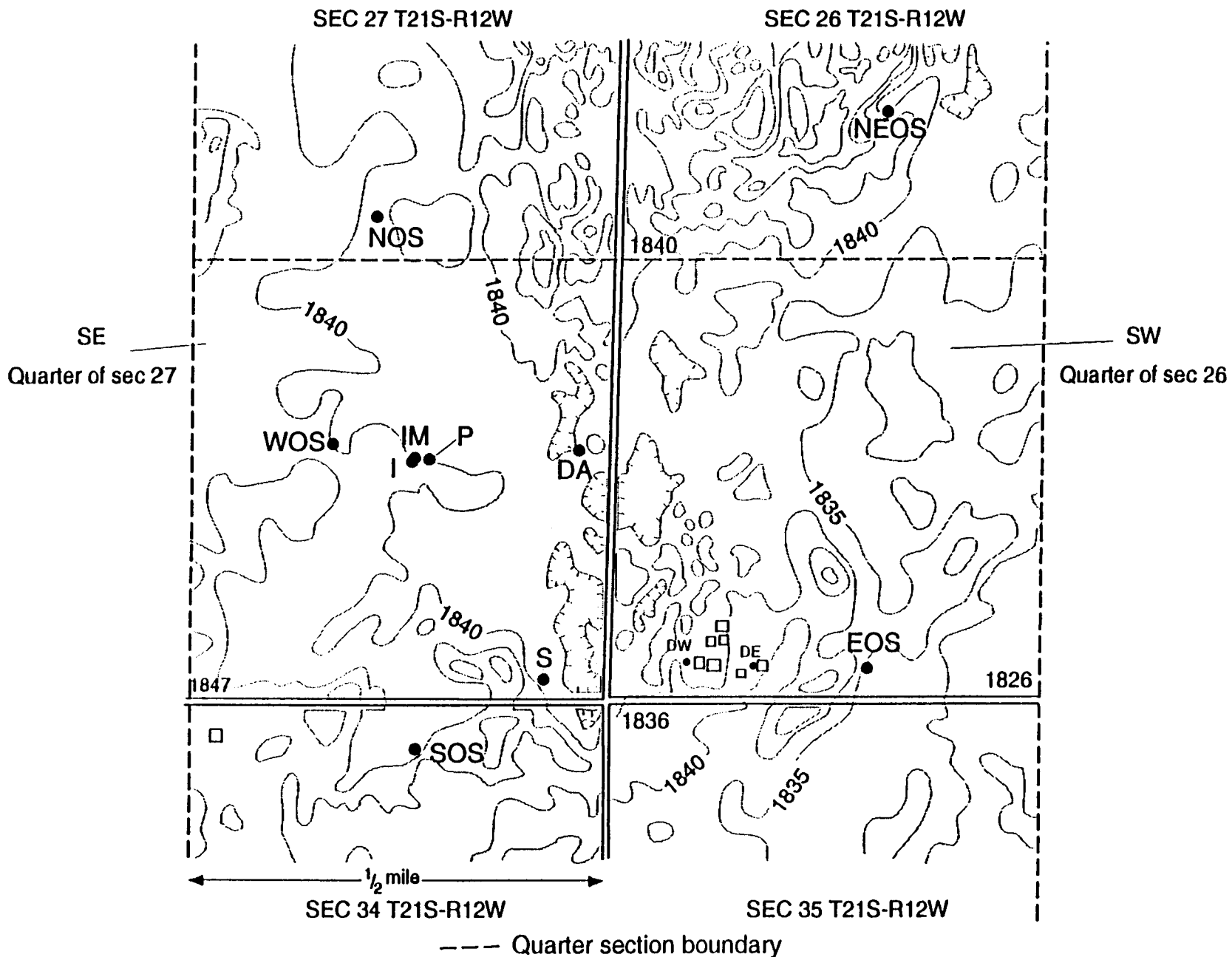


Figure 13. Wells in Siefkes intensive study area. See Table 3 for well identification and characteristics, and Table 4 for 1993 data. Contours indicate approximate elevation of land surface (feet above mean sea level).

Table 3: Information for wells in the Siefkes intensive study area.

Legal location	Well	Description	Top of screen (bls)	Depth (bls)	Land surface elev.	Elev. top of screen	Elev. bottom of well
21-12-27DACC	I	Irrigation well near center of SE Sec. 27 T21S-R12W	60	120	1840.7	1780.7	1720.7
21-12-27DBDC	WOS	Oil-field supply well west of irrigation well	65	85	1839.4	1774.4	1754.4
21-12-27DACC	IM	2" monitoring well near irrigation well	-	60	1840.7	-	1780.7
21-12-27ACDD	NOS	Oil-field supply well north of irrigation well	100	120	1839.0	1739.0	1719.0
21-12-27DDDC	S	Stock well southeast of irrigation well	80	90	1836.3	1756.3	1746.3
21-12-34AAB	SOS	Oil-field supply well south of irrigation well	80	100	1841.0	1761.0	1741.0
21-12-26CDCC	EOS	Oil-field supply well east of irrigation well	80	100	1832.9	1752.9	1732.9
21-12-27DACC	P	KGS Permian monitoring well	198	228	1839.6	1641.6	1611.6
21-12-27DADD	DA	KGS deep aquifer monitoring well	157	167	1839.8	1682.8	1672.8
21-12-26BDB	NEOS	Oil-field supply well north-east of irrigation well	90	105	1840*	1750*	1735*

*Elevations approximate, estimated from topographic map. All other elevations surveyed.

Table 4. 1993 Fluid level sin wells at the Siefkes site.

Depth to water (ft)								
Date	P	DA	IM	WOS	SOS	EOS	NOS	NEOS
3/24/93			15.2	14.2			16.8	
3/26/93						18.6		27.2
4/17/93	23	22.6						
5/20/93	22.2	20.9						
5/25/93	22	20.7	12.8	11.2	14.8	16	13.8	24.4
7/7/93	21.7	19.5	11.4	9.5	13.4	15	12.5	
7/8/93	20.9	18.8	10.8	8.9	12.7	14.4	11.8	22.6
7/27/93	19.1	18.5	10	8.1	11.5	13.5		23.3
7/29/93*	21.2	23	43.9	16.9	16.2	16.3		25.9
8/17/93*	21.1	21.6	45	17.1	15.8	16.5	15.6	26.9
8/23/93			13.4		15.4	16.4		25
8/24/93*	22.4	23.4	45.9	17.8	17.3	17.2		25.3
8/25/93	22.5	22.2	44.4	17.4	16.4	16.5		23.8
9/10/93	18.7	17.4	10.2	8.7	11.8	13.1		20.7
9/18/93	18.1	16.4	9	7	10.7	12.5		20
10/12/93*	18.4	19.6	42.2	13.9	13.1	14		21.8
10/13/93	19.1	17.5	10.4	8.2	11.9	13.5	10.7	21
10/14/93	18	17						
10/21/93	17.3	16.6	9.8	7.5	11.2	12.9	10	20.4

Fluid level elevations (ft above mean sea level)

Date	P	DA	IM	WOS	SOS	EOS	NOS
3/24/93			1825.5	1825.2			1822.2
3/26/93						1814.3	
4/17/93	1816.6	1817.2					
5/20/93	1817.4	1818.9					
5/25/93	1817.6	1819.1	1827.9	1828.2	1826.2	1816.9	1825.2
7/7/93	1817.9	1820.3	1829.3	1829.9	1827.6	1817.9	1826.5
7/8/93	1818.7	1821	1829.9	1830.5	1828.3	1818.5	1827.2
7/27/93	1820.5	1821.3	1830.7	1831.3	1829.5	1819.4	
7/29/93*	1818.4	1816.8	1796.8	1822.5	1824.8	1816.6	
8/17/93*	1818.5	1818.2	1795.7	1822.3	1825.2	1816.4	1823.4
8/23/93			1827.3		1825.6	1816.5	
8/24/93	1817.2	1816.4	1794.8	1821.6	1823.7	1815.7	
8/25/93	1817.1	1817.6	1796.3	1822	1824.6	1816.4	
9/10/93	1820.9	1822.4	1830.5	1830.7	1829.2	1819.8	
9/18/93	1821.5	1823.4	1831.7	1832.4	1830.3	1820.4	
10/12/93*	1821.2	1820.2	1798.5	1825.5	1827.9	1818.9	
10/13/93	1820.5	1822.3	1830.3	1831.2	1829.1	1819.4	1828.3
10/14/93	1821.6	1822.8					
10/21/93	1822.3	1823.2	1830.9	1831.9	1829.8	1820	1829

*indicates irrigation well pumping

Siefkes Wells

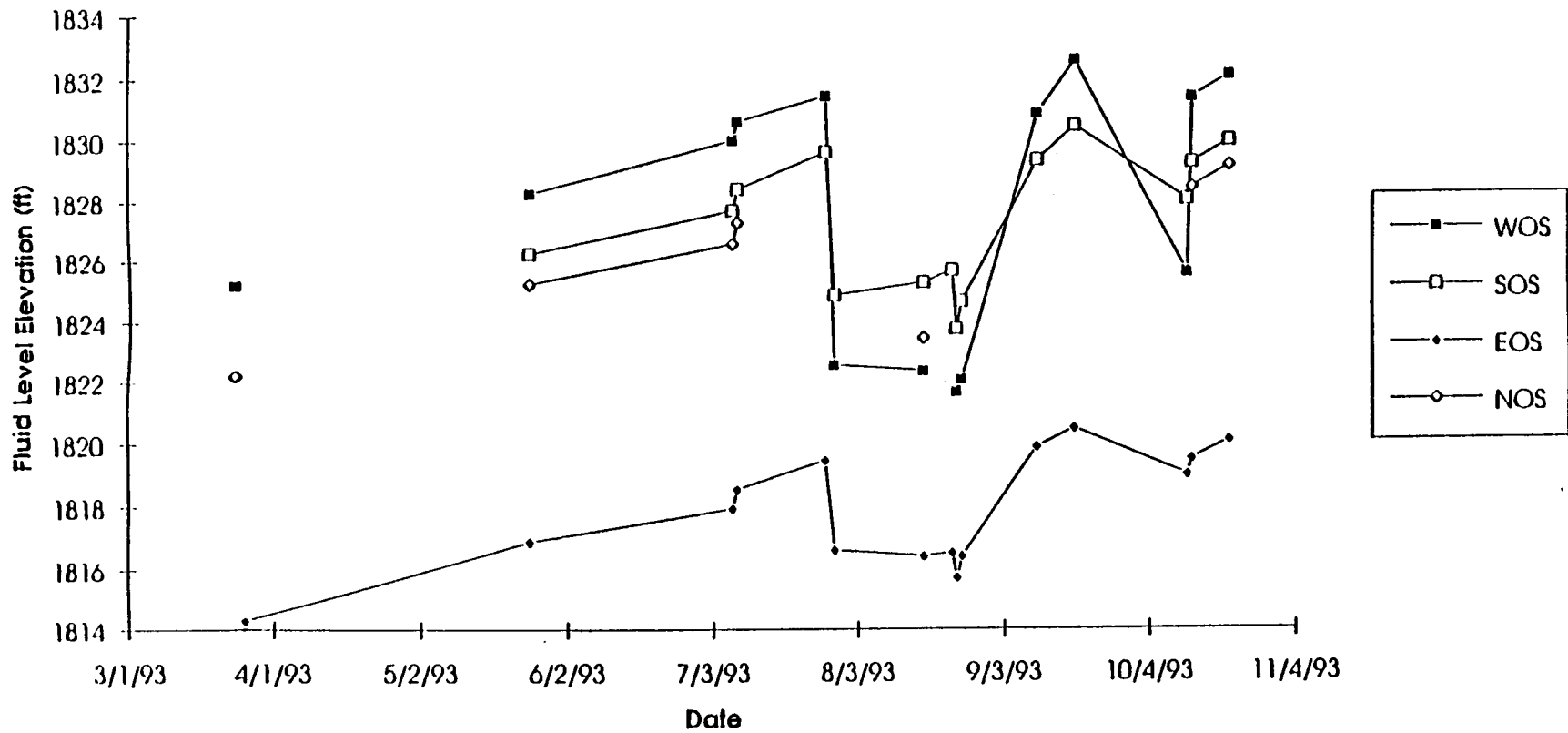


Figure 14. Hydrographs of shallow wells surrounding the Siefkes site. See Figure 13 and Tables 3 and 4 for locations, well characteristics, and data.

Siefkes Monitoring Wells

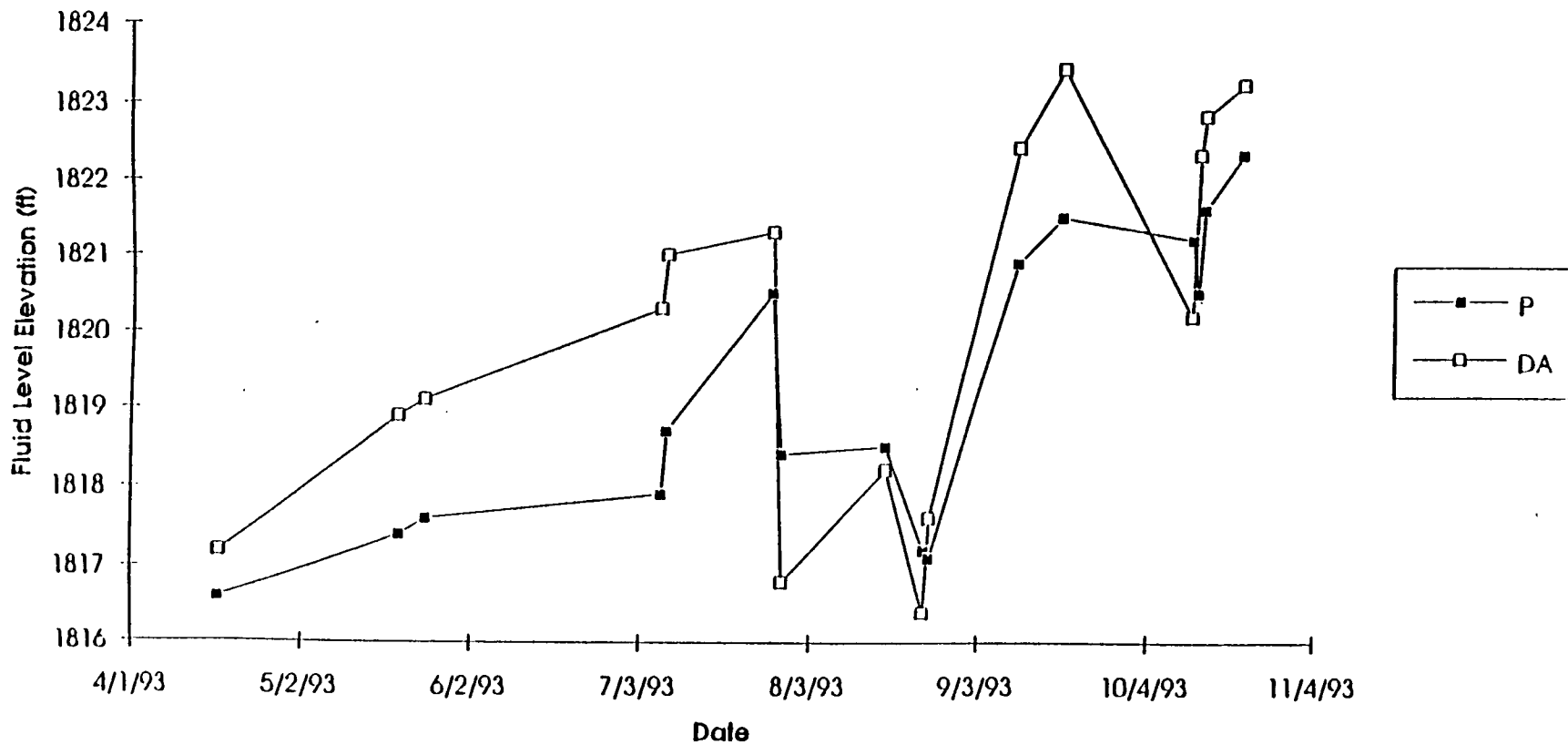


Figure 15. Hydrographs of the Permian (P) and Deep Aquifer (DA - base of Great Bend Prairie Aquifer) monitoring wells at the Siefkes site. See Figure 13 and Tables 3 and 4 for locations, well characteristics, and data.

Siefkes Monitoring Wells

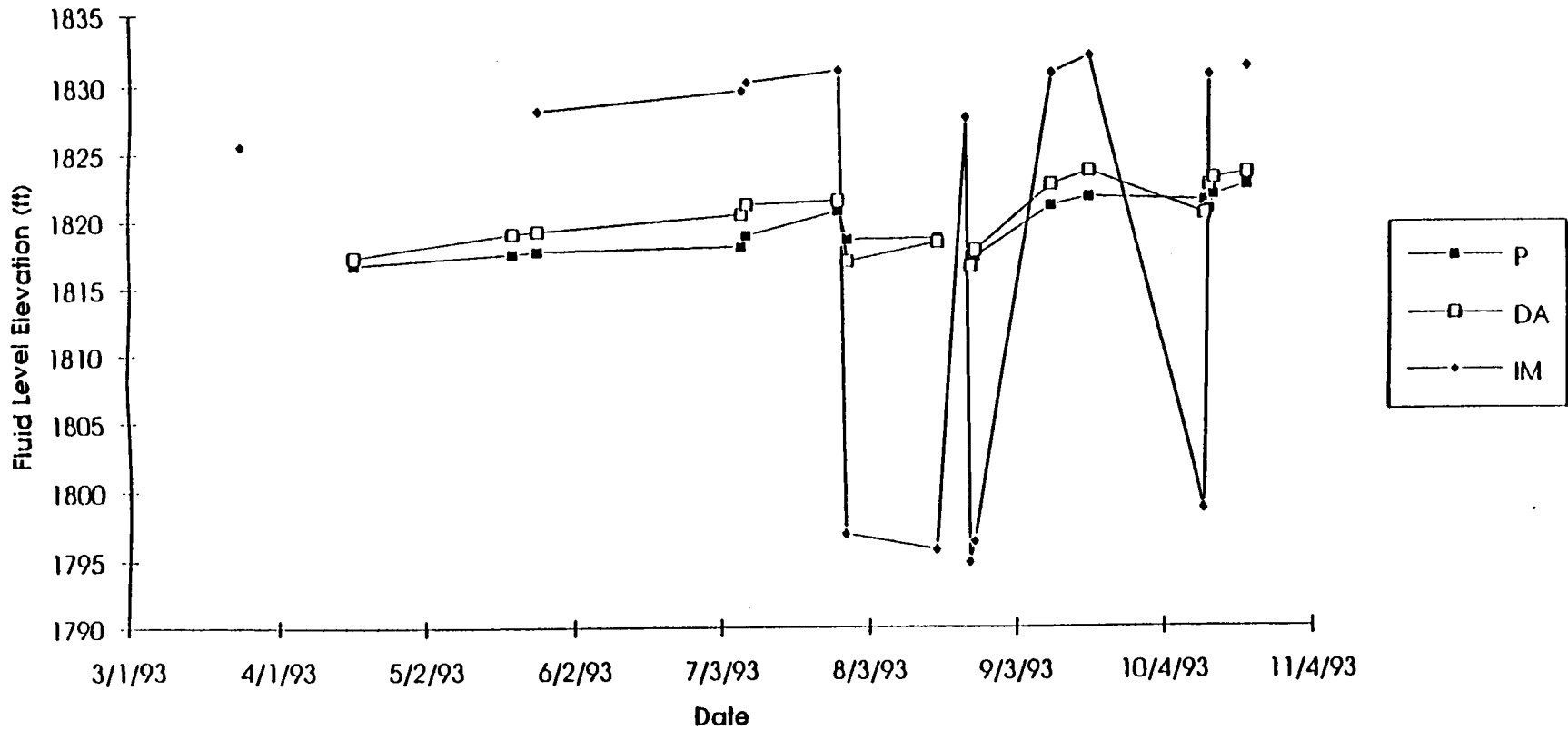


Figure 16. Hydrographs of the Permian (P) and Deep Aquifer (DA - base of Great Bend Prairie Aquifer) monitoring wells at the Siefkes site, rescaled for comparison to the hydrograph of the water table monitoring well (IM) immediately adjacent to the irrigation well. See Figure 13 and Tables 3 and 4 for locations, well characteristics, and data.

At the Siefkes site, water levels in the shallow aquifer showed a net increase of more than six feet between April and October, 1993 (see table 4 and figure 14). Large areas of the field and roads at the Siefkes site were under water much of the summer. Ponding may indicate the presence of impermeable shallow clay layers that promote perching and lateral drainage of water. Water levels in the Permian and deep aquifer wells also rose approximately six feet (table 4 and figure 15). Figures 14-16 illustrate the rapid drop in water levels when the irrigation well is turned on (for example, on July 29). Among the shallow wells (figs. 14 and 16) the response is greatest in the wells closest to the pumping well. The deep aquifer monitoring well showed a greater response to pumping than did the Permian monitoring well, in spite of being at a greater lateral distance from the pumping well. However, the head in the Permian well was less responsive to pumping than the head in the deep aquifer well, which was in turn much less responsive than the shallow well. As a result both the deep and shallow aquifer heads dropped below the Permian head during pumping cycles (see figs. 15 and 16).

IV. Distribution and Controls

A. Spatial Patterns

Examination of the distributions of saline transition zone sites and of head differentials shown in figures 10 and 11 suggests two patterns. One pattern is extensive and consistent mineral intrusion in the cluster of townships north of the Rattlesnake Creek and east of the western edge of the Permian subcrop (fig. 11). Most of the saline transition zone sites with a high percentage of saltwater in the total saturated thickness are concentrated in this area, which is why this region has been identified as a priority for investigation. Figure 17 shows the area in more detail, including the locations of two transects through wells lying along approximately east-west lines through the high-salinity area.

The two east-west cross sections from the transect area (fig. 17) are shown in figs. 18 and 19. These figures illustrate estimates of land, bedrock, water-table, and transition zone surfaces, and show clay layers or lenses based on gamma logs from the indicated sites. Because of

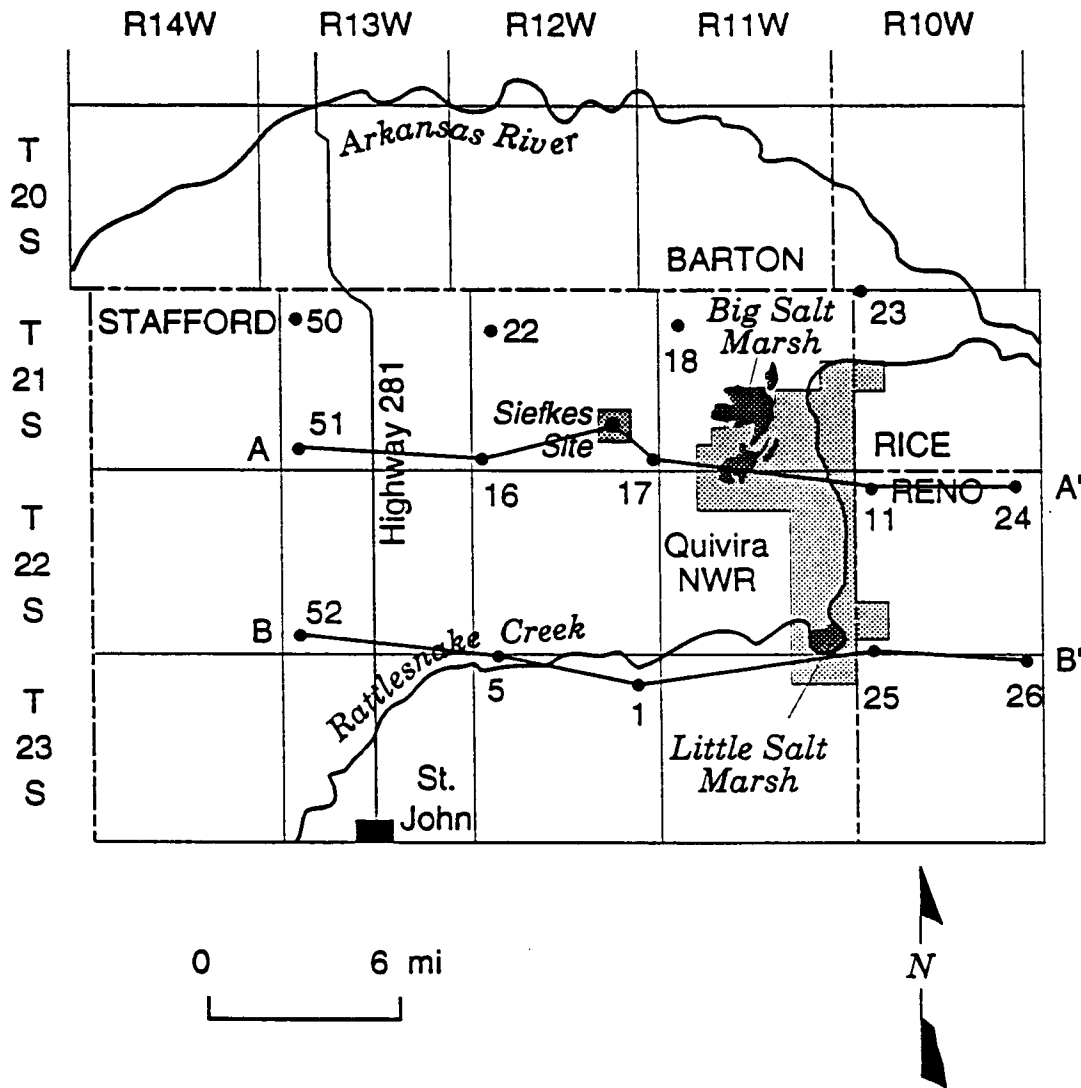
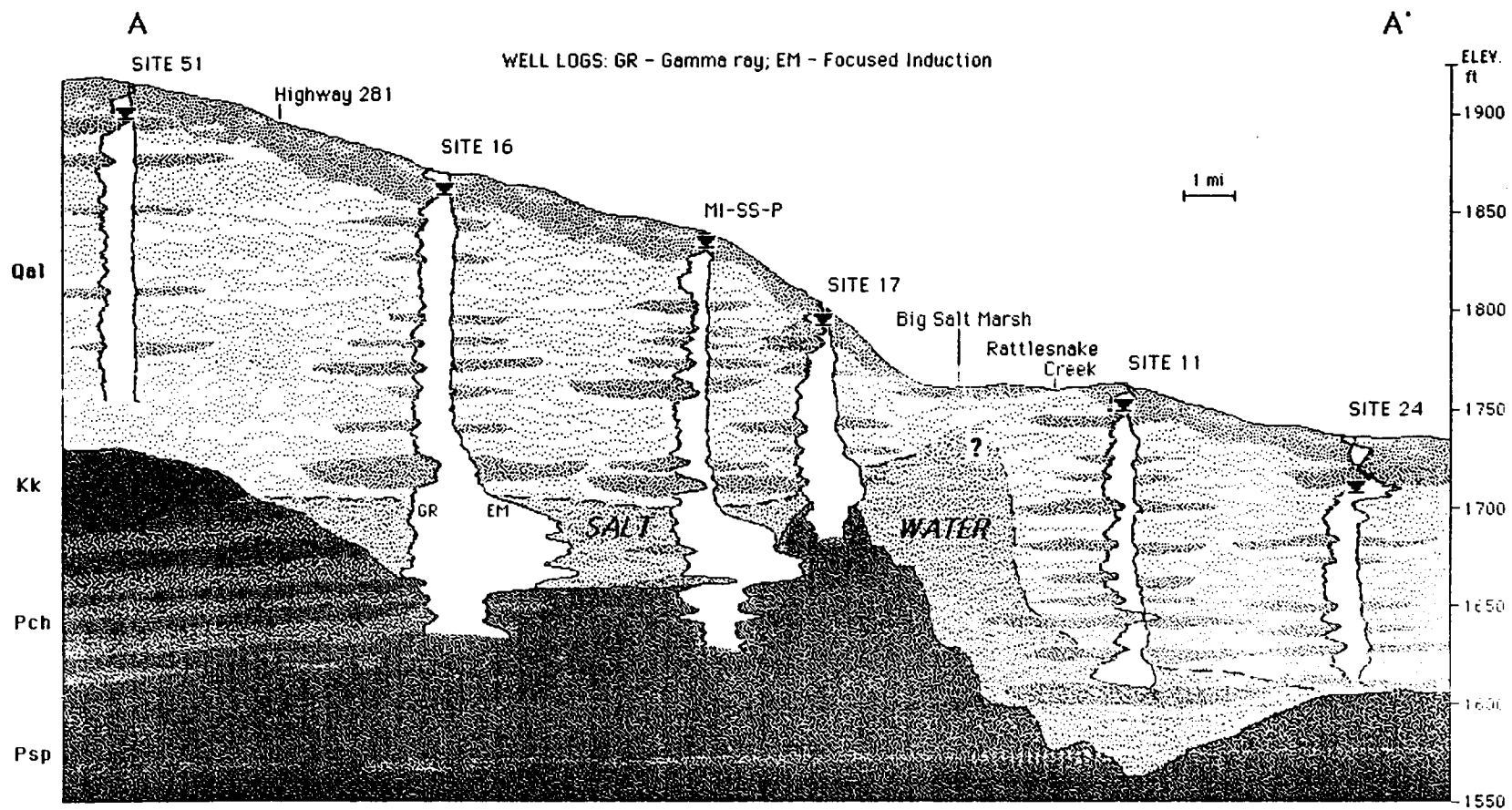
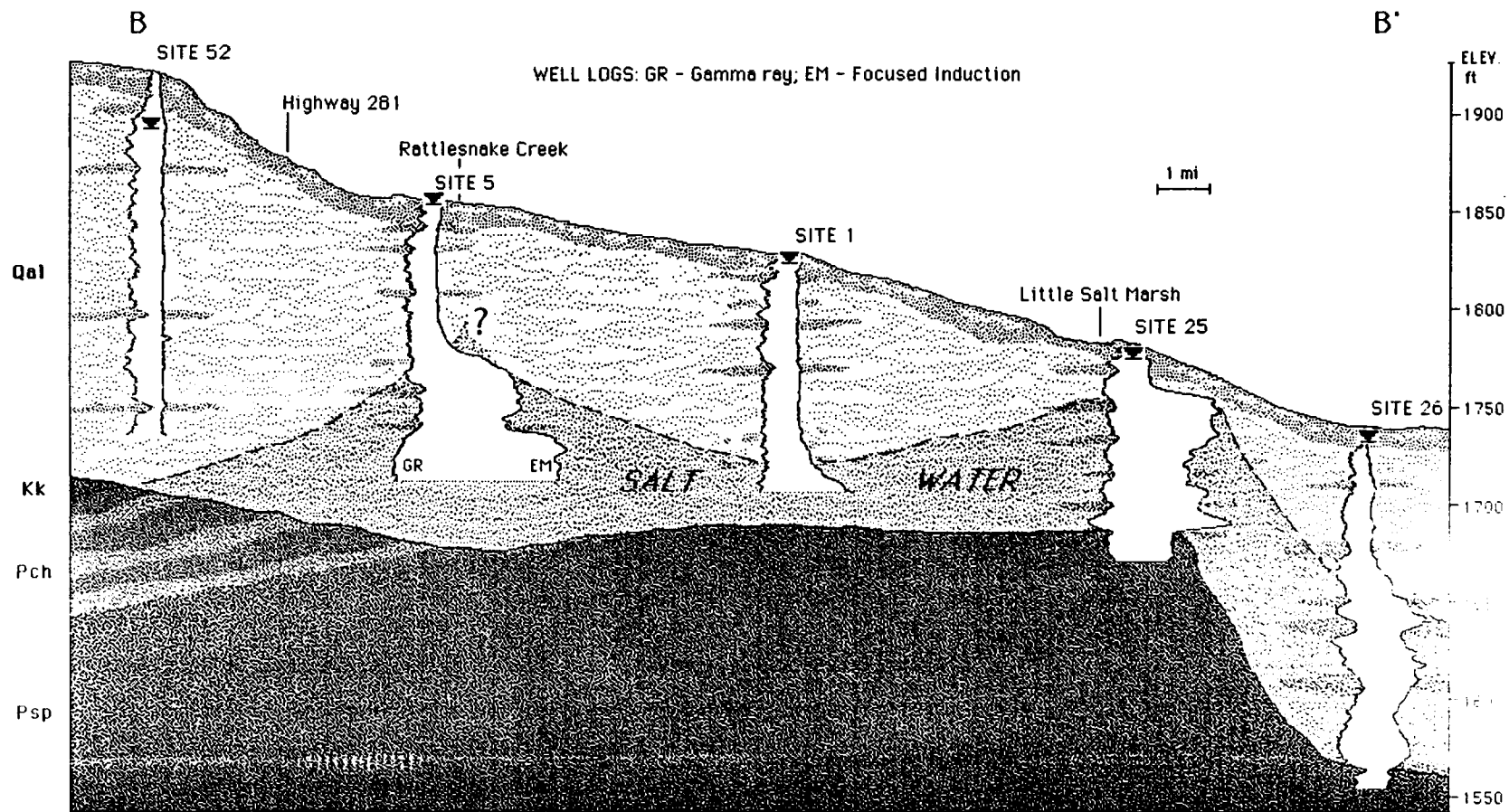


Figure 17. Monitoring-well sites in the transect corridor area of the Mineral Intrusion Project. Cross sections A-A' and B-B' are shown in figures 18 and 19.



LITHOLOGY: Qal - Quaternary alluvium (fluvial and aeolian); Kk - Cretaceous Kiowa Formation (shale); Pch - Permian Cedar Hills Formation (siltstones and sandy siltstones); Psp - Permian Salt Plain Formation (sandy siltstones and fine-grained sandstones)

Figure 18. Cross section AA' (Figure 17) showing estimates of clay lenses (dark stippling) inferred from gamma logs and of salt water distribution (light stippling) inferred from conductivity logs. The dashed line indicates the estimated elevation of the 100 mS/m (C'm) transition zone boundary. At each site the left-hand vertical trace is a reproduction of the gamma log and the right-hand trace a reproduction of the conductivity log.



LITHOLOGY: Qal - Quaternary alluvium (fluvial and aeolian); Kk - Cretaceous Kiowa Formation (shale); Pch - Permian Cedar Hills Formation (siltstones and sandy siltstones); Psp - Permian Salt Plain Formation (sandy siltstones and fine-grained sandstones)

Figure 19. Cross section BB' (Figure 17) showing estimates of clay lenses (dark stippling) inferred from gamma logs and of salt water distribution (light stippling) inferred from conductivity logs. The dashed line indicates the estimated elevation of the 100 mS/m (C'm) transition zone boundary. At each site the left-hand vertical trace is a reproduction of the gamma log and the right-hand trace a reproduction of the conductivity log.

limitations in the detailed coverage of the monitoring-well network, these figures only indicate inferences about the discharge of salt water to streams and marshes.

Two aspects of these observations are particularly important. First, there appears to be ponding of saltwater in bedrock lows or channels, which is especially noticeable in fig. 18. Second, on a large scale there is a west-to-east decline in the elevation of the transition zone, suggesting a regional flow pattern similar to that of the fresh water. However, this pattern is punctuated by local highs in transition-zone elevations in the vicinity of known (fig. 19) or suspected (fig. 18) discharge points. Consideration of the distribution of Permian heads summarized in fig. 10 reinforces these observations. Along the northern section, none of the wells show a Permian head significantly higher than the alluvial aquifer heads, suggesting that they are not in areas of major saltwater outflow from the bedrock. The indicated transition zone rise beneath the area of the Big Salt Marsh and Rattlesnake Creek is speculative, but is consistent with the slight transition-zone elevation increase noted at site 17. In contrast, along the southern section (fig. 19) both sites 5 and 25 show head gradients consistent with upward flow, and at both locations there is a high in the elevation of the transition zone in close proximity to discharge-related features (Rattlesnake Creek and the Little Salt Marsh). However, it is important to note that there is at least one site (site 41) with a Permian head higher than the alluvial head that does not have saltwater above the bedrock, and also that not all sites near a discharge point necessarily have elevated heads or saltwater above bedrock (see fig. 10).

As indicated by the preceding discussion, the other pattern that emerges from the maps of saltwater distribution is a possible association with potential discharge features—streams, rivers and marshes. A majority of the saline transition zone sites outside of the northern Stafford County area are within a mile of a fluvial or wetland feature. This is understandable on a theoretical basis, as groundwater flow in discharge areas deviates from regional horizontal flow patterns. Figure 20 depicts theoretical equipotentials and flow lines in recharge and discharge areas. Recharge enters the water table at regions of high hydraulic potential and is discharged into streams, which are at a lower potential. As figure 20 indicates, considerable flow can enter a

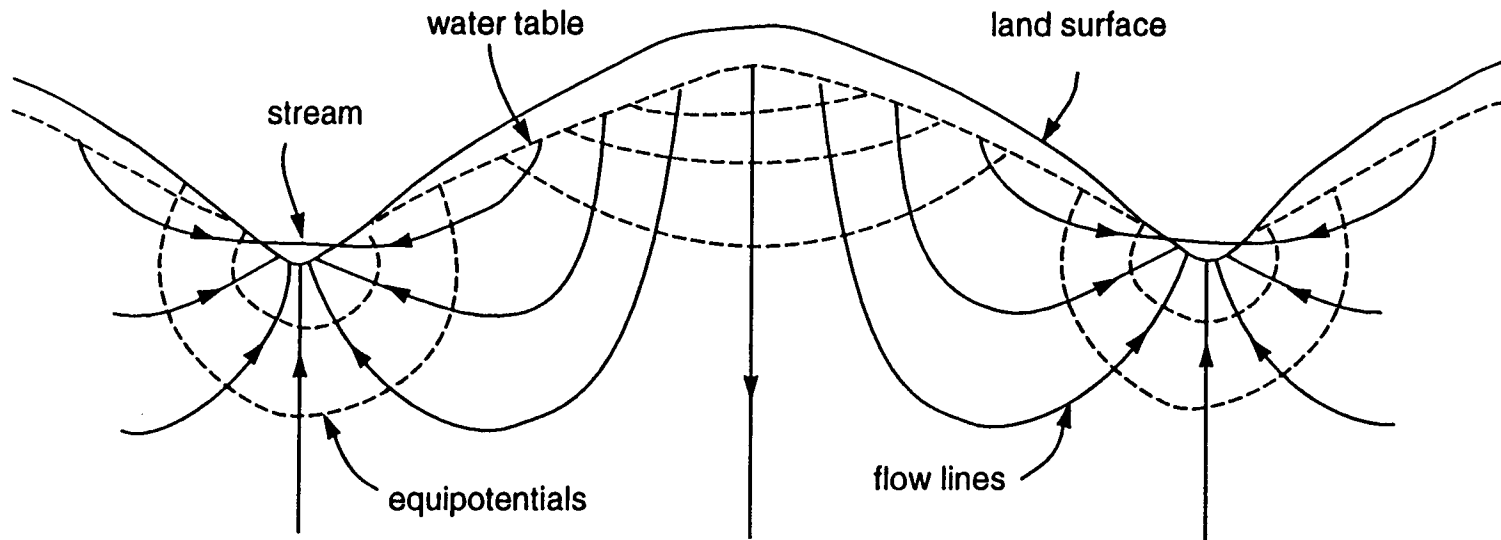


Figure 20. Approximate flow field in uniformly permeable material between the recharge distributed over the free surface and the valley sinks. Adapted from Hubbert (1940) by Cobb (1980).

discharge area or drainage feature from below. If the Permian bedrock is sufficiently permeable, significant upward saltwater flow could occur in these areas. However, upward flow should be accompanied by an appropriate head gradient, and some of the saline sites that are close to streams have Permian heads lower than the alluvial heads. This does not mean that discharge is not a source of mineral intrusion, but it does indicate that if it is, saltwater discharge at depth is not uniformly associated with the surface discharge features.

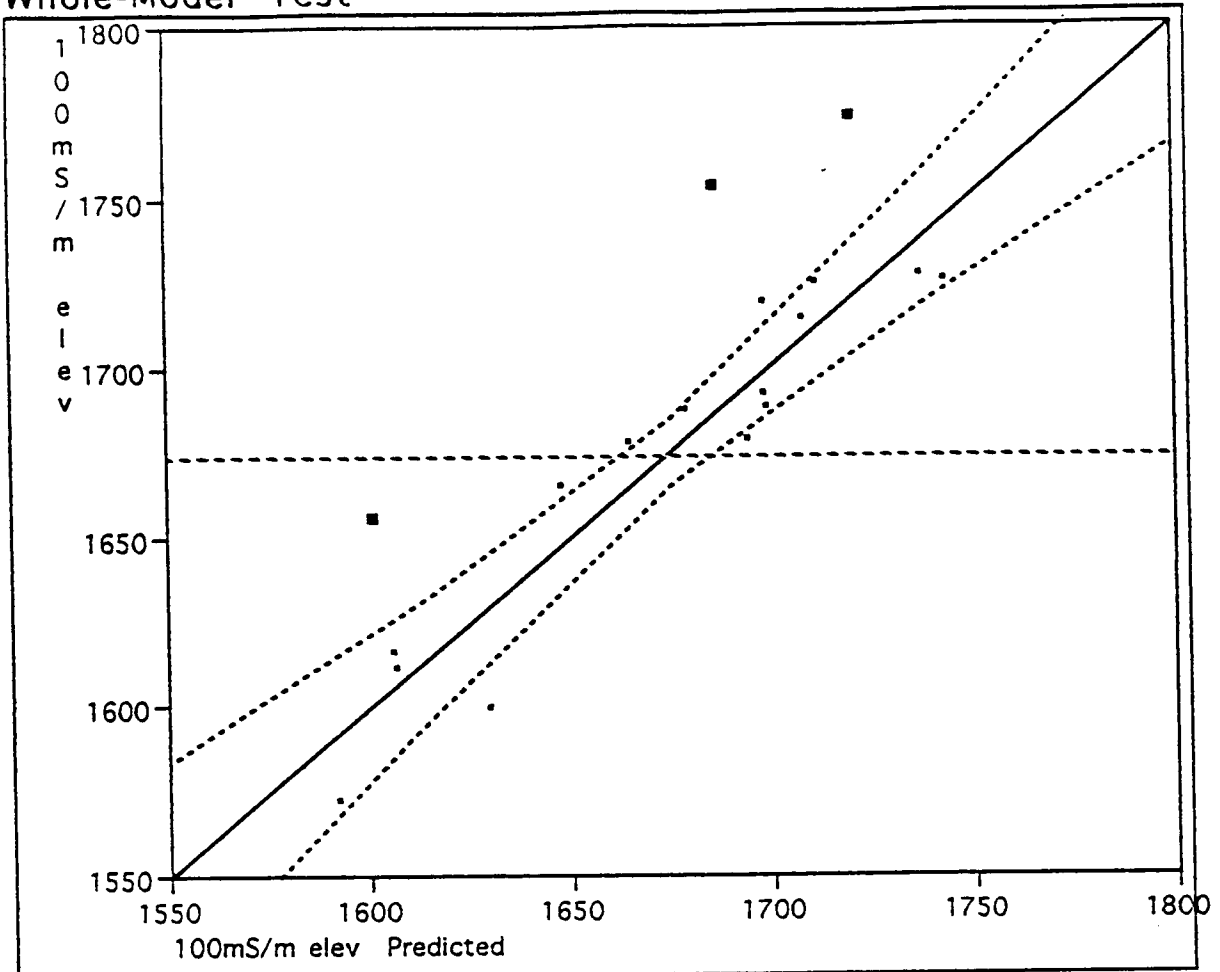
An additional feature of discharge flow is the potential for the vertical plume of salt water to migrate laterally with the horizontal flow field and establish diffuse salty regions or layers of salt water perched on local clay lenses. This may be the case at sites downgradient from areas where the transition zone is elevated due to discharge (sites 11 and 26, figs. 18 and 19).

Statistical analysis can be useful in identifying correlations that may provide information about mechanisms, and also in developing predictive relationships that may be used to regionalize local observations. We performed a multiple regression analysis using water-level elevation and bedrock elevation as independent variables and the 100 mS/m C_m' elevation as the dependent variable. The result shows a significant relationship between the elevation of the 100 mS/m level of aquifer conductance (C_m') and the elevations of the bedrock and the baseline water level when the values at sites 5, 25, and 26 are excluded (fig. 21). The relationship can be used to regionalize the 100 mS/m elevation in areas where there is widespread salt water and no major discharge features. Such an approach can be valid only where the distribution of salt water is under regional control, as appears to be the case in northern Stafford County. A bedrock and a water table elevation are available for all the sites, but not all sites have a transition zone. Thus, regionalization approaches should not be applied to areas where they are inappropriate.

B. Temporal Variation

The fall and winter of 1992 were wet and were followed by the unusually wet year of 1993 in which high rainfall and flooding resulted in unusual water-table rises. This interfered with plans to monitor transition zone changes over a normal irrigation season, but it resulted in

Whole-Model Test



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	32261.147	16130.6	56.0454
Error	12	3453.749	287.8	Prob > F
C Total	14	35714.896		0.0000

Prediction formula for elevation of the 100 mS/m level of the transition zone:

$$\text{elev} = -76.0271 + 0.4873W\text{Lelev} + 0.5331B\text{Relev}$$

where: WLelev = elevation of water level and
BRelev = elevation of the bedrock.

Figure 21. Multiple-regression analysis by JMP IN (Ver. 1.0.6) statistical software for possible relationship between the elevation of the 100 mS/m (Cm') level of the transition zone and the elevations of water level and bedrock. Dashed lines mark the 95% confidence interval as determined by JMP IN. Larger points represent sites 5, 25, and 26 which were excluded from the analysis because of elevated transition zones due to discharge to nearby streams or marshes.

an unusual opportunity to observe the effects of high recharge, and we remained able to observe some short-term pumping episodes in the late summer after the rains ceased.

The results of repeated logging in wells with a detectable 100 mS/m conductivity level are given in table 5. The striking aspect of these observations was the apparent stability of the transition zones that were logged repeatedly. In spite of seasonal, recharge-induced head changes of 10 ft or more at several sites in northern Stafford County (fig. 12) and transient irrigation-induced head changes of several tens of feet (table 4 and figs. 14-16), the only site that showed a transition zone fluctuation was a new well (SP) that was probably still recovering from drilling. Most of the changes observed are close to or below our limits of accuracy and precision for the determinations (discussed in section II above). It is not clear yet whether this indicates that the saltwater transition zone does not respond to recharge, or whether it is so slow to respond to rapid recharge that the effects have not yet been observed.

In virtually all areas the Permian heads rose by an amount similar to, but usually slightly less than, the increase in the alluvial head. This correspondence, and the synchrony of the changes (see, for example, fig. 15), indicates that the aquifers are well but not perfectly connected. The fact that the transition zone did not change correspondingly suggests that the equilibration is based on pressure rather than flow; presumably the relatively low permeability of the Permian prevents it from functioning as a prompt source or sink of saltwater. It is reasonable to expect that rising heads in the Permian have resulted or will probably result in increased discharges of salt water to the east and to the surface in discharge areas. However, the only direct observations have been those of D. Zehr, who has noted that during peak flood periods the total salt loading of the Rattlesnake Creek significantly increased.

It was noted earlier that there is generally a good correspondence between 1993 conductivity values and those measured nearly a decade ago. This, combined with the observations of seasonal stability under high recharge, suggest that the saltwater transition zone may be a relatively constant feature of the subsurface environment. However, we know that saline water upconing due to pumping stress is possible whenever there is salt water in the

Table 5. Water level and transition zone data for relogged wells.

Site	Date	WI Elev	100 mS/m Cm' Elev	Depth To 100 mS/m	Site	Date	WI Elev	100 mS/m Cm' Elev	Depth To 100 mS/m
5	9/17/93	1853.2	1775.4	79.6	22	3/25/93	1838.9	1679.3	175.7
	10/16/93	1852.9	1775.7	79.3		5/21/93	1840.6	1679.6	175.4
						7/9/93	1843.5	1679.3	175.7
11	3/27/93	1749.5	1616.6	146.4		7/30/93	1844.8	1679.4	175.6
	5/20/93	1753.0	1616.7	146.3		10/14/93	1843.0	1680.0	175.0
	7/9/93	1754.2	1616.7	146.3	25	3/28/93	1770.7	1755.0	25.0
	7/30/93	1755.2	1616.8	146.2		7/31/93	1774.8	1755.4	24.6
	9/22/93	1753.6	1616.9	146.1		9/14/93	1772.7	1755.2	24.8
	10/13/93	1753.1	1616.9	146.1		10/22/93	1772.1	1754.9	25.1
16	3/25/93	1860.0	1725.3	146.7	36	4/21/93	1866.0	1728.0	164.0
	5/19/93	1862.5	1725.3	146.7		9/16/93	1866.9	1727.9	164.1
	7/8/93	1865.0	1725.3	146.7		SP	4/17/93	ND	1692.1
	7/31/91	1866.0	1726.1	145.9	5/20/93		ND	1692.8	147.2
	9/8/93	1866.3	1725.2	146.8	7/8/93		1829.9	1692.7	147.3
	10/21/93	1865.4	1726.2	145.8					
17	3/25/93	1792.4	1720.0	84.0		7/27/93	1830.7	1692.8	147.2
	5/19/93	1792.5	1720.4	83.6		7/29/93	1796.8	1693.2	146.8
	7/8/93	1793.0	1720.5	83.5		9/18/93	1831.7	1692.8	147.2
	7/28/93	1794.3	1720.6	83.4		10/21/93	1830.9	1693.2	146.8
	9/8/93	1794.2	1720.3	83.7	SDA	4/17/93	ND	1694.0	146.0
	10/21/93	1793.3	1720.4	83.6		5/20/93	ND	1694.3	145.7
18	3/25/93	1791.0	1666.1	143.9		7/8/93	ND	1694.3	145.7
	5/21/93	1794.5	1666.3	143.7		7/27/93	ND	1694.1	145.9
	7/9/93	1799.1	1666.2	143.8		7/29/93	ND	1694.2	145.8
	7/29/93	1801.6	1666.2	143.8		9/18/93	ND	1694.3	145.7
	10/14/93	1801.5	1666.1	143.9		10/21/93	ND	1694.2	145.8

pumped aquifer, and that chloride concentrations in many irrigation wells rise during a pumping season. Continued observation to test for long-term responses to the recharge pulse and detailed observations of interface and head behavior over an irrigation season remain a high priority.

V. Summary and Discussion

Most observed variations in transition zone characteristics are so small as to be of uncertain significance; this suggests an apparent steady-state condition for the freshwater-saltwater interface within the Great Bend Prairie aquifer. If true, this would imply that the

saltwater distribution is currently in approximate equilibrium with the various controlling mechanisms such as seepage, recharge, discharge, and horizontal flow within the aquifer. Initial results suggest that most of the transition zone profiles can be described by a normal distribution of salinity, which we believe to be consistent with an equilibrium situation.

Similar heads in Permian and deep aquifer wells indicate that there is not a significant vertical flow component at many sites (see Appendices B and C). This suggests that the system is generally dominated by lateral flow, except in discharge areas such as are depicted in figure 19. Preliminary results of recent slug tests (Butler et al., 1993) indicate low permeabilities in the Permian bedrock, which would limit vertical flow. Water-level rises in 1993 were both comparable and synchronous at most sites, however, indicating that the Permian and alluvial systems are connected; however, low permeability in the Permian would be consistent with the possibility of a prompt pressure response but a very slow flow response.

Inspection of heads in the monitoring wells indicates that there is not a one-to-one correspondence between sites with high Permian heads (head reversals) and saline transition zone sites. In other words, a head reversal at a site does not necessarily imply that the site is a saline transition zone site, although this is true in a majority of the cases. Many of the sites where the Permian head is above the deep aquifer head (and many of the saline transition zone sites) occur along streams (fig. 10).

Analysis of head data also shows that at some sites groundwater pumping lowers the deep aquifer head below the Permian head, making conditions favorable for upward movement of Permian water during portions of the year. It is known that pumping induces vertical mixing and that the water quality in many irrigation wells deteriorates during the pumping season. Short-term head reversals, however, did not significantly affect the saltwater interface or transition zone characteristics at the sites studied in 1993.

The emerging picture is of a relatively stable system that may be locally perturbed by pumping but is dominated by horizontal flow of salt water. This raises the question of the source location of Permian salt water and the mechanism of saltwater movement to the aquifer. Clearly,

the study area is punctuated by locations of upflow and recharge, and there appears to be reason to suspect that the Cedar Hills Sandstone and Salt Plain Formation may be a sources of outflow in northern Stafford County (see figs. 18 and 19). Other work presents the possibility that deeper formations such as the Ninnescah Shale may be a source of salt water north of the South Fork of the Ninnescah River in Pratt County (Gillespie and Hargadine, 1993). Better identification of the salt budget, the source location(s), and the potential rate of outflow will be critical to overall understanding of salt dynamics in the study area.

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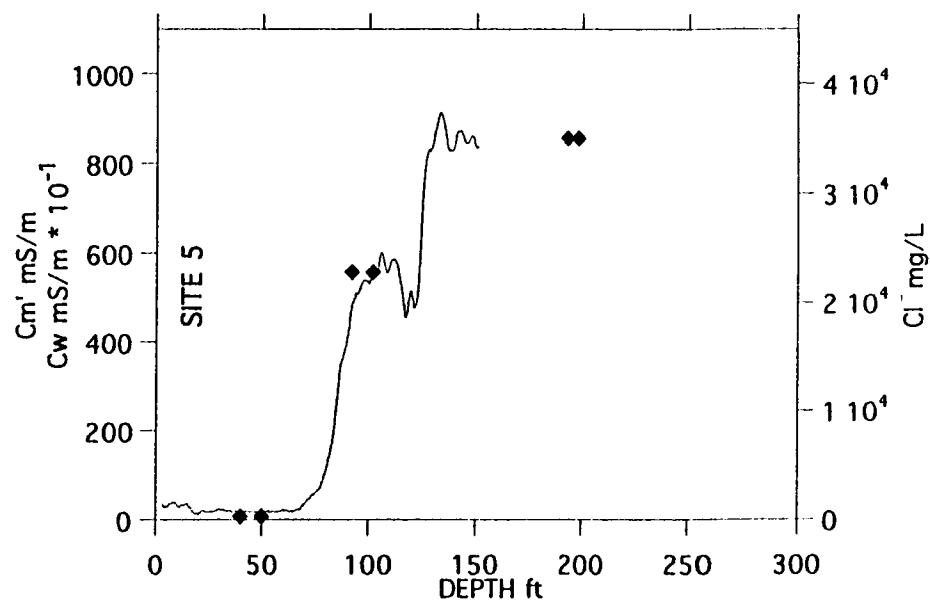
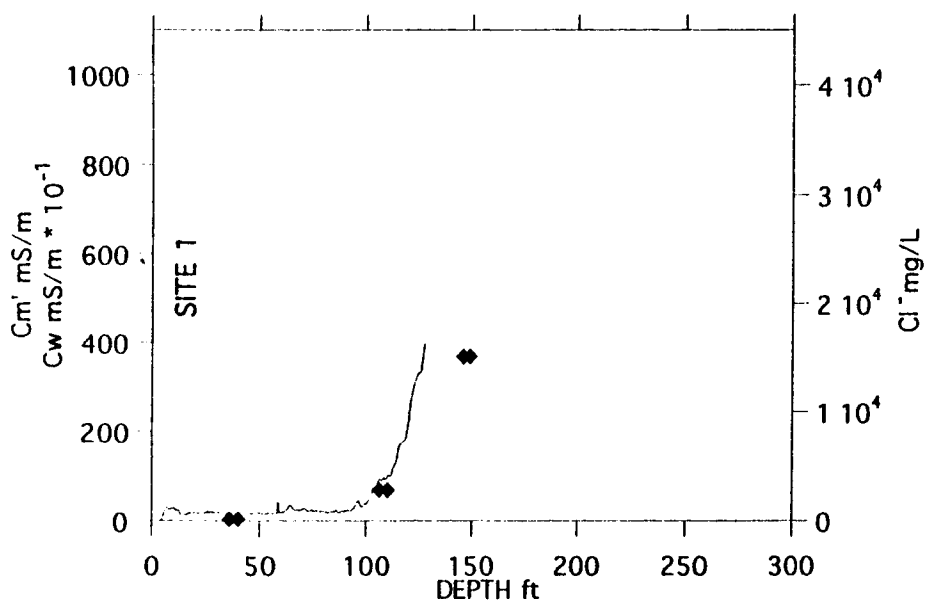
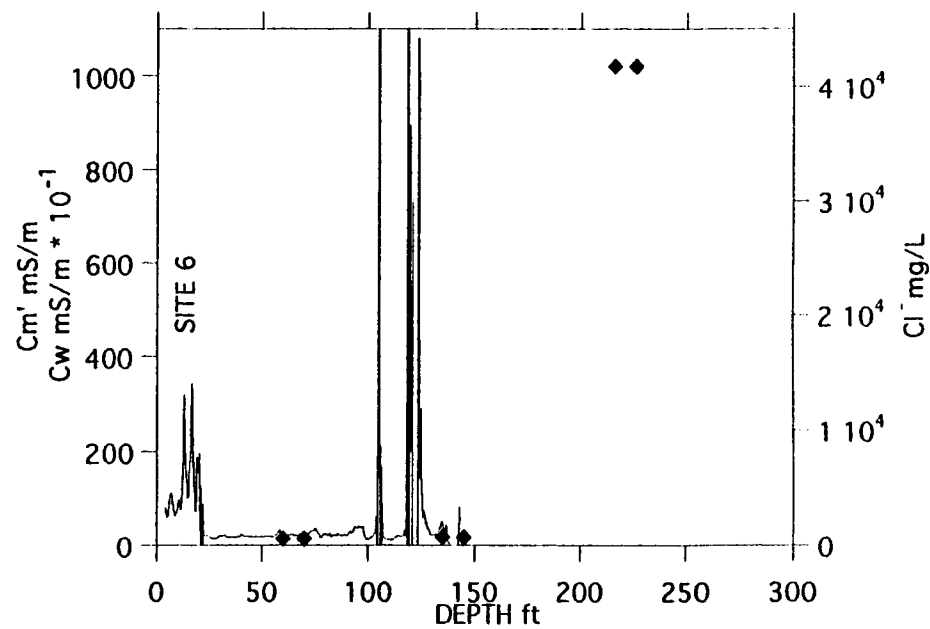
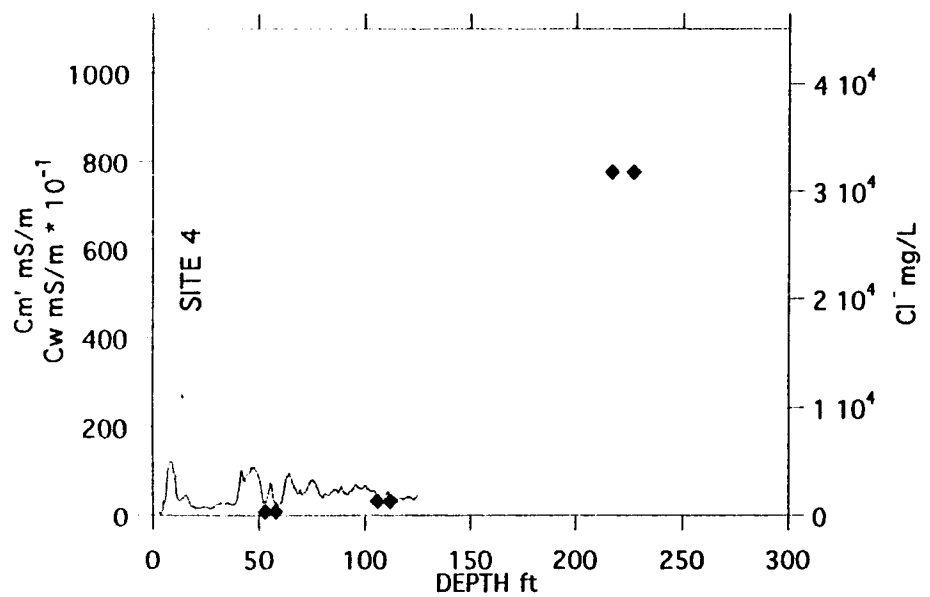
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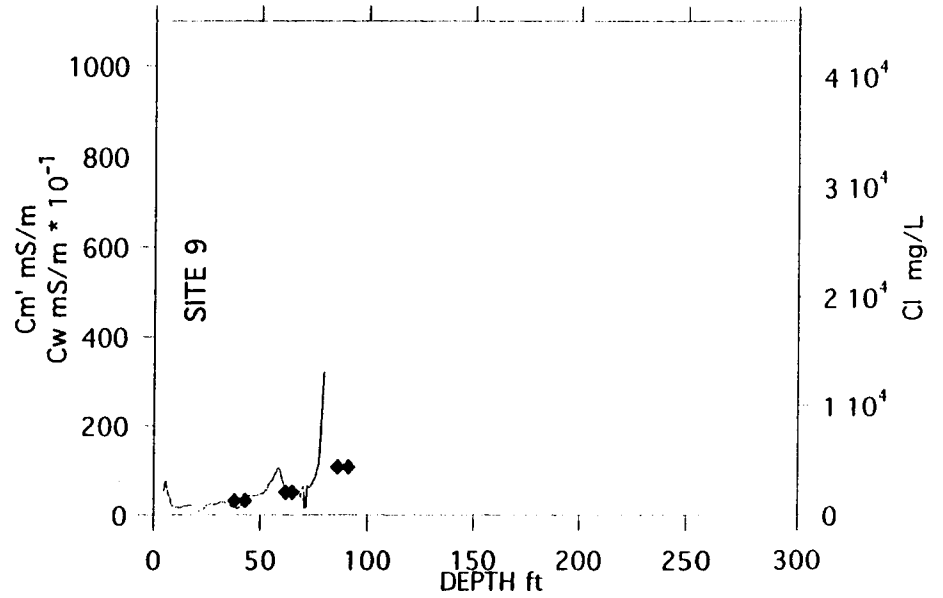
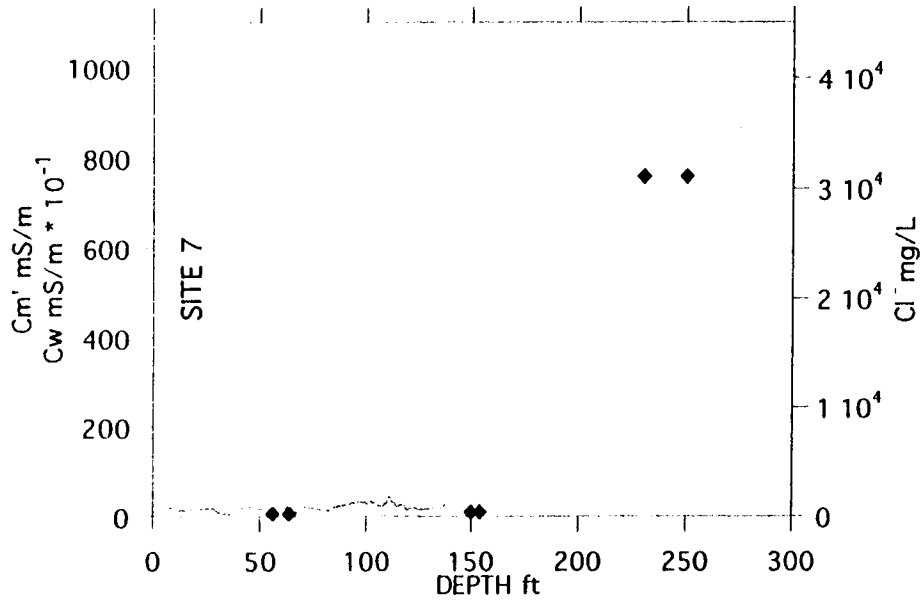
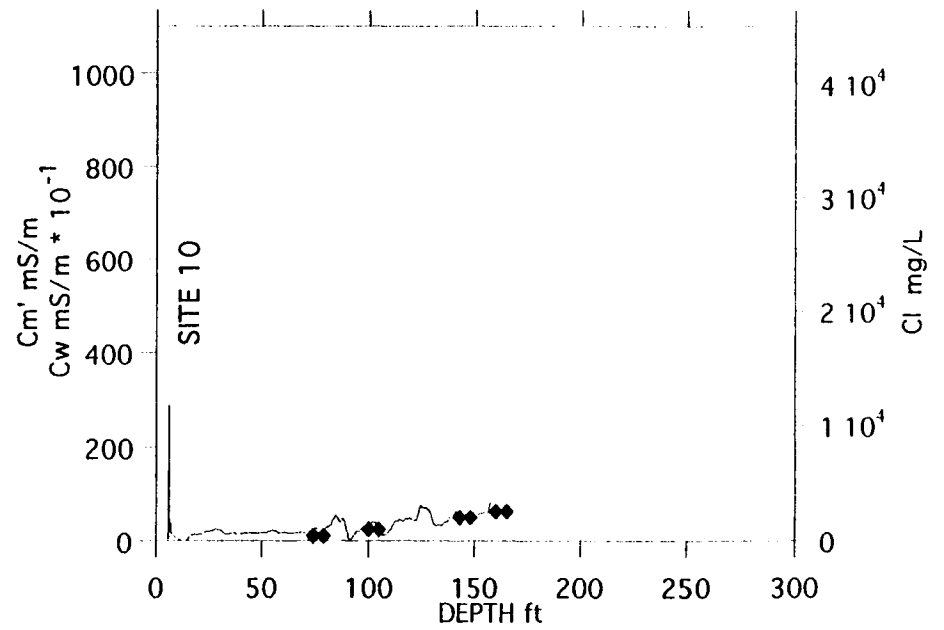
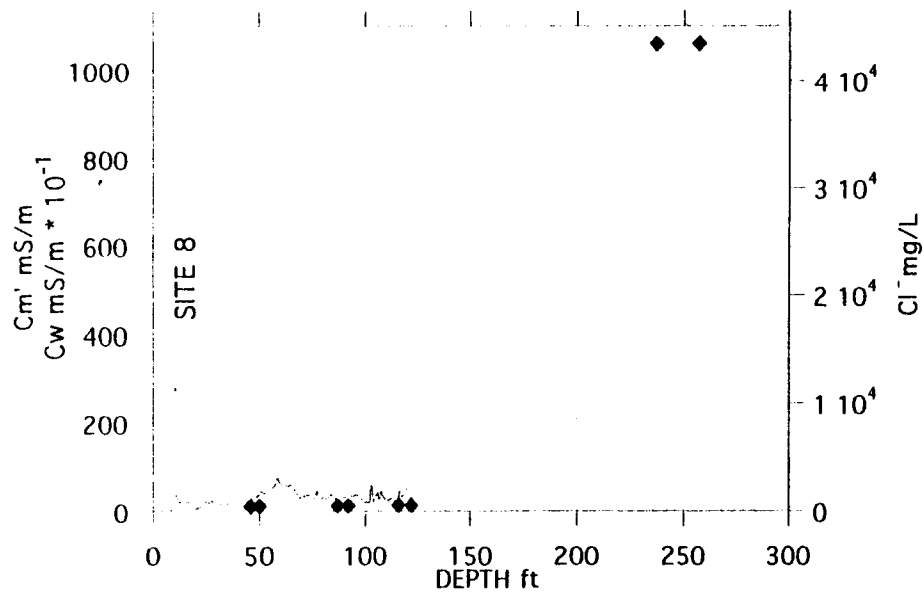
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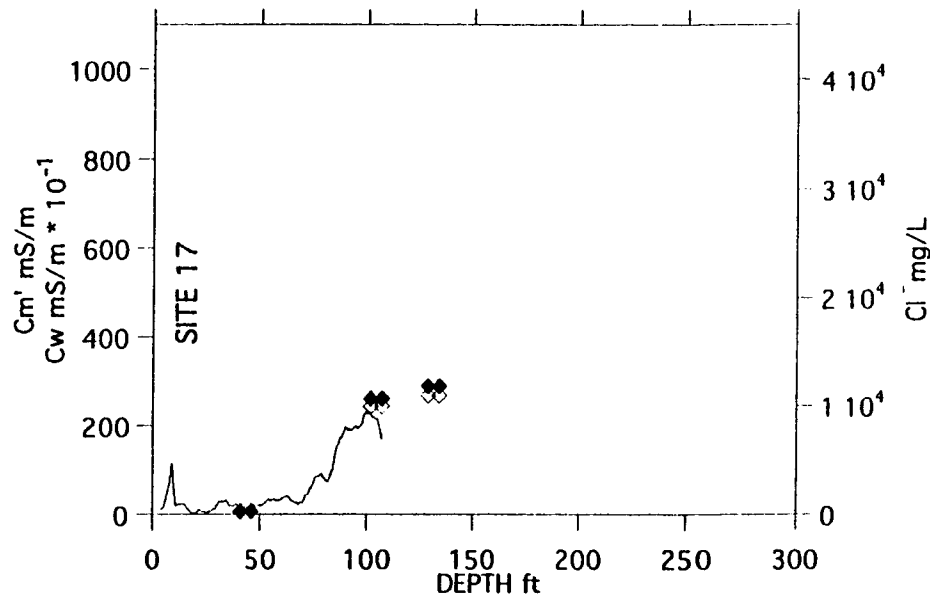
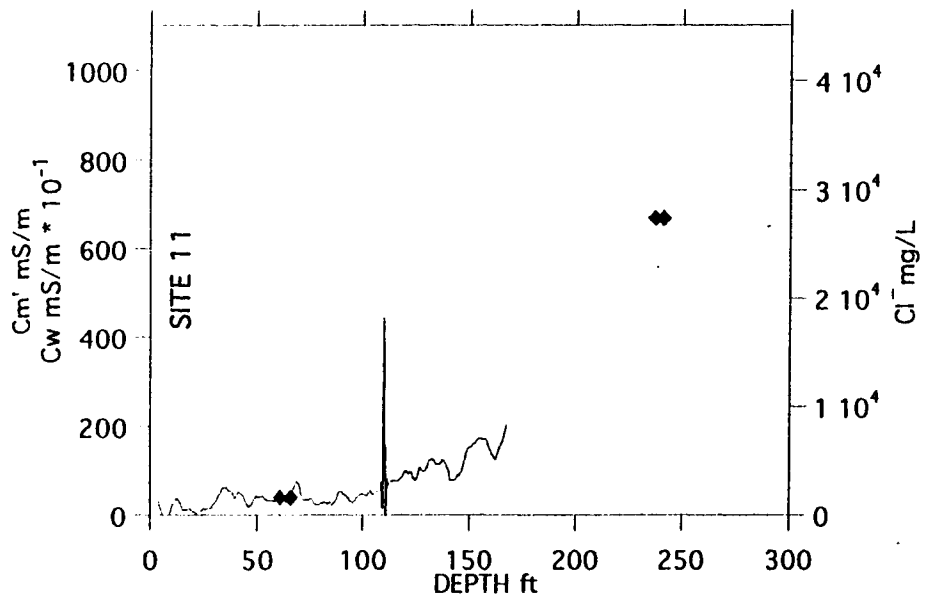
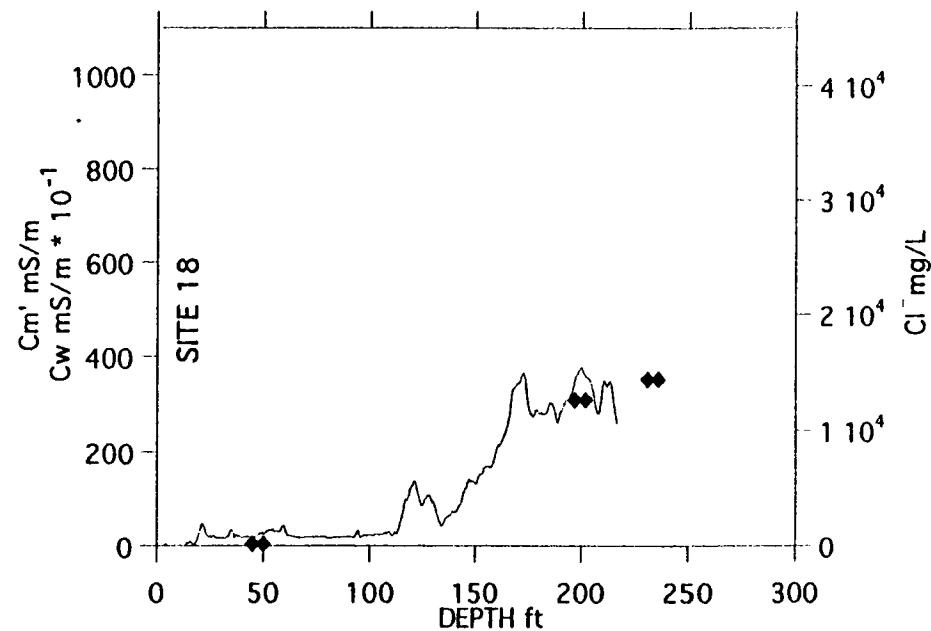
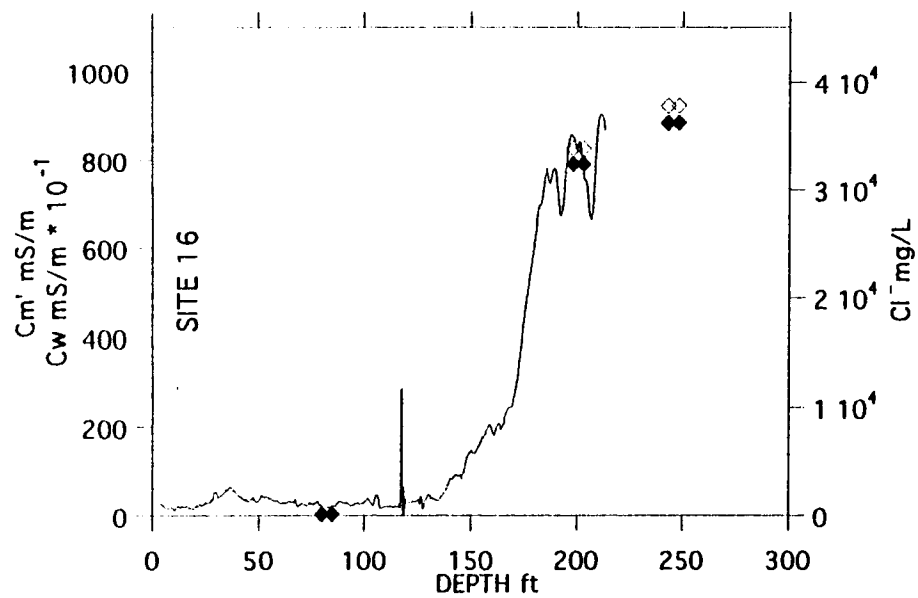
Appendix A: Corrected Conductivity Logs

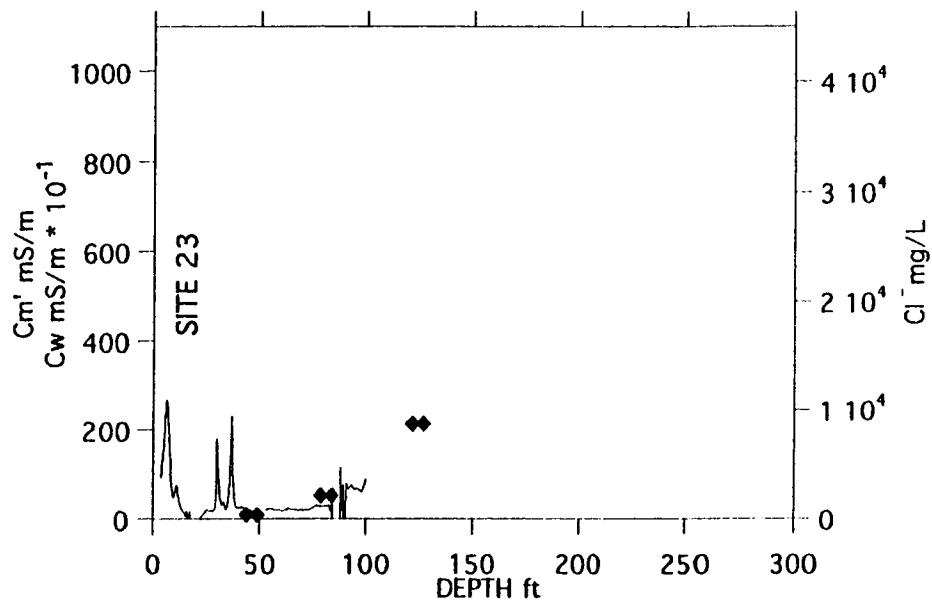
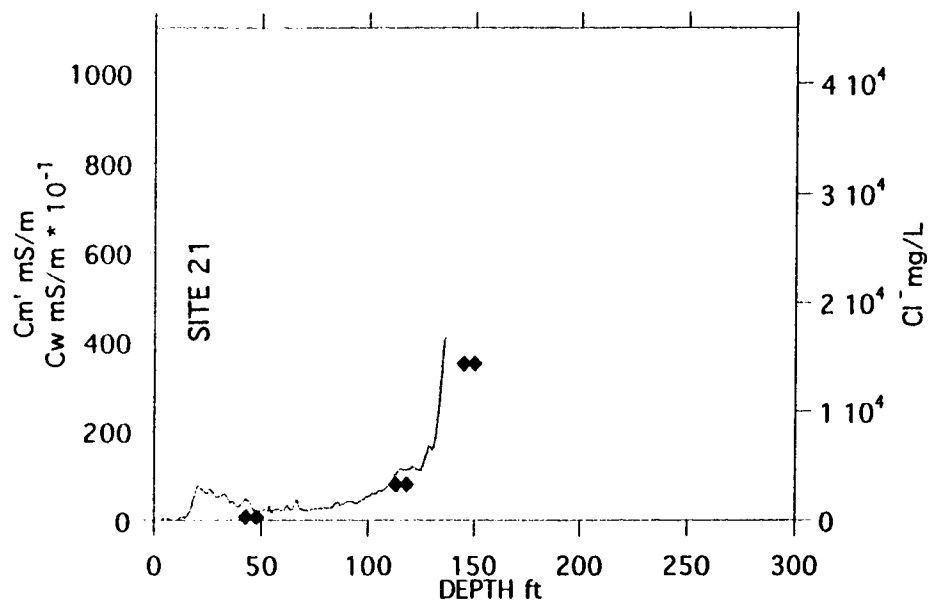
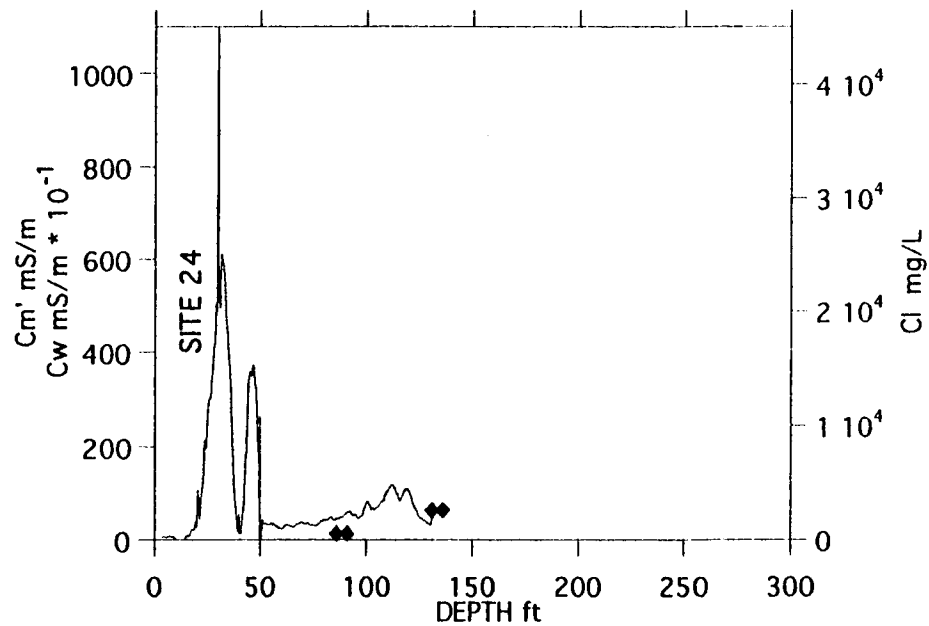
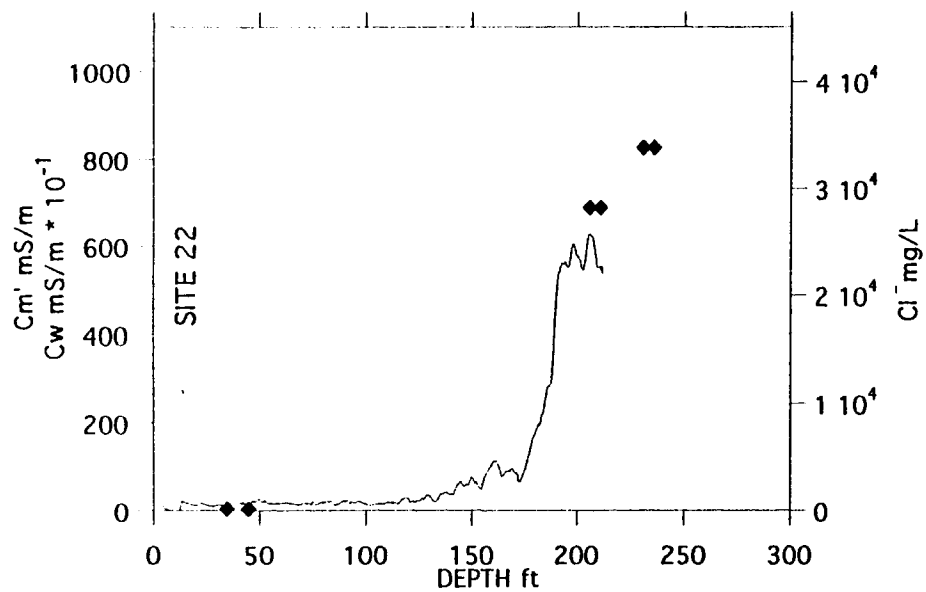
The following figures show conductivity logs for the sites logged in 1993 that exhibit a saline transition zone in the alluvial aquifer. The monitoring well logs are listed in numerical order by site number, except for sites 3, 15, 19, 30, 33 and 40. These were identified as saline transition zone sites on the basis of previous chemical measurement (Whittemore, 1993) rather than logging, and the profiles are grouped at the end of the series following sites 49, 51, and the Siefkes Site logs. Logs have been corrected for lithologic contributions of conductivity; those collected after April have also been corrected for instrument drift. The drift and lithologic corrections are explained in section IIC of this report. Only alluvial aquifer values are reported; bedrock profiles are not shown because a comparable lithologic correction has not yet been developed. The curves present depth profiles of the aquifer conductance (C_m'), and estimates of the corresponding water quality [specific conductance (C_w) and chloride concentration (Cl)] based on the conductivity and chloride concentration relationships presented in the text.

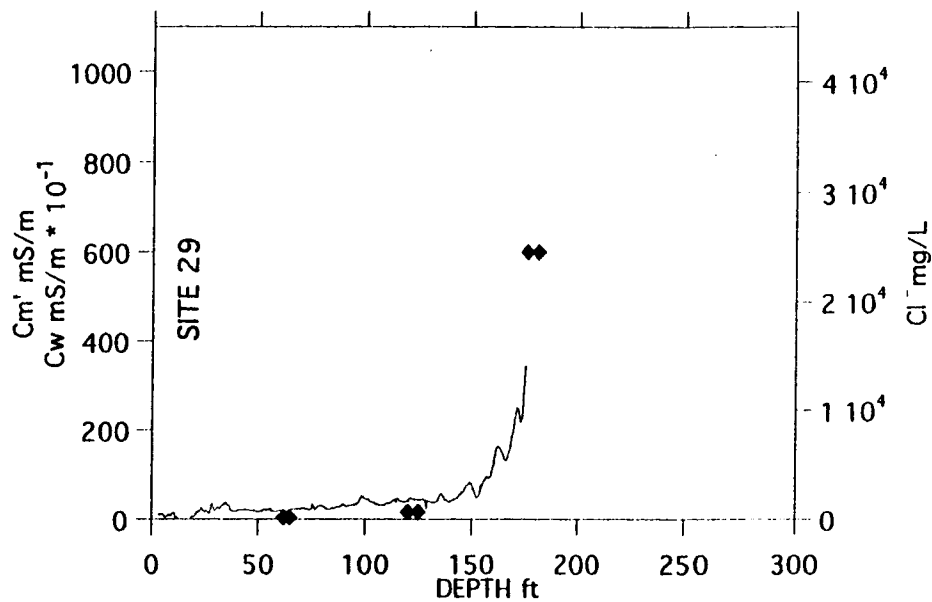
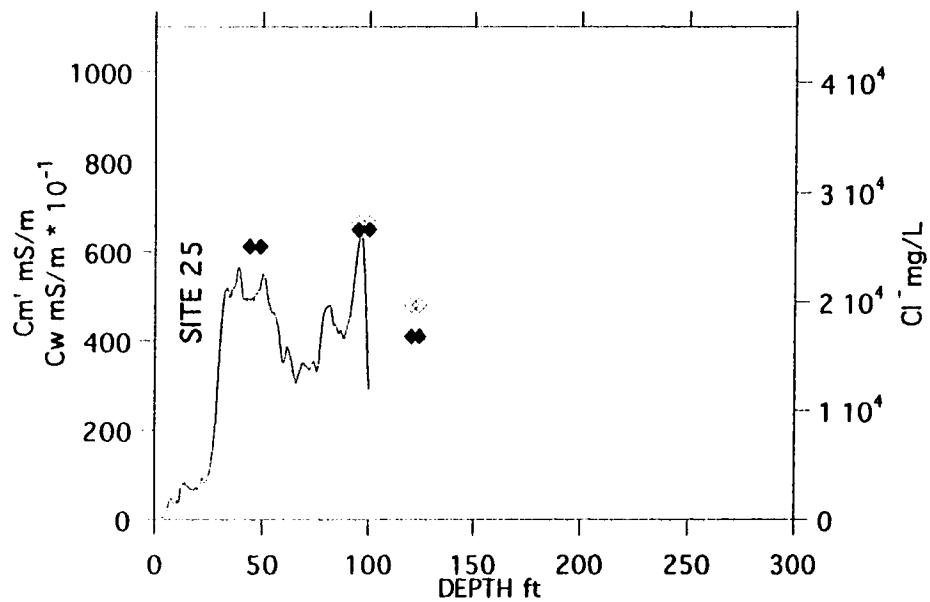
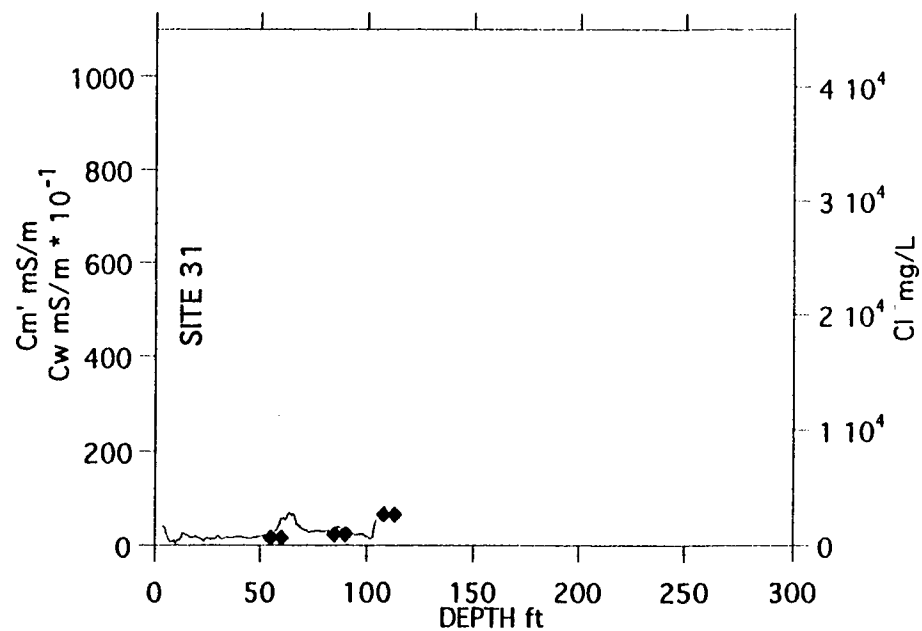
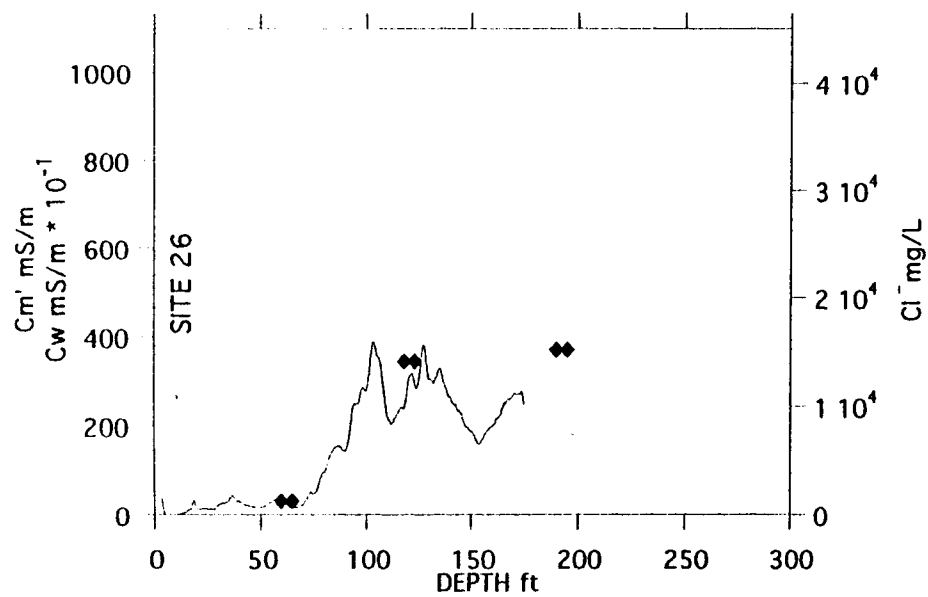
Because both C_w and chloride concentration are approximately linearly related to C_m' , we were able to scale these water-quality values onto axes for the same plots. Scales for C_w and chloride are shown on the top and bottom axes, respectively. The curves show variations in these variables with depth; the diamonds represent actual water sample analyses within the limits of the screened intervals of wells at the monitoring sites. Filled diamonds represent values from Whittemore (1993). Unfilled diamonds represent 1993 water samples. The curves are presented to illustrate changes with depth and to provide comparisons between the different sites; because of the scale of the illustrations and the approximate nature of the conversions to porewater conductivity and chloride concentration, they should not be expected to provide accurate absolute values of these parameters.

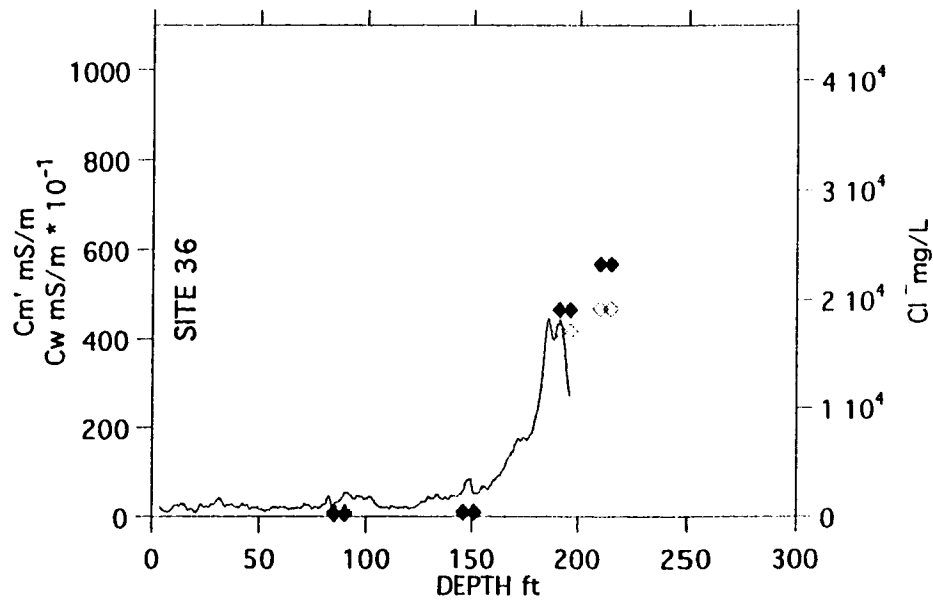
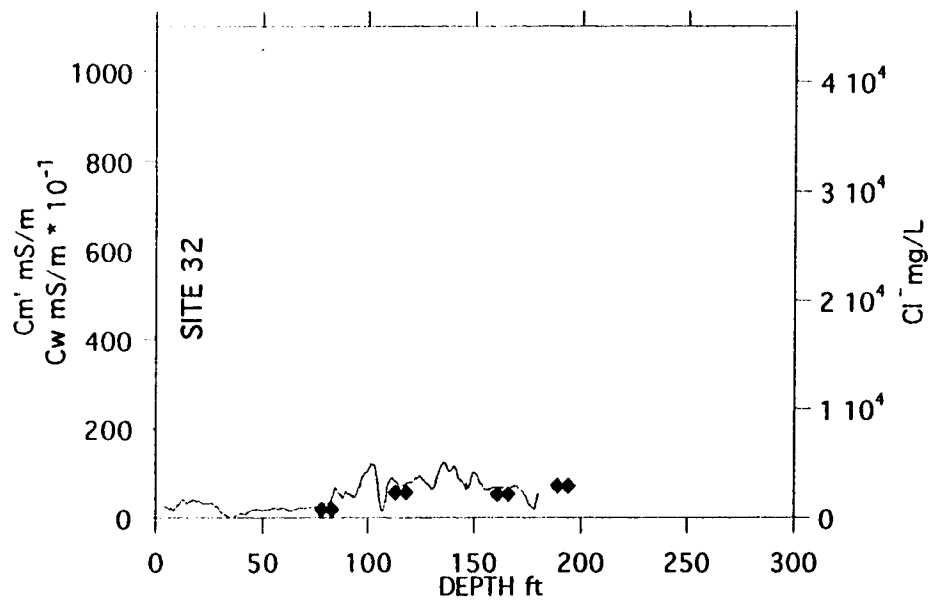
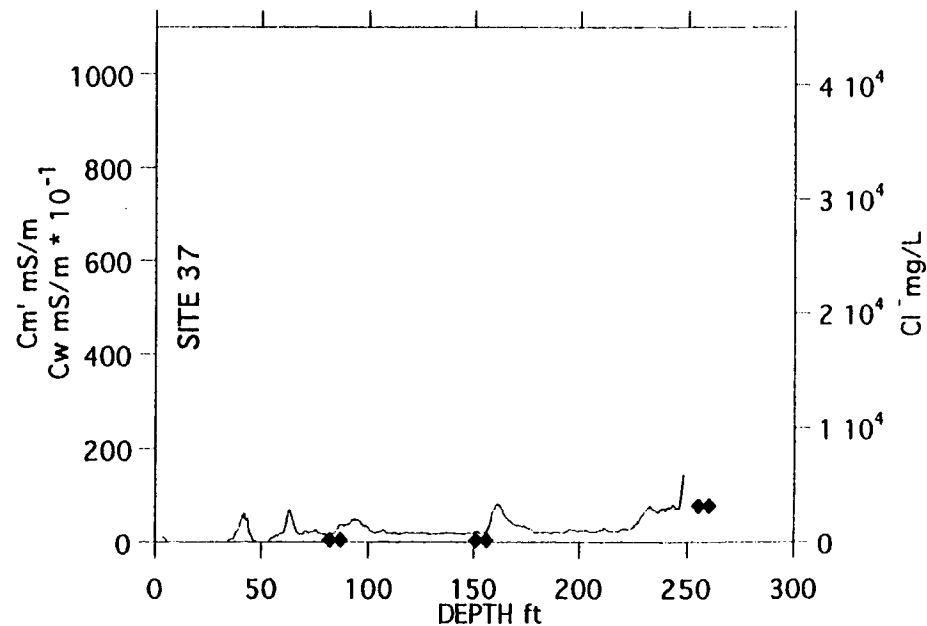
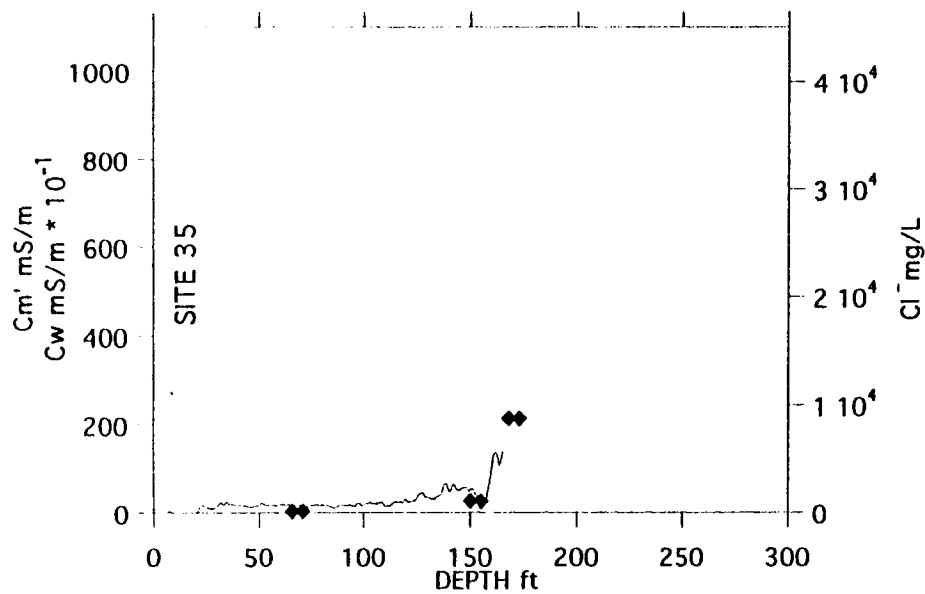


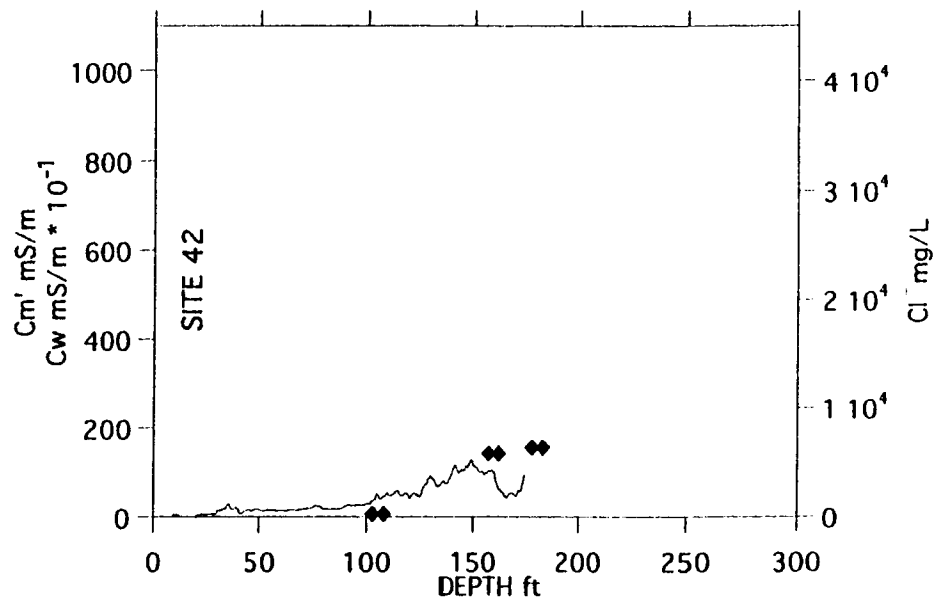
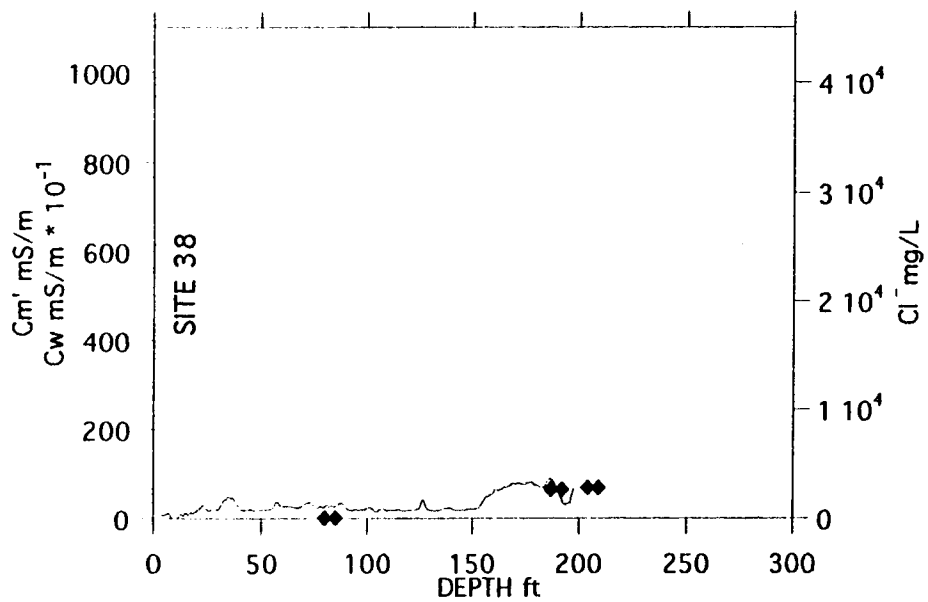
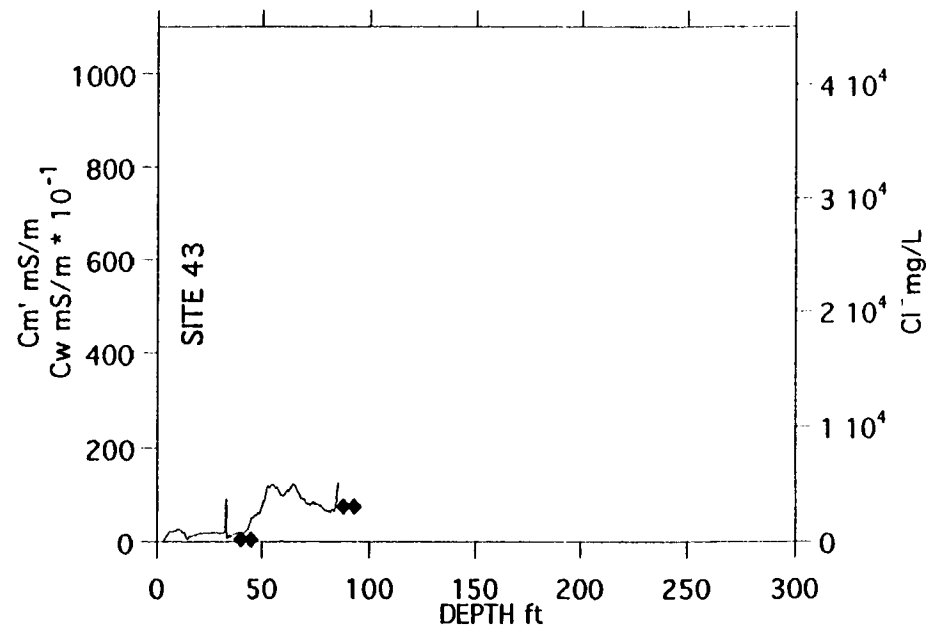
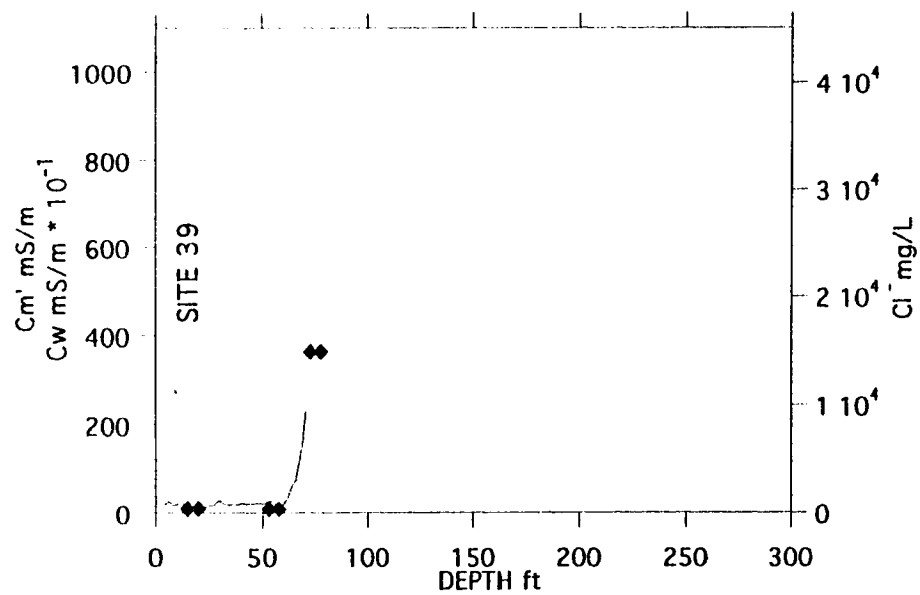


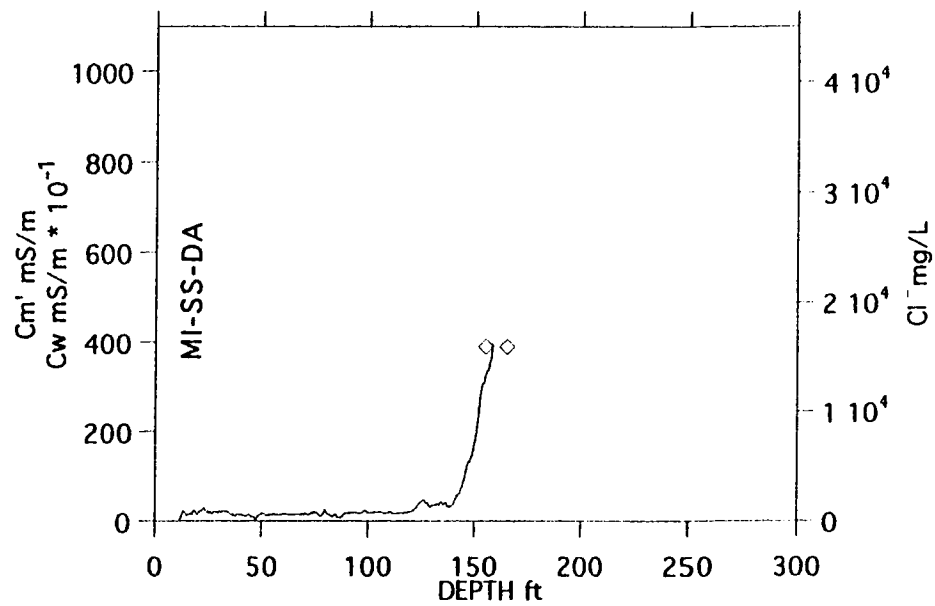
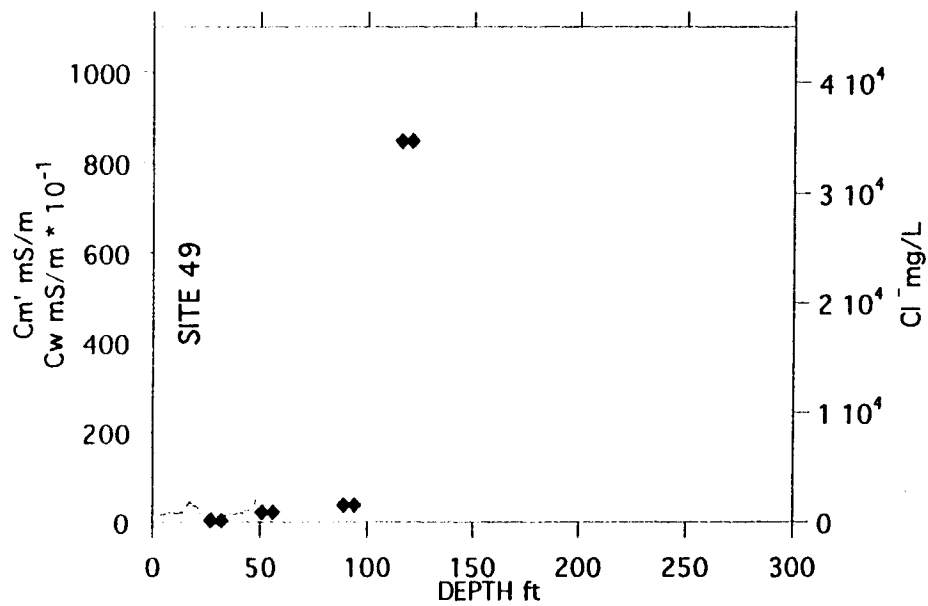
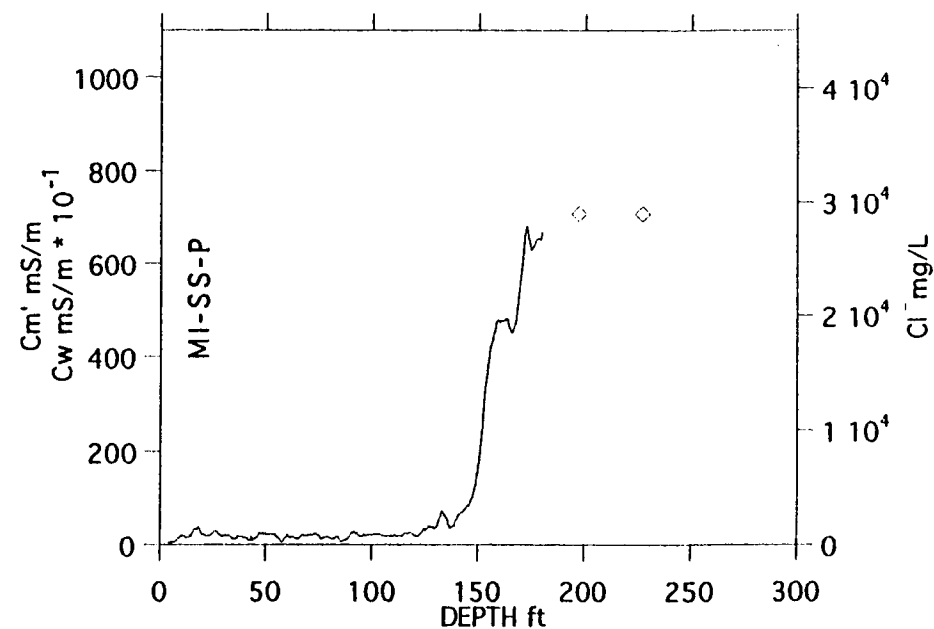
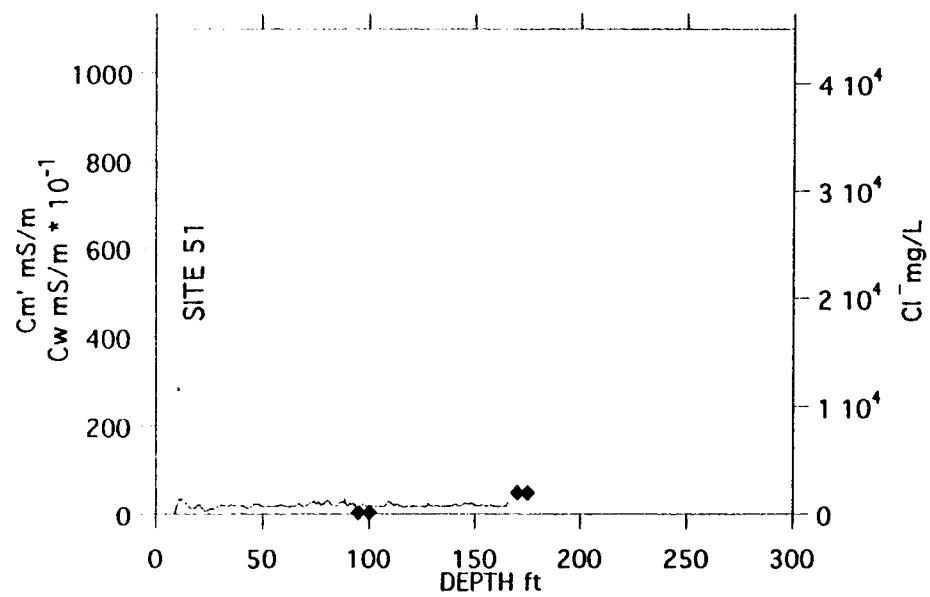


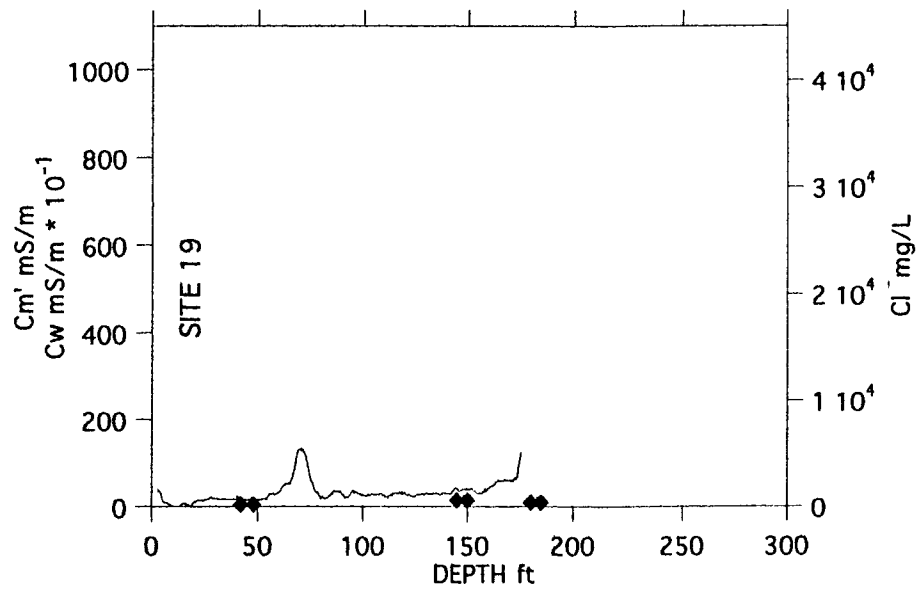
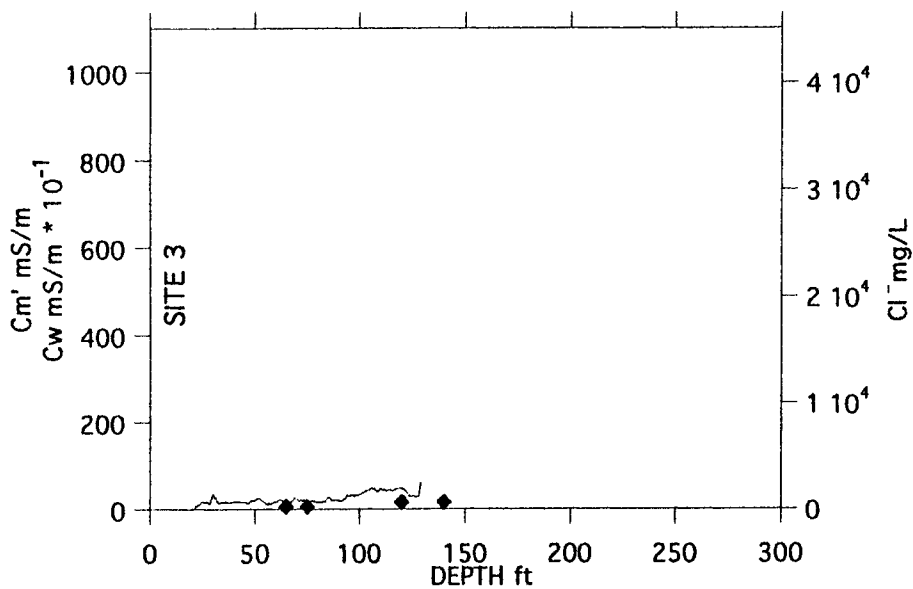
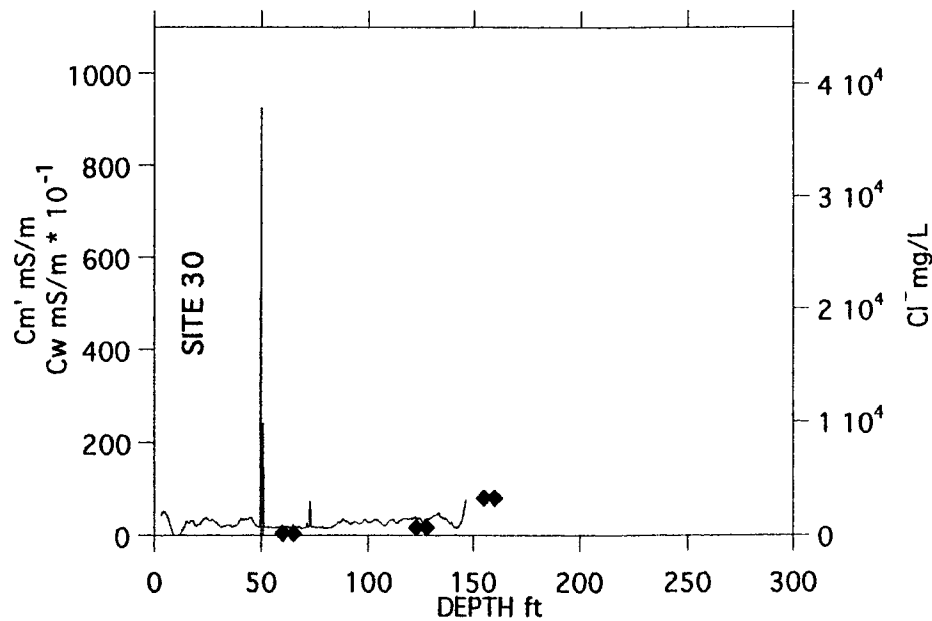
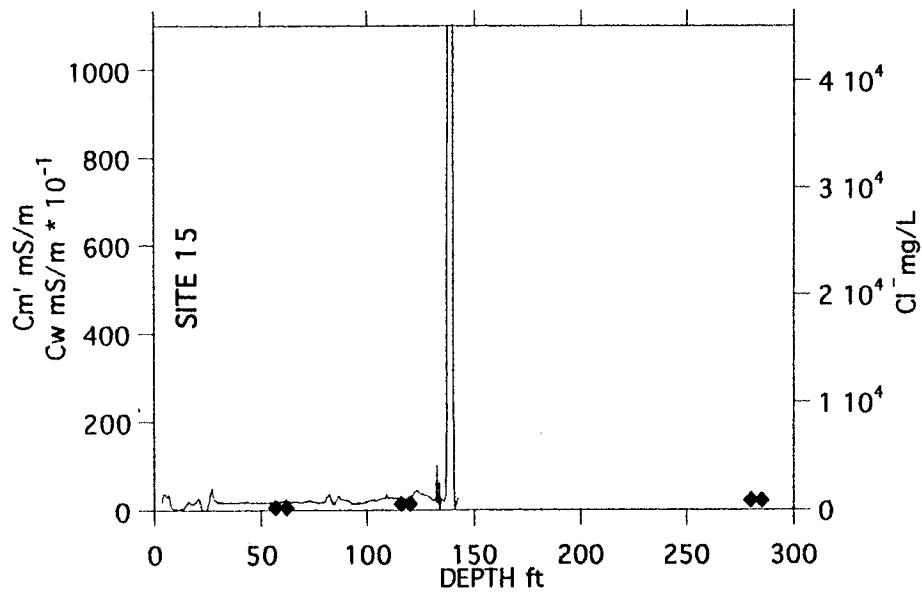


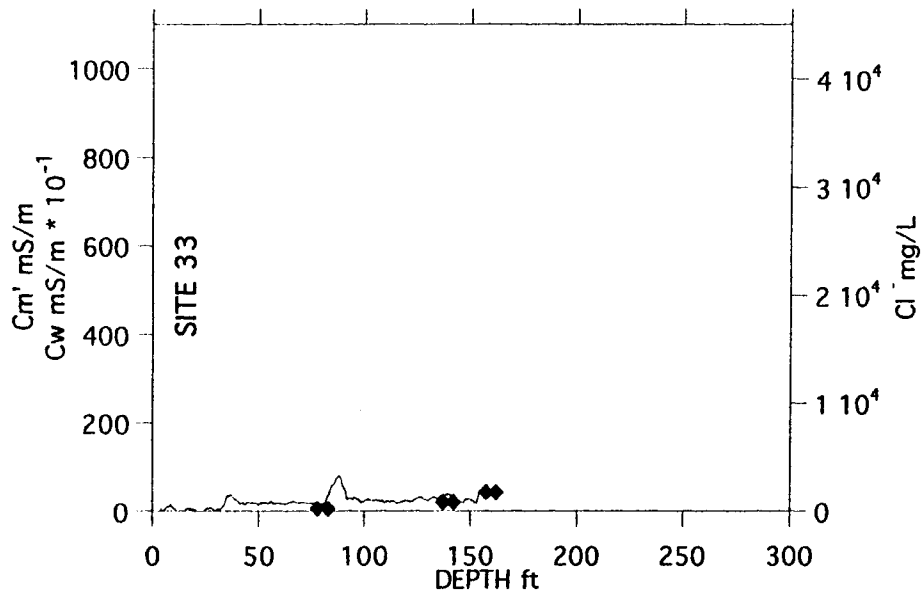
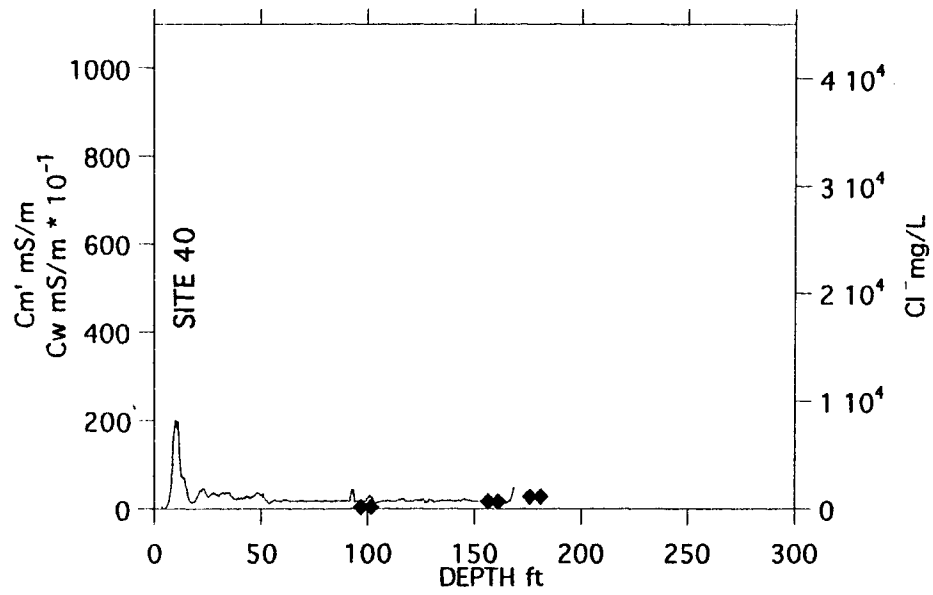












Appendix B: Depth to Water and Monitoring Site Vertical Head Differences

The following tables summarize recent water level information for the Mineral Intrusion monitoring well sites, with emphasis on 1993 observations and summary comparison data for the period 1987-1993.

The data are grouped by site number. At each site, well 1 is the deepest, normally completed in Permian bedrock. Well 1 is screened in the alluvial aquifer above bedrock at sites 50, 51, and 52. Well 2 is normally completed near the base of the Great Bend Prairie (alluvial) aquifer. At most sites, well 3 is the shallowest, completed at shallow to intermediate depths in the alluvial aquifer; at a few sites there are four wells, with 4 the shallowest and 3 at intermediate depth.

The data presented in the "well" columns are depths to water (from local ground level) in feet on the dates indicated in the left-hand column. The right-hand group of columns (labeled 1-2, etc.) give the differences (in feet) between the water levels of the indicated wells. A negative number indicates that the deeper well has a higher head than the shallower well, creating the potential for the upward flow of water. These differences are calculated on the assumption that ground level is at the same elevation for all wells at the same site; this is a reasonable approximation, but it is not strictly accurate and the actual elevations may differ by up to a foot at some sites.

Similarly-presented data for the wells at the Siefkes intensive study site (installed in 1993) may be found in Table 4 of the report text.

The rows labeled AVG 93 and STD 93 for each site give the appropriate elevation and difference averages and standard deviations for 1993 measurements. The rows labeled AVG 87-93 and STD 87-93 give the averages and standard deviations for all measurements during the years 1987-1993. These values are included to give a longer term perspective on the values and variabilities, since 1993 was an unusually high recharge year.

Depths are measured by hand to 0.01 ft, and can normally be read from recorder charts to 0.1 ft or better. The measurements, averages and standard deviations, and relative differences

(that is, changes in head difference between a pair of wells over time) can be considered accurate at the 0.1 ft level. Because of the uncertainty in detailed local ground elevations mentioned above, the absolute values of differences between wells at the same site should be assumed to have an uncertainty in the range of 0.5 ft.

SITE 1	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/13/93	9.60	8.52	8.17		1.08	1.43	0.35	
3/26/93	6.8	5.7	5.3		1.1	1.5	0.4	
3/29/93	6.90	5.75	5.34		1.15	1.56	0.41	
7/1/93	4.90	3.60	3.02		1.30	1.88	0.58	
8/25/93	7.0	5.8	5.2		1.2	1.8	0.6	
10/5/93	7.82	6.70	6.25		1.12	1.57	0.45	
AVG 93	7.17	6.01	5.55		1.16	1.62	0.47	
STD 93	1.40	1.46	1.53		0.07	0.16	0.09	
AVG 87-93	10.27	9.04	8.67		1.23	1.60	0.37	
STD 87-93	2.04	2.09	2.09		0.60	0.57	0.20	
SITE 3	WELL 1	WELL 2			1-2			
1/14/93	31.44	28.40			3.04			
2/19/93	30.64	27.86			2.78			
3/19/93	29.29	26.86			2.43			
4/19/93	28.31	25.73			2.58			
5/20/93	25.61	21.99			3.62			
6/16/93	24.97	21.75			3.22			
7/13/93	19.62	16.17			3.45			
8/10/93	17.17	13.56			3.61			
9/9/93	19.40	16.32			3.08			
10/5/93	21.05	18.00			3.05			
AVG 93	24.75	21.66			3.09			
STD 93	4.89	5.15			0.39			
AVG 87-93	28.19	25.00			3.20			
STD 87-93	4.17	4.12			0.42			
SITE 4	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/14/93	6.00	6.72	9.74		-0.72	-3.74	-3.02	
3/29/93	5.95	6.00	8.70		-0.05	-2.75	-2.70	
4/22/93	5.8	5.8	8.7		0	-2.9	-2.9	
7/1/93	5.44	5.07	7.74		0.37	-2.30	-2.67	
10/5/93	5.38	4.57	8.98		0.81	-3.60	-4.41	
AVG 93	5.71	5.63	8.77		0.08	-3.06	-3.14	
STD 93	0.26	0.75	0.64		0.51	0.54	0.65	
AVG 87-93	5.07	5.71	9.76		-0.64	-4.69	-4.05	
STD 87-93	1.74	1.41	1.29		0.90	1.33	0.81	
SITE 5	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/14/93	2.61	4.77	3.32		-2.16	-0.71	1.45	
2/9/93	1.55	3.75	2.25		-2.20	-0.70	1.50	
3/8/93	0.97	3.15	1.64		-2.18	-0.67	1.51	
3/29/93	1.43	3.60	2.09		-2.17	-0.66	1.51	
4/19/93	1.33	3.55	2.06		-2.22	-0.73	1.49	
5/20/93	0.75	3.00	1.50		-2.25	-0.75	1.50	

AVG 87-93	24.58	18.05	17.74	12.53	6.53	6.84	0.31	
STD 87-93	1.25	2.20	2.19	3.70	1.54	1.55	0.04	
SITE 9	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/6/93	9.78	9.66	9.84		0.12	-0.06	-0.18	
4/2/93	8.94	8.75	8.93		0.19	0.01	-0.18	
4/25/93	9.0	8.8	9.0		0.2	0	-0.2	
6/30/93	8.46	8.25	8.42		0.21	0.04	-0.17	
10/4/93	9.10	8.93	9.10		0.17	0	-0.17	
AVG 93	9.06	8.88	9.06		0.18	0.00	-0.18	
STD 93	0.42	0.45	0.46		0.03	0.03	0.01	
AVG 87-93	10.14	10.00	10.20		0.14	-0.06	-0.20	
STD 87-93	0.82	0.94	0.88		0.24	0.19	0.32	
SITE 10	WELL 1	WELL 2	WELL 3	WELL 4	1-2	1-3	2-3	1-4
1/6/93	25.92	25.68	23.69	20.69	0.24	2.23	1.99	5.23
3/29/93	23.89	23.71	21.77	19.25	0.18	2.12	1.94	4.64
4/25/93	22.9	22.7	20.8	18.3	0.2	2.1	1.9	4.6
6/30/93	19.29	19.06	17.19	14.03	0.23	2.10	1.87	5.26
10/4/93	17.72	17.48	15.45	11.31	0.24	2.27	2.03	6.41
AVG 93	21.94	21.73	19.78	16.72	0.22	2.16	1.95	5.23
STD 93	3.01	3.02	3.02	3.50	0.02	0.07	0.06	0.65
AVG 87-93	24.96	24.71	22.71	19.50	0.25	2.25	2.00	
STD 87-93	2.45	2.45	2.44	2.54	0.05	0.06	0.05	
SITE 11	WELL 1	WELL 2			1-2			
1/6/93	33.2	17.1			16.1			
3/27/93	31.9	13.5			18.4			
3/29/93	31.89	13.47			18.42			
5/20/93	30.6	10.0			20.6			
6/30/93	29.74	8.89			20.85			
7/9/93	29.6	8.8			20.8			
7/30/93	29.1	7.8			21.3			
8/24/93	29.1	8.7			20.4			
9/22/93	29.1	9.4			19.7			
10/13/93	29.2	9.9			19.3			
AVG 93	30.34	10.76			19.59			
STD 93	1.41	2.80			1.51			
AVG 87-93	32.07	13.49			18.56			
STD 87-93	1.72	3.09			1.49			
SITE 12	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/5/93	25.27	23.03	23.7		2.24	1.57	-0.67	
4/2/93	24.32	22.17	22.68		2.15	1.64	-0.51	
5/23/93	23.8	21.5	22.2		2.3	1.6	-0.7	
6/29/93	21.38	18.78	19.45		2.6	1.93	-0.67	

10/1/93	21.6	19.2	19.6		2.4	2	-0.4
AVG 93	23.27	20.94	21.53		2.34	1.75	-0.59
STD 93	1.53	1.67	1.70		0.15	0.18	0.12
AVG 87-93	22.23	20.13	20.48		2.11	1.75	-0.35
STD 87-93	2.36	2.55	2.65		0.34	0.52	0.46
SITE 13	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/4/93	37.34	34.89	34.94		2.45	2.4	-0.05
4/1/93	37.47	34.93	34.71		2.54	2.76	0.22
4/23/93	37.4	34.8	34.7		2.6	2.7	0.1
6/29/93	36.78	34.09	34.00		2.69	2.78	0.09
8/25/93	36.2	33.4	33.3		2.8	2.9	0.1
10/1/93	36.1	33.37	33.32		2.73	2.78	0.05
AVG 93	36.88	34.25	34.16		2.64	2.72	0.08
STD 93	0.56	0.67	0.67		0.12	0.15	0.08
AVG 87-93	36.59	34.04	34.03		2.56	2.56	0.00
STD 87-93	0.68	0.63	0.59		0.15	0.22	0.16
SITE 14	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/4/93	100.55	99.88	99.64		0.67	0.91	0.24
4/1/93	100.55	99.83	99.74		0.72	0.81	0.09
4/23/93	100.6	99.7	99.7		0.9	0.9	0
6/30/93	100.45	99.68	99.57		0.77	0.88	0.11
8/25/93	100.5	99.7	99.8		0.8	0.7	-0.1
10/1/93	100.43	99.7	99.56		0.73	0.87	0.14
AVG 93	100.51	99.75	99.67		0.76	0.85	0.08
STD 93	0.06	0.08	0.09		0.07	0.07	0.11
AVG 87-93	99.86	99.16	99.01		0.70	0.84	0.15
STD 87-93	0.50	0.51	0.52		0.20	0.22	0.12
SITE 15	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/5/93	27.22	31.63	30.66		-4.41	-3.44	0.97
4/2/93	26.78	30.81	30.00		-4.03	-3.22	0.81
4/22/93	26.8	30.7	29.7		-3.9	-2.9	1.0
6/30/93	26.70	28.08	26.99		-1.38	-0.29	1.09
8/24/93	29.2	28.6	26.7		0.6	2.5	1.9
10/4/93	25.76	28.17	26.87		-2.41	-1.11	1.30
AVG 93	27.08	29.67	28.49		-2.59	-1.41	1.18
STD 93	1.05	1.42	1.66		1.77	2.09	0.35
AVG 87-93	27.55	31.07	29.89		-3.52	-2.35	1.17
STD 87-93	1.86	1.64	1.67		1.42	1.74	0.37
SITE 16	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/13/93	30.44	21.93	14.99		8.51	15.45	6.94
2/18/93	30.15	20.94	13.84		9.21	16.31	7.10

3/18/93	29.20	19.25	11.98		9.95	17.22	7.27
3/25/93	29.0	19.2			9.8		
4/16/93	28.32	18.52	11.26		9.80	17.06	7.26
5/19/93	27.67	16.92	9.43		10.75	18.24	7.49
6/16/93	26.79	16.75	9.42		10.04	17.37	7.33
7/8/93	25.9	14.6			11.3		
7/15/93	25.57	14.1	6.86		11.47	18.71	7.24
7/31/93	24.1	12.0			12.1		
8/11/93	23.64	12.3	4.98		11.34	18.66	7.32
9/8/93	23.7	12.9	5.7		10.8	18.0	7.2
10/13/93		13.8	6.6				7.2
AVG 93	27.04	16.40	9.51		10.42	17.45	7.24
STD 93	2.36	3.23	3.29		1.00	1.03	0.14
AVG 87-93	31.22	22.04	15.66		9.10	15.61	6.56
STD 87-93	1.92	2.76	2.82		1.22	1.36	0.34
SITE 17	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/13/93	46.95	12.42	13.16		34.53	33.79	-0.74
2/18/93	46.41	11.53	12.27		34.88	34.14	-0.74
3/18/93	45.81	10.87	11.63		34.94	34.18	-0.76
3/24/93	45.7	10.8	11.6		34.9	34.1	-0.8
4/16/93	45.16	10.42	11.18		34.74	33.98	-0.76
5/18/93	44.73	9.68	10.47		35.05	34.26	-0.79
5/19/93	44.7						
6/15/93	44.61	10.60	11.35		34.01	33.26	-0.75
7/8/93	44.1						
7/15/93	43.91	8.68	9.5		35.23	34.41	-0.82
7/28/93	43.3						
8/11/93	43.41	9.12	9.94		34.29	33.47	-0.82
9/8/93	43.6	9.0	9.8		34.6	33.8	-0.8
9/10/93	43.46	9.15	10.03		34.31	33.43	-0.88
10/7/93	44.74	9.74	10.40		35.00	34.34	-0.66
AVG 93	44.71	10.17	10.94		34.71	33.93	-0.78
STD 93	1.09	1.09	1.06		0.35	0.36	0.05
AVG 87-93	46.05	13.73	14.42		32.35	31.80	-0.70
STD 87-93	3.01	1.71	1.72		2.66	2.58	0.19
SITE 18	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/6/93	35.47	34.51	21.35		0.96	14.12	13.16
1/21/93	35.32	34.34	21.25		0.98	14.07	13.09
2/19/93	34.99	33.72	20.60		1.27	14.39	13.12
3/18/93	34.32	32.76	19.25		1.56	15.07	13.51
3/25/93	34.0	32.5			1.5		
4/14/93	32.60	31.70	17.66		0.90	14.94	14.04
5/18/93	31.95	30.60	15.81		1.35	16.14	14.79
5/21/93	31.8	30.4			1.4		
6/15/93	31.03	30.30	14.37		0.73	16.66	15.93

7/9/93	30.6	29.2			1.4		
7/15/93	30.22	28.83	10.48		1.39	19.74	18.35
7/29/93	26.9	26.6			0.3		
8/11/93	27.12	27.71	6.33		-0.59	20.79	21.38
9/9/93	27.28	26.12	7.74		1.16	19.54	18.38
10/5/93	27.18	25.94	8.27		1.24	18.91	17.67
10/14/93	27.2	26.1			1.1		
AVG 93	31.12	30.08	14.83		1.04	16.76	15.77
STD 93	3.10	2.91	5.48		0.52	2.41	2.67
AVG 87-93	34.61	35.05	20.51		-0.45	13.80	14.16
STD 87-93	2.27	2.89	4.07		1.84	1.98	1.75
SITE 19	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/21/93	20.03	17.7	14.94		2.33	5.09	2.76
2/19/93	19.92	16.6	13.44		3.32	6.48	3.16
3/22/93	19.72	15.15	12.01		4.57	7.71	3.14
4/16/93	19.52	14.59	11.65		4.93	7.87	2.94
4/19/93	19.5	14.5			5		
5/20/93	19.21	12.66	10.25		6.55	8.96	2.41
6/16/93	19.16	13.72	10.95		5.44	8.21	2.77
7/15/93	18.77	11.75	9.45		7.02	9.32	2.3
8/10/93	18.68	15.35	10.55		3.33	8.13	4.8
8/25/93	18.8	17.0			1.8		
9/9/93	18.79	13.32	11.67		5.47	7.12	1.65
10/6/93	18.65	13.6	11.73		5.05	6.92	1.87
10/20/93	18.5	13.0			5.5		
AVG 93	19.17	14.53	11.66		4.64	7.58	2.78
STD 93	0.50	1.71	1.51		1.48	1.17	0.83
AVG 87-93	18.01	15.40	12.10		2.61	5.61	2.99
STD 87-93	1.69	2.79	2.38		2.37	1.96	1.34
SITE 20	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/4/93	30.77	24.40	25.90		6.37	4.87	-1.50
4/1/93	30.05	21.08	22.06		8.97	7.99	-0.98
4/19/93	29.8	20.4			9.4		
6/29/93	28.79	18.1	18.52		10.69	10.27	-0.42
8/25/93	27.9	20.1	18.5		7.8	9.4	1.6
10/4/93	27.54	18.66	18.61		8.88	8.93	0.05
10/20/93	27.4	18.1	18.8		9.3	8.6	-0.7
AVG 93	28.89	20.12	20.40		8.77	8.34	-0.32
STD 93	1.24	2.06	2.77		1.26	1.70	0.98
AVG 87-93	27.57	22.39	22.64		5.18	4.84	-0.18
STD 87-93	2.72	4.01	3.95		3.14	2.48	1.58

SITE 21	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/5/93	27.84	25.75	24.85		2.09	2.99	0.90	
4/2/93	26.70	24.43	23.24		2.27	3.46	1.19	
5/20/93	25.2	22.9	21.6		2.3	3.6	1.3	
6/30/93	24.83	22.50	21.24		2.33	3.59	1.26	
10/4/93	25.30	23.09	22.14		2.21	3.16	0.95	
AVG 93	25.97	23.73	22.61		2.24	3.36	1.12	
STD 93	1.13	1.20	1.31		0.08	0.24	0.16	
AVG 87-93	27.03	25.07	23.94		1.97	3.09	1.12	
STD 87-93	1.22	1.40	1.34		0.38	0.41	0.44	
SITE 22	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/13/93	29.75	26.68	19.31		3.07	10.44	7.37	
2/18/93	29.87	26.13	18.02		3.74	11.85	8.11	
3/18/93	29.47	24.96	16.21		4.51	13.26	8.75	
3/25/93	29.3	24.7	16.1		4.6	13.2	8.6	
4/14/93	28.62	24.00	15.58		4.62	13.04	8.42	
5/18/93	28.03	23.17	14.46		4.86	13.57	8.71	
5/21/93	28.0	23.0			5.0			
6/16/93	27.52	22.50	14.14		5.02	13.38	8.36	
7/9/93	26.9	21.3			5.6	26.9	21.3	
7/15/93	26.70	20.79	10.93		5.91	15.77	9.86	
7/30/93	25.8	18.2			7.6			
8/11/93	25.22	18.36	9.26		6.86	15.96	9.1	
9/9/93	24.89	18.89	10.76		6.00	14.13	8.13	
10/5/93	24.79	19.22	11.47		5.57	13.32	7.75	
10/14/93	24.8	19.2			5.6			
AVG 93	27.31	22.07	14.20		5.24	14.57	9.54	
STD 93	1.82	2.79	3.09		1.10	3.98	3.60	
AVG 87-93	30.18	27.80	20.17		2.38	10.32	8.01	
STD 87-93	1.68	2.95	2.94		1.46	2.41	1.56	
SITE 23	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/6/93	25.57	23.90	23.80		1.67	1.77	0.10	
3/29/93	24.22	22.99	21.42		1.23	2.80	1.57	
7/1/93	22.44	20.87	19.54		1.57	2.90	1.33	
10/5/93	21.25	18.57	19.20		2.68	2.05	-0.63	
AVG 93	23.37	21.58	20.99		1.79	2.38	0.59	
STD 93	1.65	2.06	1.83		0.54	0.48	0.90	
AVG 87-93	25.26	23.98	23.79		1.28	1.48	0.19	
STD 87-93	1.29	1.55	1.73		0.67	1.08	0.96	
SITE 24	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/6/93	33.02	31.56			1.46			
3/29/93	31.06	28.48			2.58			
4/20/93	30.0	27.3			2.7			

6/30/93	26.57	22.44	22.46		4.13	4.11	-0.02
10/5/93	23.18	20.75	20.5		2.43	2.68	0.25
10/23/93	23.8	21.2	21.0		2.6	2.8	0.2
AVG 93	27.94	25.29	21.32		2.65	3.20	0.14
STD 93	3.68	4.06	0.83		0.78	0.65	0.12
AVG 87-93	31.03	29.39	24.78		1.64	2.58	0.15
STD 87-93	3.00	3.57	3.11		0.82	0.70	0.09
SITE 25	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/6/93	15.12	15.81	9.28		-0.69	5.84	6.53
3/28/93	11.4	12.0	6.3		-0.6	5.1	5.7
3/29/93	11.41	12.01	6.30		-0.60	5.11	5.71
6/30/93	7.00	7.67	2.81		-0.67	4.19	4.86
7/31/93	5.9	6.6	2.2		-0.7	3.7	4.4
9/14/93	8.3	9.2	4.3		-0.9	4.0	4.9
10/5/93	9.15	9.97	4.70		-0.82	4.45	5.27
10/13/93	9.4	10.2	4.8		-0.8	4.6	5.4
10/22/93	9.6	10.5	4.9		-0.9	4.7	5.6
AVG 93	9.70	10.44	5.07		-0.74	4.63	5.37
STD 93	2.57	2.54	1.97		0.11	0.62	0.58
AVG 87-93	13.72	14.34	8.29		-0.62	5.42	6.05
STD 87-93	3.21	3.20	2.53		0.22	0.72	0.74
SITE 26	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/6/93	20.66	16.35	12.15		4.31	8.51	4.20
3/29/93	17.23	12.21	7.78		5.02	9.45	4.43
4/20/93	16.2	11.1	6.8		5.1	9.4	4.3
6/30/93	14.79	9.86	5.70		4.93	9.09	4.16
10/5/93	15.21	10.83	7.50		4.38	7.71	3.33
AVG 93	16.82	12.07	7.99		4.75	8.83	4.08
STD 93	2.10	2.27	2.20		0.33	0.65	0.39
AVG 87-93	20.17	15.61	11.39		4.56	8.78	4.22
STD 87-93	2.55	2.69	2.78		0.46	0.81	0.43
SITE 27	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/6/93	13.81	13.36	13.45		0.65	0.63	-0.02
3/29/93	10.75	10.10	10.12		0.66	1.04	0.38
6/30/93	8.73	8.07	7.69		0.66	1.04	0.38
10/5/93	9.80	9.29	9.46		0.51	0.34	-0.17
AVG 93	10.77	10.21	10.18		0.62	0.76	0.14
STD 93	1.89	1.96	2.09		0.06	0.30	0.24
AVG 87-93	13.14	12.41	12.51		0.73	0.65	-0.08
STD 87-93	1.92	2.07	2.10		0.53	0.52	0.17
SITE 28	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3

1/6/93	25.77	25.60	25.52		0.17	0.25	0.08	
3/29/93	24.90	24.37	24.27		0.53	0.63	0.10	
6/30/93	22.47	21.46	21.37		1.01	1.10	0.09	
10/4/93	21.87	21.28	21.18		0.59	0.69	0.10	
AVG 93	23.75	23.18	23.09		0.58	0.67	0.09	
STD 93	1.63	1.86	1.86		0.30	0.30	0.01	
AVG 87-93	24.58	24.35	24.37		0.22	0.21	-0.02	
STD 87-93	1.35	1.60	1.53		0.35	0.34	0.24	
SITE 29	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/6/93	50.99	38.56	39.25		12.43	11.74	-0.69	
4/2/93	50.50	38.20	38.72		12.30	11.78	-0.52	
4/25/93	50.3	38.0	38.6		12.3	11.7	-0.6	
6/30/93	49.60	36.27	36.80		13.33	12.80	-0.53	
10/4/93	49.29	35.09	35.66		14.20	13.63	-0.57	
10/22/93	49.3	35.1	35.6		14.2	13.7	-0.5	
AVG 93	50.00	36.87	37.44		13.13	12.56	-0.57	
STD 93	0.64	1.45	1.48		0.84	0.87	0.06	
AVG 87-93	50.19	37.15	37.69		13.04	12.49	-0.55	
STD 87-93	0.93	1.52	1.55		0.69	0.71	0.05	
SITE 30	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/6/93	20.83	19.14	19.11		1.69	1.72	0.03	
3/29/93	17.30	14.57	14.54		2.73	2.76	0.03	
6/29/93	14.86	11.95	11.93		2.91	2.93	0.02	
10/1/93	16.52	14.94	14.97		1.58	1.55	-0.03	
AVG 93	17.38	15.15	15.14		2.23	2.24	0.01	
STD 93	2.18	2.58	2.57		0.60	0.61	0.02	
AVG 87-93	21.66	20.43	20.49		1.24	1.17	-0.06	
STD 87-93	2.50	3.14	3.19		0.86	0.95	0.21	
SITE 31	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/6/93	14.71	15.02	15.62		-0.31	-0.91	-0.6	
3/29/93	13.43	13.78	13.65		-0.35	-0.22	0.13	
4/20/93	13.1	13.4			-0.3			
6/30/93	12.28	12.66	12.25		-0.38	0.03	0.41	
10/5/93	13.65	14.01	13.67		-0.36	-0.02	0.34	
10/23/93	13.7	14.1	14.0		-0.4	-0.3	0.1	
AVG 93	13.48	13.83	13.84		-0.35	-0.28	0.08	
STD 93	0.73	0.72	1.08		0.04	0.34	0.36	
AVG 87-93	14.66	14.69	15.67		-0.03	-0.95	-0.94	
STD 87-93	1.05	0.89	1.33		0.29	0.44	0.59	
SITE 32	WELL 1	WELL 2	WELL 3	WELL 4	1-2	1-3	2-3	1-4
1/6/93	48.58	48.40	5.57	7.68	0.18	43.01	42.83	40.90

3/29/93	45.83	45.88	1.48	2.60	-0.05	44.35	44.40	43.23
6/30/93	44.77	44.95	0.69	3.21	-0.18	44.08	44.26	41.56
10/4/93	45.79	46.01	2.54	6.00	-0.22	43.25	43.47	39.79
AVG 93	46.24	46.31	2.57	4.87	-0.07	43.67	43.74	41.37
STD 93	1.41	1.27	1.85	2.07	0.16	0.56	0.63	1.25
AVG 87-93	48.34	48.57	5.81	8.81	-0.23	42.54	42.76	
STD 87-93	1.69	1.86	2.96	3.51	0.42	1.47	1.31	
SITE 33	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/5/93	35.94	35.17	35.58		0.77	0.36	-0.41	
4/1/93	35.01	34.08	34.70		0.93	0.31	-0.62	
6/29/93	33.25	32.19	32.95		1.06	0.30	-0.76	
10/4/93	32.10	31.12	31.20		0.98	0.90	-0.08	
AVG 93	34.08	33.14	33.61		0.94	0.47	-0.47	
STD 93	1.49	1.58	1.68		0.11	0.25	0.26	
AVG 87-93	33.96	33.14	33.37		0.83	0.59	-0.24	
STD 87-93	1.28	1.44	1.49		0.42	0.46	0.24	
SITE 34	WELL 1	WELL 2			1-2			
1/5/93	9.19	8.34			0.85			
4/2/93	7.82	6.94			0.88			
6/30/93	7.73	6.75			0.98			
10/4/93	8.89	7.83			1.06			
AVG 93	8.41	7.47			0.94			
STD 93	0.64	0.65			0.08			
AVG 87-93	9.75	8.95			0.79			
STD 87-93	0.88	0.94			0.12			
SITE 35	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/5/93	25.90	25.17	20.93		0.73	4.97	4.24	
4/2/93	24.88	23.95	19.39		0.93	5.49	4.56	
6/30/93	22.79	21.74	16.34		1.05	6.45	5.40	
10/4/93	22.95	21.95	17.38		1.00	5.57	4.57	
AVG 93	24.13	23.20	18.51		0.93	5.62	4.69	
STD 93	1.31	1.43	1.78		0.12	0.53	0.43	
AVG 87-93	24.99	24.06	19.63		0.93	5.36	4.43	
STD 87-93	1.98	2.05	2.16		0.09	0.47	0.46	
SITE 36	WELL 1	WELL 2	WELL 3	WELL 4	1-2	1-3	2-3	1-4
1/5/93	30.64	28.85	27.12	29.53	1.79	3.52	1.73	1.11
4/1/93	30.05	27.96	26.19	28.12	2.09	3.86	1.77	1.93
4/21/93	29.9	27.8	26.0	28.0	2.1	3.9	1.8	1.9
6/29/93	28.68	26.59	24.79	26.77	2.09	3.89	1.8	1.91
9/16/93	28.7	26.6	24.8	27.1	2.1	3.9	1.8	1.6
10/4/93	28.64	27.66	24.8	27.14	0.98	3.84	2.86	1.5

10/15/93	28.6	27.6	24.8	27.2	1.0	3.8	2.8	1.4
AVG 93	29.32	27.58	25.50	27.69	1.74	3.82	2.08	1.62
STD 93	0.79	0.73	0.87	0.88	0.48	0.13	0.48	0.29
AVG 87-93	29.04	27.06	25.19	27.73	1.98	3.85	1.87	
STD 87-93	1.08	1.07	1.13	1.05	0.30	0.10	0.28	
SITE 37	WELL 1	WELL 2	WELL 3	WELL 4	1-3		3-4	1-4
1/4/93	60.93		59.61	59.14	1.32		0.47	1.79
4/1/93	60.84		59.06	58.63	1.78		0.43	2.21
6/29/93	60.16		58.77	58.26	1.39		0.51	1.90
10/1/93	60.38		59.55	58.99	0.83		0.56	1.39
AVG 93	60.58		59.25	58.76	1.33		0.49	1.82
STD 93	0.32		0.35	0.34	0.34		0.05	0.29
AVG 87-93	59.15		58.43	57.70	0.71	1.44	0.73	
STD 87-93	1.29		1.63	1.45	1.14	0.73	0.65	
SITE 38	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/5/93	33.48	32.96	28.20		0.52	5.28	4.76	
4/1/93	32.17	31.70	26.35		0.47	5.82	5.35	
6/30/93	29.98	29.42	23.82		0.56	6.16	5.60	
10/4/93	29.94	29.41	24.37		0.53	5.57	5.04	
AVG 93	31.39	30.87	25.69		0.52	5.71	5.19	
STD 93	1.51	1.52	1.73		0.03	0.32	0.32	
AVG 87-93	31.80	31.32	26.38		0.48	5.42	4.94	
STD 87-93	2.46	2.49	2.55		0.09	0.40	0.38	
SITE 39	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/5/93	6.10	4.15	2.92		1.95	3.18	1.23	
2/19/93	5.51	3.19	2.04		2.32	3.47	1.15	
3/22/93	5.14	3.00	2.00		2.14	3.14	1.00	
4/16/93	4.98	2.93	1.92		2.05	3.06	1.01	
5/20/93	4.70	2.05	1.15		2.65	3.55	0.90	
6/19/93	4.77	3.02	2.22		1.75	2.55	0.80	
7/15/93	4.95	2.50	1.13		2.45	3.82	1.37	
8/10/93	4.98	3.02	2.30		1.96	2.68	0.72	
9/9/93	5.50	3.99	3.15		1.51	2.35	0.84	
10/22/93	6.12	4.33	3.18		1.79	2.94	1.15	
AVG 93	5.28	3.22	2.20		2.06	3.07	1.02	
STD 93	0.49	0.69	0.69		0.33	0.44	0.20	
AVG 87-93	6.35	4.71	3.47		1.64	2.80	1.11	
STD 87-93	0.97	1.37	1.26		0.48	0.53	0.42	
SITE 40	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3	
1/5/93	58.46	58.44	58.57		0.02	-0.11	-0.13	
4/2/93	57.00	56.77	56.85		0.23	0.15	-0.08	

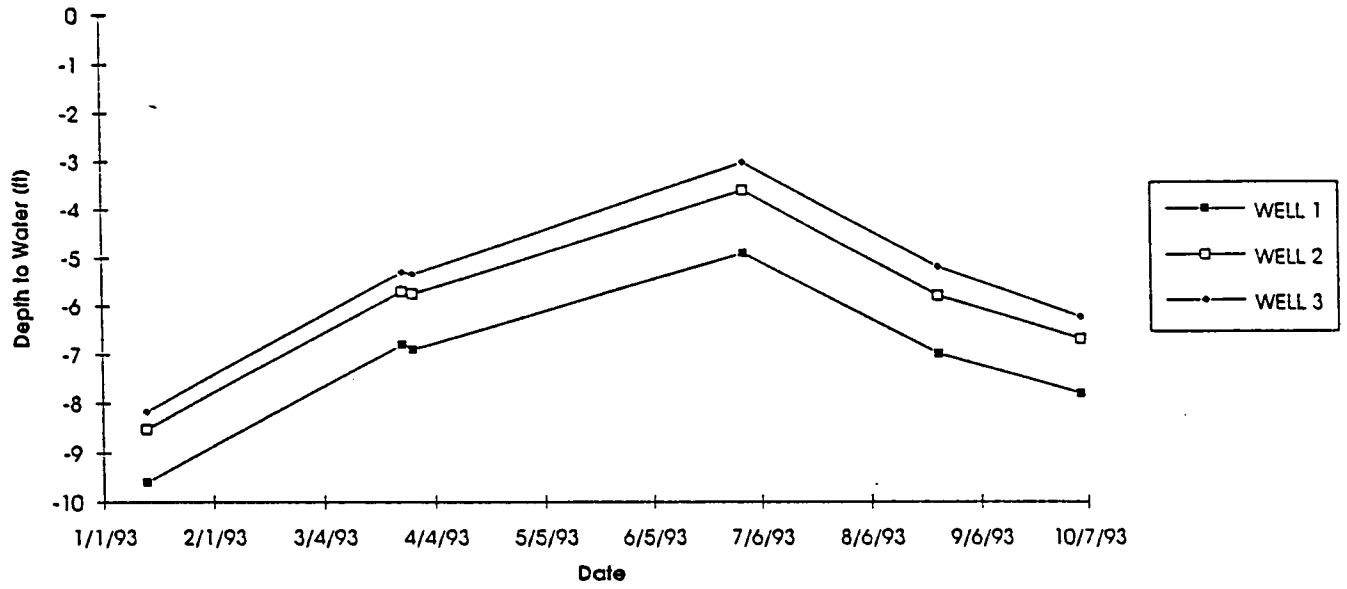
AVG 87-93	67.50	67.47	75.73	75.53	0.03	-8.24	-8.26
STD 87-93	0.91	0.91	0.70	1.28	0.05	0.28	0.26
SITE 45	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/5/93	49.42	49.42	48.58		0.00	0.84	0.84
4/2/93	48.65	48.69	47.77		-0.04	0.88	0.92
6/29/93	47.23	47.30	46.44		-0.07	0.79	0.86
10/1/93	46.66	46.71	45.78		-0.05	0.88	0.93
AVG 93	47.99	48.03	47.14		-0.04	0.85	0.89
STD 93	1.10	1.08	1.10		0.03	0.04	0.04
AVG 87-93	46.68	46.66	45.75		0.02	0.93	0.91
STD 87-93	1.99	2.02	2.06		0.04	0.16	0.14
SITE 46	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/5/93	52.03	47.89	47.83		4.14	4.20	0.06
4/1/93	51.65	47.37	47.28		4.28	4.37	0.09
6/29/93	50.74	45.17	45.13		5.57	5.61	0.04
10/1/93	50.66	45.28	45.18		5.38	5.48	0.10
AVG 93	51.27	46.43	46.36		4.84	4.92	0.07
STD 93	0.59	1.22	1.22		0.64	0.63	0.02
AVG 87-93	49.51	44.80	44.72		4.71	4.79	0.08
STD 87-93	1.96	2.65	2.63		0.79	0.77	0.04
SITE 47	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/4/93	77.11	71.94	71.51		5.17	5.60	0.43
4/1/93	77.05	71.86	71.44		5.19	5.61	0.42
6/29/93	77.21	71.36	70.93		5.85	6.28	0.43
10/1/93	77.56	71.59	71.15		5.97	6.41	0.44
AVG 93	77.23	71.69	71.26		5.55	5.98	0.43
STD 93	0.20	0.23	0.23		0.37	0.37	0.01
AVG 87-93	76.25	70.74	70.30		5.51	5.95	0.44
STD 87-93	0.66	0.80	0.82		0.26	0.27	0.04
SITE 48	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/5/93	62.86	56.40	56.54		6.46	6.32	-0.14
4/1/93	62.85	56.36	56.59		6.49	6.26	-0.23
6/29/93	62.87	55.74	55.83		7.13	7.04	-0.09
10/1/93	62.90	55.43	55.55		7.47	7.35	-0.12
AVG 93	62.87	55.98	56.13		6.89	6.74	-0.14
STD 93	0.02	0.41	0.45		0.43	0.47	0.05
AVG 87-93	61.03	53.72	53.79		7.32	7.24	-0.07
STD 87-93	1.25	1.78	1.80		0.78	0.80	0.25
SITE 49	WELL 1	WELL 2	WELL 3	WELL 4			3-4
4/1/93	CAPPED	CAPPED	0.33	-0.75			1.08

6/30/93	CAPPED	CAPPED	0.74	-0.75			1.49
7/7/93	CAPPED	CAPPED	-0.27	-1.30			1.00
10/1/93	CAPPED	CAPPED	1.60	0.56			1.04
AVG 93			0.60	-0.56			1.15
STD 93			0.68	0.68			0.20
AVG 87-93			1.06	-0.01			1.07
STD 87-93			0.57	0.61			0.12
SITE 50	WELL 1	WELL 2	WELL 3		1-2	1-3	2-3
1/14/93	26.95	28.12	27.17		-1.17	-0.22	0.95
3/29/93	25.94	26.09	26.15		-0.15	-0.21	-0.06
7/1/93	24.82	25.04	25.09		-0.22	-0.27	-0.05
9/22/93	22.60	22.84	22.96		-0.24	-0.36	-0.12
10/20/93	22.32	22.48	22.57		-0.16	-0.25	-0.09
AVG 93	24.53	24.91	24.79		-0.39	-0.26	0.13
STD 93	1.82	2.09	1.78		0.39	0.05	0.41
AVG 87-93	26.28	26.55	26.50		-0.27	-0.22	0.05
STD 87-93	1.61	1.67	1.56		0.22	0.14	0.24
SITE 51	WELL 1	WELL 2			1-2		
1/14/93	19.57	19.00			0.57		
3/29/93	17.83	17.30			0.53		
7/1/93	15.94	15.59			0.35		
10/5/93	14.05	13.78			0.27		
AVG 93	16.85	16.42			0.43		
STD 93	2.06	1.94			0.12		
AVG 87-93	19.22	18.51			0.52		
STD 87-93	1.94	2.08			0.11		
SITE 52	WELL 1	WELL 2			1-2		
1/14/93	31.40	31.53			-0.13		
3/29/93	30.40	30.79			-0.39		
7/1/93	27.87	28.64			-0.77		
10/5/93	23.98	24.00			-0.02		
AVG 93	28.41	28.74			-0.33		
STD 93	2.86	2.94			0.29		
AVG 87-93	29.02	28.80			0.22		
STD 87-93	2.55	2.49			0.43		

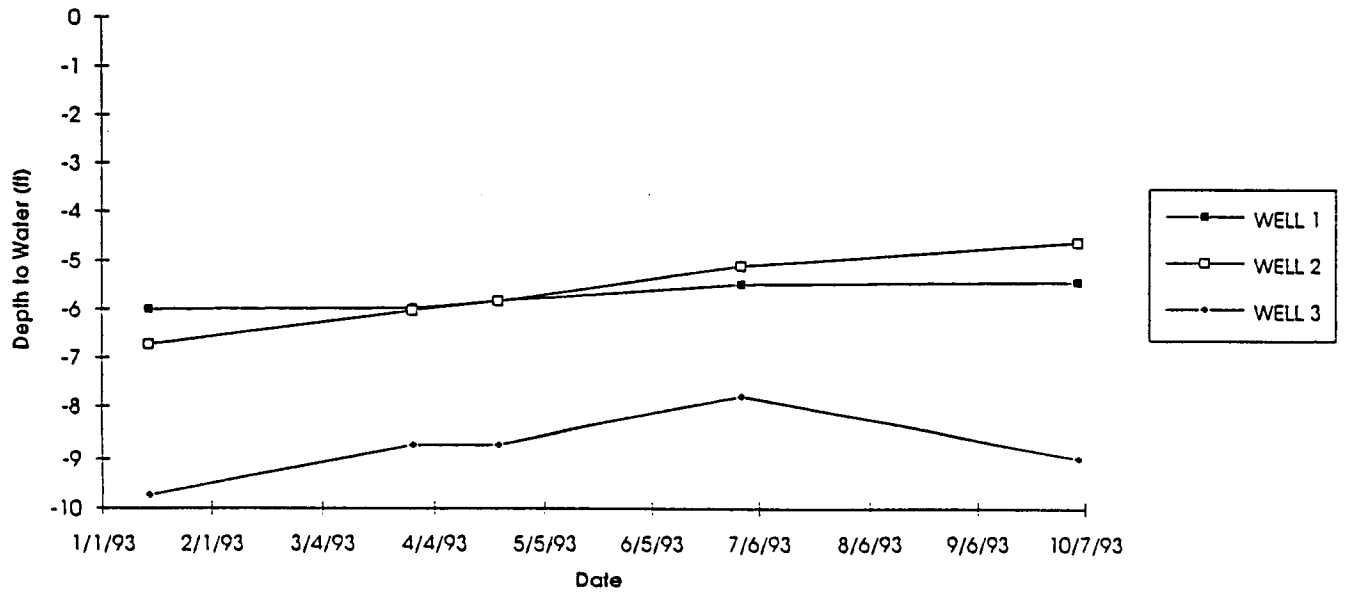
Appendix C: Monitoring Well Hydrographs, 1993

This appendix presents plots of measured water elevations during 1993 for the monitoring well sites, based on data contained in Appendix B. Similar data for the Siefkes intensive study site are presented in text Table 4 and plotted in text Figures 14-16. The lines connecting the data points are for visual assistance in identifying trends, and do not necessarily depict the actual behavior of the water elevations over those periods. See the introduction to Appendix B and the text for further discussion of the significance of the data.

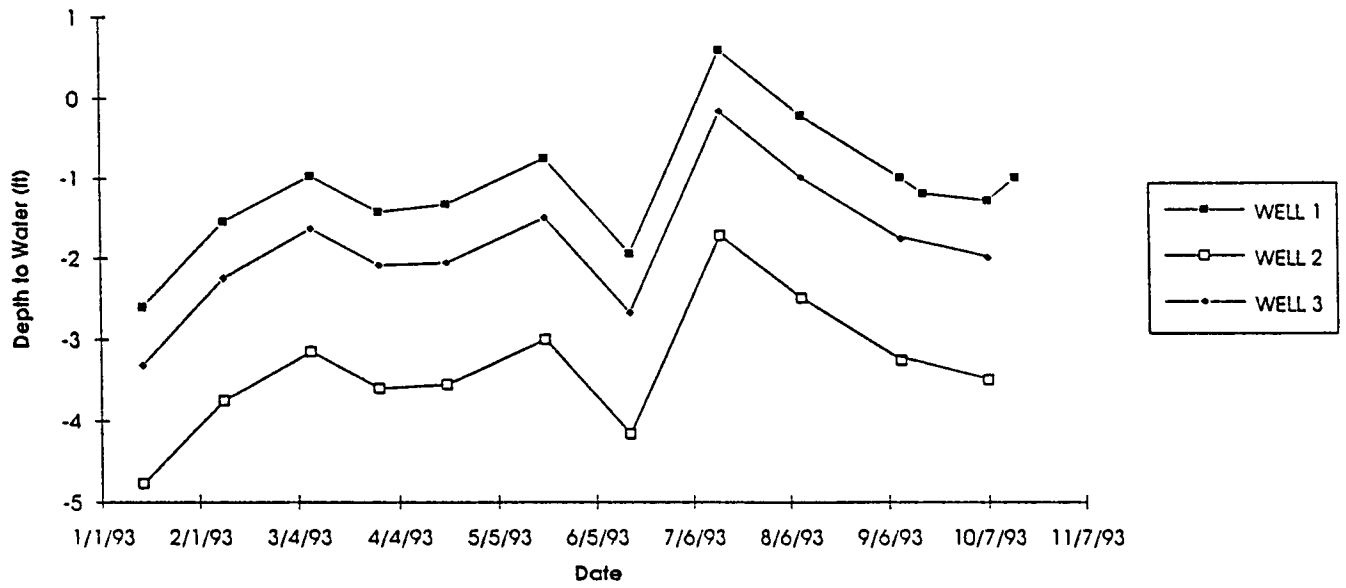
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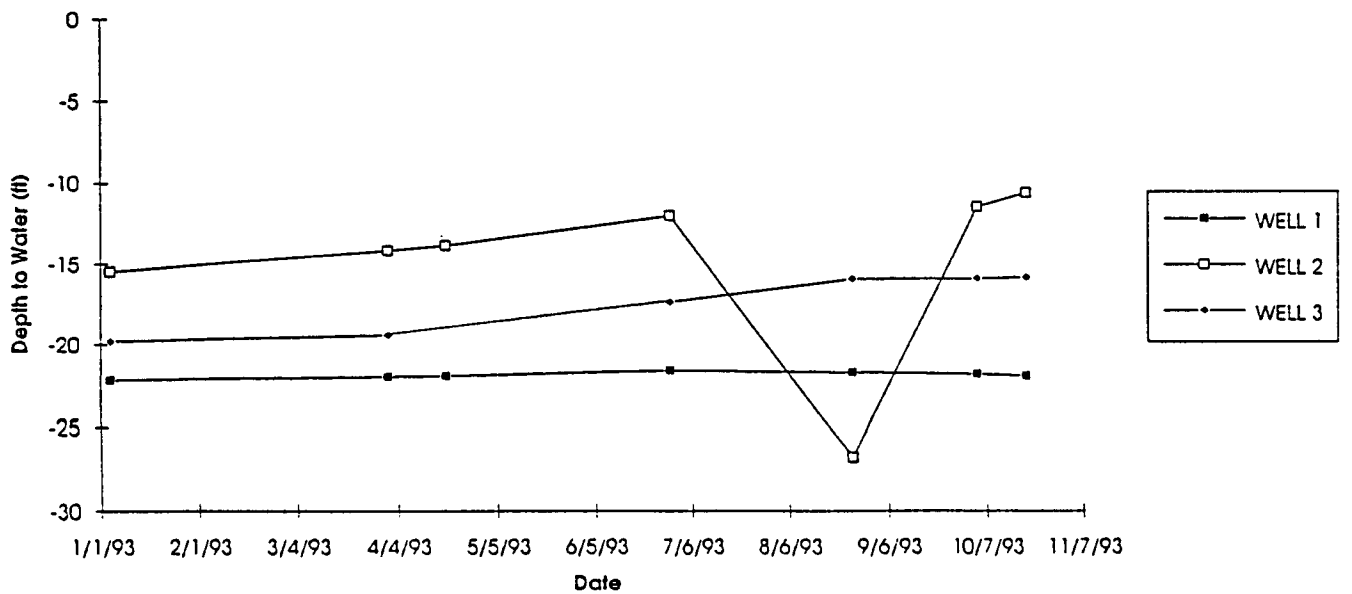
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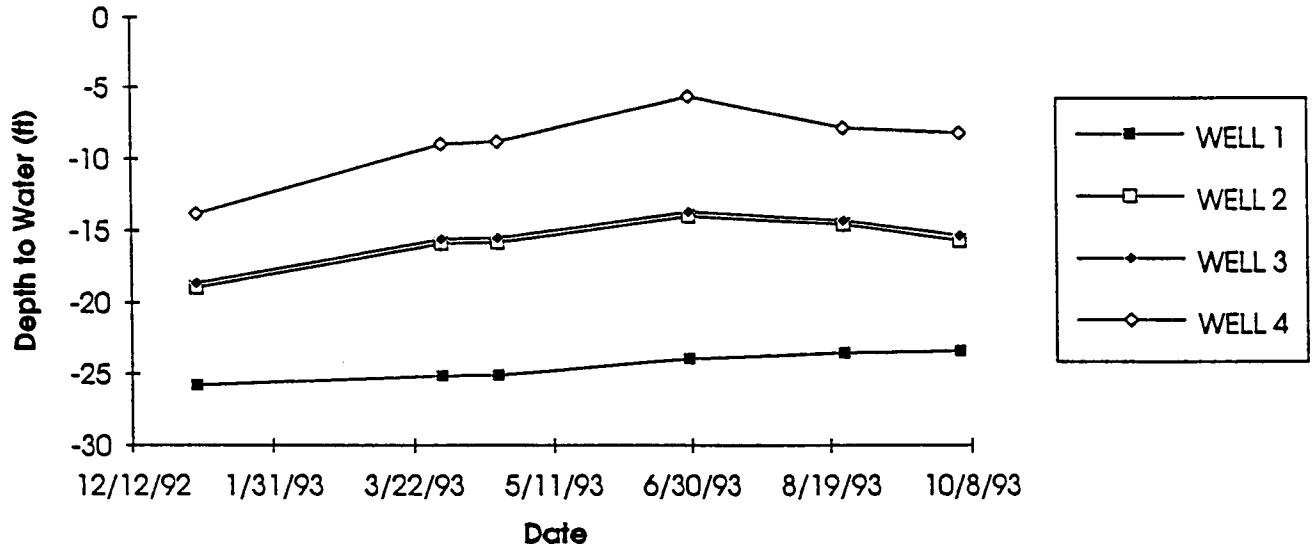
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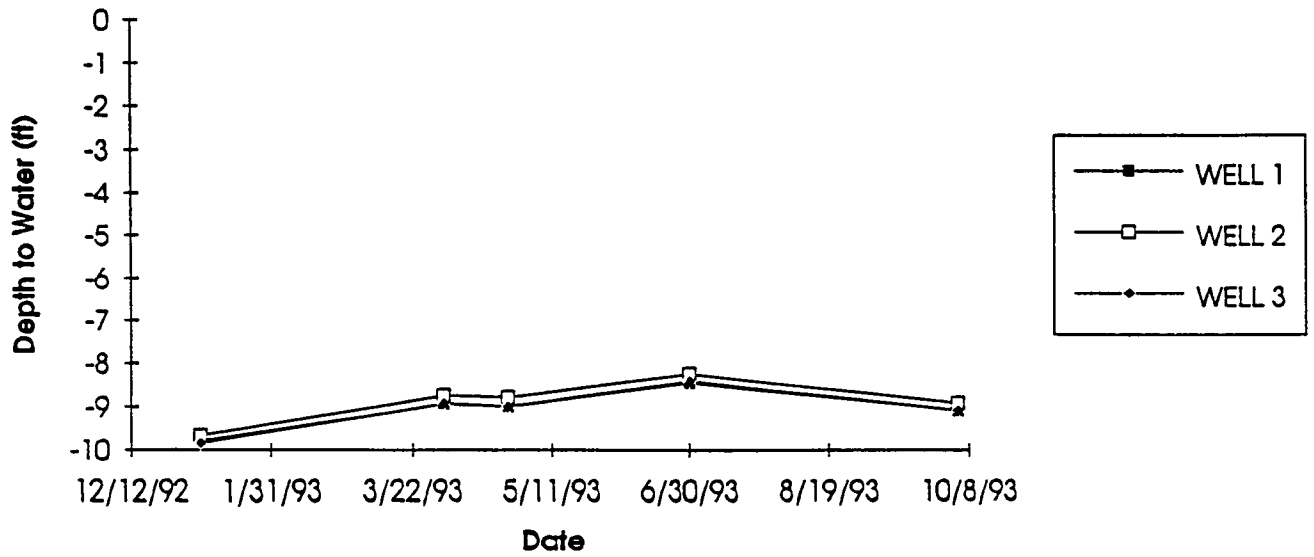
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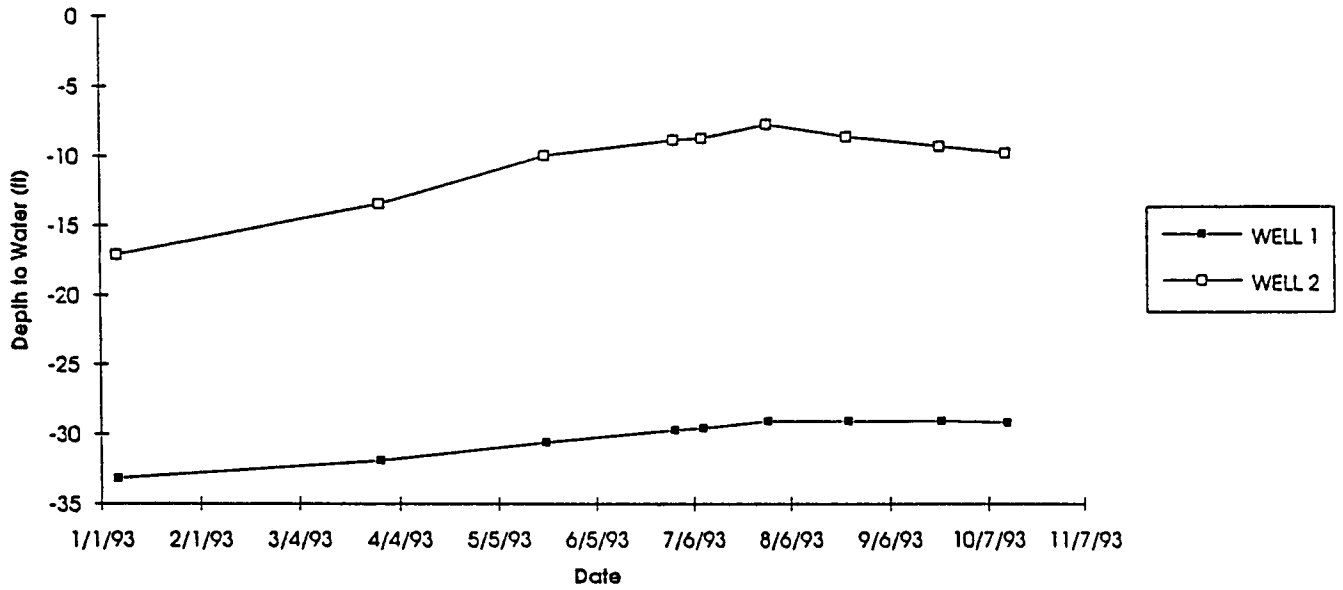
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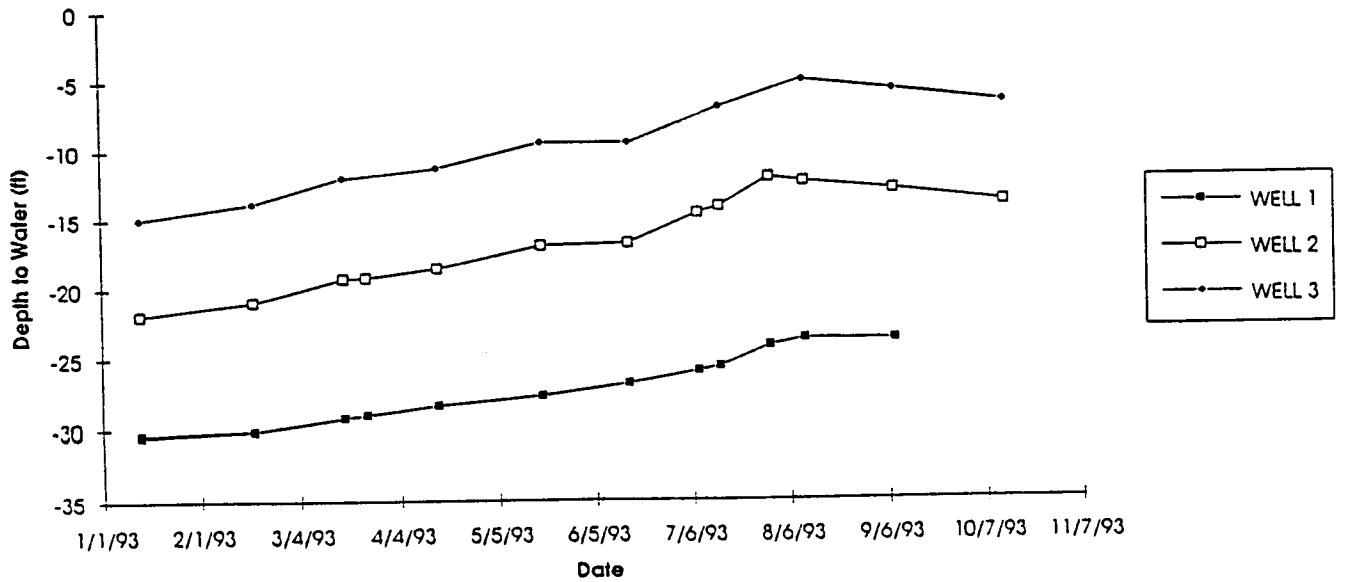
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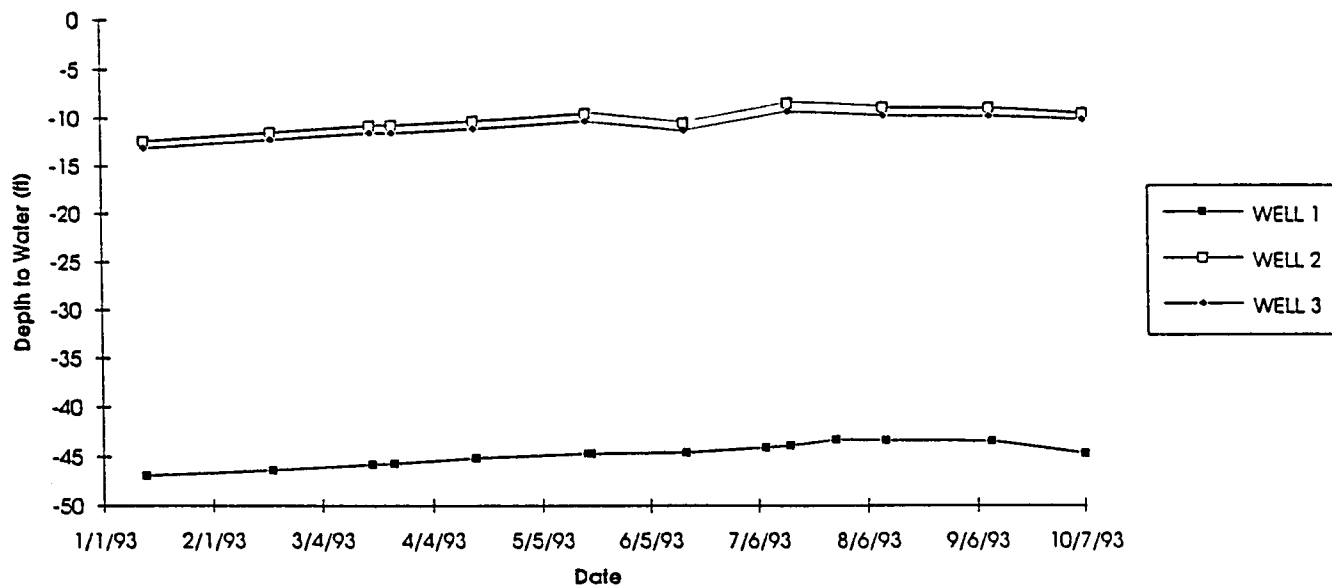
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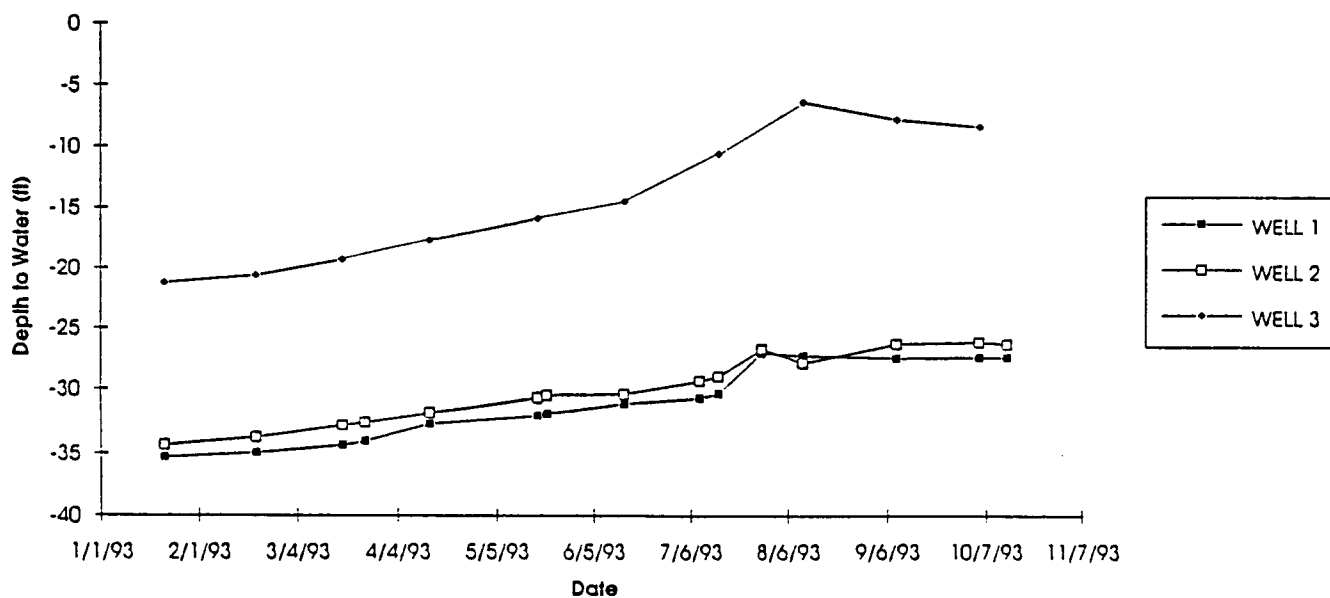
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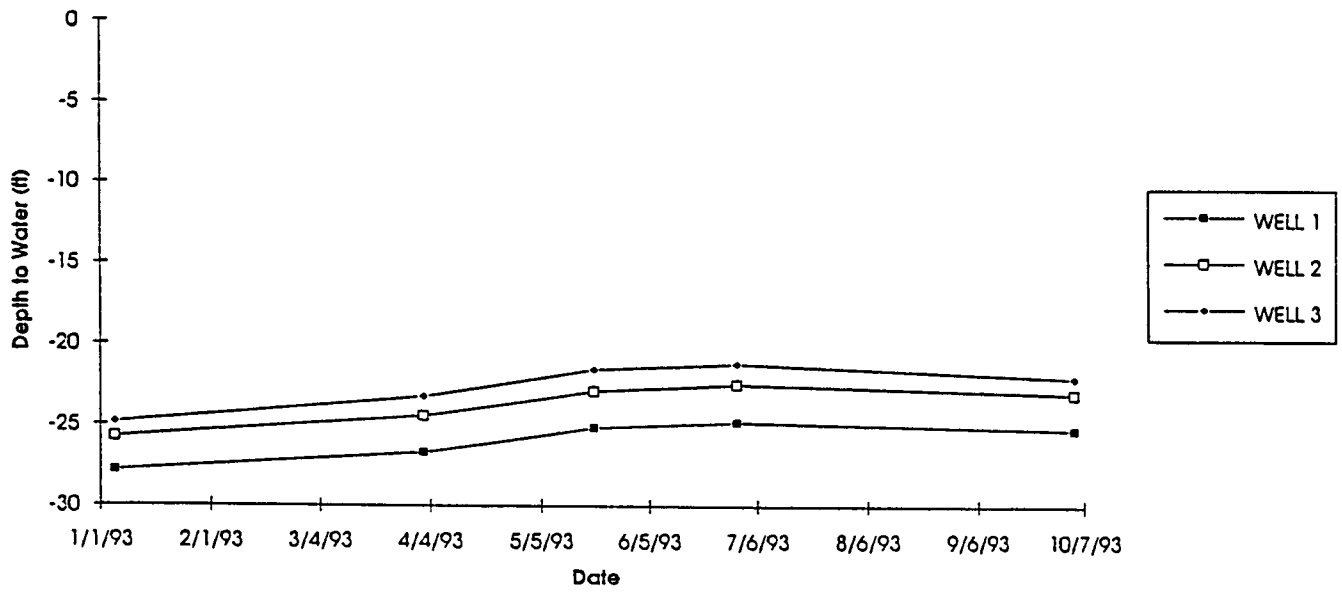
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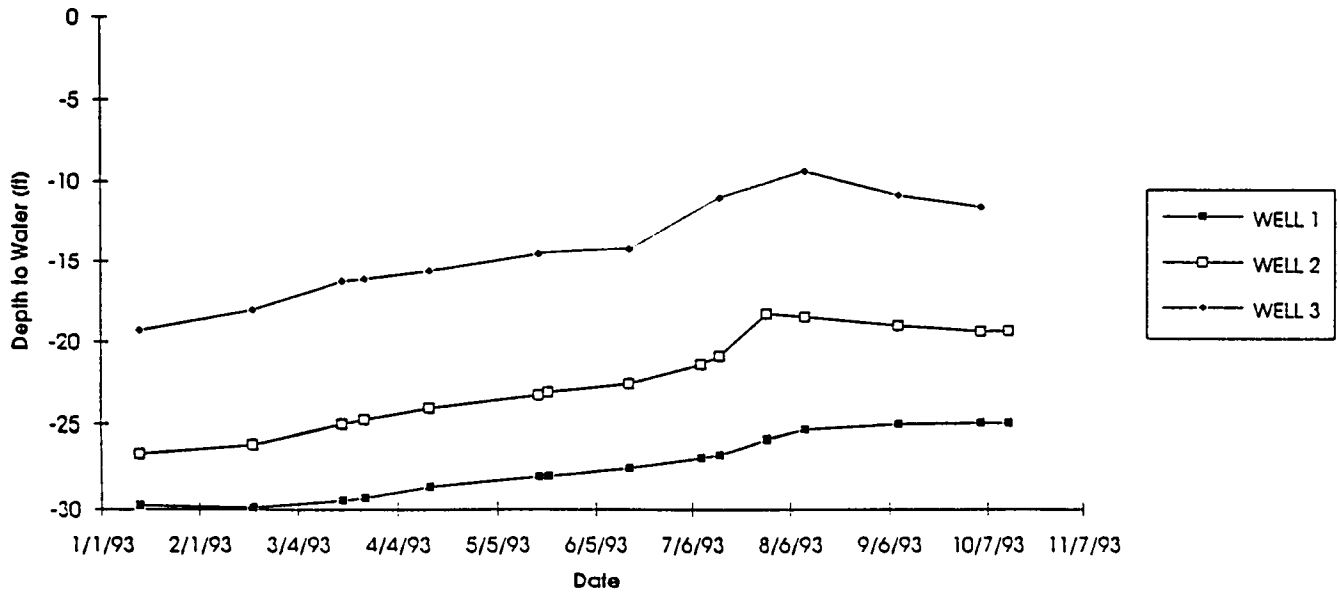
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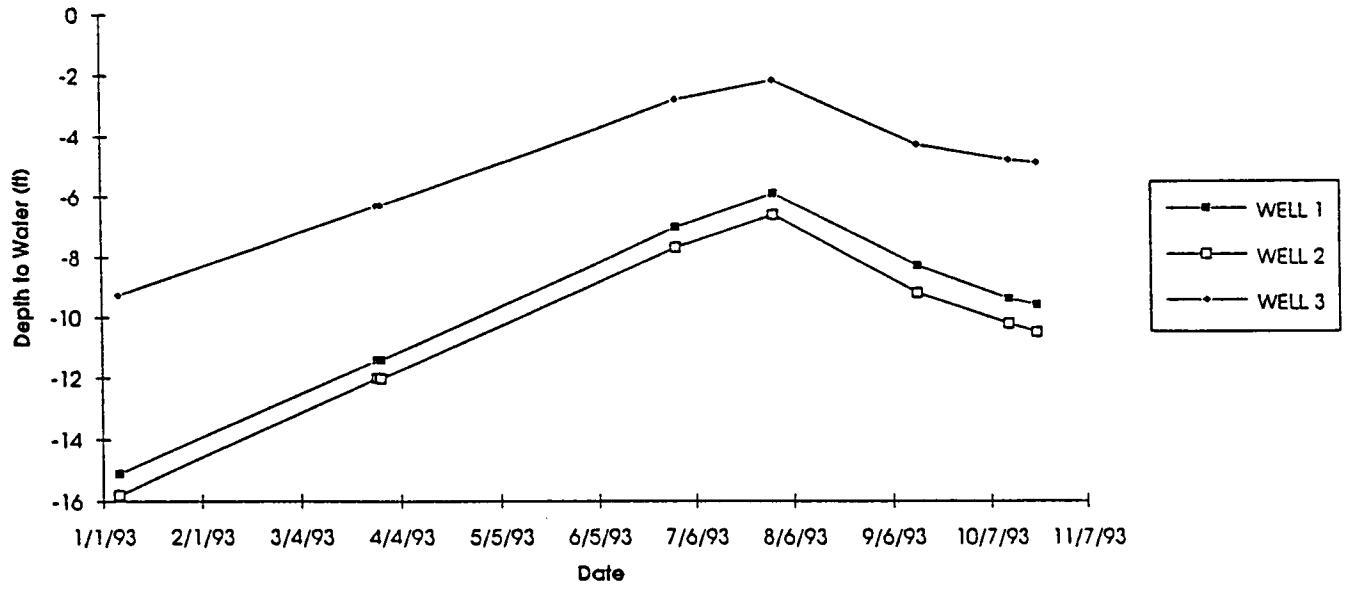
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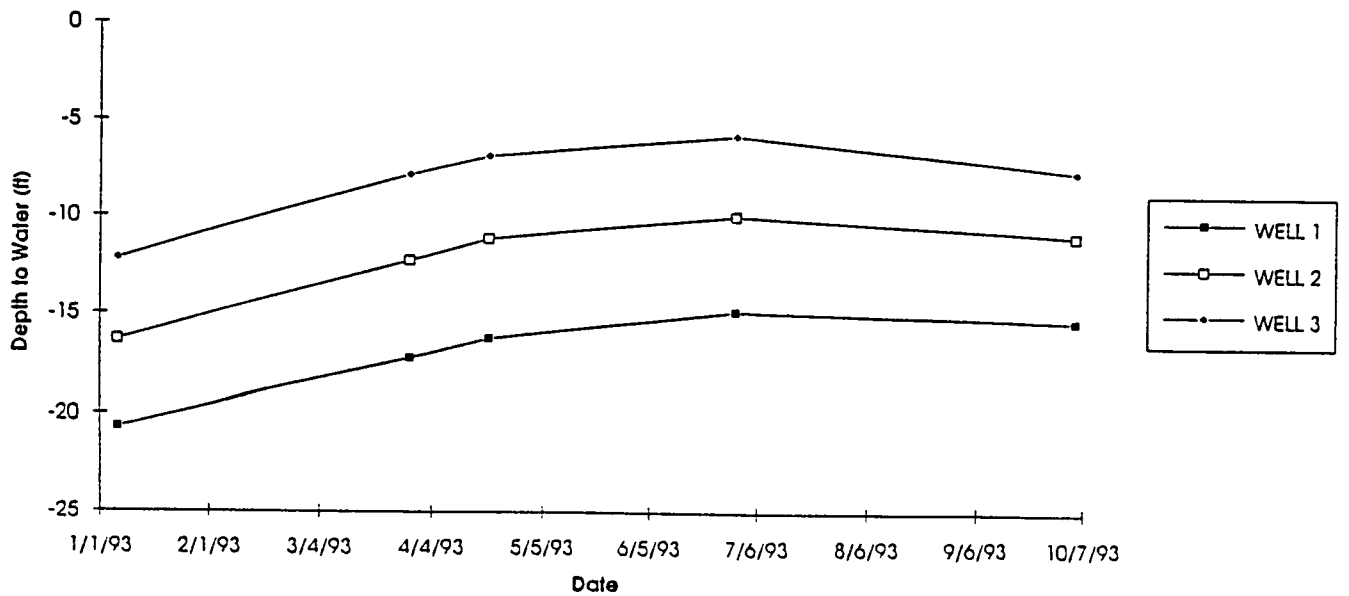
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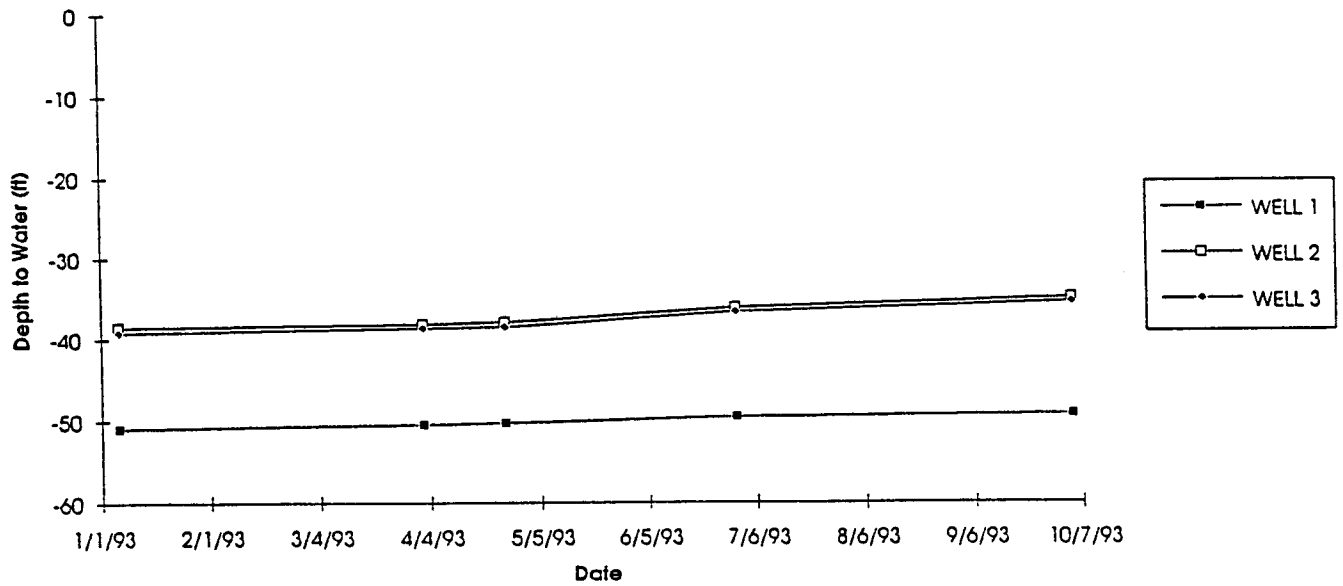
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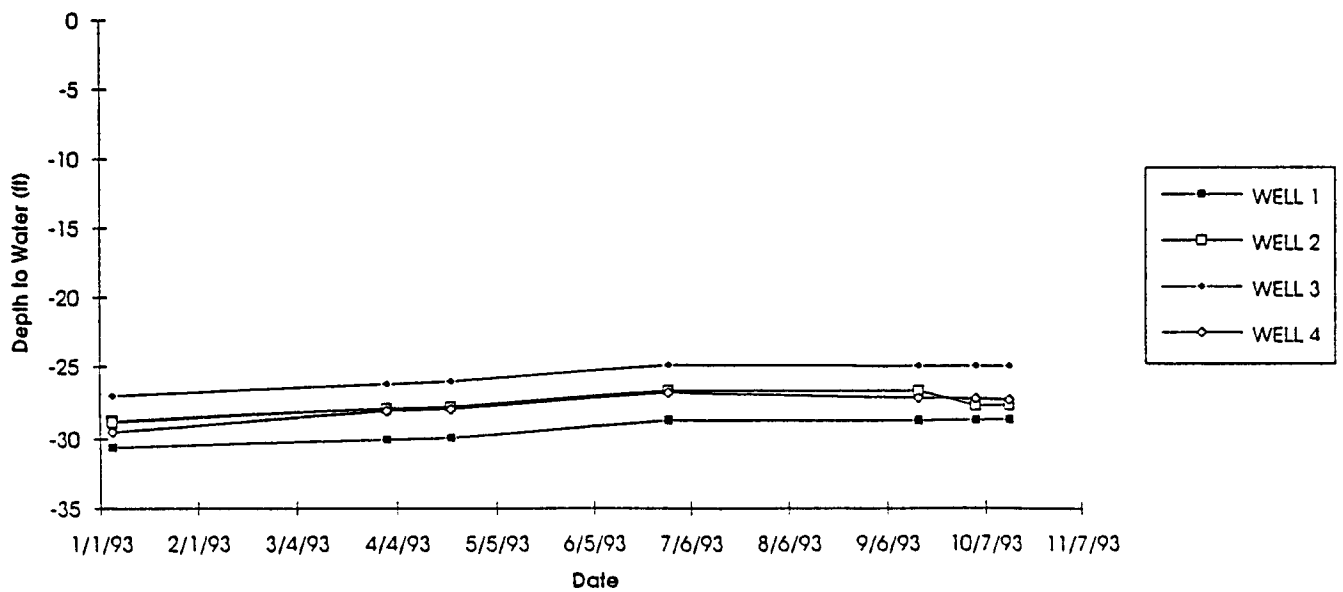
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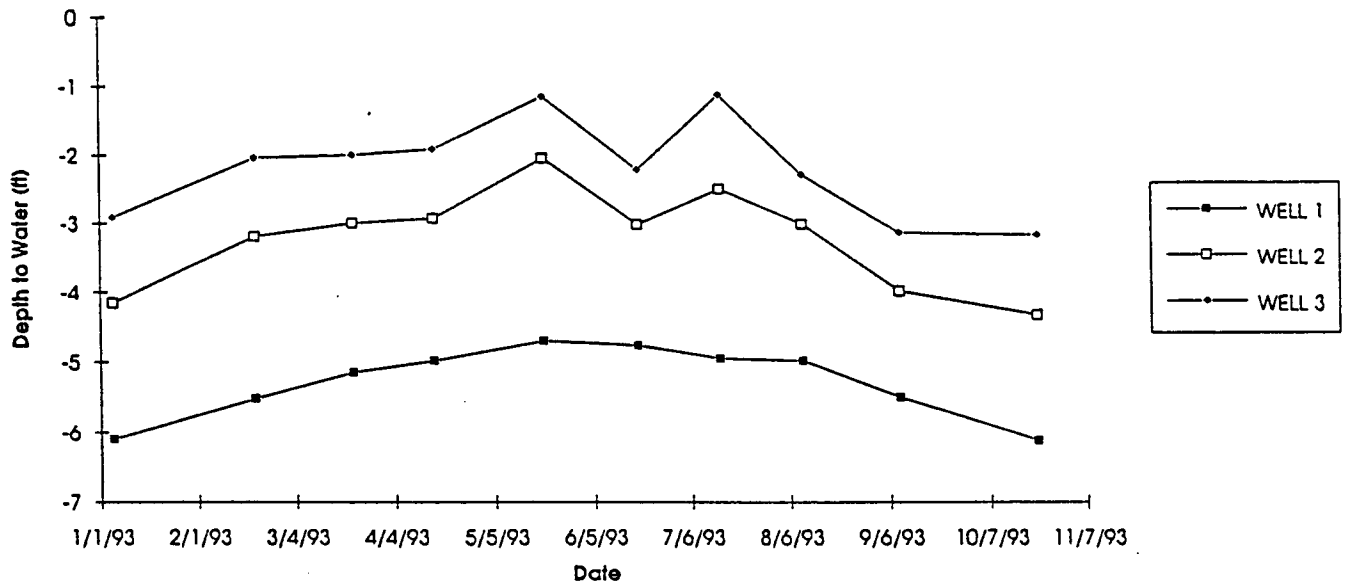
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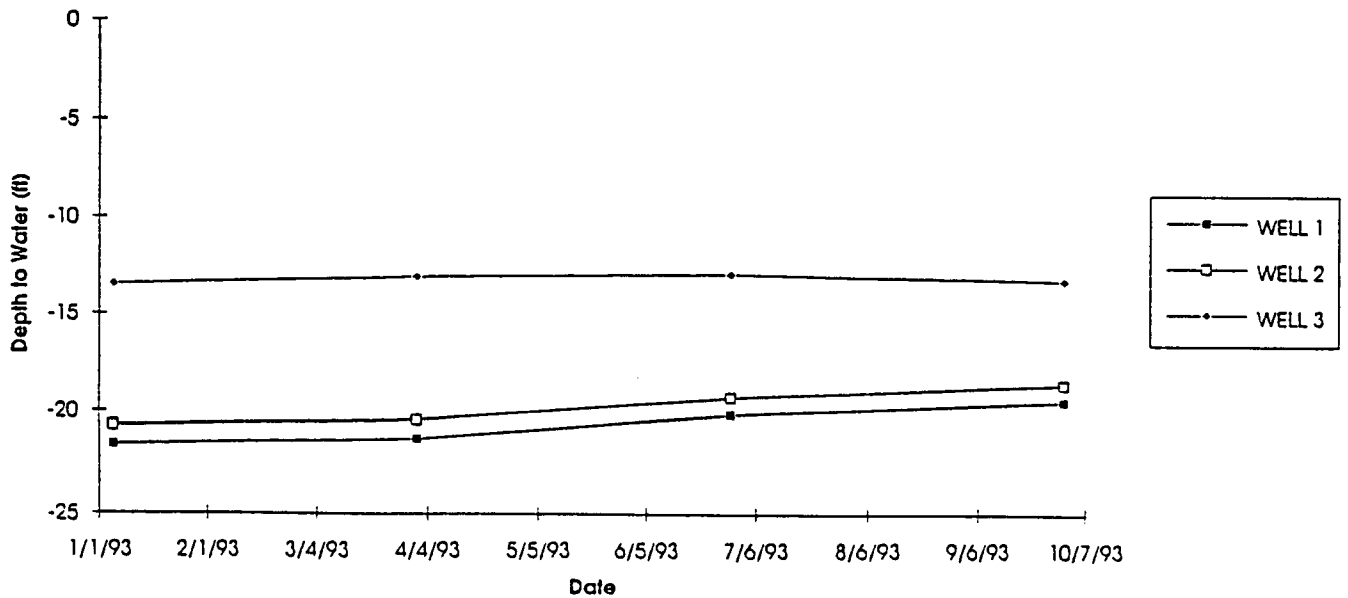
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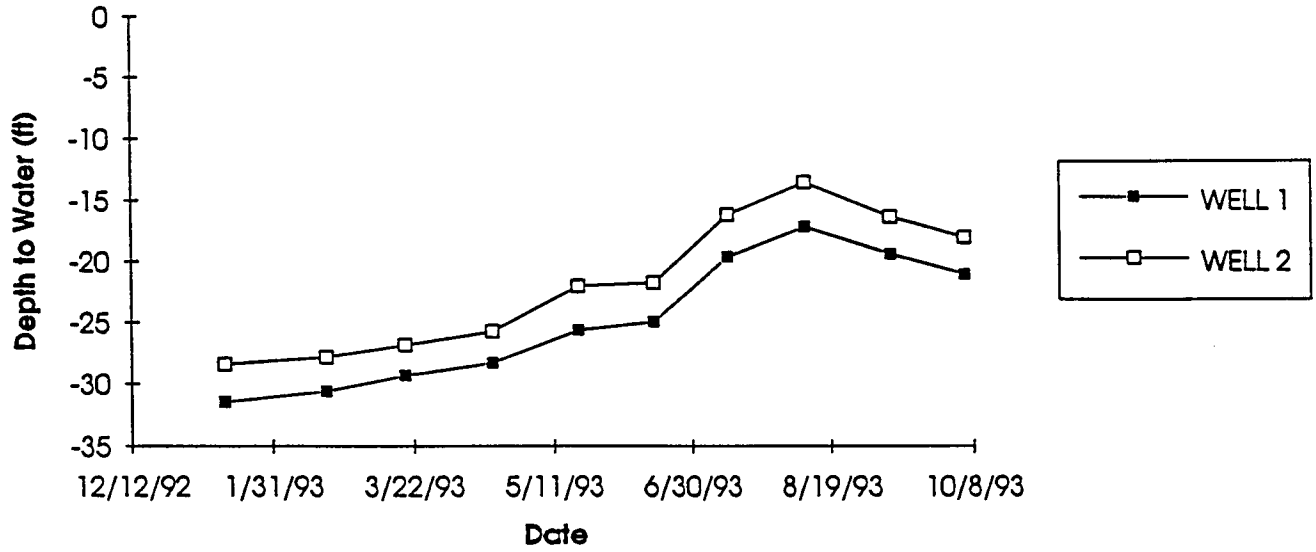
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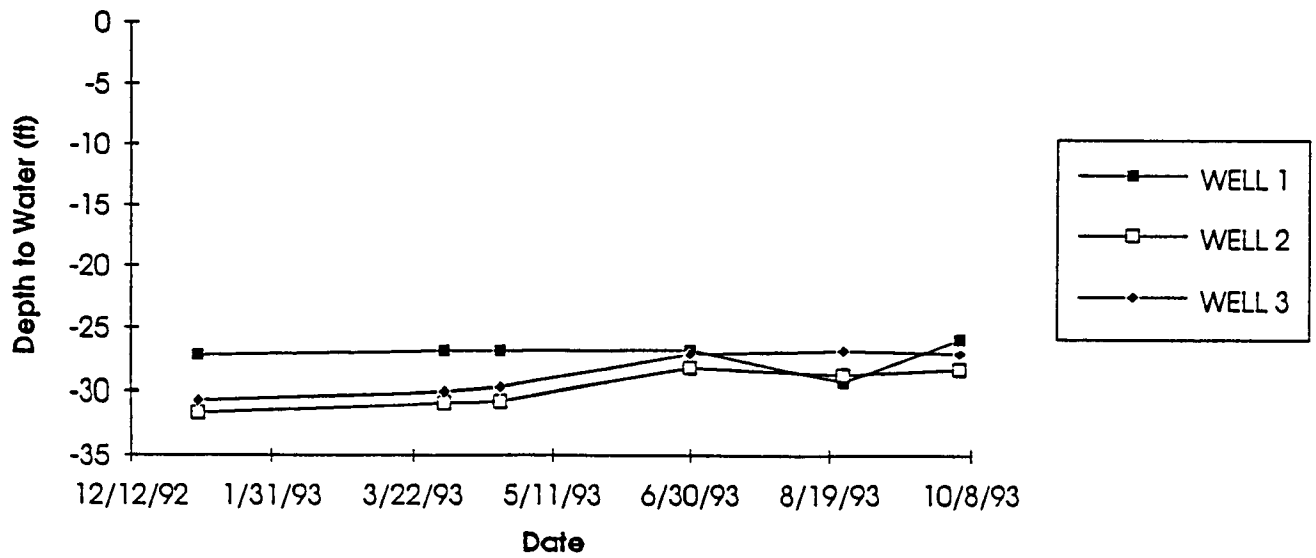
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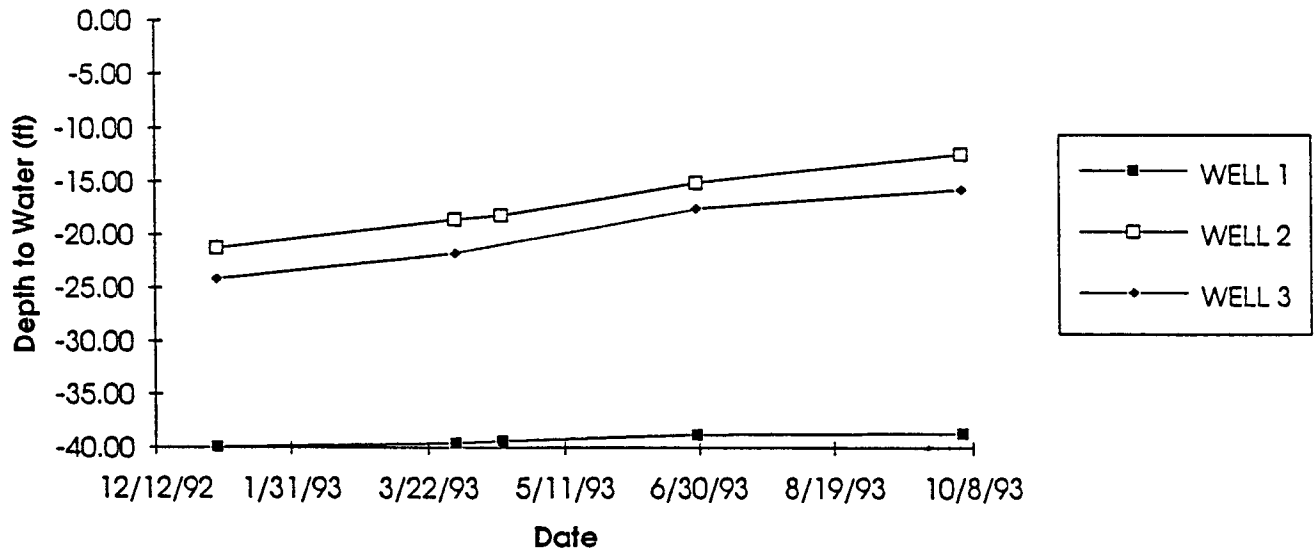
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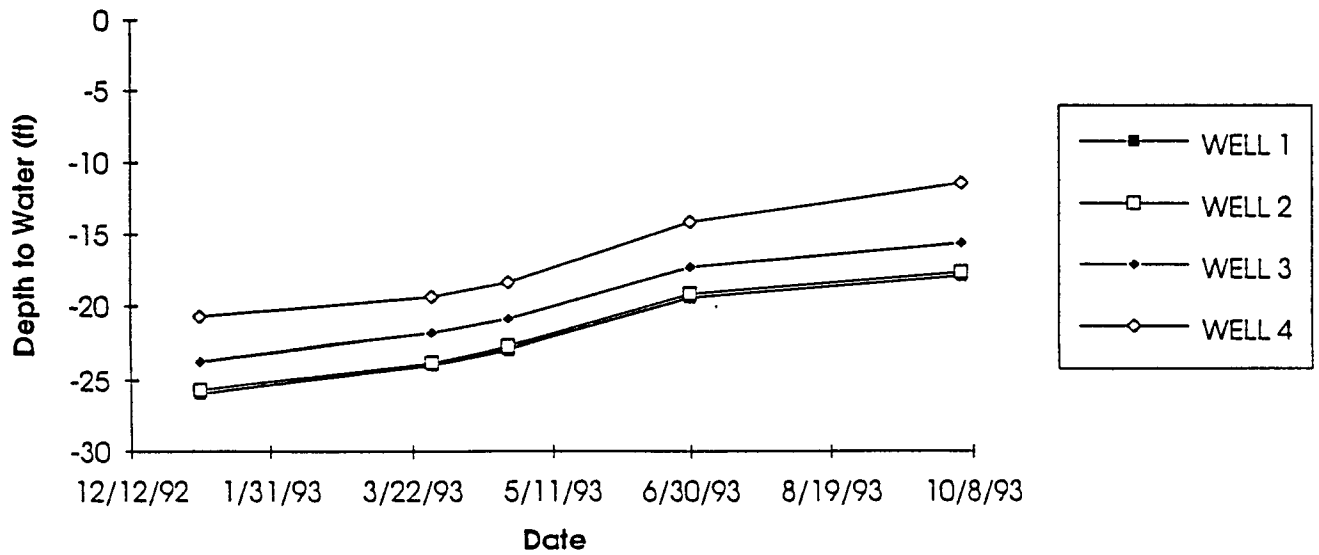
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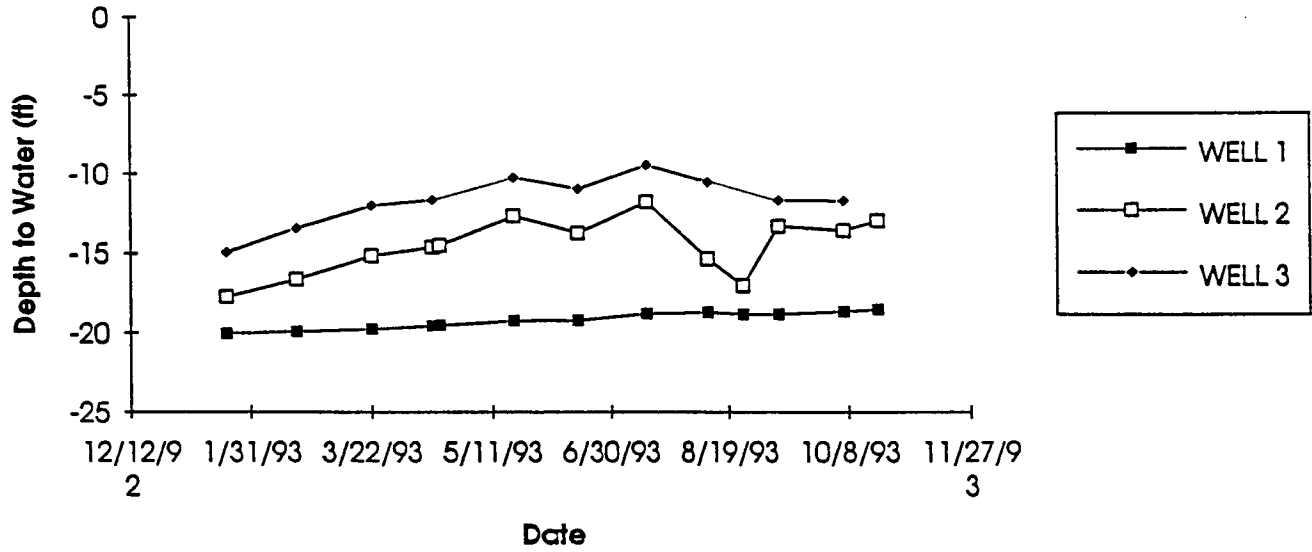
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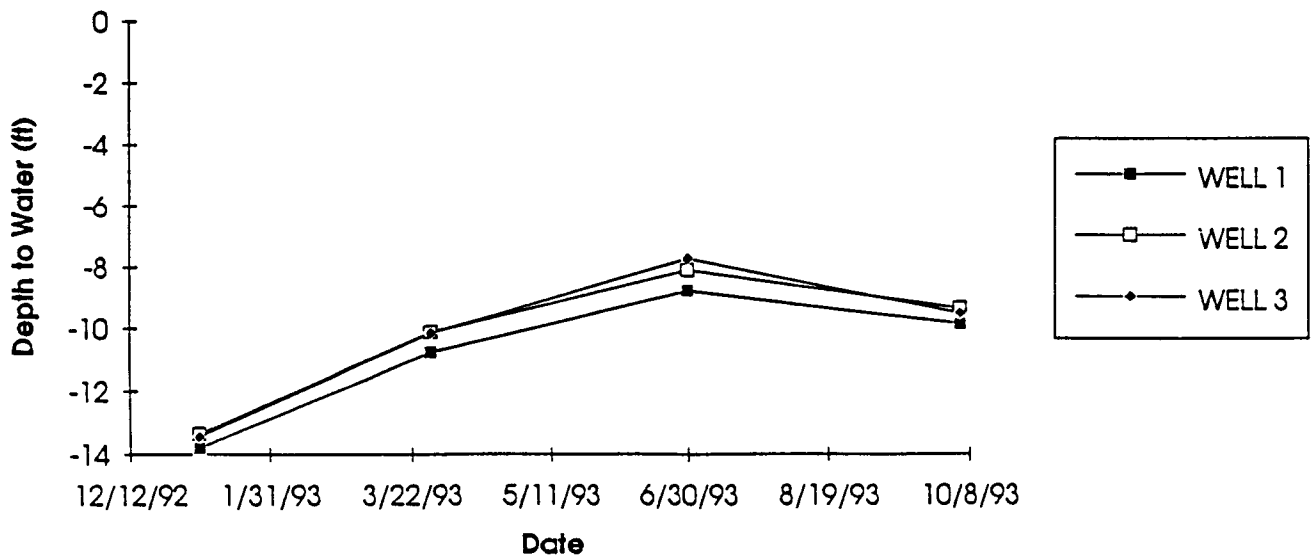
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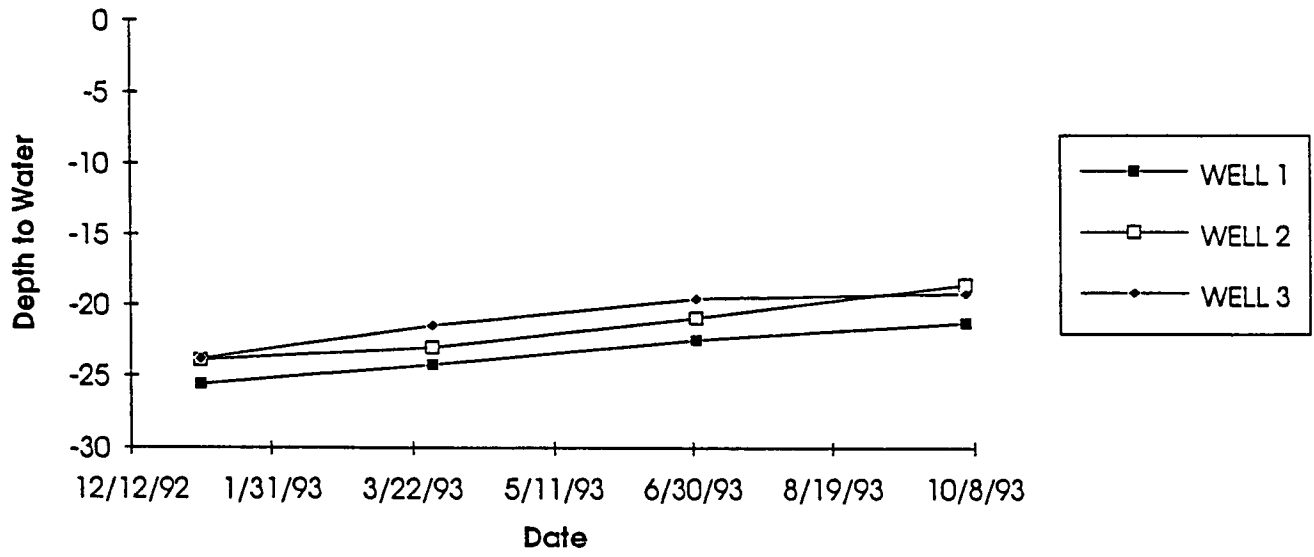
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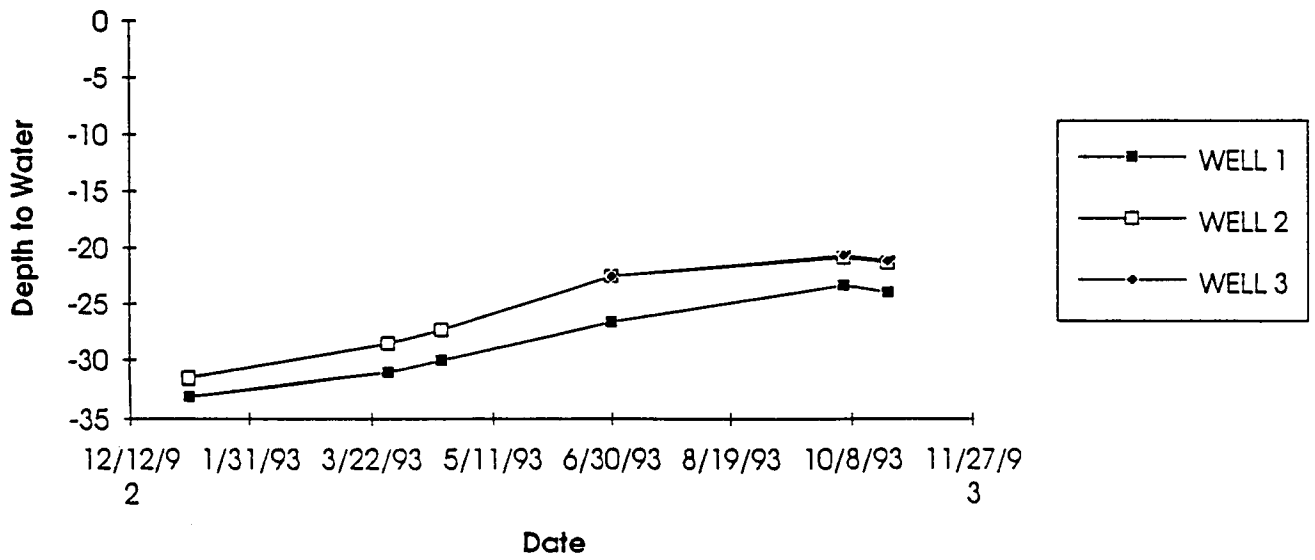
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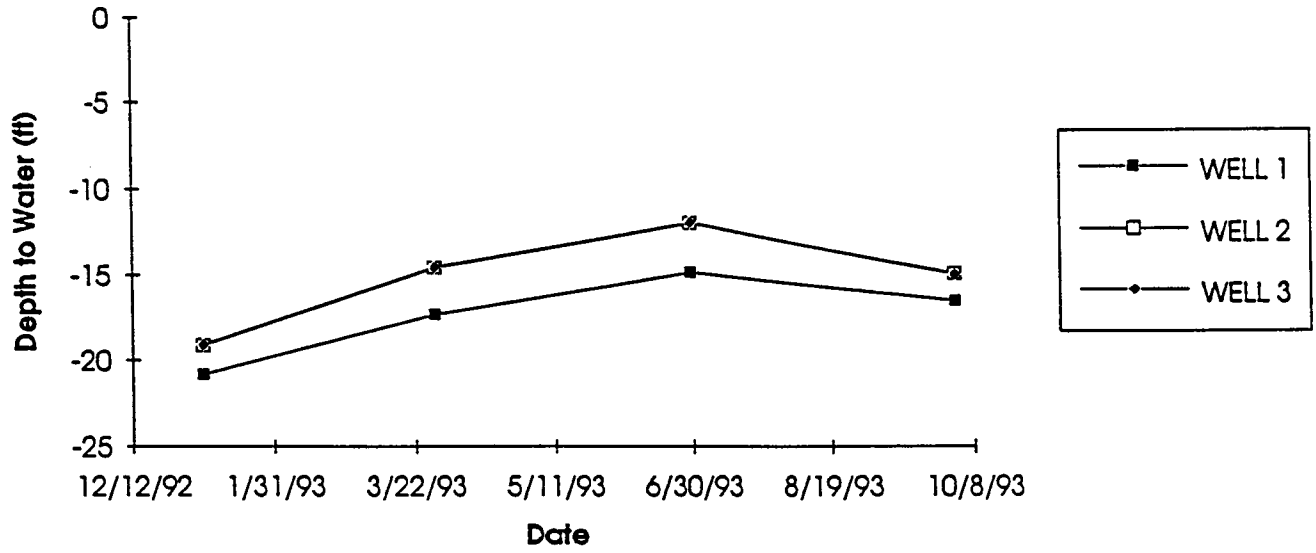
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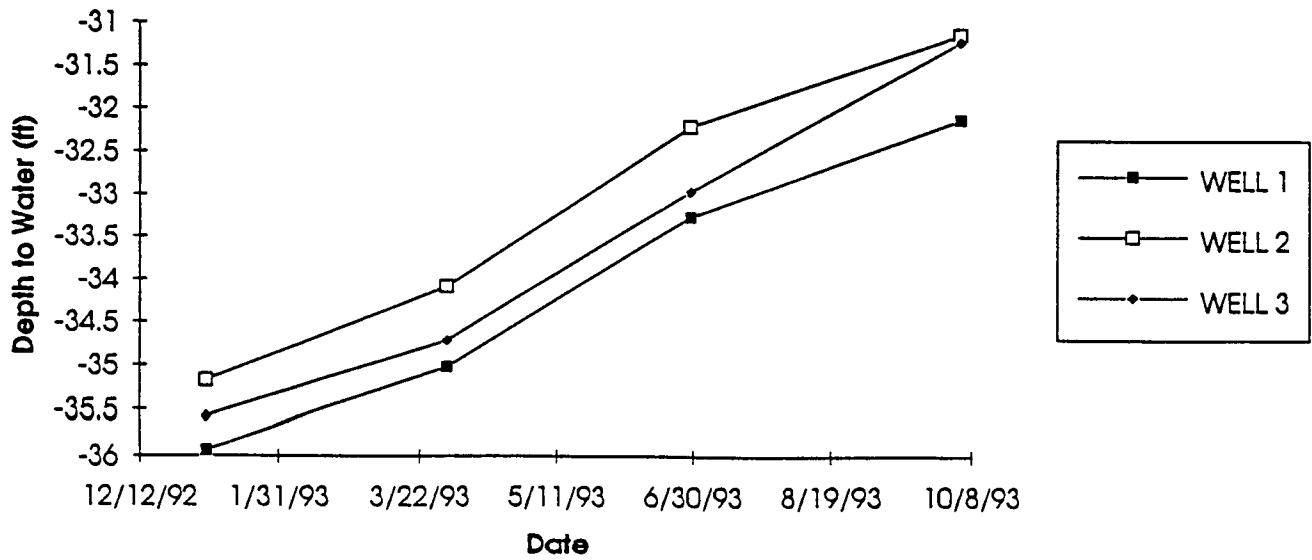
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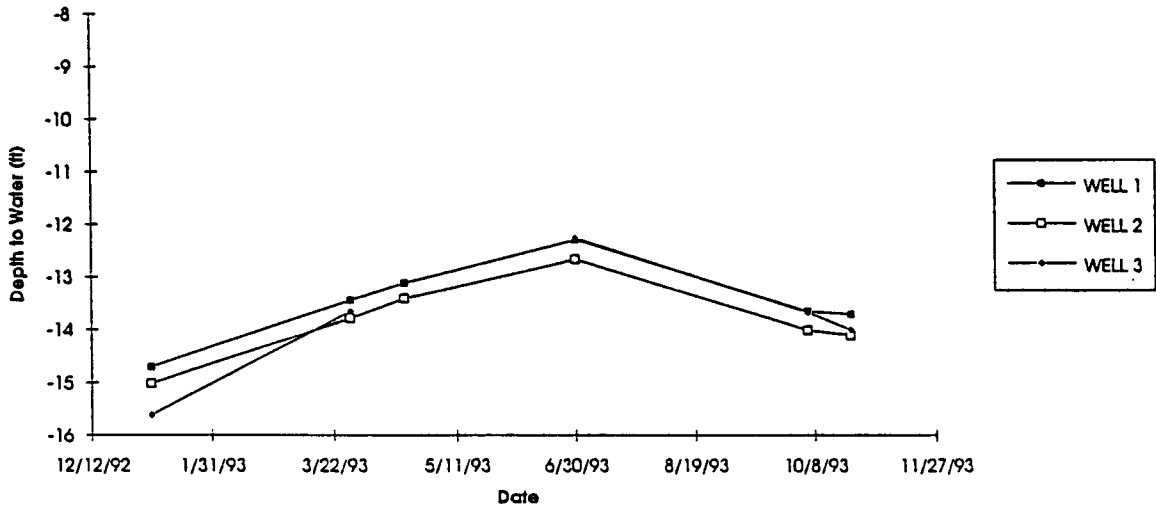
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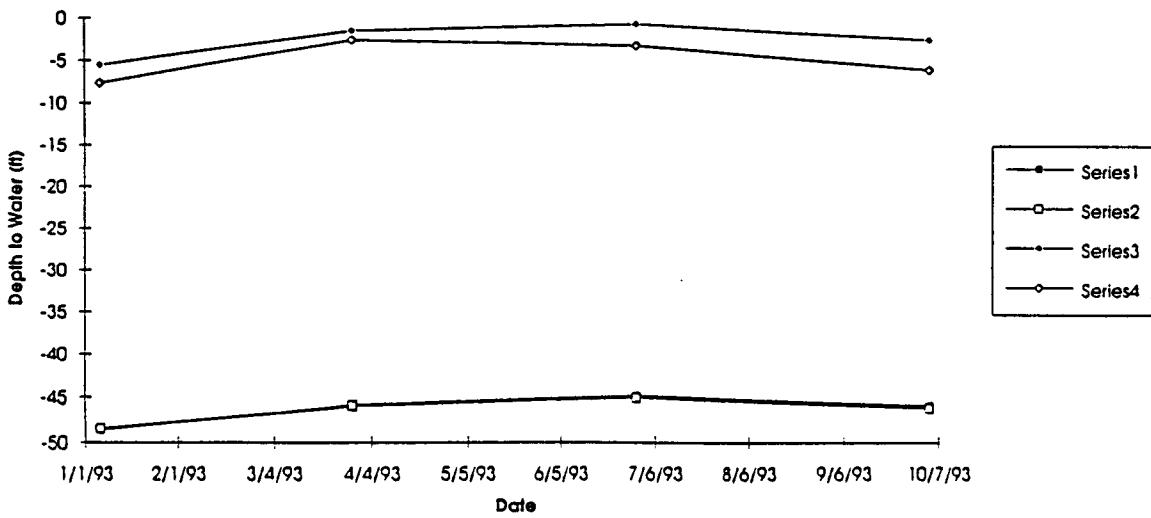
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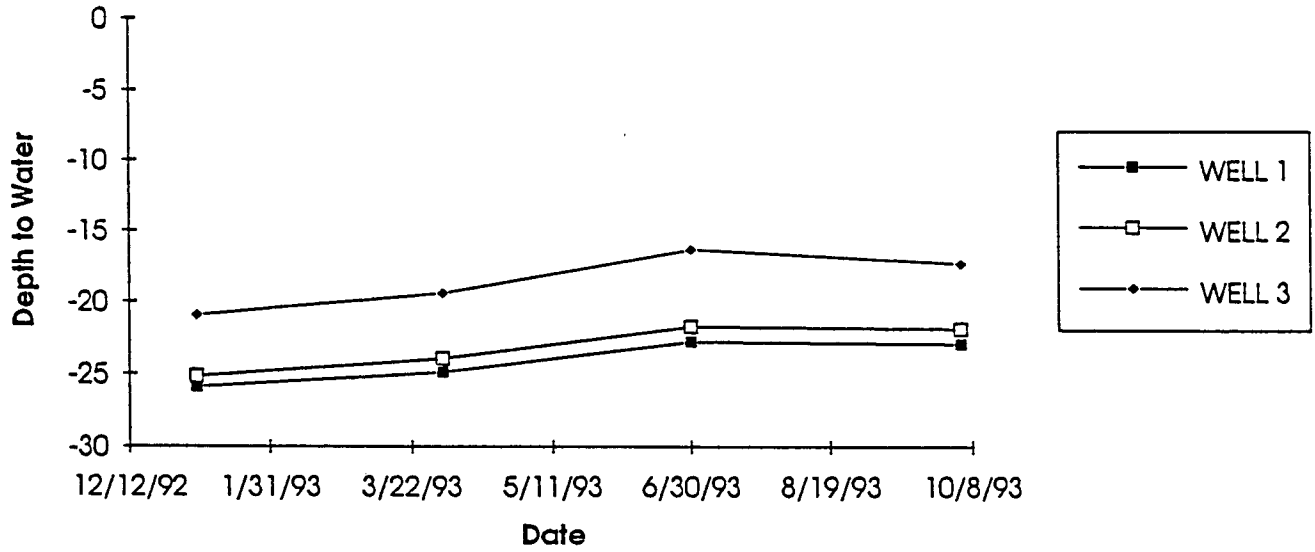
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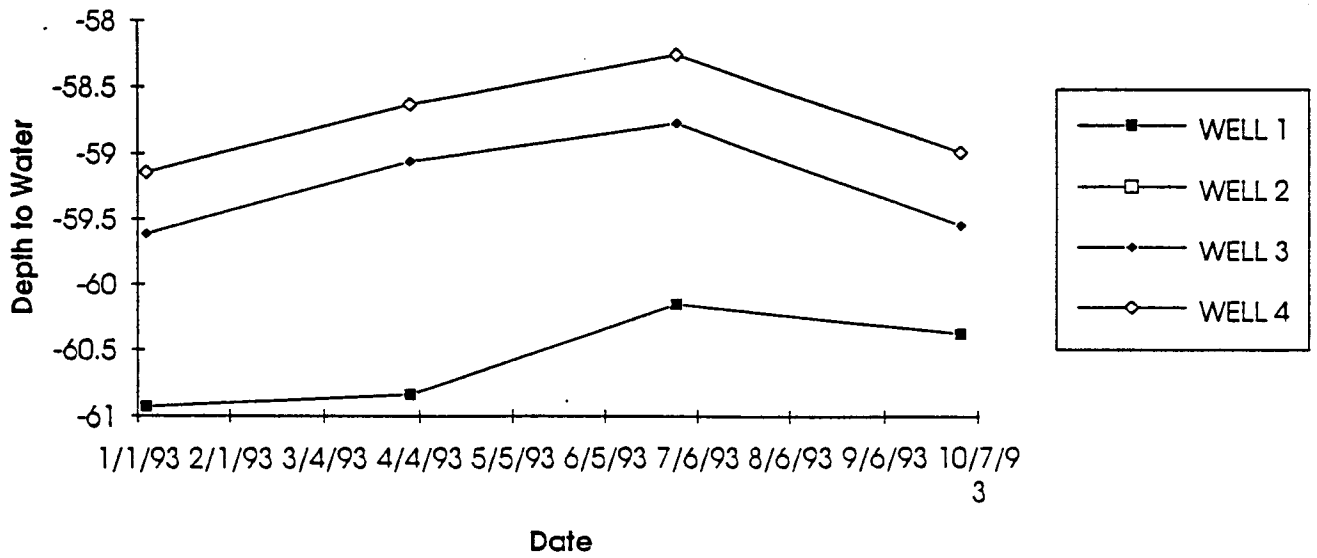
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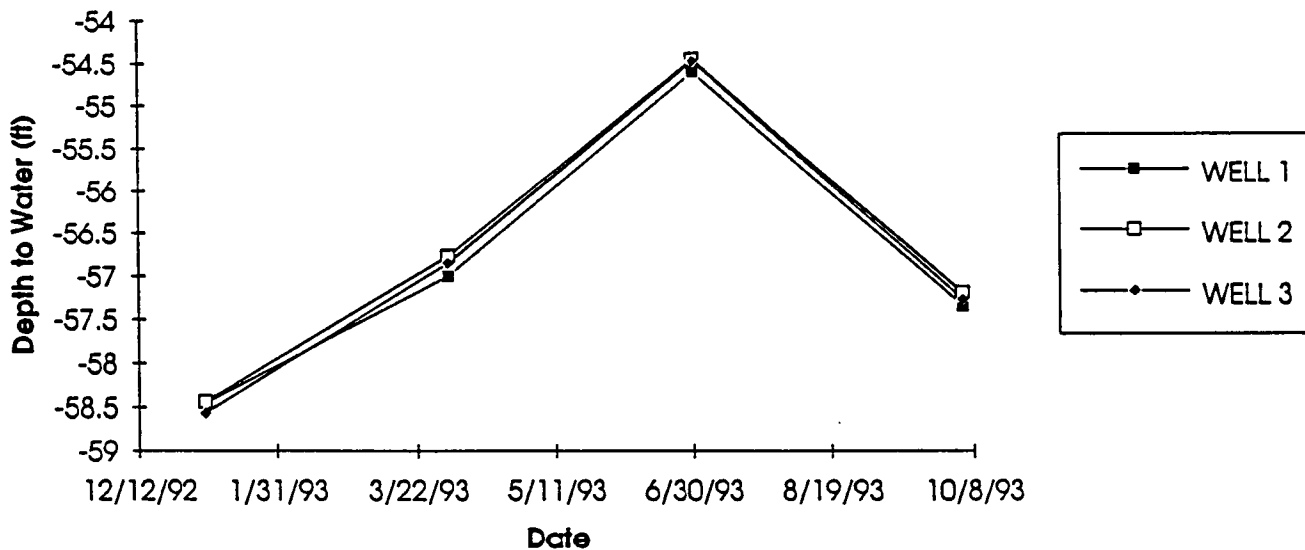
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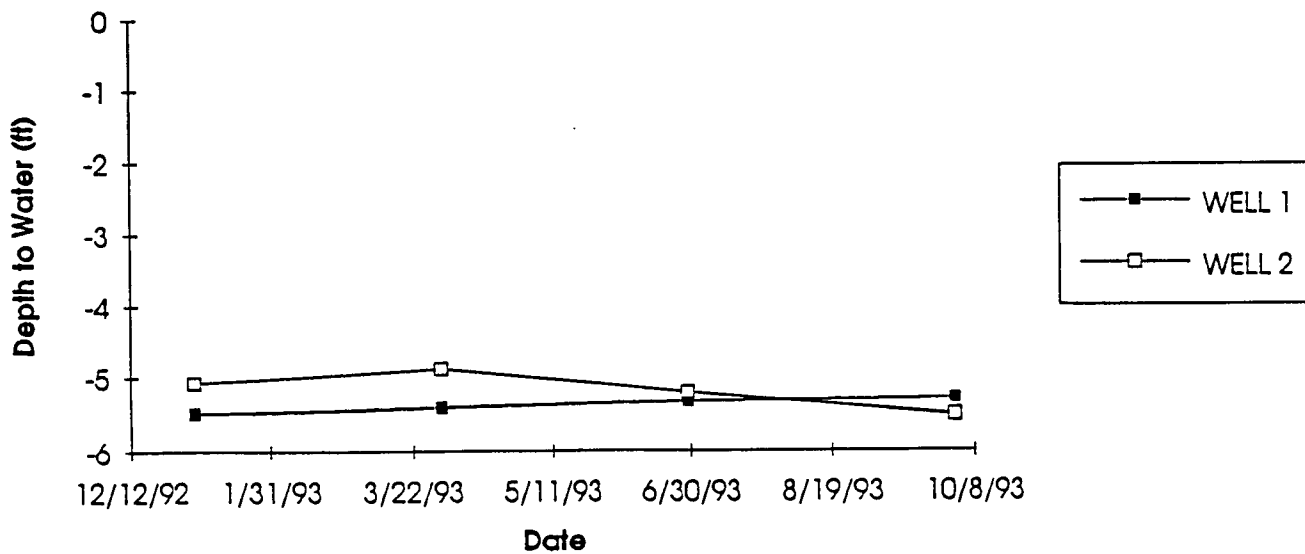
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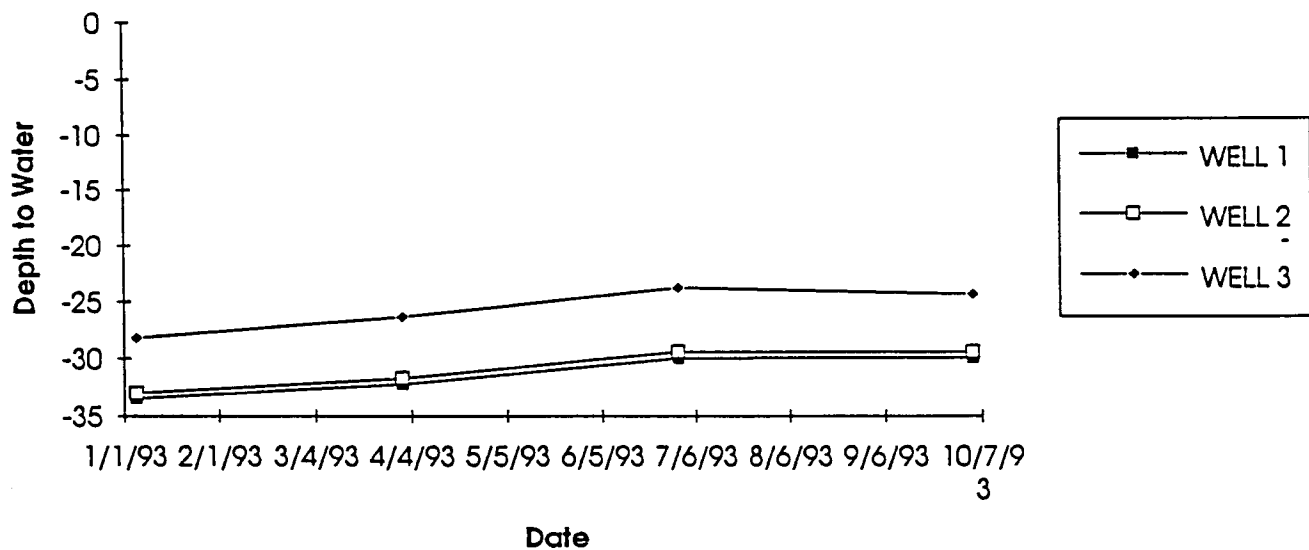
Site 40



Site 43



Site 38



Site 51

