$$K = \frac{r_c^{2} \ln(R_e/R_w) \ln(y_0/y_t)}{2Lt} \qquad (4.6)$$

Although most parameters are easily determined in the calculation, $\ln (R_e/R_w)$ is somewhat variable within various geologic environments. More specifically, the effective radius of influence will vary in relation to the depth of the underlying confining unit below the bottom of the well. Bouwer and Rice (1976) determined that $\ln (R_e/R_w)$ varies inversely with $\ln [H / R_w]$ and linearly with $\ln [(D-H)/ R_w]$. Results enabled derivation of the following two equations: eq. 4.6 for partially penetrating wells and eq (4.7) for completely penetrating wells (where D-H = 0).

$$\ln R_e/R_w = \left[\frac{1.1}{\ln H/R_w} + \frac{A + B\ln\left[(D-H)/R_w\right]}{L/R_w} \right]^{-1} \qquad (4.6)$$

$$\ln R_e/R_w = \left[\frac{1.1}{\ln H/R_w} + \frac{C}{L/R_w} \right]^{-1} \qquad (4.7)$$

Coefficients A, B, and C from equations 4.6 & 4.7 are resolved by a relationship that has been determined through an electrical node analysis (Figure 20) presented by Bouwer and Rice (1976).

In addition to the determination of the value for $\ln (R_e/R_w)$, hydraulic head values were graphed against time in a log plot (Figure 21); additional graphs are depicted in APPENDIX D. The resulting slope of the line determined an average value for $\ln (y_0/y_t) / t$ to be used in the calculation of the hydraulic conductivity.

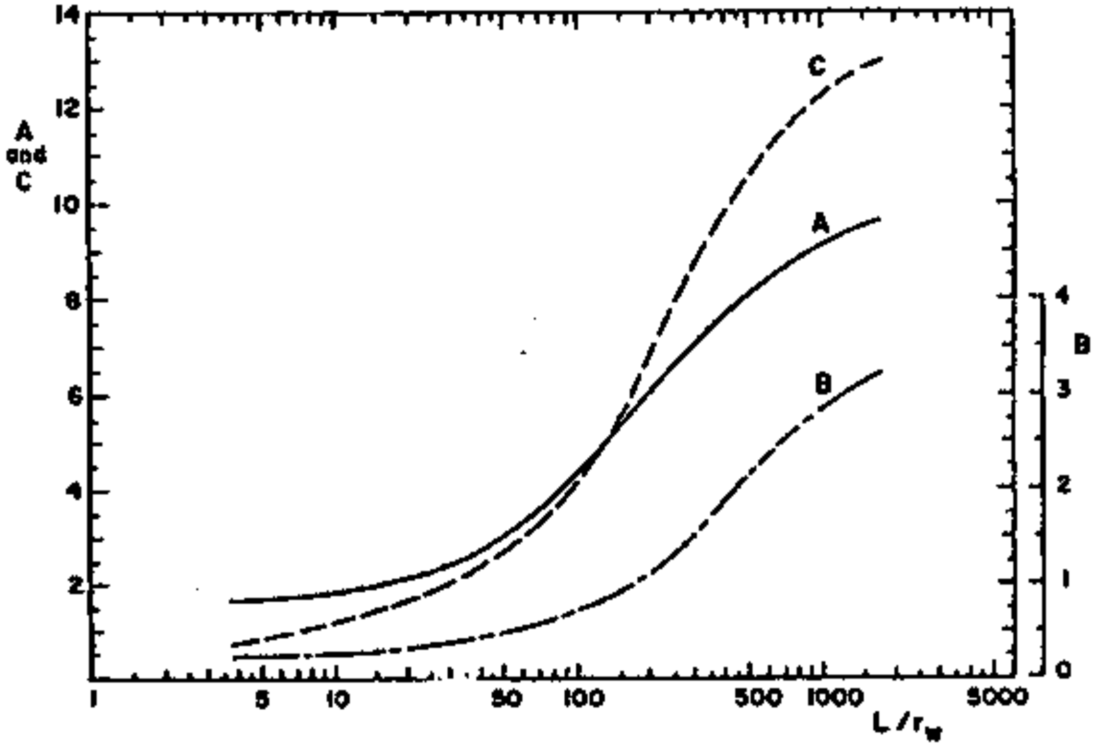


Figure 20. Relationships of A, B, & C for the Calculation of R_e/R_w. Values for dimensionless mathematical constants (A,B, & C) are shown as a relationship to the value of L/r_w. Using the resulting values in the Bouwer/ Rice formulas, a range of possible conductivities was determined for each of the pump analyses.

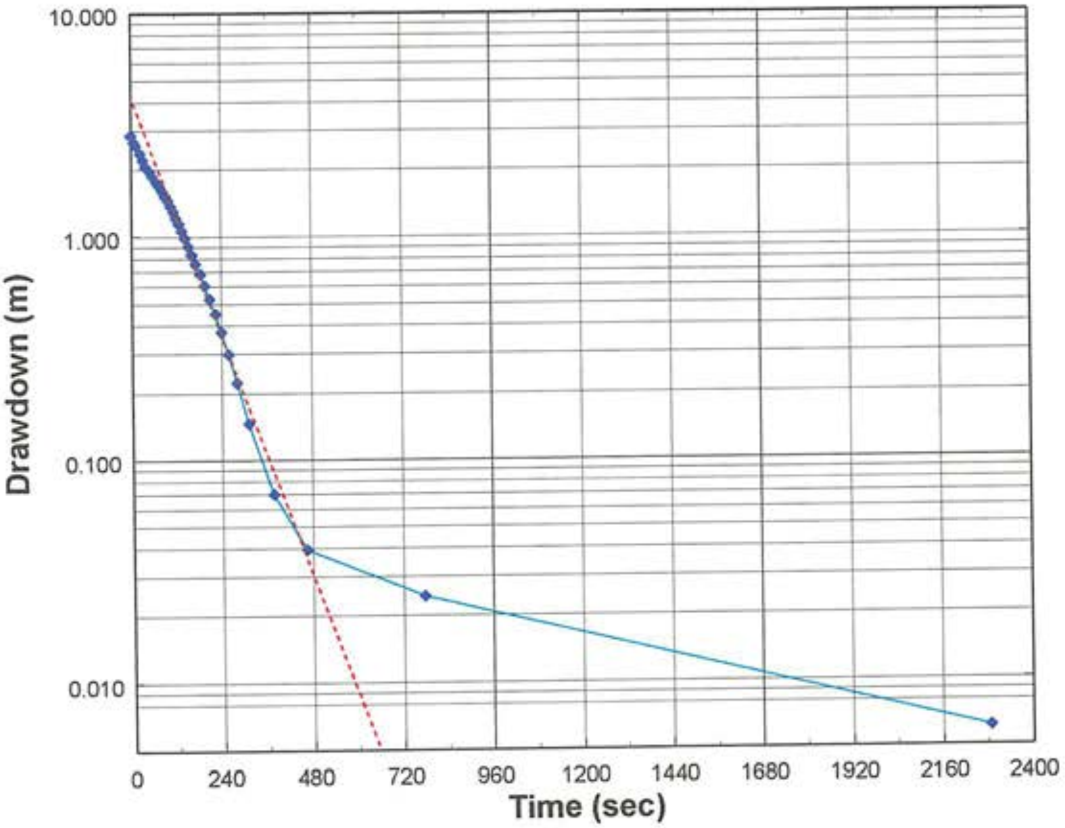


Figure 21. Drawdown vs. Time Plot for Well 18. A log plot of drawdown over time determines a relationship between the values, whereby the average slope (dashed line) is used in the calculation of conductivity as the value for *log (yo/yt)/t*.

Table 4. Conductivity Ranges for Surficial Aquifer Wells. Units for all values are in cm./sec, with maximum and minimum values approximated from individual slopes between head values in the drawdown plots.

Well	Mean	Minimum	Maximum
PP 2- 0	0.0000131	0.0000093	0.0000136
MW 1	0.0001290	0.0000900	0.0001620
MW 8	0.0000710	0.0000360	0.0001690
USGS 9	0.0001480	0.0001330	0.0002290
MW 11	0.0001700	0.0001100	0.0003480
MW 18	0.0006130	0.0002100	0.0007690
MW 21	0.0002440	0.0001700	0.0003090
MW 22	0.0002590	0.0001130	0.0003180
MW 24	0.0004370	0.0002770	0.0006960

Results for the hydraulic conductivities determined by this method (Table 4) characterize three zones of regional conductivity. Well 2-0 represents an area of a low conductivity (1.3×10^{-5} cm/sec) for the region beneath the stacks, while higher conductivities (mean ~ 3.9×10^{-4} cm / sec) are found in wells to the Northwest (RW 18, 21, 22, 24). Southward of the stack (MW 1, USGS 9, RW 8 & 11) moderate values for conductivities are found (mean ~ 1.3×10^{-4} cm/sec). A comparison of the conductivities for the wells in the south to those in the northwest finds that the highest conductivities are determined for RW 18 & 24, where values are 3 - 4 times higher than the mean for the more southern wells. This comparison is peculiar in relation to the wells' proximity to the stack, but the difference can be attributed to variations in the local geologic composition of the surficial aquifer.

Precipitation

Precipitation records from all three available sources (Piney Point, Bradenton, & Ruskin) indicated that each source was unique in its measurements, and that not all of the sources could be relied upon in correlation with the hydrologic system of the stack area. Thus, records from on-site measurements for 1995-1996 were relied upon in the correlation to precipitation, while readings from Bradenton and Ruskin were not considered.

Precipitation measurements showed a high degree of correlation with stack pond levels (Figure 22) and monitor well levels (Figure 23). Therefore, hydrologic controls of these water bodies were considered to be at relative equilibrium with their environment. Variations of water levels in the stack ponds were shown to be small on a monthly scale, with ambient levels impacted only during large precipitation events, as depicted in the record for October of 1994. Water-table elevations in monitoring wells of the surficial aquifer are seen to recover within weeks, owing to the high conductivity of the unit.

Annual precipitation for 1995 was 159.2 cm. with the highest monthly rainfall in July and August, and the lowest in December and January. Precipitation highs and lows are attributable to seasonal variations, with large annual numbers due to the area's latitude and proximity to the Gulf of Mexico. Annual totals are minimally variable from year to year, and consistent in their pattern of monthly distribution.

In summary, precipitation has been highly variable geographically on a week to week basis, but similar in annual totals from site to site. This will of course, lead to localized variations of the recharge flux into the hydrologic environment (i.e. the gypsum stack and the surficial aquifer) each week, but should even out when considered on a regional scale over longer periods of time. Large precipitation events will impact hydraulic head levels in the stack ponds for months, while influences on the surficial aquifer are found to last only weeks.

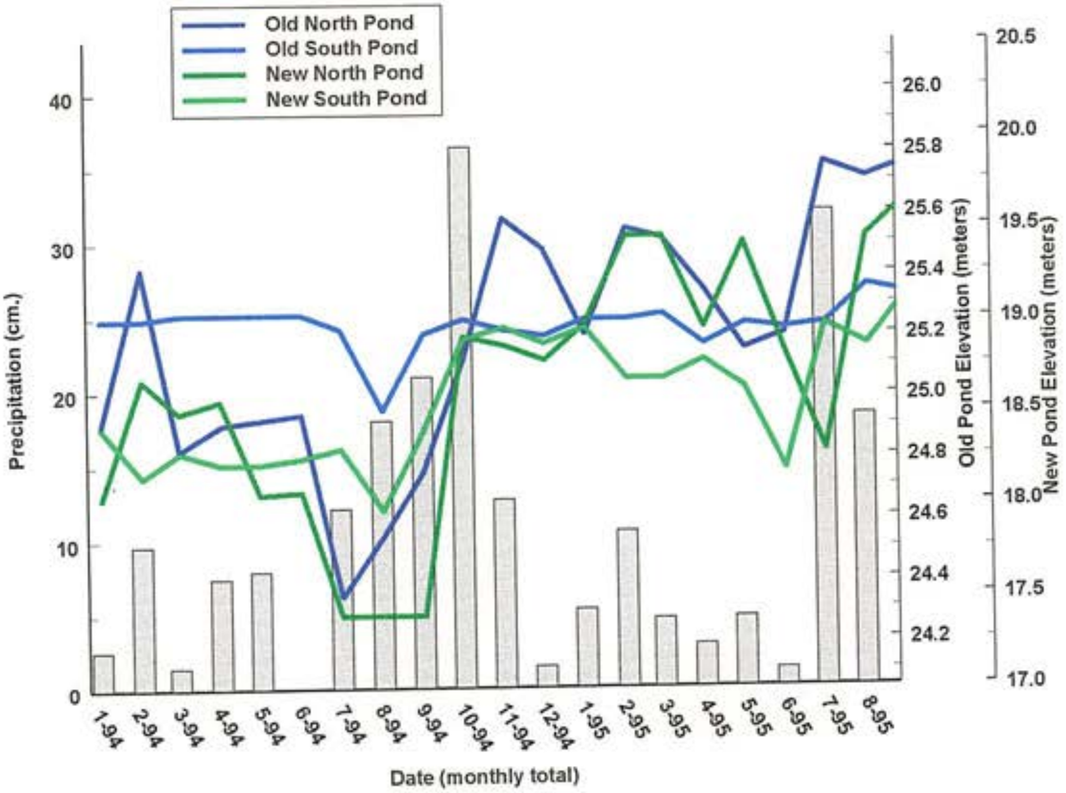


Figure 22. Comparison of Precipitation Records to Stack Pond Elevations. Bars represent individual precipitation measurements, while lines are correlative of continuous water levels in the stack ponds. Correlation between the records is important in October of 1994.

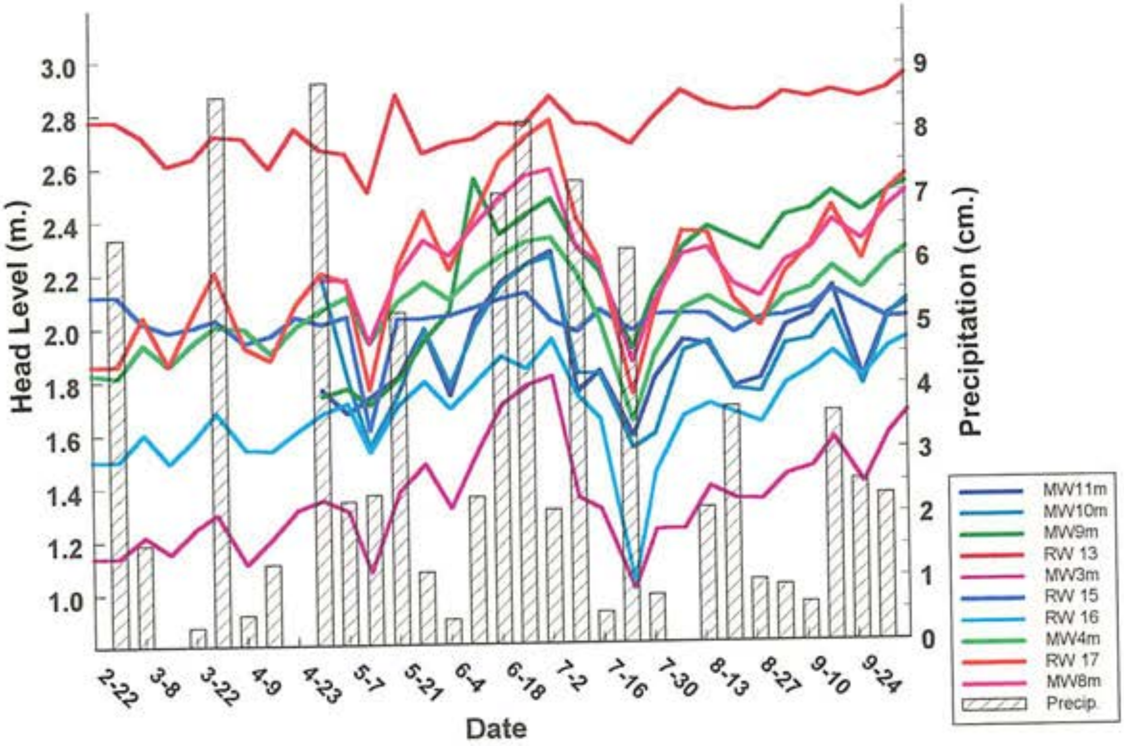


Figure 23. Comparison of Precipitation Records to Monitor Well Levels. Bars represent individual precipitation measurements, while lines are correlative of continuous water levels in the stack ponds. Correlation between the records is important during mid-June.

CHAPTER 6

GROUNDWATER FLOW MODEL

Description of the MODFLOW Model

Groundwater flow at the Piney Point facility was simulated using *Processing Modflow for Windows* (1994), a computer-simulation software package (hereinafter referred to as MODFLOW) that utilizes a three-dimensional, modular finite difference method, first developed by McDonald and Harbaugh (1988) for the U.S. Geological Survey. Finite difference makes use of a nodal network, whereby each node represents a hydraulic head and is modified through adherence to aquifer parameters (i.e., hydraulic conductivity and transmissivity) and environmental constraints (i.e., ditches, ponds, precipitation, and evaporation). These simulations may be run under transient or steady-state conditions; however, only steady-state solutions are considered here.

Mathematical Theory

Modflow simulates groundwater flow assuming constant fluid density, and generates head values for each node within its environment by solving the following partial differential equation for the hydraulic head (groundwater flow equation) as a function of space (x,y,z) and time (Anderson and Woessner, 1992):

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z}) = S_s\frac{\partial h}{\partial t} - R \qquad (5.1)$$

in which K_X, K_y, and K_z are hydraulic conductivity values in the x, y, and z coordinate directions, S_s is the specific storage of the geologic unit, h is the hydraulic head, and R is a generalized sink / source term of external nature to the system (Anderson and Woessner, 1992).

Equation 5.1 is used in its steady-state form by setting the dh/dt-term to 0. The resulting steady-state groundwater flow equation then changes to the *Poisson* form of the equation. Integration is then calculated through a finite-difference method, whereby discrete head values at each node are iterated through the equation using values from neighboring nodes, until the head change between two consecutive iterations is less than a chosen value. The numerical procedure used for the iteration process was the Preconditioned Conjugate Gradient method.

Design of the Flow Model

The Conceptual Model

Primary consideration for the design of the conceptual model was to isolate the stack-surficial aquifer boundary in the environment, so that a determination of the hydrologic flux between these two units could be made from the simulated hydraulic conditions.

The model is comprised of two layers that represent the two aquifer units being studied: the stack and the surficial aquifer (Figure 24). The overlying stack layer consists of two regions with thicknesses of 8 and 15m, representing respective new and old stack accumulations (Figure 25), while the surficial aquifer layer is constructed as a flat-lying bed of a constant 10 m thickness. Regions of the top layer not representing a gypsum unit are designed to be insignificant through construction as a very thin unit (1 mm) with high hydraulic conductivity; thus, any water contained within each unit is drained immediately into the underlying layer and does not influence other head values.

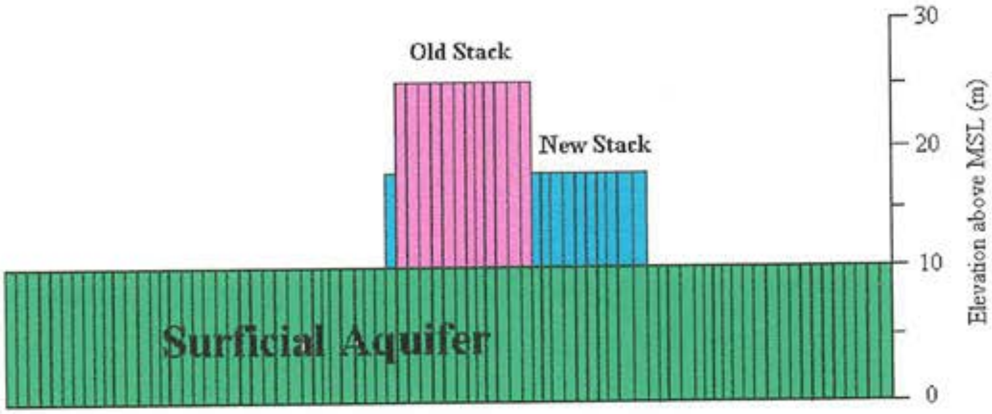
Topography of the land surface will vary at the site, but will have little influence upon the hydrologic head because in an unconfined unit this value will be affected more by the elevation of the water table. Thus, the effects of stack control on head levels in the surficial aquifer are just as easily modeled impacting a topographically flat geologic unit as a varied one.

Grid Geometry

The simulation of the stack environment encompasses an area of 11.83 hectares and is organized into 6400 cells on an 80 x 80 unit grid (Figure 25) . Each of the unit cells is in a square configuration with dimensions of 43 m x 43 m, which models an actual land surface of 1849 m^2. Although the gypsum stack represents only 6.1% of the total grid, a large modeling area was intended so that boundary conditions of the modeled environment would not have any major effect on head values in the stack region.

Hydrologic Parameters

Values for the hydraulic conductivities in both layers were adjusted so that the horizontal component was calculated from the horizontal conductivity and thickness



Vertical Exaggeration - 43X

Figure 24. Vertical Cross-section of the Modeled Environment. A schematic showing the heights of layers in the modeled environment. The cross-sectional view is from the south, and shows the stack relationship to boundary conditions in the east and west.

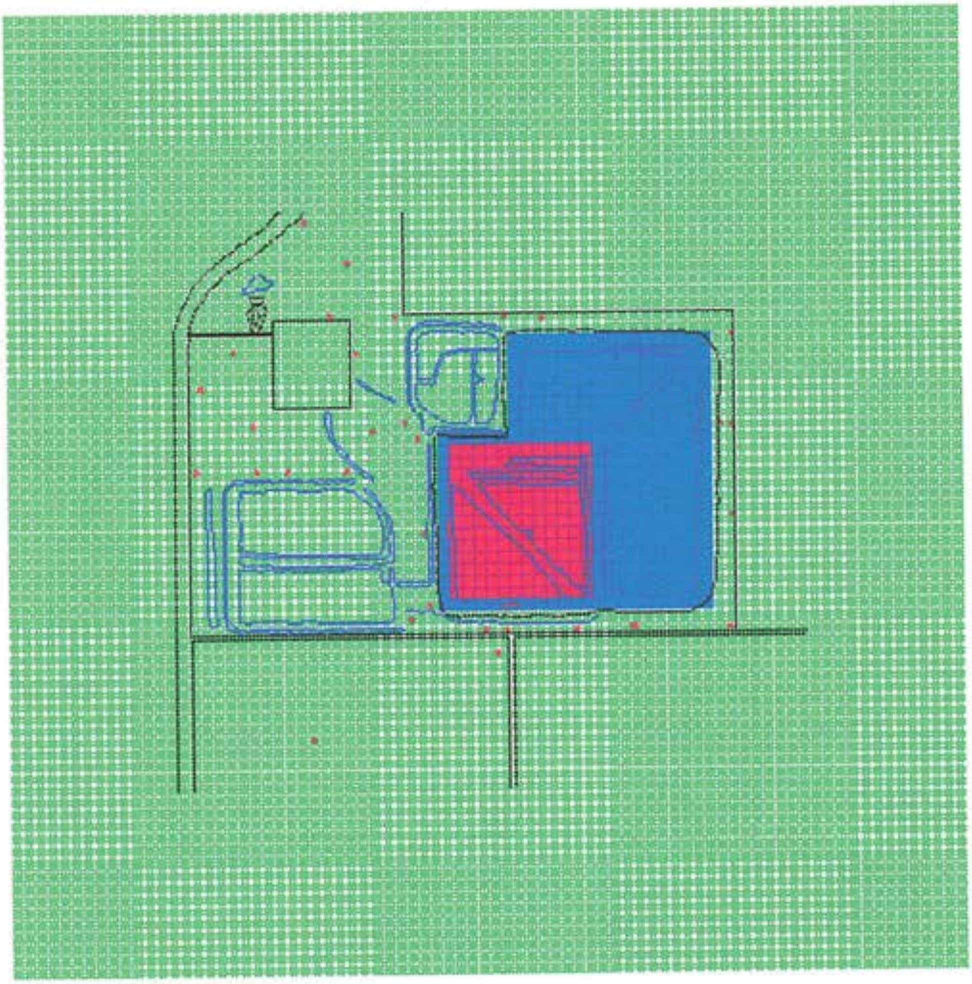


Figure 25. Specification of Layer 1 Regions. A top view of the modeled environment shows relative cell designation within the model. Pink cells are representative of values in the old stack, blue cells for values in the new stack, and green cells for the designation of insignificance in the top layer.

values, while the vertical component is modeled as leakance values between the stack and surficial aquifer. Horizontal conductivity in both units was defined by the results of the aquifer pump tests, which are essentially the estimates from the transmissivity found in well 3-1 (0.443 m^2/day) and the average of the conductivities measured in the north and south monitoring regions (1.3×10^{-6} m/s & 3.9×10^{-6} m/s). The leakance value for the stack was varied in the range of 0.01 - 0.001 day $^{-1}$, while the value for the bottom of the surficial aquifer was specified as five orders of magnitude lower, simulating the presence of the confining Bone Valley Formation.

Regions of horizontal conductivity were specified in the surficial aquifer (Figure 26) as three different sections: a sub-stack area (7.0×10^{-7} m/s); a northwest high conductivity zone (3.9×10^{-6} m/s); and a generalized hydraulic conductivity for the remainder of the modeled cells (1.3×10^{-6} m/s). Designation of such regions allowed a generalized alteration of the data so that homogenous values for the areas could be made. Modification of individual cells could be used to constrain localized heterogeneities, but would not change the large scale determination of flow from the stack area.

Boundary Conditions

Constant head cells were specified in the top layer with initial head measurements of 18 m and 25 m for the new and old stack regions, respectively (figure 27). The implication of the constant head acting as a consistent source of water from stack ponds was intended, as the ponds are kept at relatively constant levels from precipitation recharge.

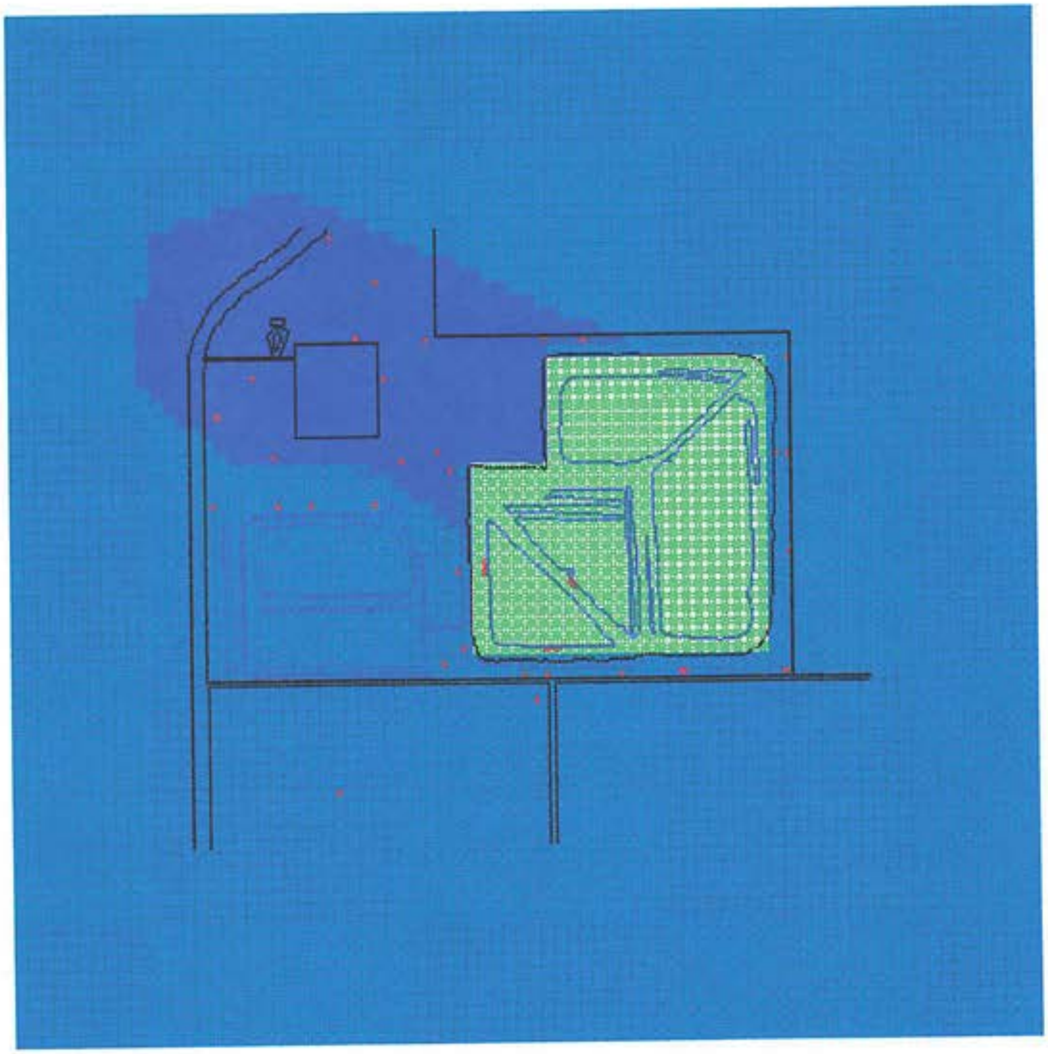


Figure 26. Zones of Hydraulic Conductivity in the Surficial Aquifer. Consecutively darker colors signify greater conductivities; dark blue denotes a conductivity of 4.0×10^{-6} m/s, light blue a conductivity of 1.3×10^{-6} m/s, and light green a conductivity of 7.0×10^{-7} m/s.

Constant head cells are also specified as Dirichlet head boundaries on the east and west edges of the grid. These cell designations were implemented to simulate the regional groundwater flow driven by a constant gradient between these boundaries. The angle and the slope of the regional head trend (determined from topographical regression in chapter 5) is generated through an offset of northward-decreasing initial head values of the constant head cells. Initial head values for variable cells of the surficial aquifer were set at 5 m.

Sources and Sinks

Sources of water in the system were generated from the constant head designation as discussed above, while sinks for the system were modeled through use of the drain package in the MODFLOW program. Drainage cells have been included in the top layer to simulate evaporation from stack flanks, while their presence in the bottom layer modeled the influence of engineered ditches around the perimeter of the stack as well as an influential pond south of the stack (Figure 27). The insertion of drainage cells involved the specification of drain conductance and the elevation of the drain. Elevation is designated as the bottom of the drain, whereas the conductance is determined by the product of the area, the hydraulic conductivity of the ditch fill, and the assumed thickness of the ditch bottom.

Drains located in the top layer are specified with an elevation of 10 m and a conductance of 43 m^2/day. Drains used to simulate ditches in the surficial aquifer are

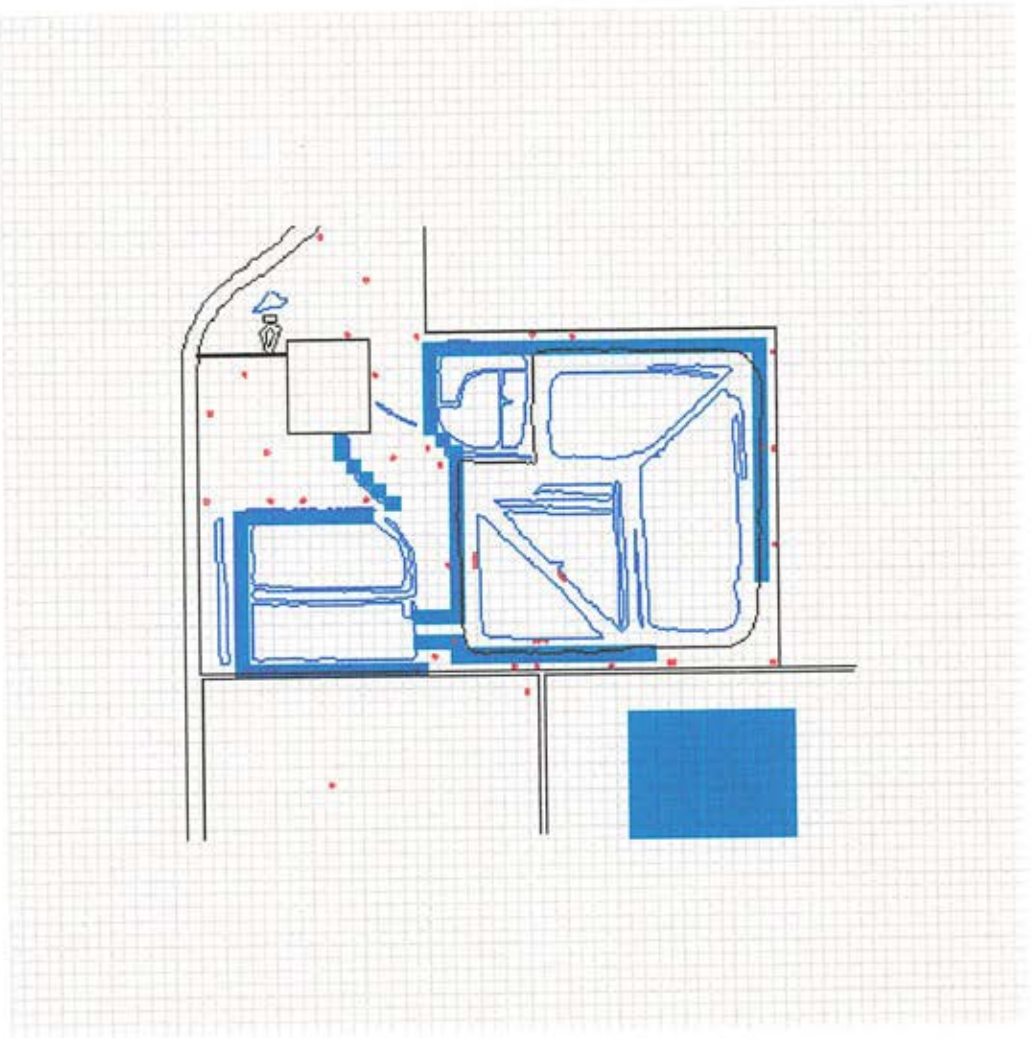


Figure 27. Designation of Drainage Cells in the Surficial Aquifer. Darkened cells of the grid are specified as sinks which conduct water out of the system. Representation as ditches and a pond is intended.

generally located at elevations of 3.0 & 6.0 m with respective conductances of 43 & 21 m^2/day. Drainage for the pond south of the stack was specified at an elevation of 3.0 m, with a conductance of 43 m^2/day.

Calibration

Water table values in the surficial aquifer did not vary enough to demand a complete calibration of the model to each set of monitoring well head levels. Thus, a calibration to within 10% of the average head value for any particular data set was accepted as satisfactory for the steady state solution. Heterogeneities that could not be determined or modeled within the aquifer environment were believed to be responsible for most of the large deviations between modeled and actual head levels.

Calibration of the head values in the model to their present form (Figure 28) was initiated as a large scale match to a set of contrived constant head cells which represented values for a data set of actual observed heads. Parameters for the model were then adjusted until aberrations caused by the constant head cells disappeared and the contours seemed adequately fit to within 1 meter. After this was accomplished, the contrived constant head values for the monitoring well data were taken out, and fine tuning of the parameter values was attempted. All parameter values were kept as uniform as possible, so as to bring out inconsistencies that would clarify local heterogeneities. Actual calibration of the model was done conceptually in four steps:

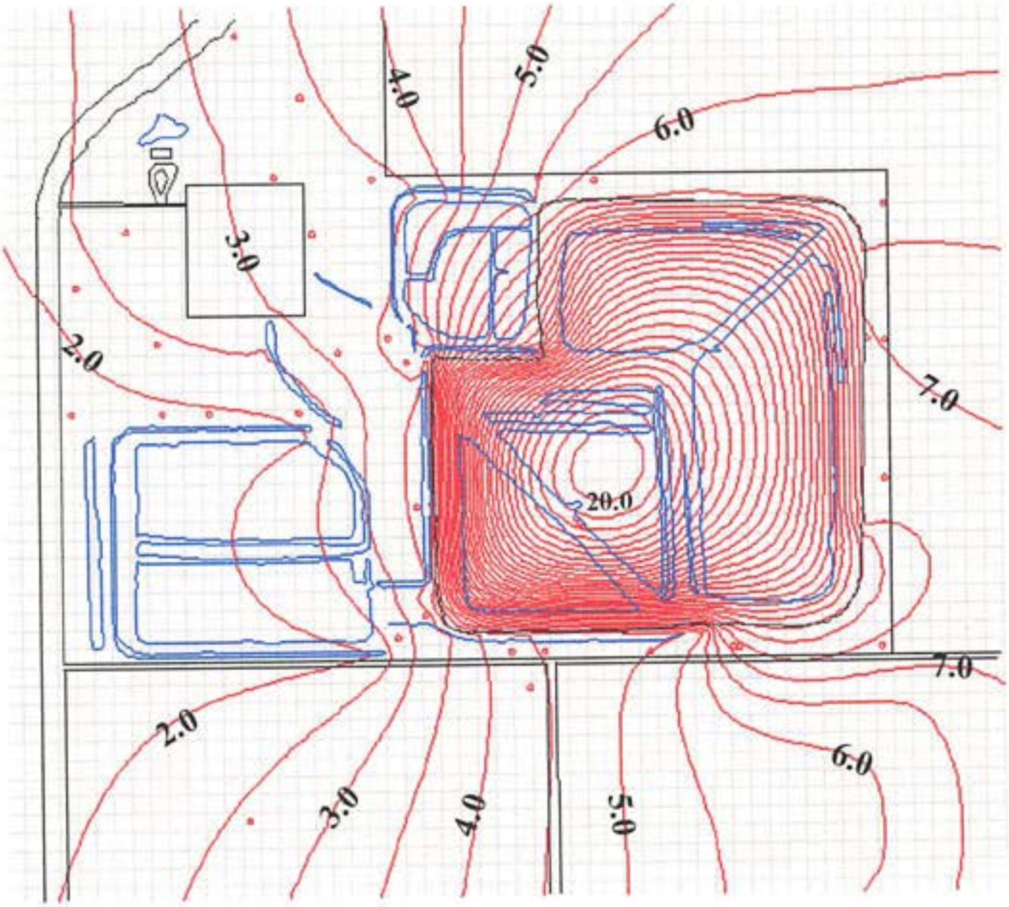


Figure 28. Contours of the Modeled Head Levels in the Surficial Aquifer. Contours are in meters. Note the large influence of the cooling pond ditches on the water table in the southwest section of the model

1) balancing of stack leakance values with sub-stack conductivity to produce a head match to well 2-0 located in the surficial aquifer,
2) adjustment of stack leakance values to generate vertical fluxes which are consistent with the effective recharge of the gypsum stack from precipitation (minus evaporation),
3) adjustment of horizontal conductivity values in the surficial aquifer to produce head values close to those of nearby monitoring wells,
4) modification of drain conductance and elevation to constrain large anomalies in head contours.

The first two steps in the calibration involved a determination of the leakance value to match both the observed hydraulic head in the surficial aquifer well 2-0 and the estimated effective recharge of the gypsum stack as calculated from the difference between precipitation and evaporation measured in the region over the last five years (see section on precipitation in the previous chapter) . Results of this calibration effort show the strong dependency of the vertical stack-aquifer flux upon the leakance value chosen (figure 29). With an estimated effective recharge of about 1600 m^3 /day over the total area of both the new and the old stack, an optimal leakance value of 3×10^{-3} /day is obtained.

In the second step, values for horizontal conductivity zones outside of the stack region were found to be accurately quantified from the aquifer pump tests, so adjustments did not need to be made. The final part of the calibration was made by changes in ditch

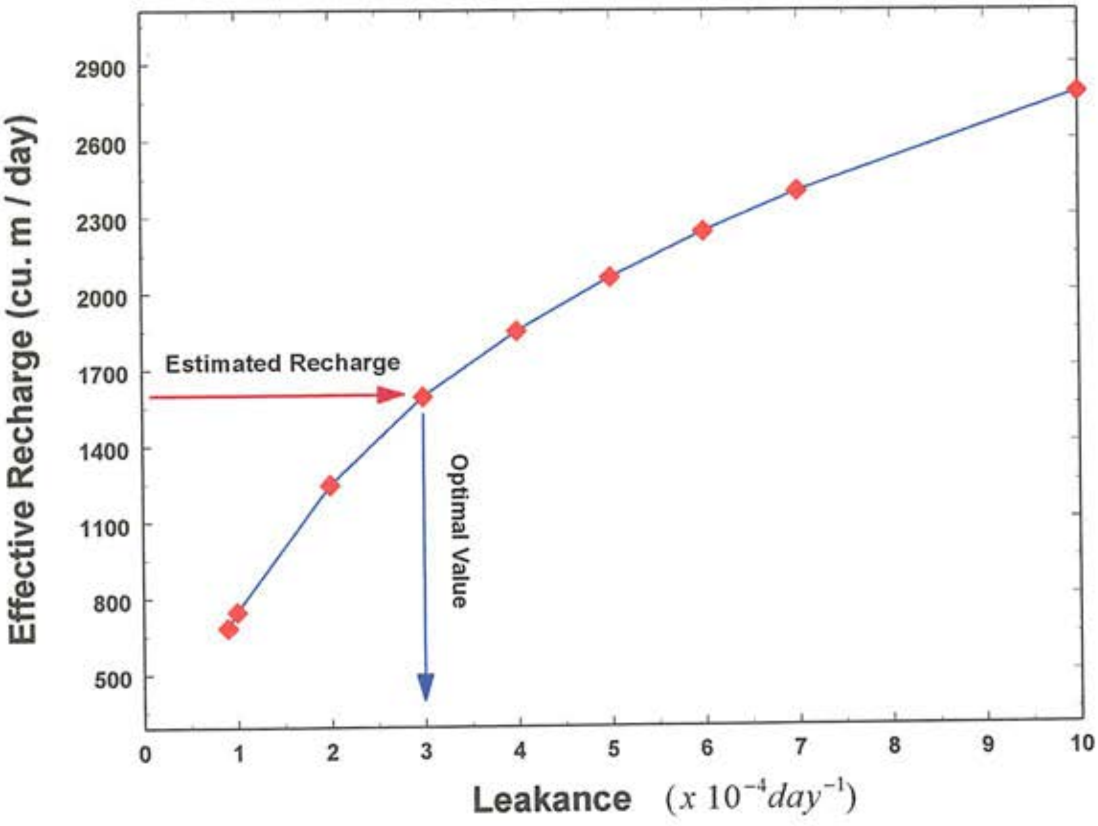


Figure 29. Relationship of Stack Recharge to Leakance Value. Leakance values in the model dictate how much recharge was to be supplied to the surficial aquifer. Estimated values for the precipitation were compared with respective leakance values, so that an optimal figure could be calculated for the model.

elevations and conductances. Within this step, the addition of drainage cells to represent a pond southeast of the stack was made. This created an additional head drop for that region, caused by the impact of evaporation from this pond. The incorporation of values in the drainage cells to simulate the pond and stack flanks was supposed, as the exact value of which was not explicitly known.

Comparison of modeled head values with observed values for September 19, 1996 (Figure 20) was made to ensure a model fit (Table 5 & Figure 30). The average deviation of modeled values from well measurements was calculated to be 24 centimeters, and approximated an 8.7% variance from actual values. The largest deviation of modeled head was found at MW 5, which is isolated in an agricultural field south of the research area, and could possibly be under influence of additional hydrologic factors not considered (i.e. irrigation pumping). Another significant deviation is exhibited at well RW 17, which by itself is an anomaly, as shown in contour plots of observed data (figures 19 & 20) by a loop in the 3 m equipotential contour around the factory area. This pattern is not quite understood, but may be reflecting the influence of a high conductivity region that hasn't been found, or the presence of additional recharge to the groundwater in that area.

Sensitivity Analysis

Values of significance to the calibration of the model were also prime candidates for a sensitivity analysis of the hydrologic parameters in both the gypsum stack and the surficial aquifer. Modeled parameters for leakance, hydraulic conductivity, and ditch

Table 5. Model Output Comparison to Actual Head Values. Comparison is expressed as both an absolute depth value (in meters above MSL) and as a percentage.

Well number	9/19/96 Value	Modeled Value	Difference	Percentage
MW 1	7.59	7.30	-0.29	-3.82
MW 2	4.17	4.30	0.13	3.12
MW 3	3.08	3.18	0.10	3.25
MW 4a	1.64	1.84	0.20	12.20
MW 5	1.74	2.61	0.87	50.00
MW 8	1.53	1.73	0.20	13.07
MW 9	6.39	5.24	-1.15	-18.00
MW 10	6.82	6.99	0.17	2.49
MW 11	7.26	7.24	-0.02	-0.28
RW 8	7.27	7.22	-0.05	-0.69
RW 9	5.55	5.00	-0.55	-9.91
RW 10	4.04	4.37	0.33	8.17
RW 11	2.73	2.72	-0.01	-0.37
RW 12	2.97	3.41	0.44	14.81
RW 13	2.91	3.54	0.63	21.65
RW 14	3.39	3.65	0.26	7.67
RW 15	2.44	2.14	-0.30	-12.30
RW 16	1.86	1.89	0.03	1.61
RW 17	3.43	2.70	-0.73	-21.28
RW 18	1.57	2.27	0.70	44.59
RW 19	2.18	2.36	0.18	8.26
RW 20	3.12	3.64	0.52	16.67
RW 21	3.20	3.23	0.03	0.94
RW 22	3.06	3.38	0.32	10.46
RW 23	2.90	3.15	0.25	8.62
RW 24	2.61	3.36	0.75	28.74
USGS 8	6.99	6.76	-0.23	-3.29
USGS 9	4.15	4.51	0.36	8.67
PZ 34	6.58	7.04	0.46	6.99
PZ 36	6.33	6.28	-0.05	-0.79
PZ 37	6.04	6.08	0.04	0.66
Stack 2 - 0	11.73	11.73	0.00	0.00
	Average		0.24	8.70

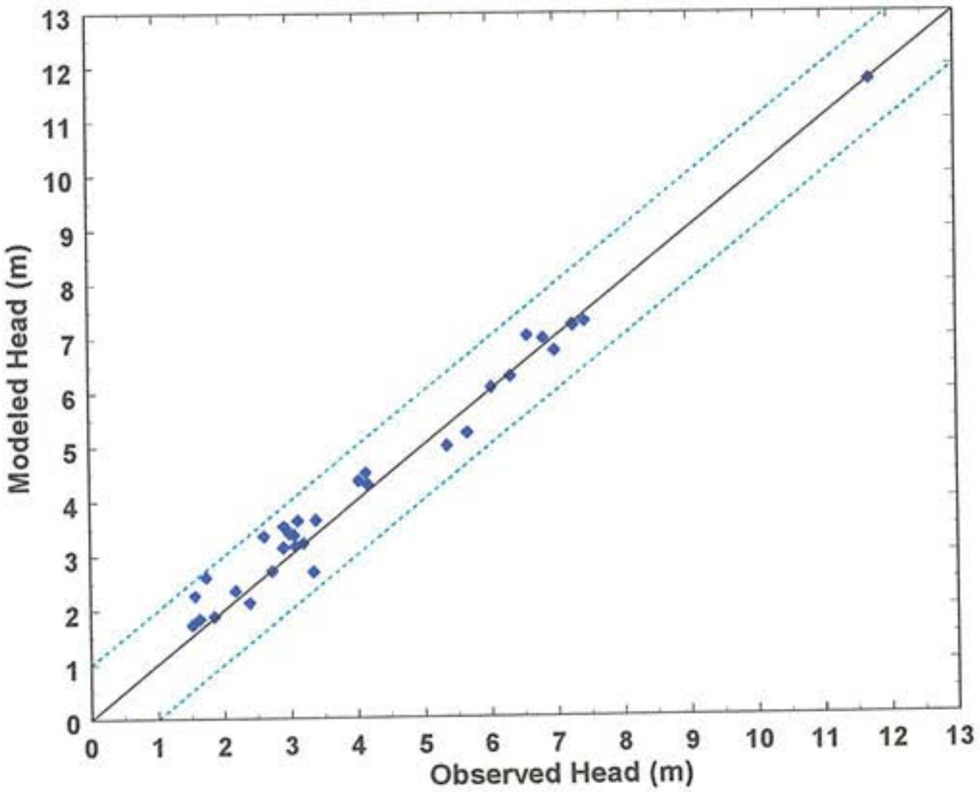


Figure 30. Modeled vs. Observed Head Values. Each plotted point shows a comparison between modeled and observed head values from table. Points plotted along the 1 : 1 line indicate a perfict model fit, while position between the neighboring dashed lines indicate an error of +/- 1 m.

specifications were modified over a range of one order of magnitude in either direction to investigate their relative effect on modeled head values.

Leakance

Uniform leakance volumes of the stack were the most critical values in reference to the overall head values for the surficial aquifer layer. Conceptually, the leakance was important in supplying additional water flowing from the stack into the surficial aquifer. The sensitivity of this effective recharge from the stack ponds can be clearly observed in Figure 29, and is for the most part fairly accurate even without variables of actual flank loss to evaporation. Variations of a unit change in the leakance value were found to increase/decrease head levels beneath the stack at the meter-scale, while a modification of the value by an order of magnitude created too much of an impact on the flux for conductivities to compensate. Thus, the physical flux of fluid through the stack base has been shown to be the most crucial impact of the environment on the observed hydraulic head levels.

Conductivities

Modeled conductivity values in the surficial aquifer zones were found to be within at least one order of magnitude of their actual, measured "group" quantity. Modification of unit changes to these values allowed for better model fits to some data sets, but not to others. Since a homogenous hydraulic conductivity was used, the most generic representation of observed head values from any particular data set for the steady state situation yielded the best fit solution (as indicated by the differences between modeled and observed heads of Table 5). Thus, modeled values for the hydraulic conductivities are within a range of 5 units from the actual values determined in the aquifer pump tests (Table 4). It is thought that internal heterogeneities of the hydraulic conductivity are responsible for localized head anomalies.

Ditch Specifications

Ditch elevation was a very important variable for modeling sinks within the hydrologic environment. Although conductance signified the degree of impact which each ditch had on the hydraulic heads, the elevation of each particular ditch was the limiting factor in determining the actual impact on the flow system. Ditches within the system were, therefore, a crucial part of the flow barrier surrounding the stack. Actual drain elevations were critical to head values nearer to the stack, and although these numbers were not directly specified from engineered specifications, slight modifications of the elevation could also be simulated as additional conductance (which was also not quantified to specifications but rather to the model fit). Regardless, ditch presence was absolutely necessary and its parameters could not be altered very much.

To illustrate the importance of ditch elevation, a trial run was modeled in which the cooling pond ditch elevation of 1.75 m (Figure 28) was increased to 2.75 m (Figure 31). Modification of the elevation caused the declination of the head contours away from

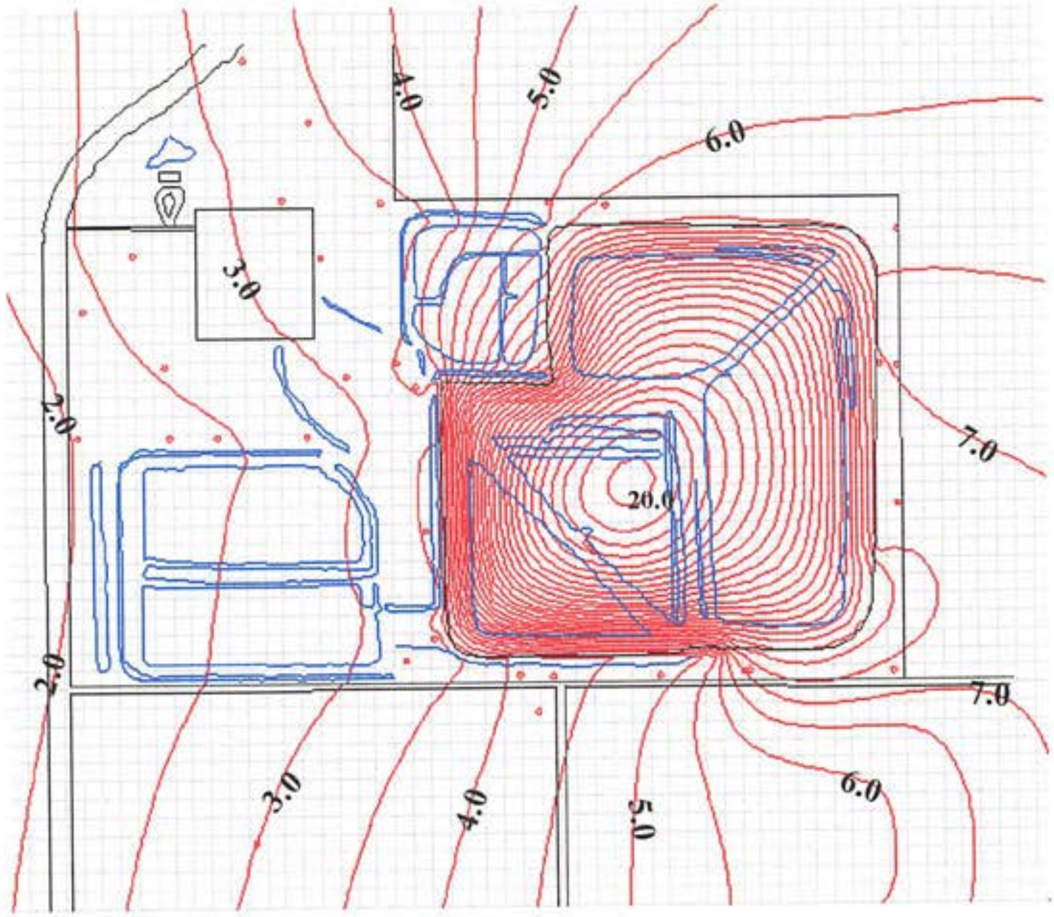


Figure 31. Sensitivity of the Cooling Pond Ditch Elevations. Water table contours are shown for the modeled environment when cooling pond ditch elevations are specified as 1 meter higher than their actual values. When compared with the final results of the modeling effort (figure 28), unacceptable head values are determined for the cooling pond region.

the cooling pond in the western part of the model. Comparison with the actual heads (Figure 20) reveals that a closer match is achieved with a ditch elevation of 1.75 m.

Predicitions for alterations in the hydrologic system are restricted to relative changes in the number, location and size of ditches, owing to the fact that hydraulic conductivities and water recharge from the stack will most likely not change. Filling in of ditches will allow a larger transfer of groundwater from the stack to the surficial aquifer, thus creating a larger "mounding effect". Quantification of this impact will depend on the amount of ditch volume actually eliminated. Greatest influence of such a change would be made to the west and southwest perimeters, as the head gradients in those ditches support the largest volume of water conducted from the system. As a recommendation for future studies of the problem, ditch elevations should be monitored more precisely than has been undertaken during the course of this investigation.

Water Budget Analysis

A volumetric flux analysis of the surficial aquifer (Figure 32) shows the actual impact of the stack on the surficial aquifer. Values for fluxes of the hydraulic system are obtained from the MODFLOW program and from measured hydrologic input parameters. Thus, such an analysis of the total water budget of the aquifer system provided clues to the exact hydraulic impact of the stack on the surficial aquifer.

The volumetric calculation of the budgets were made in terms of m^3/day and followed the generalized form of the continuity equation:

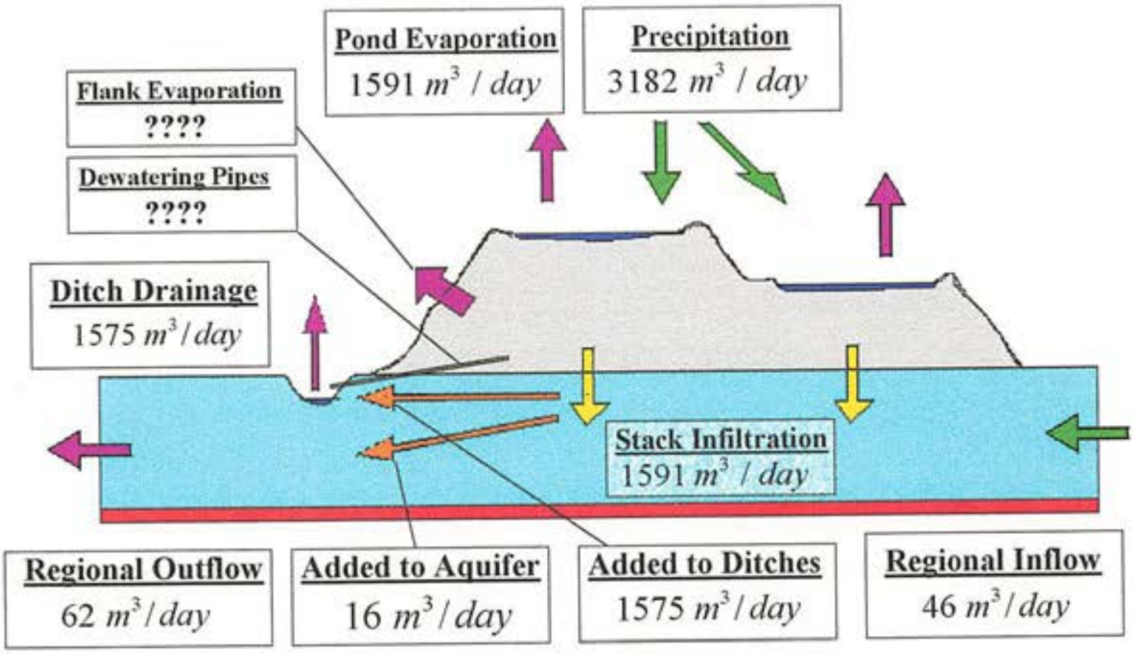


Figure 32. Water Budget Analysis. Input and output of volumetric fluxes to the gypsum stack and the surficial aquifer are represented as cubic meters per day in the direction of the arrows.

Input - Output = Change in Storage

Although there is a short term (weekly) change in storage within the stack water body (indicated by water level changes in the stack ponds), it can be assumed that there is no change in the total volume of stack water over longer periods of time. Minute changes in the pond storage are seen as volumes of water which are negligible when compared to the unit's residence times (i.e. decades and centuries). Thus, input will equal output, as required in the steady-state model. The volumetric input flux of the stack is described entirely as precipitation, with large contributors of output flux being pond evaporation and stack leakance.

Evaporation was calculated as 50 % of the input flux, while the leakance value was taken from a water budget file in MODFLOW. Actual fluxes were only modeled after larger pathways of a significant impact , so that smaller pathways of output fluxes (such as flank evaporation, dewatering pipes, and sprayers on top of the stack) were not considered. Upon determination of these smaller fluxes to the total net output, a smaller vertical flux to the surficial aquifer could be calculated in the future. The value determined here (Figure 32) is, therefore, most likely overestimated by an unspecified amount and would thus represent a worst-case scenario for the infiltration of possibly toxic leachates from the phosphogypsum tailings into the surficial aquifer.

With these reservations, inputs for the surficial aquifer unit include a (overestimated) leakance from the gypsum stack and transport of regional flow from the southeast. Outputs include the ditch system, as well as regional losses of groundwater to the northwest. Most important to this flux analysis is the comparison of regional flow input and output to the relative inputs and outputs of the stack and ditches. For the most part, volumes of water transferred from the stack are taken up entirely by the ditch system. Any volume of water not taken up by the ditches is added into the regional flow and seen as a hydrologic impact from the stack (i.e. the mounding effect).

This conceptualization of the flux budget is important to the understanding of the hydraulic control of water in the system. A relatively complete consumption of water to the ditches indicates that engineering of the hydraulic balances used to minimize impact on the groundwater are fairly adequate, and even if toxic leachate from the gypsum's stack infiltrates into the surficial aquifer, it will, to a large extent, be intercepted by the ditch drainage system. The water budget illustrates that only about 16 m^3/day of water is bypassing the ditch structure and being swept away by regional flow. Although such an amount of non-captured leachate may seem large at first glance, the value must be taken to be relative to total fluxes in the system. When compared to the input of the surficial aquifer, it is ~38% of that value; however, in a comparison with the stack leakance, this value is ~1% of the infiltrating flux. Thus, the addition of water to the system is quite small in comparison to the amount of water that could be impacting the aquifer were there no ditches. Under any circumstance, the quantity of flux to the system is quite large when considering the regional flow and must be taken as somewhat of a considerable impact to the groundwater environment in the vicinity of the phosphogypsum stack.

CHAPTER 7

CONCLUSIONS

The investigation of hydrologic controls in a phosphogypsum stack intended to produce a model upon which hydraulic flow within the stack could be demonstrated. Identification of the parameters controlling fluxes within the system, as well as quantification of certain fluxes were important. Although many of the goals achieved in this project are site-specific, much of the knowledge acquired by this research can be directly applied to other gypsum stacks.

Characterization of the hydrologic environment determined basic flow parameters, which allowed homogenous assumption of variables dictating flow patterns. The Cooper-Jacob test determined a generalized flow velocity for gypsum tailings, and yielded a transmissivity and storativity for the gypsum material that can be utilized in analyses of other gypsum stacks. The Kirkham and Bouwer-Rice methods identified three distinct flow regimes in the surficial aquifer; most important in this characterization was a region of low conductivity beneath the stack, and a zone of high conductivity to the nowthwest of the stack.

Determination of flow direction and velocity was achieved by hydraulic head comparisons of wells. Vertical distinction of gradients in the stack, in addition to horizontal gradients in the surficial aquifer were critical in assessing the greatest transfer of water within the system. These results also gave support for the theory of topographical mounding through identification of a large gradient at the stack-surficial aquifer interface, as well as an anomalous ambient head value beneath the stack.

Other hydraulic tests such as the pressure transducer and borehole flowmeter helped to support the notion of topographic mounding by identifying the presence of flow anomalies at depth in the stack. Results did not specify exact measurements of flow for all portions of the stack, but did clarify a stratification of horizontal layering throughout the section of the stack studied. A more complete investigation using these tests would yield information about flow patterns that could be critical to understanding flow in phosphogypsum stacks.

Numerical modeling of the flow environment identified many important factors at work. Identification of important variables, such as ditch elevations and evaporative loss from the pond in the south, were the main successes of the modeling effort (seen as the comparison of modeled head values to observed ones). As a result, a quantification of flux rates allowed a deeper understanding of flow within the hydrologic system. Thus, the direct hydraulic impact of the phosphogysum stack could be calculated, and was found to be 16 m^3/day.

Utilization of the numerical model in a sensitivity analysis illustrated weaker links of the model. Stack leakance and ditch elevations, the most sensitive parameters, were shown to be highly influential under small adjustments. However, effective recharge from precipitation determined an optimal value for leakage of 3×10^{-4} day $^{-1}$, and ditches were corrected to the closest values of their actual specified elevations.

A volumetric flux analysis of the phosphogypsum environment is the greatest achievement of the project, as the flux values determined can be used in further efforts to develop transport models of the system. Results of this flux analysis show that only 1% of the stack water enters the surficial aquifer; the remainder is captured by the perimeter ditches, from which it evaporates. Thus, relatively minor amounts of contaminants from the gypsum stack are impacting the surficial aquifer beneath the stack, but are mostly collected in the ditch system. Radionuclides released to the environment can be considered a minimal hazard as the effects of dilution minimize the impact.

Although stack water flux to the surficial aquifer has been modeled, estimates of additional stack water losses (flank evaporation, spray losses, and dewatering pipes) are unknown, and may actually dictate a smaller value for infiltration flux to the surficial aquifer than indicated here. A more precise evaluation of the true impact of the phosphogypsum stack onto the surficial aquifer will be possible only after a more precise quantification of these stack water losses becomes available.

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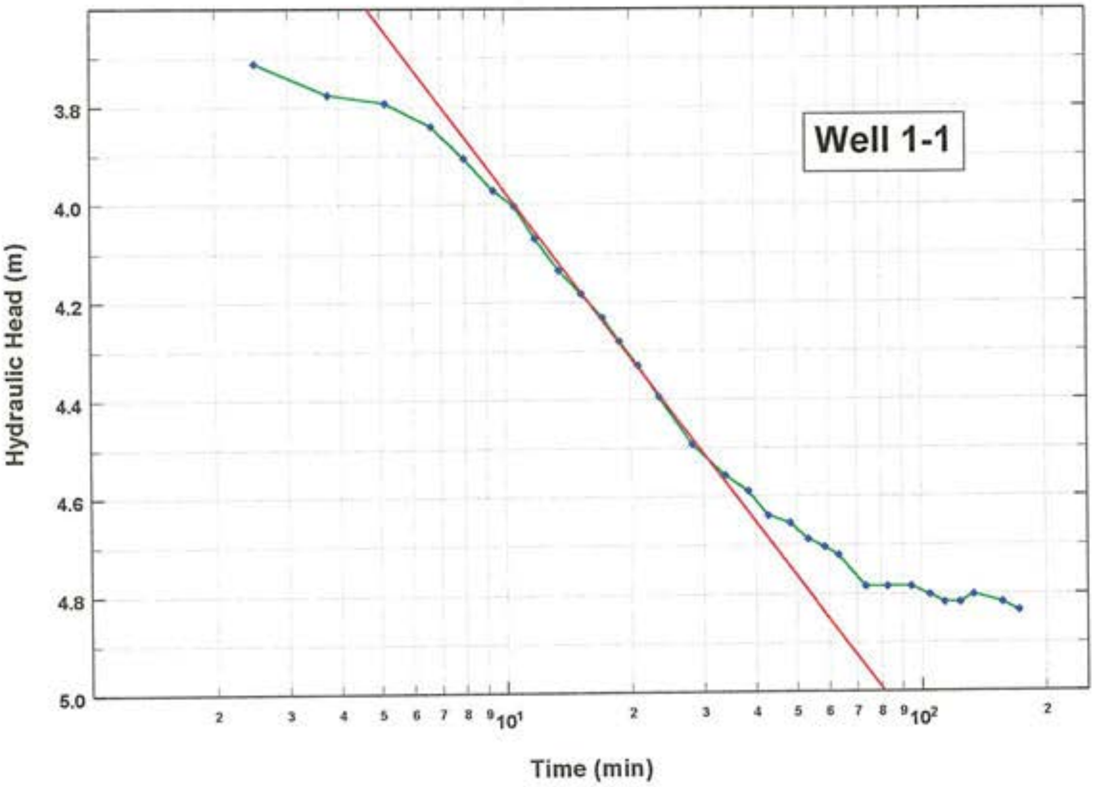
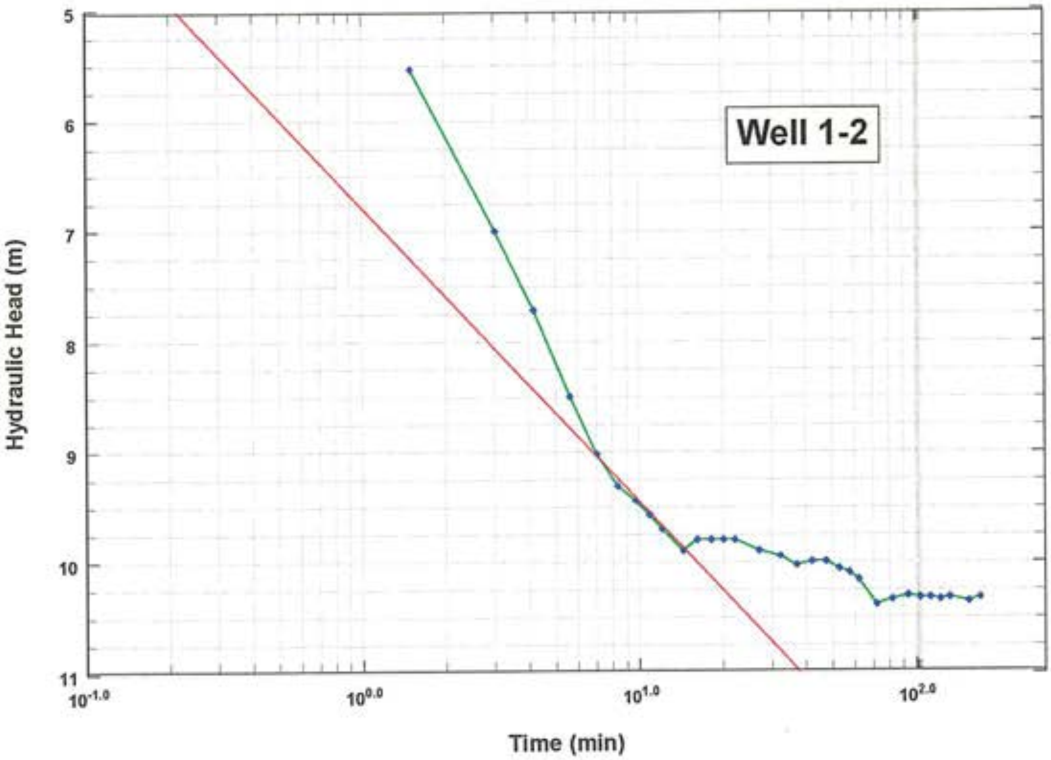
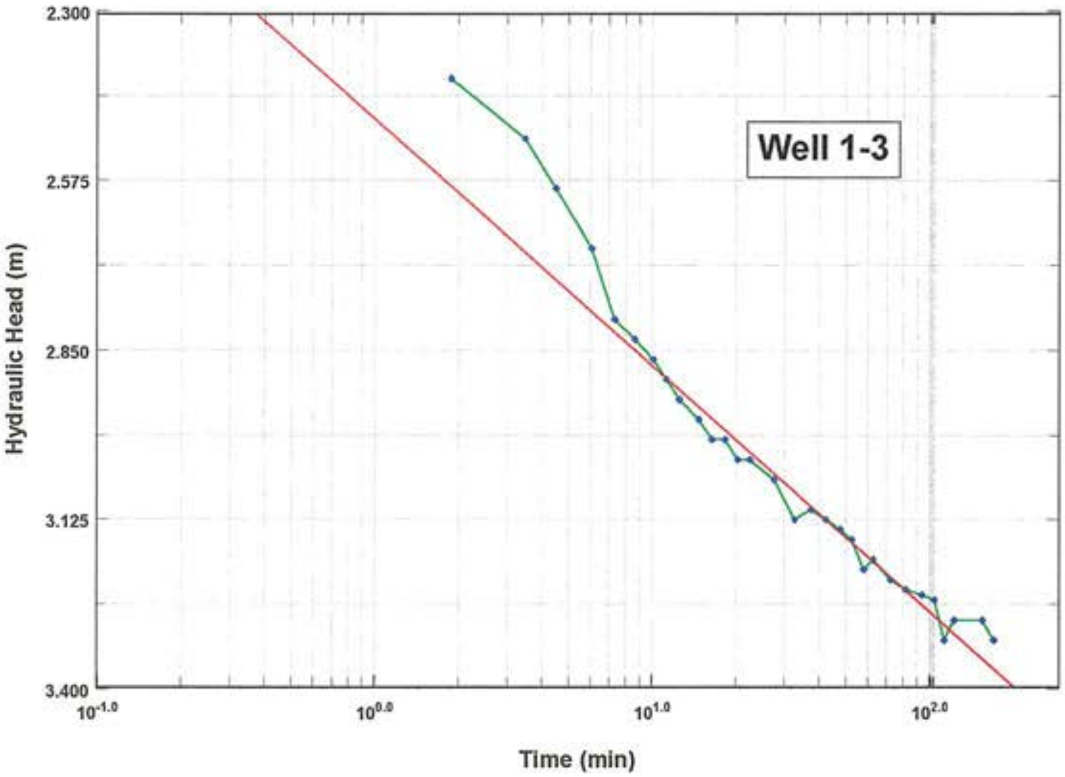
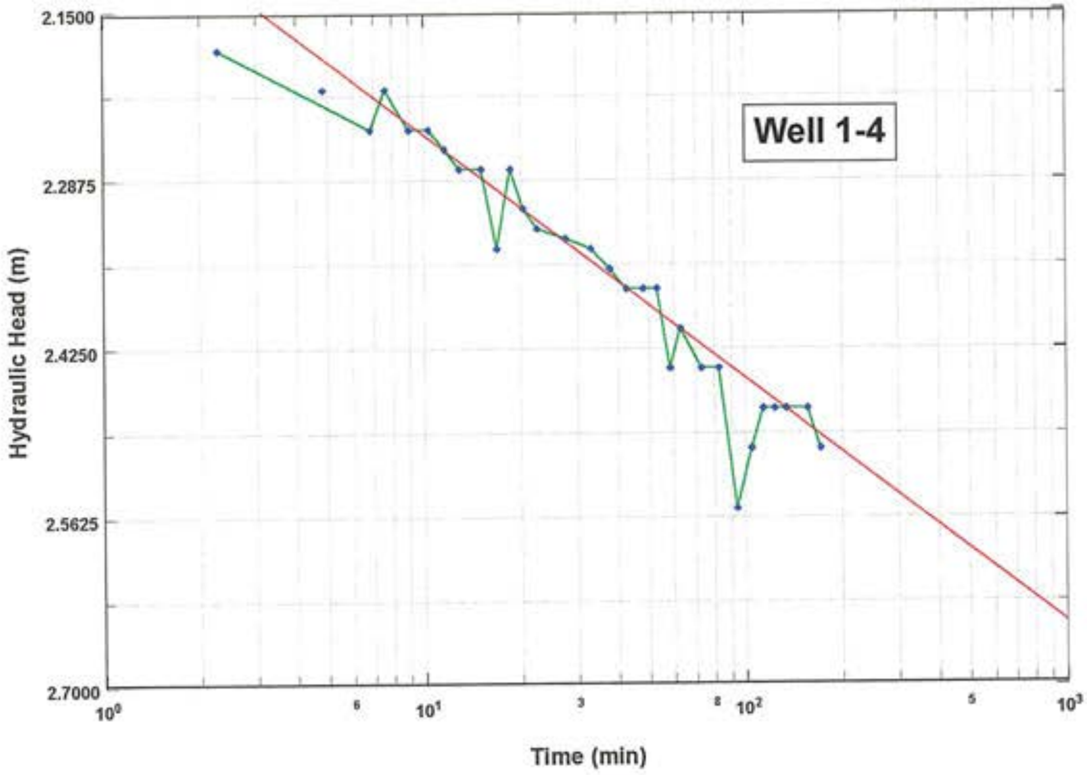
APPENDIX A

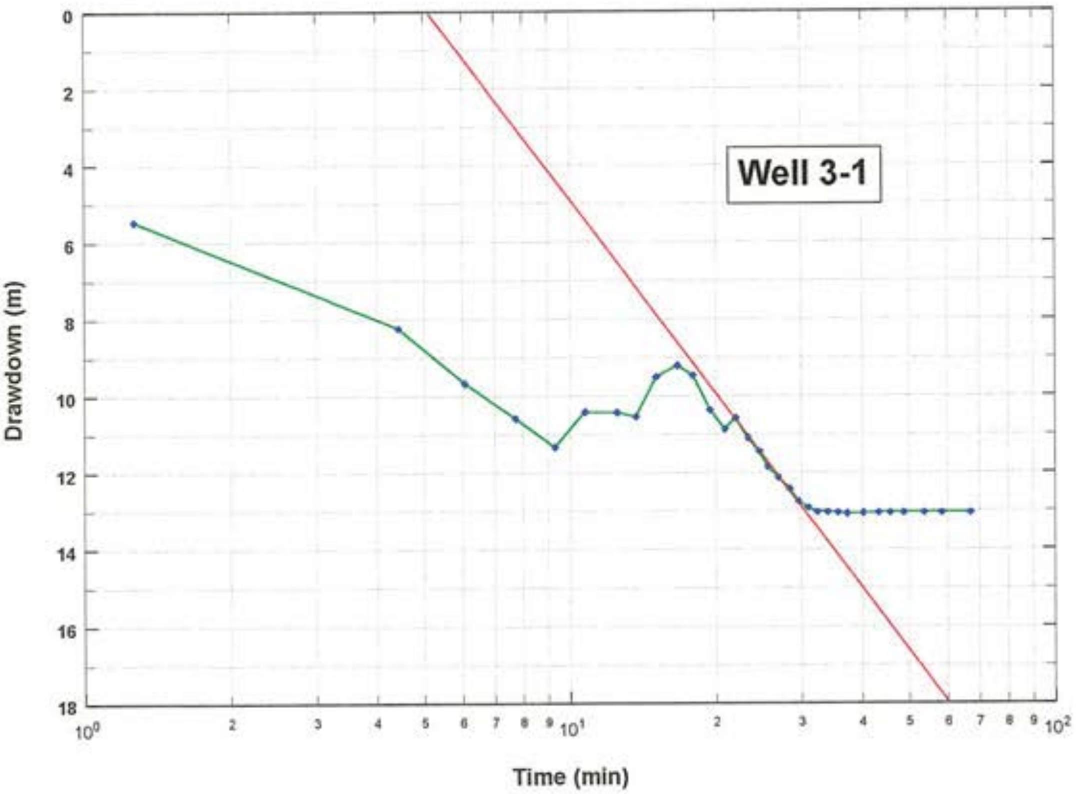
COOPER-JACOB STRAIGHTLINE PLOTS

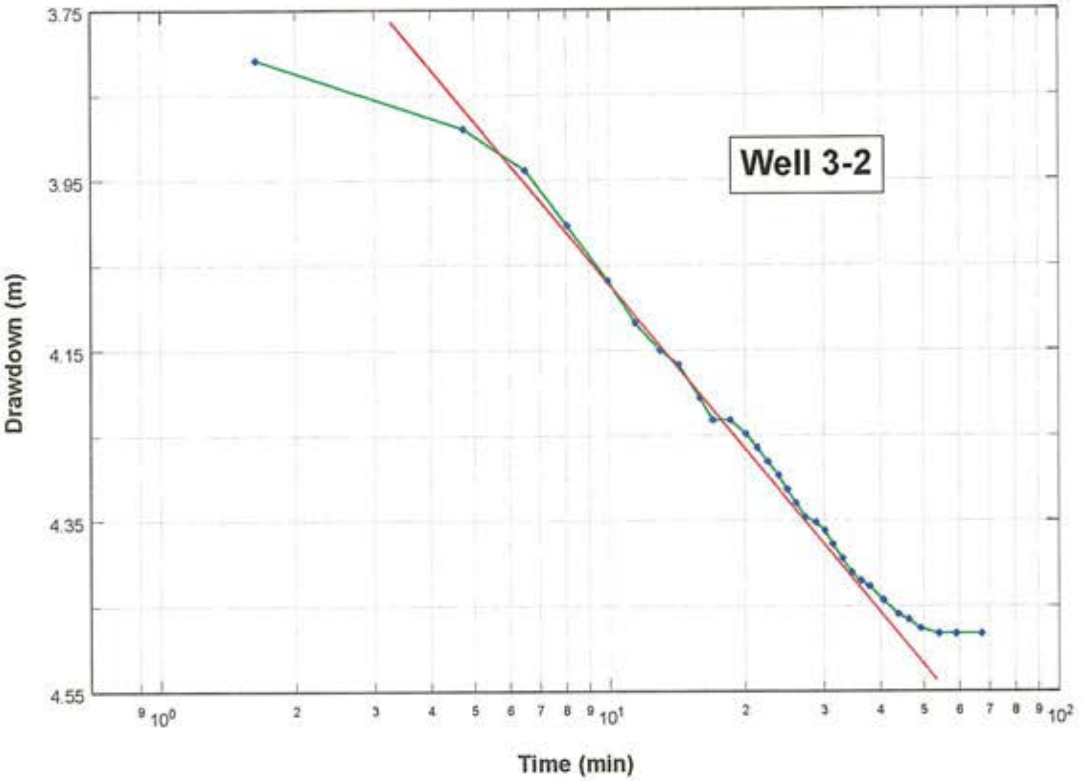


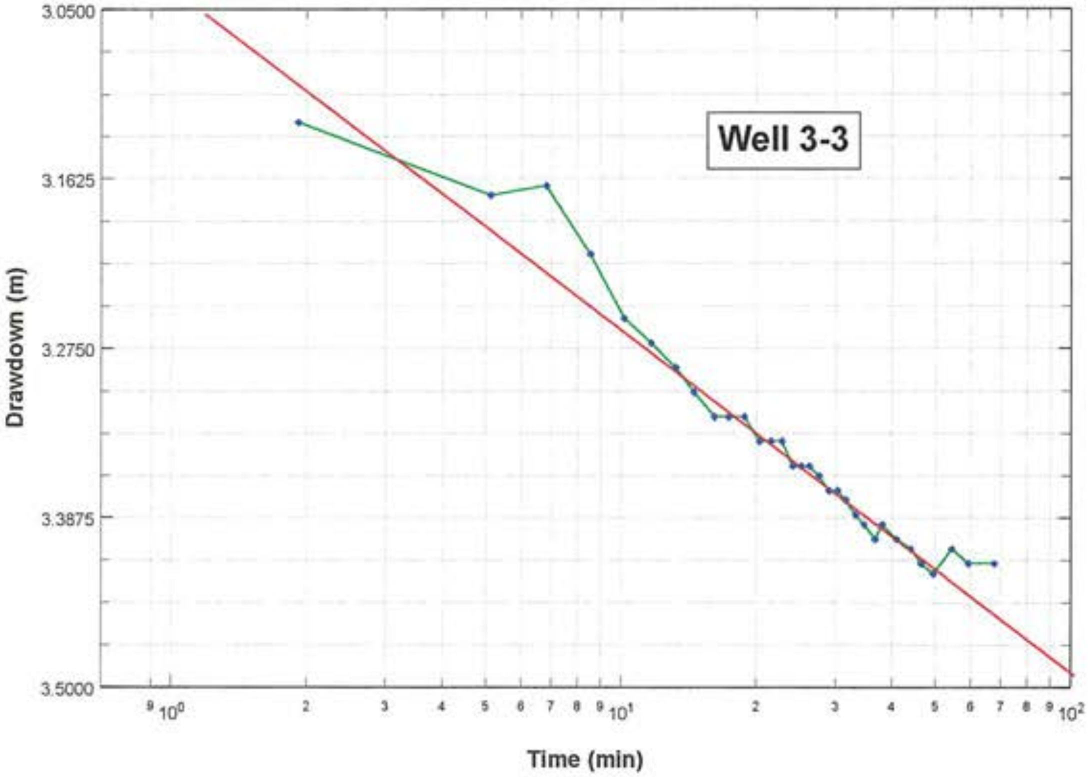

Well 1-2
Hydraulic Head (m)
5
6
7
8
9
10
11
Time (min)
10-1.0
100.0
101.0
102.0


Well 1-3
Hydraulic Head (m)
2.300
2.575
2.850
3.125
3.400
$10^{-1.0}$
$10^{0.0}$
$10^{1.0}$
$10^{2.0}$
Time (min)


Well 1-4
Hydraulic Head (m)
2.1500
2.2875
2.4250
2.5625
2.7000
Time (min)
10^0
6
10^1
3
8
10^2
5
10^3

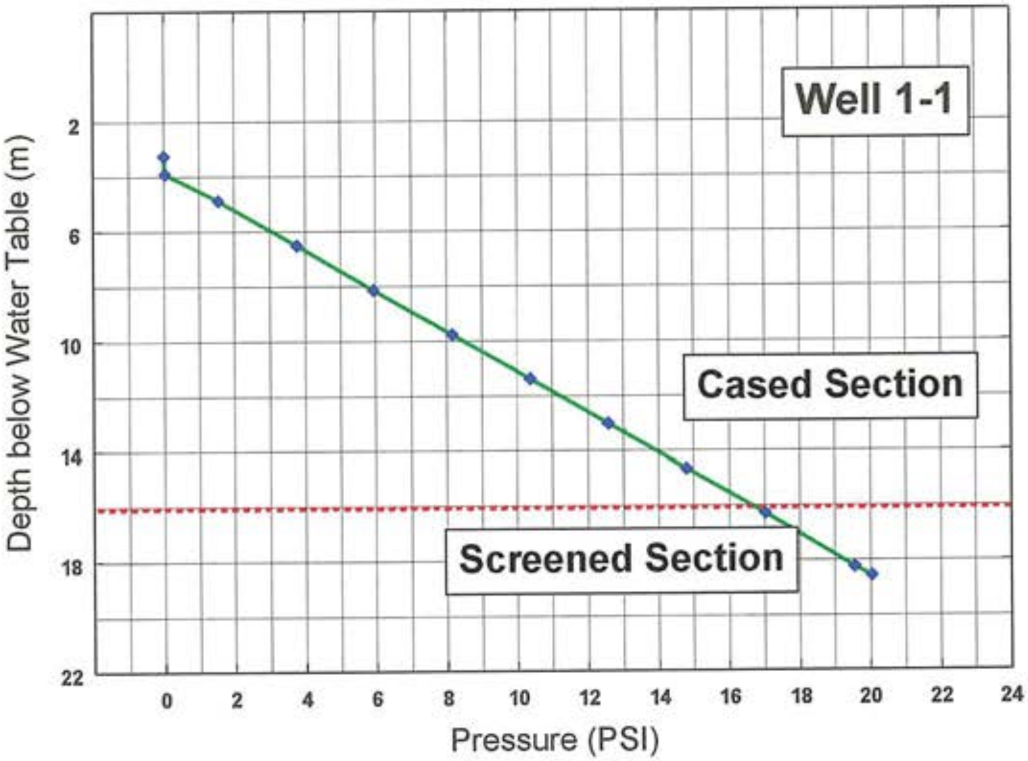

Well 3-1
Drawdown (m)
0
2
4
6
8
10
12
14
16
18
10^0
2
3
4
5
6
7
8
9
10^1
2
3
4
5
6
7
8
9
10^2
Time (min)

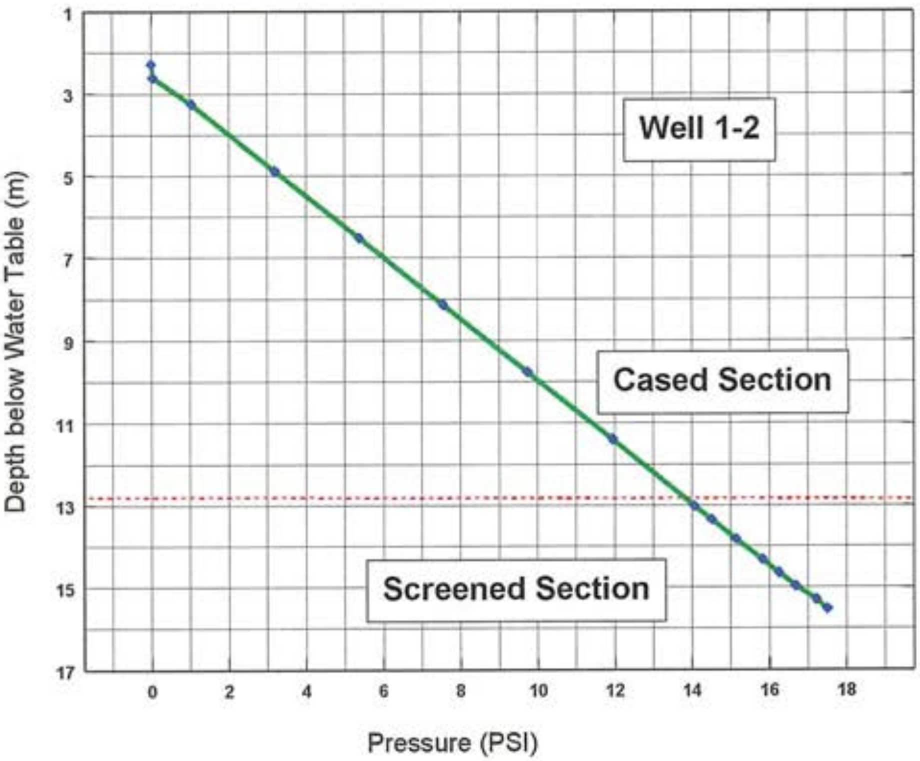

Well 3-2
Drawdown (m)
3.75
3.95
4.15
4.35
4.55
Time (min)
9
10^0
2
3
4
5
6
7
8
9
10^1
2
3
4
5
6
7
8
9
10^2


Well 3-3
3.0500
3.1625
3.2750
3.3875
3.5000
Drawdown (m)
9
10^0
2
3
4
5
6
7
8
9
10^1
2
3
4
5
6
7
8
9
10^2
Time (min)

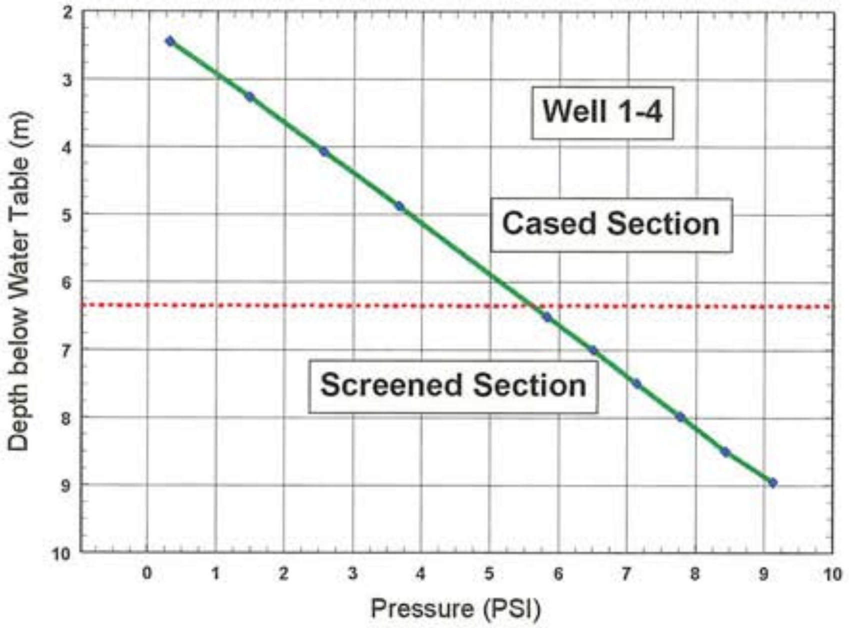
APPENDIX B

PRESSURE TRANSDUCER TESTS

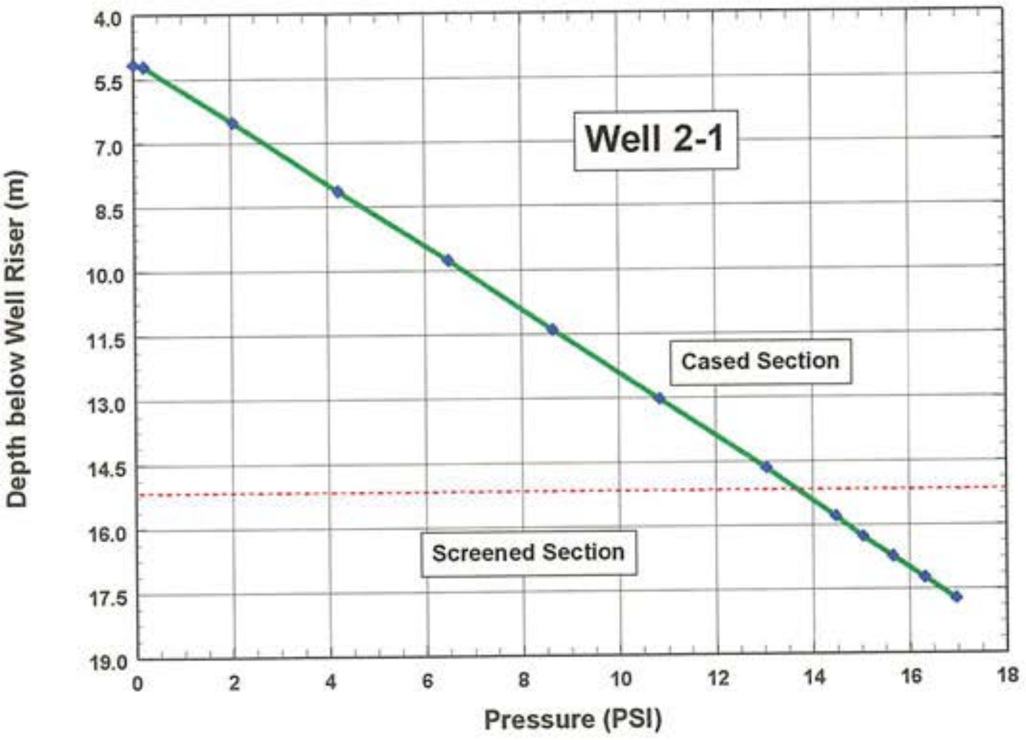


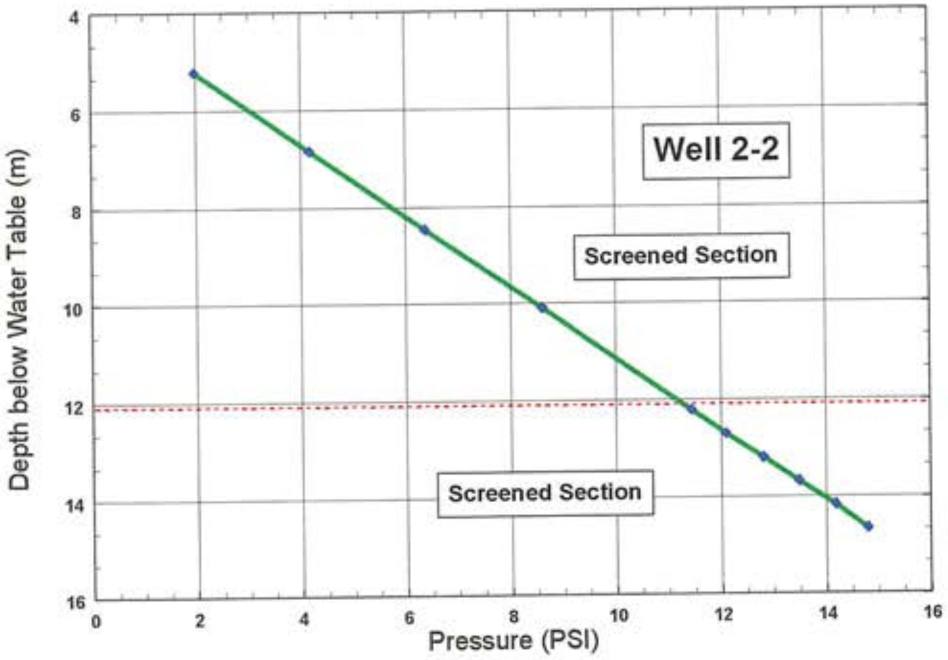


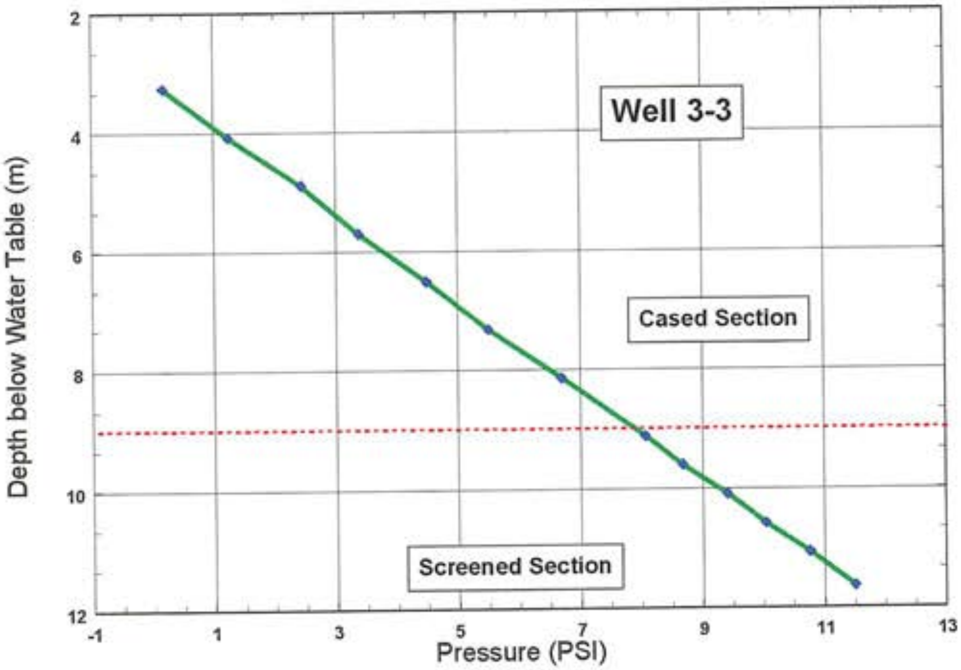
Well 1-2
Cased Section
Screened Section
Depth below Water Table (m)
1
3
5
7
9
11
13
15
17
0
2
4
6
8
10
12
14
16
18
Pressure (PSI)



Well 1-4
Cased Section
Screened Section
Depth below Water Table (m)
2
3
4
5
6
7
8
9
10
0
1
2
3
4
5
6
7
8
9
10
Pressure (PSI)

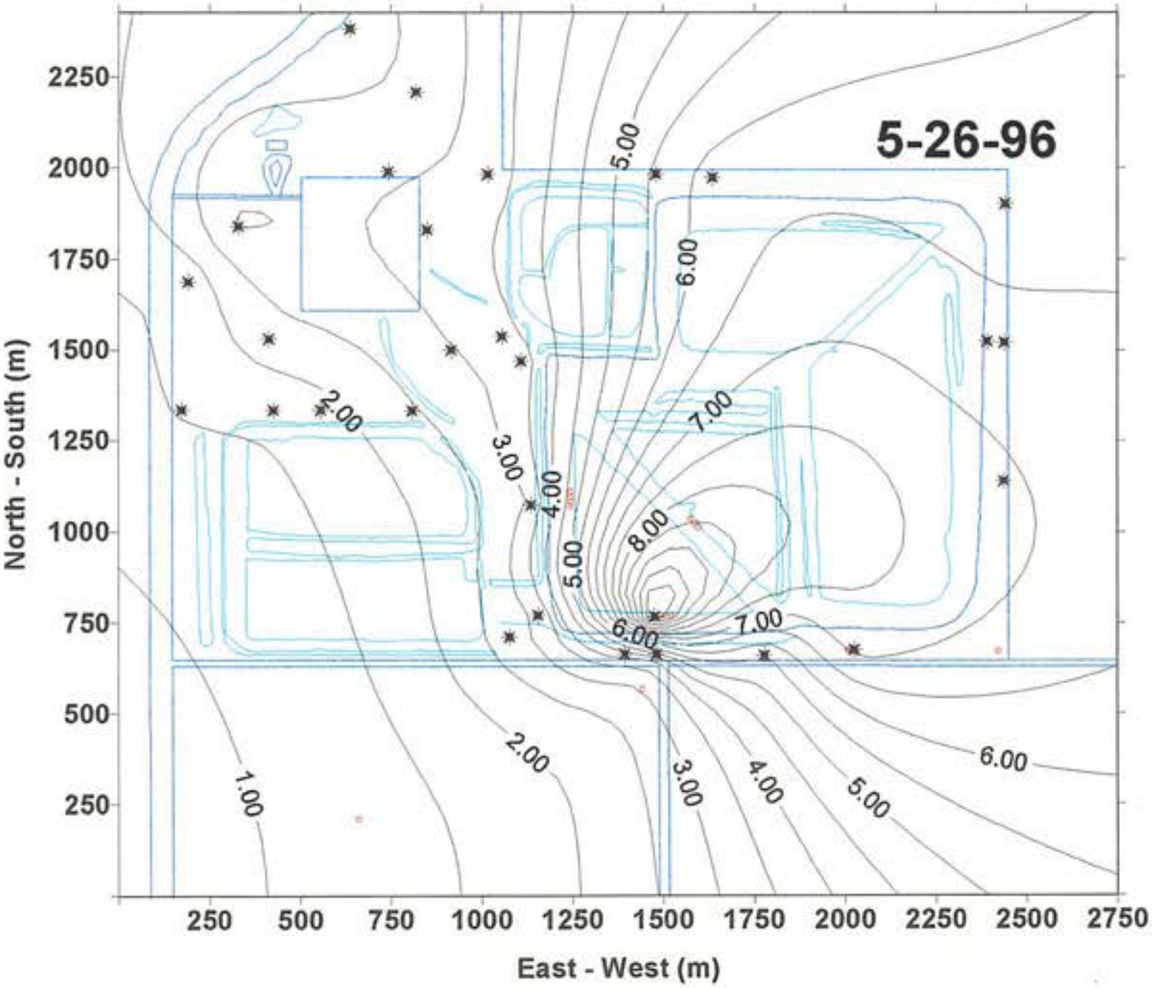

Well 2-1
Cased Section
Screened Section
Depth below Well Riser (m)
4.0
5.5
7.0
8.5
10.0
11.5
13.0
14.5
16.0
17.5
19.0
0
2
4
6
8
10
12
14
16
18
Pressure (PSI)

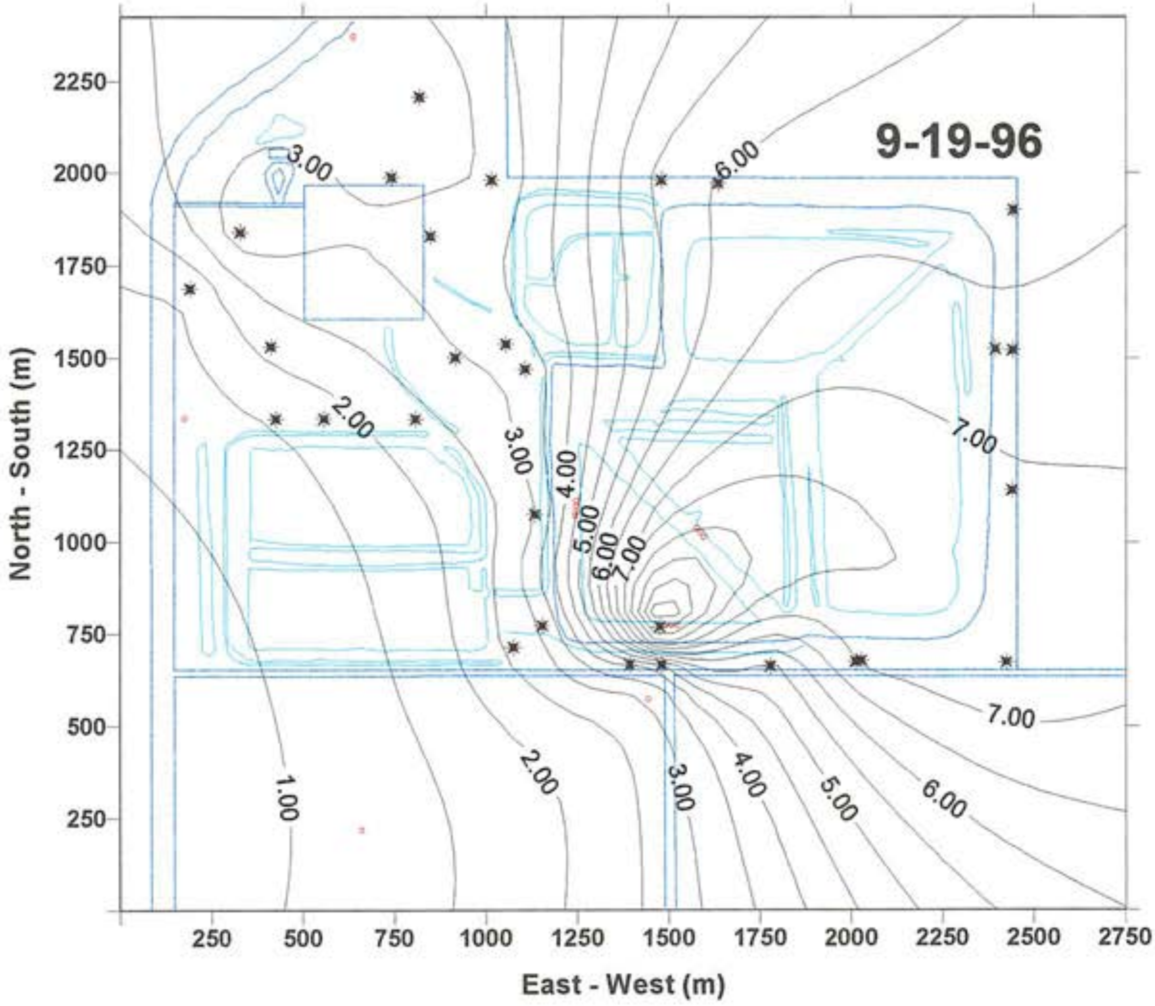

Well 2-2
Screened Section
Screened Section
Depth below Water Table (m)
Pressure (PSI)
4
6
8
10
12
14
16
0
2
4
6
8
10
12
14
16


Well 3-3
Cased Section
Screened Section
Depth below Water Table (m)
2
4
6
8
10
12
-1
1
3
5
7
9
11
13
Pressure (PSI)

APPENDIX C

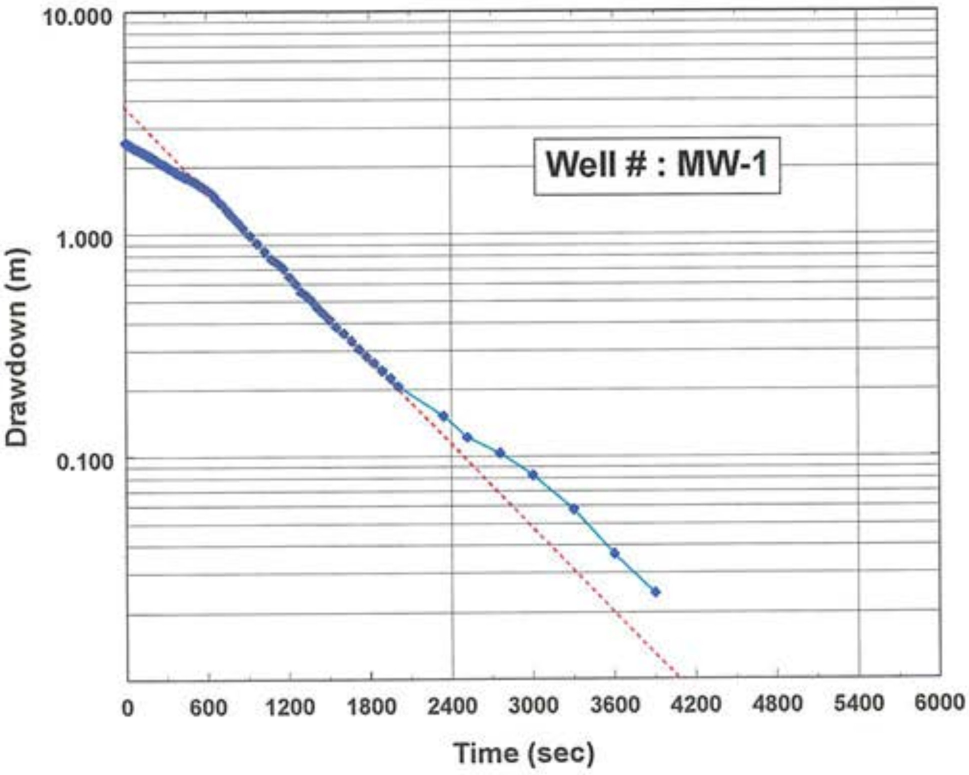
HYDRAULIC HEAD CONTOUR PLOTS

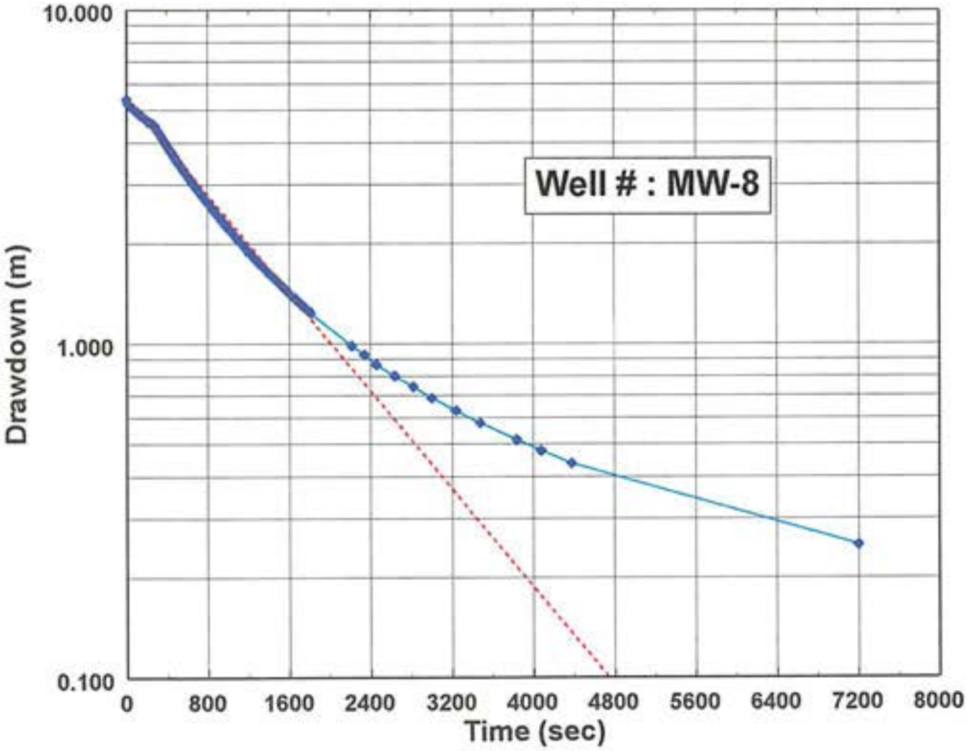



9-19-96
North - South (m)
East - West (m)
2250
2000
1750
1500
1250
1000
750
500
250
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
1.00
2.00
2.00
3.00
3.00
3.00
4.00
4.00
5.00
5.00
6.00
6.00
6.00
7.00
7.00
7.00

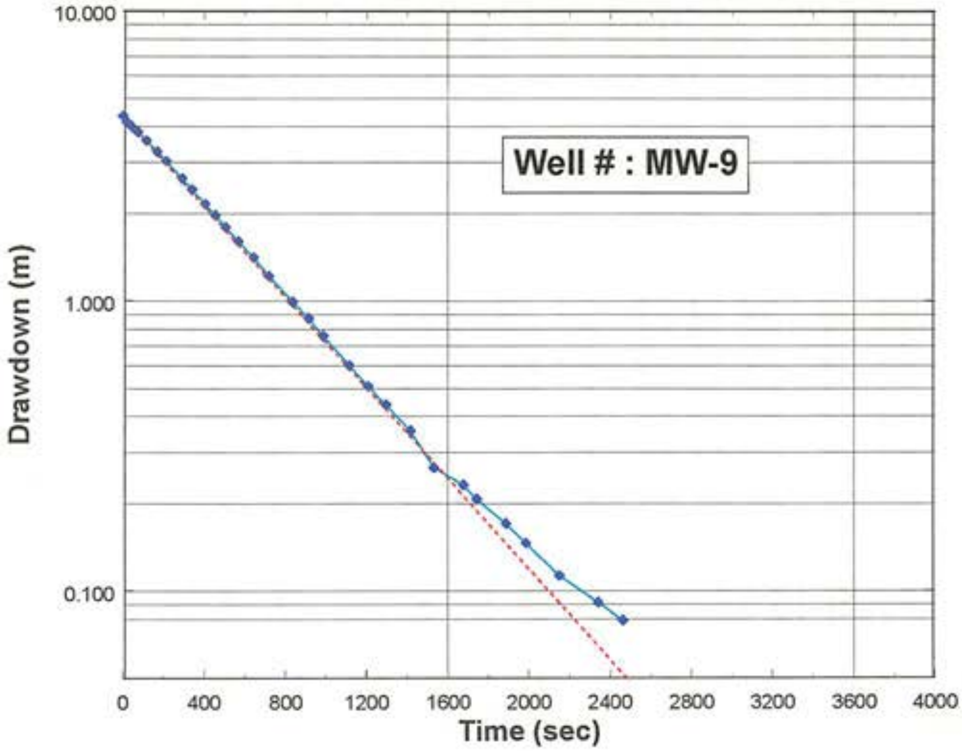
APPENDIX D

BOUWER RICE PLOTS

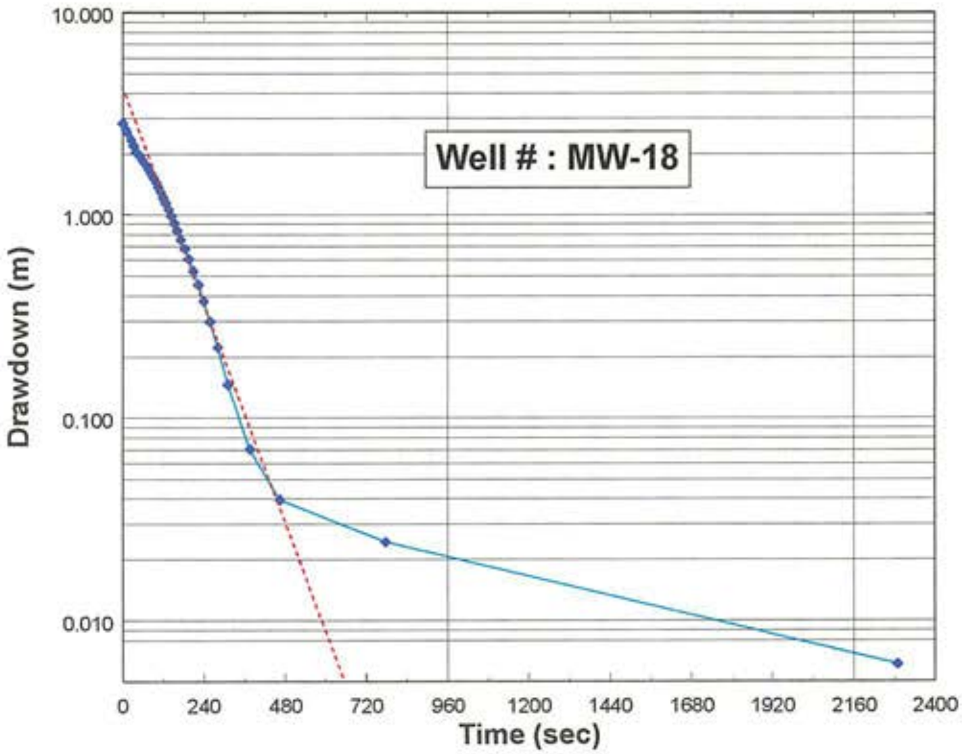


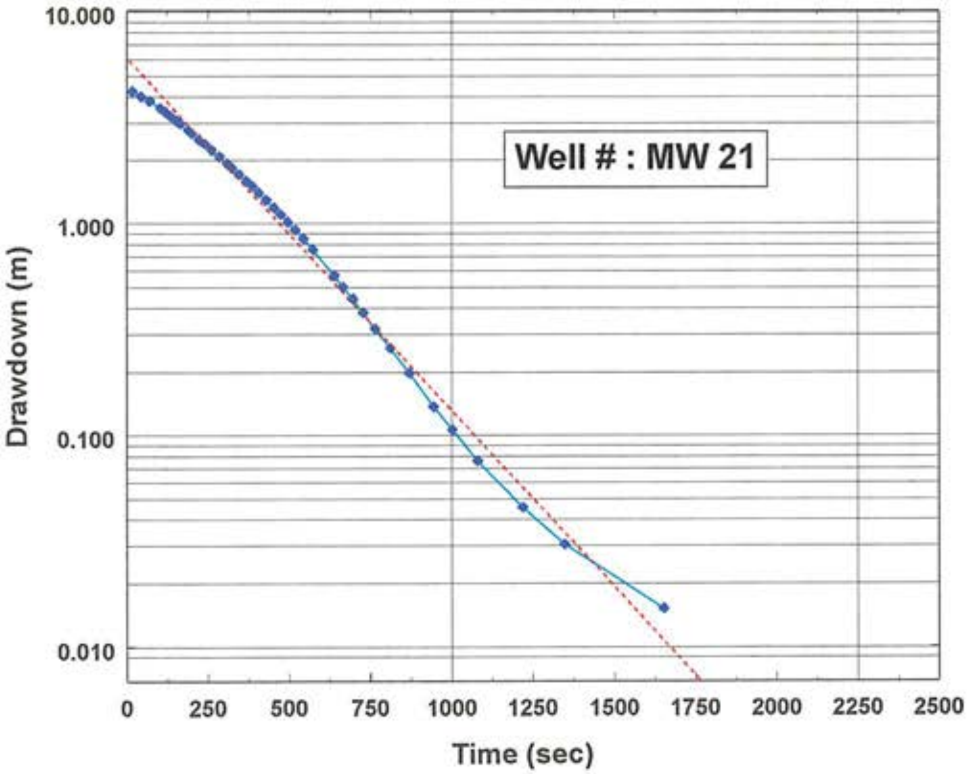


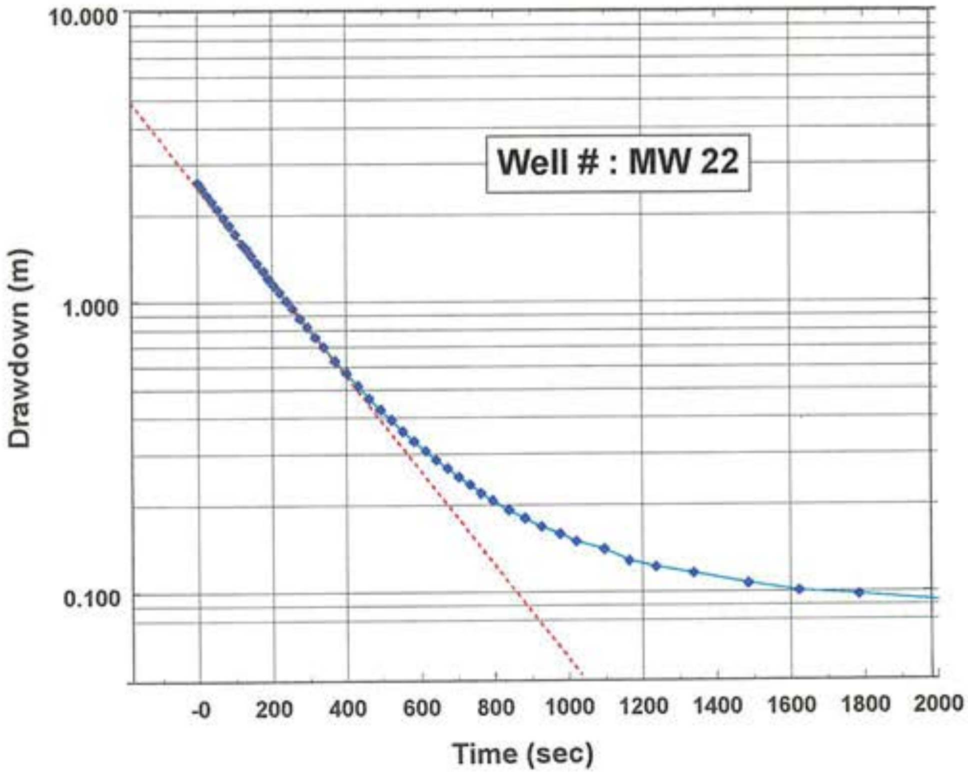
Well # : MW-8
Drawdown (m)
10.000
1.000
0.100
Time (sec)
0
800
1600
2400
3200
4000
4800
5600
6400
7200
8000

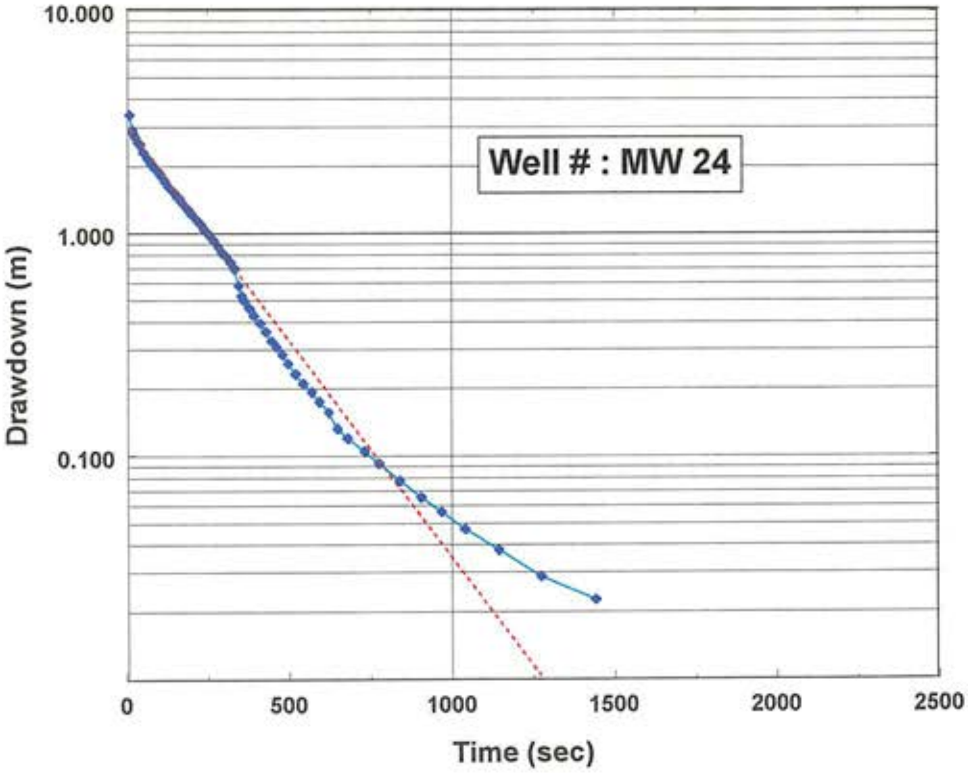


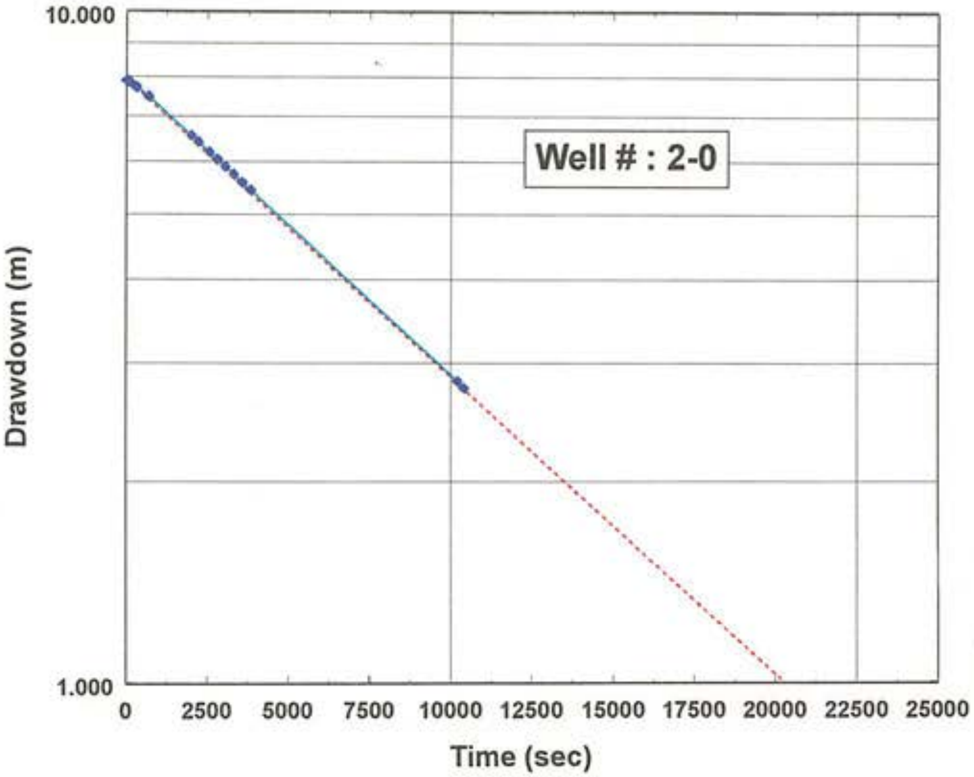
10.000
1.000
0.100
Drawdown (m)
Well # : MW-9
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000
Time (sec)


Well # : MW-18
Drawdown (m)
10.000
1.000
0.100
0.010
Time (sec)
0
240
480
720
960
1200
1440
1680
1920
2160
2400


Well # : MW 21
Drawdown (m)
10.000
1.000
0.100
0.010
Time (sec)
0
250
500
750
1000
1250
1500
1750
2000
2250
2500


Well # : MW 22
Drawdown (m)
10.000
1.000
0.100
-0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (sec)


Well # : MW 24
Drawdown (m)
10.000
1.000
0.100
0
500
1000
1500
2000
2500
Time (sec)



Well # : 2-0
10.000
1.000
Drawdown (m)
0
2500
5000
7500
10000
12500
15000
17500
20000
22500
25000
Time (sec)