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Groundwater Hydrology Study of the Ames Chemical Disposal Site

by

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MASTER

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MASTER

Groundwater hydrology study of the Ames Chemical Disposal Site

by

Tamara Lyn Stickel

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DEDICATION

I would like to dedicate this work to my Mom and Dad, Sonya and Jack Stickel. Their encouragement helped me to pursue a career in science and their love and support helped me to achieve my goals. I love you!

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INTRODUCTION

The Ames Laboratory Chemical Disposal Site is located in north-western Ames, Iowa west of Squaw Creek. From 1957 to 1966, Ames Laboratory conducted research to develop processes to separate uranium and thorium from nuclear power fuel and to separate yttrium from neutron shielding sources. The wastes from these processes, which contained both hazardous and radiological components, were placed into nine burial pits. Metal drums, plywood boxes, and steel pails were used to store the wastes. Uranium was also burned on the ground surface of the site (Rust, 1994a). The wastes were removed from the pits during the summer and fall of 1994 by OH Materials and transported to Utah for disposal (Larson, 1996).

Monitoring wells, installed by Rust Environment & Infrastructure, were placed around the waste burial pits. Groundwater testing in 1993 revealed elevated levels of Uranium 234 (U-234), Uranium 238 (U-238), beta and alpha radiation. Wells along the north side of the burial pit had elevated levels of volatile organic compounds. Samples in the East Ravine showed no volatile organics; however, they did contain elevated levels of radionuclides (Rust, 1993). These analytical results seem to indicate that the groundwater from the burial pit is flowing down hill and causing contamination in the East Ravine.

The greatest human health and environmental safety concern is groundwater contamination. There is risk of both on-site and off-site contamination. Contaminated groundwater can eventually spread to Squaw Creek (Rust, 1994b) or it could infiltrate through the soil and reach the bedrock under the site. On-site contamination of the bedrock is unlikely to occur because the hydraulic conductivity of Pre-Illinoian till, overlying the bedrock, is fairly low.

There is greater risk associated with the off-site migration of groundwater, which could travel off-site through the East Ravine and eventually reach Squaw Creek. In this ravine, the groundwater primarily travels through the Wisconsin oxidized till. It is possible that the groundwater could migrate into the alluvium zone of soil, following high amounts of

precipitation, and become surface flow, thus, leading to contamination of surface waters and soils (Jones, 1994).

A study of the geology near the chemical disposal site by Oulman and Sendlein in 1968 provided an initial understanding of the geology of the site. They found two distinct drift zones classified as an oxidized zone, displaying a light brown color, and an unoxidized zone, displaying a bluish gray color. They also discovered lenses of sand and gravel between the till layers and interspersed in the upper oxidized zone. The study further indicated that the ravine contained a three foot (one meter) deep alluvium layer of soil, which was previously weathered till that had been reworked. In lower areas of the ravine, the alluvium layer rested directly above the bedrock (Oulman and Sendlein, 1968). This soil structure causes concern that the groundwater could penetrate through the alluvium layer directly to the bedrock, easing the spread of contamination.

Although there are many avenues for the contamination to spread, the focus of this project is to understand the hydrogeology of the East Ravine and to determine the path of groundwater flow down the East Ravine. The groundwater flow data along with other existing information will be used to assess the threat of chemical migration down the East Ravine and eventually off-site.

In order to understand the flow of groundwater, monitoring wells were installed across the East Ravine and were used to record weekly water table fluctuations from November 1994 to September 1995. These wells were also used to conduct slug testing, to understand the response of the water table, and to determine the permeability of the till. During the well-installation, soil boring logs were recorded to provide additional geology and soil structure data for the East Ravine. Soil samples, obtained during well installation, were tested to determine the bulk density, particle density, and water content of the soil. Field results were used to develop a mathematical model to assess the potential for contaminant migration (Jones, 1995).

The primary objectives of the project were as follows:

- Define the geology of the East Ravine.
- Conduct slug tests to determine the hydraulic conductivity of both oxidized and unoxidized till.
- Develop a three-dimensional mathematical model using ModIME and MODFLOW to simulate groundwater flow in the East Ravine.

SITE INFORMATION

Site Location

The chemical disposal site is located next to the Iowa State University (ISU) Applied Science Complex in Ames, Iowa. The Applied Science Complex Center is located north of Ontario Street on Scholl Road (Figure 1). Figure 2 shows a map of the chemical disposal site and the ravines surrounding the site, including the location of monitoring wells installed by Rust Environment & Infrastructure.

The groundwater hydrology study was performed off-site of the chemical disposal area in the East Ravine. From late October 1994 to July 1995, thirty-eight monitoring wells were installed by hand and power augers. These monitoring wells were used to weekly measure the water table elevations and to conduct slug testing. Soil samples were also obtained during well installation for further analysis. Placement of the monitoring wells was designed to capture flow down the ravine and to provide well nests, containing both oxidized and unoxidized soil zones, which were used to observe the changes in the water table.

After monitoring well installation, a survey was conducted to establish the state plain coordinates of the wells. To facilitate a comparison for future surveys, three Rust wells were also included in this survey. Figure 3 shows a contour map of the monitoring wells locations, relative to three of the wells installed by Rust. The control point for the Rust survey was at an angle of 88.24° and 623 ft (190 m) from MW-6A. The location of the monitoring wells are reference by northings and eastings in state plain coordinates. The well locations and ground surface elevations are displayed in Table 1.

Figure 4 displays a site ground surface profile that was developed using SURFER, a contouring and three dimensional surface mapping program (Golden Software, 1994). This profile creates a representative illustration of the East Ravine surface contour. From Figure 4, it is evident that the East Ravine has steep side slopes.

Figure 1. Location of Ames Chemical Disposal Site (Rust, 1994a)

Figure 2. Ames Chemical Disposal Site and area ravines (Rust, 1995a)

MW7B | 197383.7752 | 1956576.375 | 945.7

note: Northings and Eastings are state plain coordinates
Surface elevations are mean sea level

Figure 3. Topographic site plan of monitoring well locations relative to Rust MW-6A

note: Northings and Eastings are state plane coordinates
 Surface elevations are mean sea level

Figure 4. Surface profile of monitoring wells

Regional and Site Geology

The Pleistocene ice age is responsible for the till composition in Iowa and occurred in four stages lasting over 2.5 million years. Prior to the Pleistocene age was the Tertiary period, characterized by erosion and the development of streams in the valleys. The climate of this period was very warm, unlike the Pleistocene age. The duration of the Pleistocene era included the Nebraskan, Kansan, Illinoian, and Wisconsin glacial stages and three interglacial stages which included the Aftonian, Yarmouth, and Sangamon stages.

The first ice age occurred during the Nebraskan stage which reached from Canada, to Iowa and extended to Central Missouri. The drift depth is between 100 to 150 feet (30.5 to 45.7 meters). The Nebraskan drift covered most of the Iowa bedrock surface. As the glacial form moved into Iowa, it deposited clay, sand, gravel, and silt onto the surface. The wind, rain, and sun caused significant changes in the drift due to oxidation, resulting in a change of color from a dull gray to a yellow or red. This period began the creation of the Aftonian interglacial period. Some of the rock material was dissolved by groundwater, carrying the material into the subsoil layers. Over time, limestone and other materials were leached into the soil. During this transition, oxidation continued and contributed to the formation of an oxidized and an unoxidized zone to be developed in the soil layers. Chemical changes were also occurring and organic acids were formed. Materials were broken down to smaller sizes, due to weathering of glacial till. These smaller rock sizes formed a layer, referred to as gumbotil, that ranged 8 to 9 feet (2.4 to 2.7 meters) thick. The oxidized zone of the Nebraskan glacial was about 3 feet (0.91 meter) thick, located below the gumbotil layer. The oxidized zone contained a leached layer, where limestone and carbonates had worked their way through the soil. There was also an unleached layer, where there were no signs of calcium carbonate deposits. The bottom layer of the zones contained a layer of unoxidized and unleached till.

The Kansan glacial stage covered all of Iowa, except northeast Iowa, and extended into Central Missouri. The average depth of this stage ranges from 50 to 60 feet (15.2 to 18.3

meters) (Anderson 1983). The Kansan drift contained boulder clay, sand, and gravel. This glacial stage overlaid the Nebraskan drift. Weather, air, and groundwater created another change in the drift, causing more oxidation to occur and creating the Yarmouth interglacial period. Following the Kansan period, deposits of sand and gravel were found deposited on top of the Kansan material. The soil structure contained an 8 foot (2.4 meters) thick layer of gumbotil material from the Yarmouth period, a Kansan oxidized (leached and unleached) layer and a Kansan unoxidized layer (Kay, 1944).

The Illinoian glacial period moved into Iowa from the East and caused the Mississippi River to move West, but was confined to southeastern Iowa (Anderson 1983). The average thickness of the gumbotil layer is less than 5 feet (1.5 meters). It is thought that part of the Kansan drift was eroded, leading to the theory that the Illinoian till may rest on top of the Nebraskan glacial till (Kay, 1944). The Sangamon interglacial period formed on the upper portion of the Illinoian glacial sheet in Iowa. There were also deposits of sand and gravel associated with the Sangamon period (Anderson, 1983).

The most prominent period, which impacts the research site, occurred during the last glacial period with the Wisconsin glacier age. This period occurred in four stages which were the Mankato (late Wisconsin), Cary (Middle Wisconsin), Tazewell (Early Wisconsin), and the Iowan stage (Kay, 1944). The Cary-Mankato drift occurred 13,000 years ago and is often referred to as the Des Moines Lobe. The Des Moines Lobe covers from northern Iowa to central Iowa (Figure 5) (Anderson 1983). The glacial till is made up of both a yellowish or light brown oxidized layer and a blue or gray unoxidized layer; however, it does not contain a gumbotil layer. Due to the young age of the Mankato till, the leaching is restricted to the upper depths of the soil. The till, composed of pebbles and sand, contains carbonates from 2 to 5 feet (0.61 to 1.5 meters) from the surface (Kay, 1944). The average thickness of the Cary-Mankato till is 35 feet (10.7 meters) (Anderson and Welp, 1960). There is a transition zone between the oxidized, unleached till and the unoxidized, unleached till which contains a mixture of colors. The latter zone showed no signs of weathering or oxidation (Kay, 1944).

Figure 5. Landform regions of Iowa (Rust, 1994 a).

Site Soils

The soils located around the Ames Chemical Disposal site are part of the Clarion-Webster-Nicollet and Hayden-Lester Storden soil types. Clarion-Webster-Nicollet soils are typically found in areas with level or moderate slopes and have either poor or good drainage properties. This soil is usually formed in a glacial till and contains an alluvium layer as top soil. Hayden-Lester Storden soil is a well-drained, loam soil, generally occurring in areas with gentle or steep slopes (USDA, 1984).

The Hayden was the most common soil type at the chemical disposal site (Rust, 1994 a). The top 8 inches (0.2 meters) of this soil is a dark gray or brown loam soil. The next 45 inches (1.1 meters) consist of a soil with dark yellow and brown colors (USDA, 1984). These soil color characteristics agree with the findings of Oulman and Sendlein in 1968. The East Ravine is primarily characterized by Storden soils (See Rust, 1994a). The top 9 inches (0.05 meters) of this soil is typically a dark, brown loam. The next layer is a yellowish or brown soil containing limestone (USDA, 1984).

EXPERIMENTAL PROCEDURES

Well Installation

Thirty-four monitoring wells were installed by use of hand augers and four of the wells were installed by a Little Beaver power auger. The hand augers ranged in width from 2.75 to 3.25 inches (0.07 to 0.08 meters). Using five foot extension rods with the hand auger, bore holes were excavated to desired depths. During the augering of the wells, soil log notes were recorded to observe changes in soil structure. These soil logs are found in Appendix A. During the summer of 1995, two wells (Al-Pz 7 and Al-Pz 23) were removed from the site due to well tampering.

Monitoring wells, placed in the oxidized till, were designed with a 4 foot (1.2 meters) slotted screen, while wells placed in unoxidized till were designed with a 1 to 2 foot (0.3 to 0.6 meters) slotted screen. The monitoring wells were made of one-inch diameter (0.02 meters) threaded polyvinyl chloride (pvc) pipe and five feet (1.5 meters) in length. The slotted screens were pre-cut by the manufacturer.

The bottom of each well was equipped with an pvc end cap connected to the slotted screen. Solid pvc pipe was attached to the screen to reach above the ground surface. The top end of the monitoring well also had an end cap to prevent precipitation from falling directly into the well. This end cap had a small hole to allow the pressure in the well to remain at atmospheric conditions. The monitoring wells were labeled Al-Pz #, which signified Ames Lab Piezometers.

The assembled monitoring well was lowered into the auger hole. Pea gravel was then placed around the monitoring well, from the bottom of the well to one foot (0.3 meters) above the top of the slotted screen. The purpose of the gravel was to serve as an effective screen to allow water to flow in and out of the well. Bentonite was then used to fill the auger hole from the top of the pea gravel to the ground surface and served as a seal to prevent water from running down the pipe. Table 2 provides a summary of well characteristics.

Table 2. Summary of monitoring well characteristics

Well #	Type ^a	Depth to Oxidized ft	Depth to Unoxidized ft	Screen Length ft	Ground to Bottom of well ft	Top of well to Bottom of well ft	Bore hole size inches	Date Installed	Method of Installation
1	ox	2	11.5 ^b	5.83	7.16	9.97	2.75	10/31/94	Hand auger
2	ox	3	7	5.92	7.25	10.00	2.75	11/2/94	Hand auger
3	ox	2	6 ^c	5.83	7.16	10.00	2.75	11/2/94	Hand auger
4	ox	3	-	5.75	7.25	10.00	2.75	11/3/94	Hand auger
5	ox	2	-	6.25	8.00	10.01	2.75	11/7/94	Hand auger
6	ox	2	-	6.58	7.75	10.00	2.75	11/7/94	Hand auger
7	ox	2	-	5.79	7.17	9.96	2.75	11/8/94	Hand auger
8	ox	2	-	6.46	7.31	10.15	2.75	11/9/94	Hand auger
9	ox	2	11 ^d	8.00	8.75	10.12	2.75	11/10/94	Hand auger
10	ox	3	11	10.00	11.25	15.11	2.75	11/10/94	Hand auger
11	ox	3	12	11.70	13.75	15.11	2.75	11/11/94	Hand auger
12	ox	3	14	10.79	14.46	15.14	2.75	11/14/94	Hand auger
13	unox	1	5	1.98	12.17	16.63	2.75	11/15/94	Hand auger
14	ox	2	-	11.00	12.75	14.99	3.25	11/16/94	Hand auger
15	t	2	14 ^e	2.08	14.50	16.67	3.25	5/24/95	Hand auger
16	unox	2	11	3.25	15.25	16.64	2.75	12/5/94	Hand auger
17	ox	3	11 ^f	5.67	7.95	10.11	2.75	12/2/94	Hand auger
18	ox	3	12 ^g	5.50	7.92	10.11	2.75	12/2/94	Hand auger
19	unox	3	12	2.17	12.92	16.70	2.75	1/25/95	Hand auger
20	unox	4	12	5.98	19.31	21.66	2.75	1/18/95	Hand auger
21	ox	2	11.5 ^b	5.50	9.92	15.16	2.75	4/5/95	Hand auger
22	unox	1	6	2.00	8.50	11.67	2.75	4/13/95	Hand auger
23	ox	3 ^h	-	5.50	7.83	10.05	2.00	5/16/95	Power auger

Table 2. Continued

Well #	Type	Depth to Oxidized ft	Depth to Unoxidized ft	Screen Length ft	Ground to Bottom of well ft	Top of well Bottom of well ft	Bore hole size inches	Date Installed	Method of Installation
24	unox	3 ^h	12 ^h	2.08	21.56	26.72	2.00	5/16/95	Power auger
25	unox	3 ^h	12 ^h	2.08	18.69	21.74	2.00	5/16/95	Power auger
26	unox	3 ^h	16 ^h	2.08	17.69	21.58	2.00	5/17/95	Power auger
27	ox	1.5	-	5.50	7.00	10.03	2.75	5/19/95	Hand auger
28	ox	2	-	5.50	7.00	10.05	3.25	5/24/95	Hand auger
29	t	2	14 ⁱ	5.42	10.00	15.04	3.25	5/25/95	Hand auger
30	t	3	10 ^e	3.08	9.33	11.55	3.25	5/31/95	Hand auger
31	t	3	9 ^e	2.25	9.67	11.54	2.75	6/6/95	Hand auger
32	ox	2	9 ^j	5.50	6.92	10.00	2.75	6/6/95	Hand auger
33	ox	0.5	6	3.00	4.00	7.59	2.75	7/2/95	Hand auger
34	ox	1	5	5.50	6.92	10.03	2.75	7/6/95	Hand auger
35	ox	1.5	-	5.50	6.92	10.00	2.75	7/6/95	Hand auger
36	ox	1.5	-	5.50	7.08	10.00	3.25	7/7/95	Hand auger
37	ox	1.5	-	6.33	7.83	10.07	3.25	7/11/95	Hand auger
38	ox	1.5	5.5 ^k	4.50	5.50	9.10	3.25	7/11/95	Hand auger

^a ox = oxidized zone, unox = unoxidized zone, t = transition zone

^b assumed value based on Rust well MW-6A (After Rust b, 1995)

^c assumed value based on well Al-Pz 22

^d assumed value based on well Al-Pz 20

^e assumed transition zone was top of unoxidized zone

^f assumed value based on well Al-Pz 16

^g assumed value based on well Al-Pz 19

^h assumed values based on observation of borings by power auger

ⁱ assumed value based on well Al-Pz 15

^j assumed value based on well Al-Pz 31

^k assumed value based on Rust well MW-7A/B (After Rust b, 1995)

Soil Analysis

Soil samples were obtained during well installation to determine the bulk density, particle density, and moisture content of these samples based on procedures detailed by Black and others (1965). The gravimetric water content was measured to obtain the moisture content of the soil. The water content was calculated by weighing the wet soil, then oven drying the soil sample, and obtaining a dry soil weight. The difference in the wet and dry weights are equivalent to the water content of the soil. The gravimetric water content is found by the following equation:

$$\theta_m = \frac{m_{ws+t} - m_{ds+t}}{m_{ds+t} - m_t} \quad (1)$$

where θ_m is the gravimetric water content (g/g), m_{ds} is the dry mass of the soil clod (g), m_{ws} is the wet mass of the soil clod (g), m_t is the mass of weighing tin (g), m_{ds+t} is the dry mass of the soil clod and weighing tin (g), and m_{ws+t} is the wet mass of the soil clod and weighing tin (g).

Bulk density is used to provide an estimate of the compactness of the soil and is measured as the mass of oven-dried soil divided by the total volume of the soil (Singer and Munns, 1991). To measure the bulk density of the soil samples, the clod method was used. This method is based on Archimedes' principle and theory of displacement (Black et al., 1965). The bulk density is calculated by the following equations:

$$V_1 = \frac{m_w}{(\rho_w)} \quad V_2 = \frac{m_p}{(\rho_p)} \quad (2 \text{ a, b})$$

$$\rho_b = \frac{m_{ds}}{(V_1 - V_2)} \quad (3)$$

where V_1 is the volume of the soil clod and paraffin coating (cm^3), m_w is the mass of aggregate, thread, and paraffin wax immersed in water (g), ρ_w is the density of water (g/cm^3) at the observed temperature, V_2 is the volume of the paraffin coating (cm^3), m_p is the mass of paraffin wax (g), ρ_p is the density of paraffin wax (g/cm^3), m_{ds} is the dry mass of the soil clod (g), and ρ_b is the bulk density of the soil (g/cm^3). Equation 4 calculates the volumetric water content which was based on the gravimetric water content and bulk density and is given by the following equation:

$$\theta_v = \theta_m * \rho_b \quad (4)$$

where θ_v is the volumetric water content of soil sample (cm^3/cm^3).

The particle density of a soil is the mass of the solid phase of the soil particles divided by the volume of the solid phase. The pycnometer method was used to measure the particle density of the soil sample, which is calculated by equation 5:

$$\rho_s = \frac{\rho_w * (W_{p+s} - W_p)}{(W_{p+s} - W_p) - (W_{p+s+w} - W_{p+w})} \quad (5)$$

where ρ_s is the particle density of soil sample (g/cm^3), ρ_w is the density of water at the observed temperature (g/cm^3), W_p is the weight of the pycnometer (g), W_{p+s} is the weight of the pycnometer and the oven dried soil sample (g), W_{p+w} is the weight of the pycnometer and the water (g), and W_{p+s+w} is the weight of pycnometer, soil sample, and water (g) (Black et al., 1965).

The porosity of the soil represents the amount of volume soil occupied by air and water. Porosity is the volume of the void space divided by the total volume (Singer and Munns, 1991) and is calculated by the following equation:

$$\varepsilon = \frac{V_l + V_g}{V_t} = \frac{\rho_s - \rho_b}{\rho_s} \quad (6)$$

where ε is the porosity of the soil, V_l is the volume of the liquid phase in the soil, V_g is the volume of the gas phase in the soil, and V_s is the volume of the solid phase. The void ratio is the total volume of voids divided by the total volume of solids and is given in equation 7:

$$e = \frac{V_l + V_g}{V_s} = \frac{\varepsilon}{(1 - \varepsilon)} \quad (7)$$

where e is the void ratio (Marshall and Holmes, 1988).

Slug Testing

Slug tests were performed on several wells in both the oxidized and unoxidized soil zones. Using a Druck PDCR-830 pressure transducer, changes in pressure were determined as the water level was altered in the well. The slug tests were conducted by changing the water level instantaneously by the following procedures: using a pressure transducer as a slug to increase the water level, adding water to the well to increase the water level, and bailing water out of the well to decrease the water level if the well was under partial penetration. The tests were allowed to continue until 90% recovery was obtained. Data was obtained on an hourly basis and was collected by a Campbell Scientific data logger. However, if the testing occurred for several days and there was not 90% recovery, the test was terminated. This was because changes in barometric pressure caused severe fluctuations in the data.

The data obtained from the data logger was given in terms of voltage. Prior to using the pressure transducers, a calibration curve was developed for each transducer. The calibration equations are given as follows:

$$y = 2.3824x - 0.0635 \text{ for the old blue pressure transducer} \quad (8)$$

$$y = 1.7585x - 0.1616 \text{ for the new white pressure transducer} \quad (9)$$

$$y = 2.4424x - 0.5225 \text{ for the new blue/white pressure transducer} \quad (10)$$

$$y = 2.419x + 0.3993 \text{ for the old pressure transducer} \quad (11)$$

where y is the change of head in feet and x is the pressure reading in millivolts.

Some of the wells were developed after initial testing to determine the effects on hydraulic conductivity. Well development was performed by using a rod with a rubber gasket to create a surge of pressure in the well. In turn, this cleared the screen of gravel and sand that would otherwise inhibit water flow. However, this did not effect the results of the hydraulic conductivity, therefore, well development was not performed on the remaining wells due to lack of time.

The Bouwer-Rice method was used to analyze the slug test data. The following equation represents the flow into the well using Darcy's equation:

$$Q = 2\pi K L_e \frac{y}{\ln\left(\frac{R_e}{r_w}\right)} \quad (12)$$

where Q is the flowrate into the well (cm^3/sec), K is the hydraulic conductivity (cm/sec), L_e is the length of the screen (cm), R_e is the effective radius of the well (cm), r_w is the radius of the well (cm), and y is the change in head (cm). The instantaneous change in the water level of the well is given by:

$$\frac{dy}{dt} = -\frac{Q}{\pi r_c^2} \quad (13)$$

where dy/dt is the rate of rise (cm/sec) and r_c is the inside radius of the well casing (cm).

The hydraulic conductivity is calculated by equation 14:

$$K = \frac{r_c^2 \ln\left(\frac{R_e}{r_w}\right)}{2L_e} \frac{1}{t} \ln \frac{y_o}{y_i} \quad (14)$$

The data was then plotted on a graph of applied head versus time. The slope of the best fit line through the data is represented as $[(\ln(y_o/y_i))/t]$ in the above equation. There are two cases which can occur in the field.

If the water table is above the screened level of the well, then $L_w < H$, where L_w is the length of the well from the water table to the bottom of the well, and H is the aquifer thickness below the water table. It was assumed that H was 30 feet (914 cm) for the calculations. Figure 6 shows the well geometry for this case. Equation 15 is used to determine $\ln(R_e/r_w)$:

$$\ln \frac{R_e}{r_w} = \left[\frac{1.1}{\ln \frac{L_w}{r_w}} + \frac{A + B \ln \frac{(H - L_w)}{r_w}}{\frac{L_e}{r_w}} \right]^{-1} \quad (15)$$

where A and B are dimensionless parameters that are determined by Figure C in Bouwer-Rice, 1976.

Figure 6. Well geometry for slug test using Bouwer-Rice Analysis
(After Bouwer and Rice, 1976, Bouwer 1989)

Case 2, referred to as partial penetration, occurs if the water level is in the screened region of the well, then $L_w = H$ for the Bouwer-Rice analysis. Figure 7 shows the well geometry for partial penetration. The value of $\ln(R_e/r_w)$ is calculated in equation 16 and is given as follows:

$$\ln \frac{R_e}{r_w} = \left[\frac{1.1}{\ln \frac{L_w}{r_w}} + \frac{C}{\frac{L_e}{r_w}} \right]^{-1} \quad (16)$$

where C is a dimensionless parameter found in Figure C in Bouwer-Rice, 1976. For case 2, the water is spreading out of the well into the gravel pack. To account for this phenomena, the porosity of the gravel pack must be incorporated into the solution. This is done by calculating the cross-sectional area by the following equation:

$$A_e = r_c^2 \pi + \pi(r_w^2 - r_c^2) \Theta \quad (17)$$

where A_e is the cross-sectional area (cm^2) and Θ is the porosity of the gravel pack. The effective radius is used in place of the radius of the casing for the calculation and is determined by the following:

$$r_e^2 = r_c^2 + (r_w^2 - r_c^2) \Theta. \quad (18)$$

The hydraulic conductivity is then calculated by the following equation for wells with partial penetration (Bouwer and Rice, 1976):

$$K = \frac{r_e^2 \ln \left(\frac{R_e}{r_w} \right)}{2L_e} \frac{1}{t} \ln \frac{y_o}{y_t}. \quad (19)$$

Figure 7. Well geometry for slug test using Bouwer-Rice Analysis
with well in partial penetration (After Bouwer and Rice, 1976, Bouwer 1989)

Three-Dimensional Computer Modeling

Introduction

Once the field data has been obtained, a mathematical model of the East Ravine can be developed. This model will use the field data to create a computer simulation of the groundwater flow down the East Ravine. Models are instrumental in predicting groundwater flow. However, the disadvantage of modeling is the numerous inputs of data required to run the model. Without an extensive amount of field data, input parameters must be assumed to run the model. Poorly assumed input values can lead to results that may not be representative of the field conditions (Anderson, 1992). However, there are usually previous studies of a similar region which can be used to improve the choice of assumed parameters for a given site.

One of the most popular groundwater programs is MODFLOW, which is a modular three-dimensional finite-difference groundwater flow model developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988). This model was used to simulate the regional groundwater flow of the East Ravine. Another computer program, ModIME, developed by S.S. Papadopoulos & Associates, was used to incorporate existing site data files from SURFER into MODFLOW and view the results graphically (Zhang et al., 1993).

MODFLOW is based on the following governing equation, which assumes a nonequilibrium condition with flow in material that is heterogeneous and anisotropic. The governing equation is derived from Darcy's law and conservation of mass and is given in equation 20.

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t} \quad (20)$$

where K_{xx} , K_{yy} , and K_{zz} are the hydraulic conductivities in the x, y, z directions (length/time), respectively, h is the head (length), W is the volumetric flux per unit volume (1/time), S_s is the

specific storage ($1/\text{length}$), and t is time (McDonald and Harbaugh, 1988). For the modeling of the East Ravine, a two-dimensional model was used to simulate the flow. This is based on the assumption that the model contains only one layer, from this assumption, the partial derivative in the z direction is zero. The volumetric flux W acts as an internal flux which represents sources and sinks, such as recharge rate. For the modeling, it is assumed that the horizontal hydraulic conductivity K_{xx} is equal to the vertical hydraulic conductivity, K_{yy} . However, no analytical solutions exist for the governing equation, therefore, numerical methods are used to analyze the data, which includes computer programs such as MODFLOW.

MODFLOW was developed using Fortran 77 code and contains a main program with several independent subroutines. Each simulation was divided into stress periods, which were further divided into time steps. The time steps are necessary for iterations to run the simulation (McDonald and Harbaugh, 1988). ModIME served as an integrator between retrieving data for array values and running the MODFLOW simulation. Input data required for the simulation of the East Ravine included the following: top elevations of the first model layer, model layer thickness, boundary conditions, initial flow conditions, starting heads, horizontal and vertical hydraulic conductivities, confined storage coefficients, unconfined specific yield, well locations, general head boundaries, and recharge rates.

After the data was entered into ModIME, a program was executed to generate files for MODFLOW. Then, the MODFLOW simulation began. The results were displayed in various formats. The plan and cross-sectional contours of the water table elevations could be examined graphically, or by the hydrographs, showing the water table elevations over time (Zhang et al., 1993). This data can also be retrieved as a data file and examined in a spreadsheet to compare with actual field measurements.

East Ravine Model Inputs

The groundwater flow simulation was conducted from July 28, 1995 to September 11, 1995 in order to observe groundwater flow down the ravine in oxidized till, during low

rainfall. This period was divided into 7 stress periods, with the following time steps of 5, 5, 7, 7, 7, 7, and 10 days. Table 3 shows how the simulation period was divided into stress periods. The starting and end dates of each period, as well as, the dates that water levels were measured at the site are also included in this table.

In order to import grid files from Surfer and to set boundary conditions, the site had to be divided into grid cells that matched both Surfer and ModIME scales. Figure 8 is the grid

Table 3. Time step intervals for computer simulation

Stress Period	Length (days)	Time Step (days)	Date Start	Date Water Levels Taken	Date End
1	5	0-4	7/26/95	7/28/95	7/30/95
2	5	5-9	7/31/95	8/2/95	8/4/95
3	7	10-16	8/5/95	8/8/95	8/11/95
4	7	17-23	8/12/95	8/16/95	8/18/95
5	7	24-30	8/19/95	8/23/95	8/25/95
6	7	31-37	8/26/95	8/29/95	9/1/95
7	10	38-47	9/2/95	9/8/95	9/11/95

layout of the East Ravine that was used for the computer simulation. The grid was divided into 29 vertical cells, with each cell representing 5.01 ft and 15 horizontal cells, with each cell representing 6 ft. The grid was set in state plain coordinates which ranged from 1956432 to 1956572 in the x-direction and 197342 to 197426 in the y-direction. Each cell was assigned values for boundary conditions, hydraulic conductivities, a recharge rate, an unconfined specific yield and a confined storage coefficient.

The purpose of the computer simulation was to simulate groundwater flow in the oxidized till of the East Ravine. Well locations were specified in the Well Package of ModIME. The Well Package also specifies the pumping rate and concentration of the wells, which were assumed to be zero for this computer simulation. Table 4 contains the grid

Figure 8. Grid layout of computer model

Table 4. Oxidized monitoring well locations for computer model

Well #	Northing ¹ ft	Easting ¹ ft	Grid Locations	
			X Grid	Y Grid
Al-Pz 1	197384.6	1956501.79	14	8
Al-Pz 2	197395.87	1956464.27	7	7
Al-Pz 3	197375.64	1956480.59	10	10
Al-Pz 4	197361.8	1956492.8	13	12
Al-Pz 5	197370.01	1956459.68	6	11
Al-Pz 6	197373.4	1956552.49	25	10
Al-Pz 8	197364.55	1956535.35	21	12
Al-Pz 9	197380.39	1956439.1	2	9
Al-Pz 12	197415.1	1956485.02	11	3
Al-Pz 14	197351.08	1956460.92	6	14
Al-Pz 17	197352.29	1956537.86	22	14
Al-Pz 18	197375.54	1956539.11	22	10
Al-Pz 32	197382.8	1956465.5	7	9
Al-Pz 33	197374.09	1956487.27	12	10
Al-Pz 34	197373.03	1956495.44	13	10
Al-Pz 35	197368.95	1956504.34	15	11
Al-Pz 36	197368.89	1956518.51	18	11
Al-Pz 37	197364.15	1956542.11	22	12
Al-Pz 38	197369.85	1956564.47	27	11

¹Northings and Eastings are referenced in state plain coordinates

locations of the oxidized wells used in the model. Figure 9 displays the monitoring well locations as they appear on the grid.

The thickness of the layer was based on the depths of till from the ground surface to the top of the unoxidized zone. The unoxidized zone was assumed to be an impervious boundary for the simulation, through which no water would infiltrate. The depths to

Figure 9. Monitoring well locations for computer model

unoxidized till ranged from 6 to 12 feet, based on soil boring logs (Appendix A). Table 5 contains the input data for the model layer thickness.

After conducting a site survey of the East Ravine, the northings, eastings, ground surface elevations of the site were entered into SURFER for Windows. In order to incorporate the data into ModIME, a grid file was created based on the above mentioned scaling factors, which were used to define the grid line geometry. Kriging was used to interpolate elevations for the remaining cells in the model (Golden Software, Inc., 1994). Table 6 contains the ground surface elevations (top elevations) of the model for each grid cell.

Table 7 contains the measured water table elevations which were also used in the computer model. As before, the data was entered into SURFER and kriging was performed to interpolate water table elevations for the remaining cells. Table 8 contains the grid cell input data for the starting heads of the model.

Assigning the proper boundary conditions can greatly affect the results of the analysis. There are typically three types of boundary conditions used in modeling and include specified head, specified flow, and head-dependent flow boundaries. When the head is known for the well, it is classified as a specified head boundary (Anderson, 1992). Initial boundary conditions were set for the top and bottom of the ravine by using the measured heads at monitoring wells Al-Pz 9 and Al-Pz 38. To obtain the known heads, the water table elevations for these wells were entered into the General Head Boundary Package in ModIME. These elevations were applied to every stress period and assumed to be constant for each time step of the stress period (see Table 7 for measured heads). The cells (column 2, rows 7-11 and column 27, rows 9-13) around Al-Pz 9 (column 2, row 9) and Al-Pz 38 (column 27, row 11) were assumed to have the same general head boundaries as Al-Pz 9 and Al-Pz 38. The sides of the ravine were set as no-flow boundaries, which implies that the flux across the boundary is zero. The interior of the ravine was set as a variable head boundary to observe the change in water table elevations across the East Ravine. Figure 10 illustrates the boundary conditions used for the model.

Table 5. Input data for thickness of layer for computer model

Grid no.	1	2	3	4	5	6	7	8	9	10
1	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
2	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
3	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
4	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
5	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
6	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
7	12.0	11.7	11.7	11.7	10.0	9.0	8.0	8.0	9.0	9.5
8	12.0	11.7	11.7	11.7	10.0	9.0	8.0	8.0	9.0	9.5
9	12.0	11.5	10.8	10.5	10.0	9.0	8.0	8.0	8.0	8.0
10	12.0	11.6	11.1	10.9	10.0	9.0	8.0	8.0	8.0	8.0
11	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	9.0	9.0
12	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	9.0	9.0
13	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	11.0	11.0
14	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
15	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

Table 5. Continued

Grid no.	11	12	13	14	15	16	17	18	19	20
1	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
2	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
3	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
4	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
5	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
6	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
7	10.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
8	10.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
9	8.0	9.3	9.3	9.3	9.0	9.0	10.0	11.0	11.0	11.0
10	8.0	8.0	8.0	8.0	8.0	8.0	9.0	9.0	9.0	9.0
11	9.0	8.5	8.0	8.0	8.0	8.0	8.0	8.0	8.0	7.5
12	9.0	9.0	9.0	9.0	8.0	7.0	7.0	7.3	7.8	8.0
13	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
14	12.0	12.0	12.0	13.0	12.4	12.5	12.3	12.0	12.0	11.7
15	12.0	12.0	12.0	14.0	12.0	12.0	12.0	12.0	12.0	12.0

Table 5. Continued

Grid no.	21	22	23	24	25	26	27	28	29
1	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
2	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
3	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
4	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
5	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
6	11.0	11.0	11.0	11.0	11.0	10.3	10.3	10.3	10.3
7	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
8	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
9	11.0	11.0	11.0	11.0	11.0	10.0	10.0	10.0	10.0
10	9.0	12.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
11	7.5	8.0	8.0	7.5	7.0	6.0	5.5	5.5	5.5
12	8.0	8.0	8.0	7.5	7.0	6.0	5.5	5.5	5.5
13	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
14	11.5	11.4	11.3	11.2	11.2	11.3	11.4	11.3	11.0
15	12.1	12.0	11.9	11.7	11.7	11.7	11.6	11.5	11.3

Table 6. Input data for top elevation for computer model

Grid no.	1	2	3	4	5	6	7	8	9	10
1	969	969	969	969	968	968	968	968	968	968
2	969	969	969	968	968	968	967	967	967	968
3	969	969	969	968	968	967	967	967	967	967
4	969	969	968	968	967	966	966	966	966	966
5	969	969	968	967	966	965	965	965	964	965
6	969	968	967	966	965	964	964	963	963	963
7	967	967	966	965	964	964	964	962	962	961
8	965	965	964	963	962	962	961	961	960	960
9	965	964	964	963	962	961	961	960	959	958
10	965	964	963	962	962	959	959	958	957	956
11	967	965	965	964	963	962	962	962	961	959
12	969	968	968	967	964	963	965	964	963	962
13	970	969	969	968	966	965	965	965	964	964
14	970	970	970	969	969	968	968	968	967	966
15	971	971	970	970	970	968	969	969	968	967

Table 6. Continued

Grid no.	11	12	13	14	15	16	17	18	19	20
1	968	967	967	966	965	964	963	961	961	960
2	968	968	967	966	965	964	963	962	961	961
3	967	968	967	966	965	964	963	962	962	962
4	966	966	966	965	964	963	963	962	962	962
5	965	965	964	964	963	962	962	962	962	961
6	963	963	963	962	962	961	961	961	960	959
7	961	961	961	960	960	960	959	959	958	957
8	959	959	958	958	958	958	957	957	956	955
9	958	958	955	956	956	956	955	955	954	953
10	956	955	955	955	954	953	953	953	952	952
11	959	958	956	955	952	952	952	952	951	951
12	961	960	959	958	954	954	953	954	952	951
13	963	962	961	960	958	958	957	956	955	954
14	965	964	964	964	961	960	959	958	960	958
15	966	966	965	964	963	962	961	962	963	961

Table 6. Continued

Grid no.	21	22	23	24	25	26	27	28	29
1	960	959	958	957	956	955	954	953	952
2	960	959	958	957	956	955	953	952	951
3	961	960	959	957	955	954	953	951	950
4	961	960	959	957	955	953	951	950	949
5	960	959	958	956	954	952	950	949	948
6	959	958	956	955	952	950	948	947	947
7	957	956	954	953	950	948	947	946	946
8	955	954	952	951	949	948	946	945	945
9	953	952	951	950	949	947	945	944	944
10	952	952	950	949	948	947	945	944	944
11	950	948	947	947	947	944	944	944	943
12	947	946	946	946	946	945	945	944	944
13	953	952	950	950	948	950	950	951	950
14	956	954	953	951	951	951	952	952	952
15	958	956	954	953	952	952	952	953	952

Table 7. Water table elevations for input data of computer simulation

Well no. AL-PZ	Water Table Elevations (mean sea level)						
	7/28/95	8/2/95	8/8/95	8/16/95	8/23/95	8/29/95	9/8/95
1	951.46	951.19	950.99				
2	957.84	956.69	956.63	956.70	956.64	956.64	956.65
3	955.16	954.53	953.62	953.65	953.77	952.98	951.74
4	952.28	952.12	952.00	952.84	952.49	952.23	951.89
5	957.84	957.12	956.57	956.87	955.89	955.22	954.95
6	942.53	942.20	942.23	942.11	941.86	941.68	941.01
8	942.98	943.27	943.36	943.49	943.44	943.38	943.22
9	961.84	961.36	960.73	961.38	960.38	959.60	958.05
10	963.00	962.05	960.56	961.12	960.62	959.77	958.33
11	965.12	964.41	964.00	964.10	963.35	962.38	961.16
12	954.58	954.01	953.73				
14	957.95	957.54	957.21	956.84	956.58	956.43	955.89
17	945.41	945.20	945.08	944.95	944.92	944.91	944.81
18	944.48	944.23	944.09	943.88	943.71	943.58	943.49
21	949.00	949.01	949.00	949.00	949.00	949.00	948.99
27	948.11	948.04	948.05	948.05	948.01	948.00	948.02
28	956.00	956.00	956.00	956.01	956.00	956.01	955.99
29	949.51	949.51	949.51	949.51	949.51	949.51	949.51
32	957.55	956.51	956.20	955.90	955.47	955.31	954.98
33	952.57	951.74	951.38				
34	946.53	946.49	946.46				
35	947.39	947.60	947.89	945.92	946.41	946.56	946.71
36	945.45	945.46	945.44	945.09	945.07	944.88	944.31
37	940.27	940.86	941.16	940.92	941.27	941.34	941.33
38	942.58	943.02	942.08	943.51	942.34	941.74	940.93

Table 8. Input data for starting heads for computer model

Grid no.	1	2	3	4	5	6	7	8	9	10
1	957	957	956	956	956	956	955	955	955	955
2	958	957	956	956	955	955	955	955	955	955
3	958	957	956	956	956	955	954	954	954	954
4	959	957	957	956	955	955	955	955	955	956
5	959	958	957	956	956	955	954	954	954	954
6	964	963	962	961	958	959	958	957	957	956
7	964	963	962	961	960	958	958	957	956	955
8	963	963	962	961	960	958	958	957	957	955
9	963	962	961	961	960	958	958	957	957	955
10	962	962	961	960	959	958	957	957	956	955
11	962	961	961	960	958	958	957	957	956	955
12	962	961	961	960	959	957	957	957	956	955
13	961	961	960	960	959	957	958	957	956	956
14	958	958	957	957	959	958	958	957	957	956
15	958	958	958	958	959	958	958	957	956	956

Table 8. Continued

Grid no.	11	12	13	14	15	16	17	18	19	20
1	955	955	954	953	952	951	950	949	948	948
2	955	955	954	953	952	951	950	949	948	948
3	955	955	955	955	952	951	950	950	949	948
4	955	955	955	953	952	952	951	951	951	951
5	954	954	954	953	952	952	951	950	9250	949
6	955	954	954	956	955	954	953	952	950	949
7	954	953	952	952	952	952	951	950	949	948
8	954	952	949	951	951	951	950	949	948	947
9	954	952	947	948	949	949	948	948	947	946
10	955	953	946	948	948	948	947	946	946	945
11	954	953	951	949	947	947	947	945	945	945
12	955	954	952	951	950	948	947	946	945	945
13	954	953	952	951	950	948	947	947	946	946
14	954	953	952	951	950	949	948	947	947	946
15	954	953	952	952	951	949	949	951	950	948

Figure 10. Input data for initial boundary conditions for computer model

Results from the slug tests for monitoring wells Al-Pz 9, Al-Pz 3, Al-Pz 6, and Al-Pz 38 were used as input for the model. The cells surrounding these wells were assumed to have the same horizontal hydraulic conductivities. Some of the cells were altered by a factor of 10 to improve simulation results. An average hydraulic conductivity was used for the remaining cells. Table 9 contains the values of the hydraulic conductivities used. Figure 11 illustrates the variable hydraulic conductivities of the site. It was assumed that the horizontal hydraulic conductivity was equal to the vertical hydraulic conductivity.

Table 9. Values of hydraulic conductivities used for computer simulation

	Well Number Al-Pz	Hydraulic Conductivity (cm/sec)	Hydraulic Conductivity (ft/day)
Measured Values	3	1.08E-07	3.06E-04
	6	3.50E-06	9.92E-03
	9	1.94E-06	5.49E-03
	37	6.74E-07	1.91E-03
	38	3.34E-06	9.47E-03
Adjusted Values	Average		5.00E-03
	5		0.5
	17		1.91E-02

There are several parameters which had to be estimated. These include the confined storage coefficient, unconfined specific yield, and the recharge rate. The confined storage coefficient typically ranges from 0.005 to 0.0005 in confined aquifers (Freeze and Cherry, 1979). The unconfined specific yield ranges from 0.01 to 0.30 in Hydrology in Practice by Shaw and from 0.02 to 0.30 in Applied Hydrogeology by Fetter. For the computer simulation, the confined storage coefficient was assumed to be 0.005 and the unconfined specific yield was assumed to be 0.04. The recharge rate of 0.003 in/day (2.5×10^{-4} ft/day) was initially used for the model, which was based on the assumption of 3% recharge of the total rainfall over the 47 day simulation period. However, to improve the model results, the recharge rate was adjusted to 3.0×10^{-5} ft/day (0.1314 in/yr).

Figure 11. Input data for horizontal hydraulic conductivities for computer model

RESULTS AND DISCUSSIONS

Soil Zones

The soil boring logs in Appendix A were used to develop an understanding of the soil layers in the ravine. Throughout the East Ravine, the soil logs were very similar. Typically, the top two to four feet (0.6 to 1.2 meters) of soil was a soft, moist alluvium or top soil and was dark black or brown in color. The next five to ten feet (1.5 to 3 meters) changed drastically in color and in texture. The soil was a light brown or yellowish color and was intermixed with iron oxides, which were orange in color. Several soil borings contained small to large amounts of white calcium carbonate deposits. The calcium carbonates have been leached through the soil over time. This layer was typically dry and it was easy to cut through with a hand auger. There were also pockets of sand lenses found in some of the soil borings. This zone was referred to as Wisconsin oxidized till or the weathered zone. The weathering process of the soils is typically characterized by a loss of primary minerals, with an increase of clay minerals which are more stable (Sidle et al., 1985).

The next two to three feet (0.6 to 0.9 meters) contained the transition zone between the oxidized and unoxidized zone. This area was more compact and contained small mixtures of gray and blue in color. Below the transition layer was the Wisconsin unoxidized zone. The major differences between the oxidized and unoxidized layers were observed with color and compactness. The unoxidized zone was dry, very compact and very hard to cut with the hand auger. The colors of this layer were typically all blue and gray, showing no signs of yellow or light brown and no signs of calcium deposits.

The ravine, itself, had large amounts of erosion due to the impact of raindrops and high surface runoff. Therefore, the alluvium layer was only one to two feet (0.3 to 0.6 meters) in depth. Below the alluvium layer was the oxidized zone, which consisted of sand seams and was intermixed with rocks ranging in diameter from one to three inches (2.5 to 7.6 cm). Table 10 is a compiled listing of the soil zones determined from soil logs done by

Table 10. Approximate elevations of the soil zones of Rust wells (After Rust, 1995b)

Well number	MW4B	MW5B	MW6A	MW7B	MW8B	MW9B	MW10B	MW11B
Ground Elevation (ft)	992.83	980.44	960.6	945.09	926.91	926.45	981.91	985.69
Depth to bottom of zone from ground surface (ft)								
Alluvium	-	-		940	919	919		
Wisconsin till - oxidized	978	961	955				965	967
Wisconsin till - unoxidized	958	958					958	958
Pre-Illinoian till - oxidized	953	953	949				952	952
Pre-Illinoian till - unoxidized	948	923	917	906	912	919	932	933

Huntingdon Engineering & Environmental Inc., during the installation of monitoring wells and cross-sections developed by Rust Environment & Infrastructure. This information was used to further define the soil zones in the East Ravine. From this data, it can be concluded that near the bottom of the ravine the top layer was alluvium soil, followed by Pre-Illinoian unoxidized till (Rust, 1995b).

Precipitation and Water Table Elevations

There are several factors which effect the water table elevation. The water table will tend to rise occur if there is a low-intensity rainfall which occurs over a long period of time or if the soil is already moist (Freeze and Cherry, 1979). During a low intensity rainfall, the soil has time to absorb precipitation which infiltrates through the soil matrix. The moisture continues down through the soil matrix by gravity flow and eventually reaches the water table and causes an increase in the elevations. There are periods in which the top soil zones are saturated with moisture and the lower soil zones are unsaturated. After a precipitation event, the moisture will be pulled through the soil zones by gravity and recharge the water table elevations. On a microscopic scale, as water infiltrates into the soil matrix, it is filling air voids, which forces the elevation of the water table to rise (Fetter, 1994). Other factors which effect water levels include air entrapment during groundwater recharge, which results in a large rise in water table elevations during a heavy rainstorm, and atmospheric pressure, which increases the water table if the pressure decreases (Freeze and Cherry, 1979). The effect of these parameters were observed during this study.

Precipitation data, from November 16, 1994 to September 30, 1995, for Ames was obtained from the United States Department of Commerce through the ISU Agronomy department. This data is presented in Figure 12. During the duration of this project, water table levels were taken weekly by a water level indicator to observe the change of head over time. Appendix B contains water table elevations for all of the monitoring wells from

Figure 12. Rainfall data for Ames, Iowa from November 16, 1994 to September 23, 1995 (USDC 1990-1995)

Figure 13. Change in head of water levels in oxidized ravine wells

Soil Zones and Water Table Elevations

Once the water table elevations and soil logs were obtained, a comparison could be developed to determine the location of the water table in the soil layers. The East Ravine was divided into one horizontal cross-section and three vertical cross-sections for these comparisons. The cross-sections illustrate the elevations of top soil, oxidized, and unoxidized zones in the East Ravine, as seen in Figure 14. Water table elevations are also included for three dates to illustrate the location of the water table in these soil zones. To smooth out the curves, engineering judgment was used to estimate the elevations of the soil zones, based on notes from Appendix A and from Rust Environment & Infrastructure's 1995 Preliminary Report. If engineering estimation was used for soil and water table elevations, then it was denoted by "?" on the figures.

Cross-section A-A' (Figure 15) is a horizontal cross-section running down the ravine. It appears that the top soil or alluvium is approximately one to three feet (0.3 to 0.9 meters) thick. The oxidized zone follows the contour of the ravine and ranges from three to eight feet (0.9 to 2.4 meters) below the ground surface. The unoxidized zone also appears to follow the contour of the ravine. Water table elevations were also included for February, July, and September. All three time periods illustrate similar trends that the water table resides in the oxidized zone of the East Ravine.

Cross-section B-B' (Figure 16) is a vertical cross-section running across the top of the ravine. The contours of the oxidized and unoxidized zones follow the contour of the surface profile. The depth of the top soil ranges from two to three feet (0.6 to 0.9 meters) below the ground surface. The oxidized zone extends to approximately eight to ten feet (2.4 to 3 meters) below the surface. Excessive spring rains caused the water table to rise to the top soil zone; however, during the summer and fall, the water table fell down to the oxidized zone.

A vertical cross-section of the middle of the ravine is presented in Figure 17. As before, the contours of the oxidized and unoxidized zones follow the surface profile. Due to

Figure 15. Horizontal cross-section A-A' referenced from well Al-Pz 20

Figure 16. Vertical cross-section B-B' referenced from well Al-Pz 2

Figure 17. Vertical cross-section C-C' referenced from well Al-Pz 28

dry wells, water table elevations were estimated for the side wells (Al-Pz 15, 28, 29) based on previous elevations. However, the water table elevation also occurs in the oxidized zone, as in Figures 15 and 16.

Figure 18 (Cross-Section D-D') is another vertical cross-section at the bottom of the ravine. As before, the top soil zone contains two to four feet (0.6 to 1.2 meters) of alluvium zone, followed by a six to eight feet (1.8 to 2.4 meters) of the oxidized layer, and then an unoxidized zone. The water table followed the same trends as other vertical cross-sections. During May, the water table was in the alluvium zone and fell to the oxidized zone during drier periods.

Figures 15 through 18 show similar trends. There is an alluvium zone that ranges between one and four feet (0.3 to 1.2 meters) from the surface, followed by an oxidized zone ranging from six and eight feet (1.8 to 2.4 meters) in depth. There is an unoxidized zone underneath the oxidized zone, which acted as an impervious boundary in relation to the water table elevations. During the spring, the water table elevations were elevated, such that, the levels were in the alluvium zone. As the water drained off, the water table elevations remained in the oxidized zone, but did not infiltrate into the unoxidized zone. The path of the water table typically followed the contour of the ravine slopes. This agreed with the findings of Zaslavsky, who determined that vertical infiltration will contain a component that flows with the slope of the terrain (Wallach and Zaslavsky, 1991).

Soil Analysis

Soil samples were obtained during the monitoring well installations. The results of the lab analysis conducted on the soil samples are presented in Table 11. The samples labeled MW-6A are from a Rust Environment & Infrastructure soil boring sample and the samples labeled Al-# represent the piezometer wells in the East Ravine. The data used for the analysis can be found in Appendix C.

Figure 18. Vertical cross-section D-D' referenced from well Al-Pz 18

Table 11. Results of soil properties by lab analysis

Well #	Soil Type	Depth from the surface feet	θ_m g/g	θ_v cm ³ /cm ³	ρ_b g/cm ³	ρ_s g/cm ³	ε	e
MW-6	Wis. ox	0-5	0.191	0.318	1.665	2.608	0.362	0.567
	Pre-III. ox	5-10	0.196	0.321	1.635	2.650	0.383	0.621
	Pre-III. unox	10-15	0.137	0.263	1.927	2.647	0.272	0.374
Al-21	oxidized	2.33-2.67	0.184	0.329 ^a	1.789	2.709	0.339	0.514
Al-21	oxidized	3.8-4.3	0.138	0.266	1.928	2.686	0.282	0.393
Al-22	oxidized	3.33	0.223	0.368	1.653	2.657	0.378	0.608
Al-22	oxidized	8.66	0.256	0.410	1.602	2.761	0.420	0.724
Al-15	oxidized	4.75-5.25	0.154	0.290	1.876	2.652	0.293	0.414
Al-27	oxidized	3.5-4.17	0.148	0.272	1.838	2.633	0.302	0.433
Al-29	top soil	2-3	0.165	0.305	1.849	2.663	0.306	0.441
Al-29	oxidized	6.25-7.08	0.156	0.293	1.882	2.668	0.295	0.418
Al-29	oxidized	9.33	0.153	0.300	1.959	2.804	0.302	0.432
Al-30	oxidized	5.08	0.214	0.357	1.664	2.627	0.367	0.579
Al-30	transition	10	0.199	0.341	1.715	2.614	0.344	0.524
Al-31	top soil	3.33	0.182	0.320	1.760	2.630	0.331	0.494
Al-31	oxidized	5.67	0.194	0.340	1.756	2.684	0.346	0.528

^a adjusted value based on correction factor

Samples were obtained at various depths for some of the wells. Table C1 contains the data used for the calculations of the gravimetric water content. The results of the analysis showed that the gravimetric water content (θ_m) generally decreased as the depth from the surface increased. As the water particles move through the soil matrix by gravity flow, air voids are displaced with water. Eventually, the infiltration rates decrease and the quantity of available water decrease, resulting in a lower soil moisture water content. The gravimetric water content increases from monitoring wells Al-Pz 31 and Al-Pz 22. These results agree with Kirkby who stated that as the distance from the hilltop increases down the ravine, the gravimetric water content will increase (Kirkby, 1978). During a precipitation event, some of

the precipitation will remain as surface water and flow down the hill. Once it reaches the bottom of the hill, it has time to infiltrate into the soil, thus, increasing the moisture content.

The volumetric water content (θ_v), which was calculated from the gravimetric water content and bulk density, also decreased with depth. This results would indicate that as the depth from the surface increases, the soil moisture decreases, based on the reasons previously mentioned. It should be noted that some of the values have a higher water content as the depth increases (Al-Pz 22 and 31). This discrepancy is attributed to experimental error in analysis due to a delay in testing time between obtaining the sample and oven-drying the sample to obtain the water contents.

Table C2 is the lab data used for the calculation of bulk density (ρ_b) based on the clod method. Table 11 shows that the bulk density ranged from 1.6 to 1.9 g/cm³. These results are typical of a soil that is either composed of a sandy texture or a sandy loam (Marshall and Holmes, 1988). The bulk density for wells near the top of the ravine (Al-Pz 30 and 31) were higher than the values in the ravine (Al-Pz 22). The wells outside of the ravine (Al-Pz 21, 15, 27, and 29) also have a higher bulk density than the ravine well. Over time, the ravine has washed out, while the hillslopes have remained unchanged over time, resulting in a higher bulk density for the side slopes. The varied results agree with a study of sloping terrain by Malo and others. The results showed that erosion and sedimentation greatly effect the soil properties at different positions on the slope of a hill (Malo et al., 1974).

Some of the values obtained for bulk density by the clod method were overestimated; thus, contributing to an error in volumetric water content. A correction factor was determined such that the porosity was higher than the volumetric water content. There are several reasons for the overestimation. During the coating of the wax on the soil clod, wax penetrated into the pores of the soil. Therefore, there is not as much wax on the outside surface, which will decrease the volume of wax; thus resulting in a higher bulk density. Another error occurred if all of the soil clod was not covered in wax. When placing the soil clod into the water, air bubbles can penetrate into the soil pores; therefore, the amount of water displaced is less than the actual value, which will effect the bulk density (Horton, 1995).

Table C3 is the lab data used to calculate the particle density (ρ_s) based on the pycnometer method. The particle density was fairly consistent between soil samples and ranged from 2.6 to 2.8 g/cm³, which is the typical range for most soils (Marshall and Holmes, 1988). Monitoring wells Al-Pz 22 and 29 have some variability in the values of particle density. The trend indicates a higher particle density as the depth from the ground surface increases. This variation could be attributed to a difference in material structure as the unoxidized zone is approached.

The porosity (ϵ) ranged from 0.27 to 0.42, indicating the material is mostly made of sand, gravel, and silt with no indication of the presence of limestone or shale (Freeze and Cherry, 1979). The void ratio (e) ranged from 0.37 to 0.72. Values typically range between 0 and 3 (Freeze and Cherry, 1979).

A particle size analysis was performed by the ISU agronomy department on a soil sample obtained from a Rust Environment & Infrastructure monitoring well (MW-6A). The results are listed in Table 12. Using a soil texture triangle, the soil from 0 to 5 feet deep is classified as loam, the soil from 5 to 10 feet and 10 to 15 feet is classified as clay loam.

Table 12 Particle size analysis for Rust Well (MW-6A)

Depth from the surface ft	Soil Type	Sand %	Coarse Silt %	Fine Silt %	Clay %
0-5	oxidized	50.8	13.3	13.0	22.9
5-10	oxidized	32.0	12.1	20.3	35.6
10-15	unoxidized	32.4	14.2	23.4	30.0

The results of the soil analysis aid in understanding the East Ravine soil morphology. If time had allowed, more sampling and testing would have been conducted to develop a better understanding of the soil characteristics. The soil parameters indicate that the soil is mostly a loam or clay loam mixture, with sand and gravel intermixed in the makeup of the soil system.

Slug Testing

Slug tests were performed on several wells to determine the hydraulic conductivity of the soil. After data from the slug test was collected, the data was evaluated using the Bouwer-Rice Method (Bouwer and Rice, 1976, Bouwer, 1989). The Bouwer-Rice Slug Test Analysis computer program, developed by Dr. LaDon Jones, was used to analyze the data.

Table 13 is a summary of the hydraulic conductivity values obtained from analysis. Appendix D contains the data used for the analysis. This appendix shows a graph of applied head versus time of the test period for each well. From this figure, the slope of the line is determined for input into the analysis. The slope of the line was taken from the earlier portion of the data set. It was assumed that this method produced the a fairly accurate result of the field conditions. As previously stated, the recovery time in the wells was very slow and after a few days, the barometric pressure greatly affected the results. Appendix D also contains the well dimensions which were used as input into the computer program. The results of the analysis and the hydraulic conductivity are also provided in this appendix.

There was an obvious difference between the values for oxidized till and unoxidized till. The oxidized soils tend to have a higher rate and range from 1.94×10^{-6} to 6.74×10^{-7} cm/sec (average value 1.9×10^{-6} cm/sec). The transition soils ranged from 8.68×10^{-7} to 1.65×10^{-8} cm/sec (average value 4.4×10^{-7} cm/sec) and the unoxidized soils ranged from 2.93×10^{-7} to 4.14×10^{-9} cm/sec (average value 1.1×10^{-7} cm/sec).

These results seem to agree with other studies of weathered (oxidized) and unweathered (unoxidized) till. In a study by Ruland and others in Southwestern Ontario, the hydraulic conductivity was greater than 10^{-7} cm/sec for the first three meters (9.8 feet) of the soil and was between 10^{-7} and 10^{-8} cm/sec below three meters (9.8 feet) of the soil (Ruland et al., 1991). Lab tests by Grisak and Cherry showed the hydraulic conductivity of fractured clay-loam till to be 1.8×10^{-7} cm/sec (Grisak and Cherry, 1975). Keller and others determined that the vertical hydraulic conductivity of unweathered till in Saskatchewan was

Table 13. Results of slug testing using Bouwer-Rice method

Well Number Al-Pz	Soil Type	Depth from ground level to bottom of well (ft)	Screen Length from bottom of well (ft)	Hydraulic Conductivity (cm/sec)
3	oxidized	7.16	5.83	1.08E-07
6	oxidized	7.75	6.58	3.50E-06
9	oxidized	8.75	8	1.94E-06
37	oxidized	7.83	6.33	6.74E-07
38	oxidized	5.5	4.5	3.34E-06
30	transition	9.33	3.08	1.65E-08
31	transition	9.67	2.25	8.68E-07
16	unoxidized	15.25	3.25	4.44E-08
20	unoxidized	19.31	5.98	8.15E-08
25	unoxidized	18.69	2.08	4.14E-09
26	unoxidized	17.69	2.08	2.93E-07

3.5×10^{-9} cm/sec (Keller et al., 1986). Cravens and Ruedisili discovered that unweathered till in South Dakota was 10 to 200 times lower than the hydraulic conductivity of weathered till (Cravens and Ruedisili, 1987).

Hendry found in his study of glacial till in Alberta that the hydraulic conductivity of weathered till was on the ranged from 10^{-5} to 10^{-7} cm/sec and of unweathered till was on the order of 10^{-8} cm/sec (Hendry, 1982). Dr. Jones determined that unweathered till in Iowa has a hydraulic conductivity of 10^{-7} cm/sec (Jones, 1993).

D'Astous suggests that installing wells by augers will create a smearing down the bore hole, which will result in lower values for hydraulic conductivity (D'Astous et al., 1989). To account for this problem, some wells were developed and retested, however, there was very little difference in recovery rates for the wells.

D'Astous suggests that the weathered till contains more fractures and root holes which allows for more flow of water through the weathered till. There is also an increase of biological and chemical processes in weathered till (D'Astous et al., 1989). These factors will result in increased flow through the weathered till, thus, creating a higher hydraulic conductivity.

Additional slug testing was conducted by Rust Environment & Infrastructure during the summer of 1995. Refer to Figure 2 for Rust monitoring well locations and Figure 3 for the location of Rust wells relative to the Ames Lab piezometers. Rust results are presented in Table 14. Rust Monitoring well 7A is located near well Al-Pz 38. The hydraulic conductivity is varied by a magnitude of 100. This variation is attributed to several factors which include differences in well construction, size, and development and the methods used for testing and analysis. The other results of the Rust wells show that the hydraulic conductivity ranges from 10^{-4} cm/sec to 10^{-6} cm/sec for both oxidized and unoxidized till (Rust, 1995b).

Three-Dimensional Computer Modeling

Using the previous results of slug testing and the water table elevations, a three-dimensional mathematical model was developed to simulate the groundwater flow in the East Ravine using ModIME and MODFLOW. Once the computer simulation was completed, the results were compared to the measured water table elevations. The results of the model were consistent with field results of the groundwater flow in the East Ravine.

The results of the MODFLOW runs have been presented in Figures 20 through 26. To provide a comparison to the model results, the measured water table elevations have been included on these figures. In the figure legends, the model data is represented as Well # and the field data is represented as Al-Pz #. The East Ravine was divided into one horizontal cross-section and three vertical cross-sections for these comparisons, as seen in Figure 19.

Table 14. Results of slug testing for Rust Environment & Infrastructure (After Rust, 1995b)

Well number	Well type	Depth from ground level to bottom of well (ft)	Well screen length below surface (ft)	Falling head K (cm/sec)	Rising head K (cm/sec)
MW4A	Wisconsin till - oxidized	17	7-17	1.3E-04	1.2E-04
MW4B	Wisconsin till - unoxidized	34	24-34	4.1E-06	
MW5A	Wisconsin till - oxidized	17	7-17		1.9E-06
MW5B	Wisconsin till - unoxidized	25	20-25		1.8E-06
MW7A	Alluvium	6	3.5-6		5.3E-08
MW7B	Pre-Illinoian till - unoxidized	33	23-33	1.9E-02	
MW8A	Pre-Illinoian till - unoxidized	7	4.5-7		6.0E-04
MW8B	unoxidized	15	10-15	7.9E-05	
MW9A	Wisconsin till - oxidized	6	3.5-6		2.8E-05
MW9B	Wisconsin till - unoxidized	14	9-14	7.9E-06	
MW10A	Wisconsin till - oxidized	17	7-17	1.5E-04	2.1E-04
MW10B	Wisconsin till - unoxidized	24.5	19.5-24.5	1.1E-04	8.8E-05
MW10B	Wisconsin till - unoxidized	24.5	19.5-24.5	1.8E-04	1.2E-04
MW11A	Wisconsin till - oxidized	17	7-17		2.3E-06
MW11B	Wisconsin till - unoxidized	29	24-29	2.0E-06

Figure 19. Horizontal and vertical cross-sections E-E' to H-H'

Figure 20. Horizontal cross-section E-E', comparing model and field data for July 28, 1995

Figure 21. Horizontal cross-section E-E', comparing model and field data for September 8, 1995

Figure 22. Horizontal cross-section E-E' (top of ravine)

Figure 23. Horizontal cross-section E-E' (bottom of ravine)

Figure 25 (Cross-Section G-G') is a vertical cross-section across the middle of the ravine. The model results agree very closely with the actual field results. Monitoring well Al-Pz 1 went dry August 16, 1995 (See Appendix B), however, the model continued to interpolate a value for the well.

Figure 26 (Cross-Section H-H') is a vertical cross-section along the bottom of the ravine. Measured water table elevations for monitoring wells Al-Pz 8, 17, and 18 agree very well with the predicated results. However, the model result for well Al-Pz 37 was one to two feet higher than the measured results.

There are several factors that affect water table elevations in the field. These include groundwater recharge, evapotranspiration, and atmospheric pressure effects (Freeze and Cherry, 1975). Computer simulations were performed with the ModIME evapotranspiration package, unfortunately, there was limited data to accurately simulate the evapotranspiration in the East Ravine. As previously stated, there were many computer simulations that were executed to improve the results of the modeling. The confined storage coefficient was adjusted between 0.005 to 5×10^{-5} , however, there was no change in water elevations. The unconfined specific yield was altered from 0.01 to 0.3. As the unconfined specific yield was lowered, the water table elevations increased. The recharge rate was one of the controlling elements in the program and was ranged from 0.003 to 2×10^{-6} ft/day. If the recharge rate was increased, there was a drastic increase in the that measured water levels. Therefore, a low recharge rate of 3×10^{-5} ft/day was assumed for the simulation.

The hydraulic conductivities also effected the results of the model. The first trial runs assumed a uniform hydraulic conductivity of 0.005 ft/day (based on the average of the measured oxidized hydraulic conductivities). This uniform assumption caused the model water table elevations to range from one foot below to five feet higher than the measured elevations. The next trial runs used the measured hydraulic conductivities of several oxidized wells and provided the most accurate representation of the water table elevations. It was assumed that the surrounding cells around these wells had the same hydraulic conductivity.

Figure 24. Vertical cross-section F-F'

Figure 25. Vertical cross-section G-G'

Figure 26. Vertical cross-section H-H'

For areas of the East Ravine that did not have a measured value, a value was assumed based on the overall average hydraulic conductivity or the value was adjusted, by factors of 10, until desired results were obtained. In general, some of the parameters caused enough change in some wells to improve the results, while these same parameters would cause change in other wells to worsen the results. This effect had to be carefully considered for each parameter to determine which values would provide the best results.

To further compare the model and field water table elevations, overlay contours and surface profiles were created using SURFER for Windows. Figure 27 is an overlay map of both measured data and model data for the start of the computer simulation on July 28, 1995. As expected, the two maps are very similar in the overlay. The top of the ravine contains less survey points, thus, contributing to interpolation errors associated with the kriging function of SURFER, which is used to import field data to ModIME. This would lead to some variation in the overlays.

Figures 28 and 29 represent a surface and contour profile of the measured water table elevations and model results for July 28, 1995, respectively. The surface contours are very similar, as expected, since it is the start of the simulation. From these figures, it is evident that the water table follows the contour of the surface, when compared to Figure 4.

Figure 30 is an overlay of the model and field data for the middle of the simulation on August 16, 1995. As with Figure 27, there is some interpolation errors in the field data to account for unknown areas in the East Ravine; however, the overlays are very similar in shape. The ravine is detailed by the curvature of the overlays, which compares very well with the ground surface contour of Figure 3. This figure further illustrates that the water table follows the contour of the ground surface.

Figure 31 illustrates the overlay of predicated and measured data for the end of the simulation on September 8, 1995. A surface and contour profile of the field and model data are presented in Figure 32 and Figure 33, respectively. As before, the model results agree very well with the measured water levels, especially in the ravine.

Figure 27. Overlay of field and model contours for July 28, 1995

Figure 28. Surface and contour profiles of water table elevations for field data on July 28, 1995

note: Northings and Eastings are state plain coordinates
Surface elevations are mean sea level

Figure 29. Surface and contour profiles of water table elevations for model data on July 28, 1995

note: Northings and Eastings are state plain coordinates
Surface elevations are mean sea level

Figure 30. Overlay of field and model contours for August 16, 1995

note: Northings and Eastings are state plane coordinates
 Surface elevations are mean sea level

Figure 31. Overlay of field and model contours for September 8, 1995

note: Northings and Eastings are state plain coordinates
Surface elevations are mean sea level

Figure 32. Surface and contour profiles of water table elevations for field data on September 8, 1995

note: Northings and Eastings are state plain coordinates
Surface elevations are mean sea level

Figure 33. Surface and contour profiles of water table elevations for model data on September 8, 1995

Figures 27-33 provide another way to visually examine the results of the modeling analysis and compare the results with measured water table elevations. The model provides a consistent representation of the groundwater flow down the ravine. The model also supports the theory that the flow down the ravine follows the contour of the ground surface.

The model requires many input parameters; however, there was a great deal of field data used in the model. The boundary conditions were controlled by using water table elevations for wells Al-Pz 9 and Al-Pz 38 as known head boundaries. Starting heads were also based on measured water elevations. The measured hydraulic conductivities worked extremely well in the program and provided consistent results. Based on the positive results between the measured water table elevations and model, the model data is representative of field conditions.

CONCLUSIONS

Several conclusions are developed from the field data and the modeling and are discussed below.

Soil Zones

The East Ravine is characterized by four soil zones. The top two to four feet of soil are classified as top soil or alluvium, characterized by a soft, moist, dark brown or black soil. The next four to ten feet are classified as weathered or oxidized till, composed of yellow or light brown soil, containing traces of iron oxides and calcium carbonate deposits. The oxidized till was followed by a transition zone, approximately two to three feet deep. A mixture of colors, including blue and gray, are the first indications of the unoxidized till in this layer. The unoxidized or unweathered till, dominated by very compact blue and gray soil, occurs approximately 12-15 feet below the ground surface.

Soil Analysis

Soil testing indicated that as the soil depth from the ground surface increased, the gravimetric water content decreased and the bulk density increased. It was also determined that the bulk density was higher on the hill slopes than in the ravine, which contained alluvium till. The results of a particle size analysis suggest that the soil is possibly a loam or clay loam mixture.

Hydraulic Conductivity

Hydraulic conductivity greatly varied between the oxidized and unoxidized till. The hydraulic conductivity of the oxidized zone ranged from 1.94×10^{-6} to 6.74×10^{-7} cm/sec, transition soils ranged from 8.68×10^{-7} to 1.65×10^{-8} cm/sec, and the unoxidized till ranged from 2.93×10^{-7} to 4.14×10^{-9} cm/sec. These results indicate groundwater moves much faster through the oxidized till as compared to the unoxidized till. However, the overall hydraulic conductivity is

fairly low, implying that a considerable amount of time would be required for water (or chemicals) to move through the soil zone.

Water Table

Based on water table elevations and soil logs, the water table lies in the oxidized zone across the East Ravine. Only on a few occasions, following heavy periods of precipitation, did the water table rise into the alluvium till. Over time, the water table eventually declined back to the oxidized zone. These results indicate that there is a potential for surface water contamination when the water table reaches the alluvium zone and could migrate onto surface soils. The contour of the water table followed the ground surface profile throughout the entire East Ravine, suggesting the groundwater follows the slope of the terrain, which is useful in tracking the potential migration of chemicals down the East Ravine.

Modeling

The three-dimensional computer modeling results were consistent with the measured results and provided an accurate representation of groundwater flow down the East Ravine. The model also showed that the water table follows the slope of the terrain. These results indicate the chemicals from the Disposal Site could migrate down the East Ravine through the oxidized till. Once the chemicals reach the bottom of the ravine, there is a potential for further migration off-site. The potential exists for surface water contamination following heavy precipitation which causes a subsequent rise in the water table into the alluvium till. Once groundwater reaches the alluvium till, which is very soft and permeable, there is a greater possibility that surface water could also be exposed to chemical contamination.

The model used measured field parameters as input data for the simulation. The results of the simulation are consistent with the measured field values and provide a good representation of the field conditions.

RECOMMENDATION FOR FUTURE RESEARCH

Due to the limited time frame of the project, there was not an opportunity to perform all of the field testing desired for a complete understanding of the groundwater flow. To fully understand the groundwater flow, there are several areas of further research that should be considered.

Continued monitoring of the water levels in the wells would contribute to the existing data base and will allow a comparison of data over several years to determine the effects of precipitation. Additional water level data would allow a better comparison of computer simulations to actual data for longer simulation periods.

During the springtime, it would be very beneficial to install surface weirs to determine the flow of surface water down the ravine. This data could be used to estimate the surface water flow at various locations along the ravine. Relationships could then be used to determine the effects of ground water on surface flow.

It would also be beneficial to install a few more monitoring wells at the end of the East Ravine, running both north and south for additional groundwater levels and soil data. Monitoring wells should also be placed in the northwest and northeast corners of the East Ravine, to improve the contours used in modeling. Wells placed along the South Ravine would also contribute to a better understanding of the overall regional groundwater flow.

Slug testing should be continued to check the previous results and tests should be conducted on the remaining oxidized and unoxidized wells. The hydraulic conductivity of the top soil layer should also be determined. If possible, the slug tests should be conducted during the spring time, when the wells contain enough water to allow for a dramatic change in head.

Additional soil sampling and testing would be beneficial in further defining the soil morphology of the East Ravine. Special attention should be devoted to analyzing the samples at various depths down and across the ravine.

To validate previous results of hydraulic conductivities, tracer experiments should be conducted in the spring, when water levels are higher, to observe the groundwater flow through oxidized till down the ravine. Sampling on a daily or weekly basis would provide a large database of information for modeling use. A particle tracking computer program could be used to determine the time it takes for groundwater to migrate through the oxidized zones; thus, providing an estimation of the travel time from the Ames CDS to the bottom of the East Ravine.

Based on the proposed additional work, new data should be entered into ModIME and revised simulation runs conducted, improving the accuracy of the results. An optimization program could also be developed to further improve the results of the modeling.

REFERENCES

- Anderson, D.A. and Welp, T.L., 1960. An Engineering Report on the Soils, Geology, Terrain and Climate of Iowa. Iowa State Highway Commission, Iowa, 96 pp.
- Anderson, M.P. and Woessner, W.W., 1992. Applied Groundwater Modeling-Simulation of Flow and Advective Transport. Academic Press, Inc., New York, 381 pp.
- Anderson, W.I., 1983. Geology of Iowa: Over Two Billion Years of Change. Iowa State University Press, Ames, IA, 268 pp.
- Black, C.A., Evans, D.D., Ensminger, L.E., White, J.L. and Clark, F.E., 1965. Methods of Soil Analysis - Part 1: Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling. American Society of Agronomy, Inc., Madison WI, 770 pp.
- Bouwer, H. and Rice, R.C., 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resources Research, 12(3): 423-429.
- Bouwer, H., 1989. The bouwer and rice slug test - an update. Ground Water, 27(3): 304-309.
- Cravens, S.J. and Ruedisili, L.C., 1987. Water movement in till of east-central South Dakota. Ground Water, 25(5): 555-561.
- D'Astous, A.Y, Ruland, W.W, Bruce, R.G., Cherry, J.A. and Gillham, R.W., 1989. Fracture effects in the shallow groundwater zone in weathered Sarnia-area clay. Canadian Geotechnical Journal, 26: 43-56.
- Fetter, C.W., 1994. Applied Hydrogeology, 3rd ed. Prentice-Hall, Inc., Englewood Cliffs, NJ, 691 pp.
- Freeze, R.A. and Cherry, J.A., 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ, 604 pp.
- Golden Software, Inc., 1994. SURFER for Windows, User's Guide. Golden Software, Inc., Golden, CO.
- Grisak, G.E. and Cherry, J.A., 1975. Hydrologic characteristics and response of fractured till and clay confining a shallow aquifer. Canadian Geotechnical Journal, 12: 23-43.

- Hendry, M.J., 1982. Hydraulic conductivity of a glacial till in Alberta. *Ground Water*, 20(2): 162-169.
- Horton, R., 1995. Personal communication.
- Jones, L., 1995. Project Summary: Modeling Groundwater Flow from the Ames Laboratory Chemical Disposal Site. Iowa State University, Ames, IA.
- Jones, L., 1994. Modeling Groundwater Flow from the Ames Laboratory Chemical Disposal Site. Proposal for Ames Laboratory. Iowa State University, Ames, IA.
- Jones, L., 1993. A comparison of pumping and slug tests for estimating the hydraulic conductivity of unweathered Wisconsin age till in Iowa. *Ground Water*, 31(6): 896-904.
- Kay, G.F., 1944. The Pleistocene Geology of Iowa. "The Pre-Illinoian Pleistocene Geology of Iowa," "The Illinoian and Post-Illinoian Pleistocene Geology of Iowa," "The Bibliography of the Pleistocene Geology of Iowa." Iowa Geological Survey Special Report. Des Moines, IA.
- Keller, C.K., van der Kamp, G. and Cherry, J.A., 1986. Fracture permeability and groundwater flow in clayey till near Saskatoon, Saskatchewan. *Canadian Geotechnical Journal*, 23: 229-240.
- Kirkby, M.J., 1978. *Hillslope Hydrology*. John Wiley & Sons, Ltd, New York, 389 pp.
- Larson, Craig, 1996. Personal communication.
- Malo, D.D., Worcester, B.K., Cassel, D.K. and Matzdorf, K.D., 1974. Soil-landscape relationships in a closed drainage system. *Soil Science Society America Proceedings*, 38: 813-818.
- Marshall, T.J. and Holmes, J.W., 1988. *Soil Physics*, 2nd ed. Cambridge University Press, New York, 374 pp.
- McDonald, M.G. and Harbaugh, A.W., 1988. Techniques of Water-Resources Investigations of the United States Geological Survey, Chapter A: A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. U.S. Geological Survey open-file report 83-875.

- Oulman, C.S. and Sendlein, L.V.A., 1968. The movement of radionuclides through soil formations. Engineering Research Institute, Iowa State University, Ames, IA.
- Ruland, W.W., Cherry, J.A. and Feenstra, S., 1991. The depth of fractures and active ground-water flow in a clayey till plain in southwestern Ontario. *Ground Water*, 29(3): 405-417.
- Rust Environment & Infrastructure, 1993. Ground and Surface Water Sample Results (August 31 - September 2, 1993) for Ames Laboratory Chemical Disposal Site. Rust Environment & Infrastructure, Minneapolis, MN.
- Rust Environment & Infrastructure, 1994a. Remedial Investigation Report - Ames Laboratory Chemical Disposal Site -Volume 1. Rust Environment & Infrastructure, Minneapolis, MN.
- Rust Environment & Infrastructure, 1994b. Draft Feasibility Study - Ames Laboratory Chemical Disposal Site. Rust Environment & Infrastructure, Minneapolis, MN.
- Rust Environment & Infrastructure, 1995a. Final Phase II Remedial Investigation Work Plan- Ames Laboratory Chemical Disposal Site. Rust Environment & Infrastructure, Minneapolis, MN.
- Rust Environment & Infrastructure, 1995b. Draft Preliminary Report - Phase II Remedial Investigation - Ames Laboratory Chemical Disposal Site. Rust Environment & Infrastructure, Minneapolis, MN.
- Shaw, E.M., 1988. *Hydrology in Practice*, 2nd ed. Van Nostrand Reinhold, London, 539 pp.
- Sidle, R.C., Pearce, A.J., O'Loughlin, C.L., 1985. *Hillslope Stability and Land Use*. Water Resources Monograph Series #11, American Geophysical Union, Washington, D.C., 140 pp.
- Singer, M.J. and Munns, D.N., 1991. *Soils -An Introduction*, 2nd ed. Macmillan Publishing Company, New York, 473 pp.
- United States Department of Agriculture (USDA), 1984. *Soil Survey of Story County*. USDA, Soil Conservation Service.
- United States Department of Commerce (USDC), 1990-1995. *Climatological Data*, National Oceanic and Atmospheric Administration, Washington, D.C.

- Wallach, R., and Zaslavsky, D., 1991. Lateral flow in a layered profile of an infinite uniform slope. *Water Resources Research*, 27(8): 1809-1818.
- Weast, R.C., ed, 1965. *CRC Handbook of Chemistry and Physics*, 46 ed. The Chemical Rubber Co., Cleveland, OH.
- Zhang, Y., Zheng, C., Nevill, C.J., and Andrews, C.B, 1993. User's Guide: ModIME - An Integrated Modeling Environment for MODFLOW, PATH3D, and MT3D, version 1.0. S.S. Papadopoulos & Associates, Inc., Bethesda, MD.

APPENDIX A

FIELD NOTES OF SOIL BORING LOGS

Field notes of soil observations during installation of monitoring wells by hand augers, unless otherwise noted.

Well #	Depth from surface (feet), Soil description (color, material, zone)
Al-Pz-01	0-1.5 black, leached; 1.5-3 brown, some carbonates, oxidized; 3-4 brown, sandy, carbonates; 4-5 brown, some gray, sandy, starting transition zone; 6-7 more gray, tighter soil
Al-Pz-02	0-1 black, leached; 1-2 some leaching, dark brown; 2-3 color transition to yellow-brown, some sand, gravel, carbonates oxidized; 3-4 yellow, very dry, some carbonates; 4-5 whitish, yellow color, lots of carbonates, dry; 5-6 carbonates, transition zone; 6-7 more gray; 7 unoxidized (?)
Al-Pz-03	0-1 black top soil; 1-2 light brown, orange traces, lots of gravel, sand, iron, oxidized; 2-4 light brown, white traces, lots of carbonates, oxidized; 4-7 gray traces, some carbonates, small rocks (1-3" diameter)
Al-Pz-04	0-1 dark brown/black, leached; 1-2 light brown, some leaching, carbonates, oxidized; 2-3 color transition from brown to yellow; 3-4 yellow, lots of carbonates
Al-Pz-09	0-1 black top soil; 1-2 oxidized; 7-8 yellow/brown, sandy, some carbonates; 8-8.5 yellow/brown, some gray, lots of sand, carbonates; 8-8.75 yellow/brown, more gray, little sand, carbonates
Al-Pz-10	0-1 brown/black, leached, dry; 1-2 brown, leached, some carbonates, dry; 2-4 brown/yellow, unleached, carbonates, some gravel; 4-5 yellow, more carbonates; 5-6 some orange, lots of iron oxides, lots of carbonates; 6-7 less carbonates, lots of iron oxides; 7-8 no carbonates, moister soil, cobbles and rocks; 8-9 light brown, sand, still moist; 9-10 yellow, sandy, some gravel, dry; 10-11 some gray, sandy, clay; 11 blue/gray, tighter soil, transition or unoxidized zone
Al-Pz-12	0-1 brown/black, leached; 2-3 yellow/brown, some carbonates, dry, clay, oxidized; 3-4 sand, dry; 4-7 orange traces, iron oxides, sand, clay; 7-8 carbonates; 8-9 more moisture; 9-10 more clay and less sand; 12-13 sand, gravel seam; 13-14 sand, gravel, carbonates, transition zone

- Al-Pz-13 0-0.5 black/brown, leached; 0.5-1 yellow/gray, clay, oxidized; 1-2 yellow, brown, gray, some carbonates, clay; 2-3 more gray, some orange traces, iron oxides, lots of carbonates; 3-4 tight soil; 4-5 black, tight soil; 5-7 black/brown, carbonates, clay, sand, unoxidized; 7-8 black, very hard, carbonates, clay, very little sand; 8-12 black, very tight, some carbonates, very little sand
- Al-Pz-14 0-1 black/brown, leached, dry, very loose soil; 1-2 light brown/yellow, dry, some carbonates, oxidized; 2-3 brown/yellow, clay, carbonates, some moisture, iron traces, some gravel and pebbles; 3-4 yellow/brown, dry, lots of carbonates; 4-5 yellow, dry, carbonates, sand, silt, clay; 5-6 yellow, dry, more clay, gravel, and pebbles; 6-7 yellow, carbonates, sand, silt, clay, some gravel, pebbles, and cobbles; 7-8 yellow, lots of iron deposits, sand, silt, clay, carbonates, some moisture
- Al-Pz-15 0-1 black, top soil; 1-2 dark brown, light brown/yellow, very sandy, traces of iron oxides, moist, oxidized; 2-3 traces of iron oxides, some carbonates, small gravel and pebbles, moist, very sticky; 3-5 light brown, very sandy, very sticky, pebbles; 5-6 some iron, very wet, very sandy, lots of pebbles, some carbonates, rocks with diameter 1-2"; 6-7 light brown, gray, lots of carbonates, dry, dense; 7-8 more gray, some iron, carbonates, sandy, small pebbles, dry; 8-9 more gray, lots of iron, very sandy, very wet, pebbles; 9-10 lots of gray, drier, lots of iron oxides, sandy; 14 very dark, little brown, dry, sandy, unoxidized, hit a rock
- Al-Pz-16 0-1 dark black/brown loam; 1-2 lighter yellow/brown, some carbonates, dry, oxidized; 2-3 white, lots of carbonates, soil clumps together, dry; 3-4 lots of carbonates; 4-5 some blue/gray streaks, lots of carbonates; 5-6 more blue/gray, darker brown, less yellow and white, less carbonates; 6-7 more brown, blue/gray, no carbonates, some sand; 7-8 more sand; 8-9 brown, gray, some sand; 9-11 more gray, some sand; 10-13 mostly dark gray, little sand, small pieces of rock, unoxidized; 13-15 solid gray, very tight
- Al-Pz-17 0-1 black loam, moist; 1-2 some brown, dry; 2-3 lighter brown, traces of yellow and gray, small traces of carbonates, oxidized; 3-4 yellow/brown, gray, very dry, very loose, more carbonates; 4-6 yellow, brown, gray, white, lots of carbonates; 6-8 darker brown, iron oxides present, less carbonates
- Al-Pz-18 0-1 black loam, moist, sticky; 1-2 some brown, dryer; 2-3 lighter brown, traces of yellow and gray, small traces of carbonates, very loose, oxidized; 3-4 more gray, very dry, very loose, lots of carbonates; 4-5 white, lots of carbonates; 5-6 darker brown, less carbonates; 7-8 brown/gray, very little carbonates, traces of iron oxides

- Al-Pz-19 0-1 black, loam, moist; 1-2 black turning brown; 2-3 light brown, dry, oxidized; 3-4 some gray, lots of carbonates; 4-6 brown/gray, lots of carbonates; 6-7 lots of gray, traces of iron oxides, lots of carbonates, very dry, some gravel; 7-8 more gray, iron oxides, sand, gravel; 8-9 brown/gray, some iron oxide, no carbonates, lots of sand; 9-10 lots of sand (pockets of sand between gray and brown clumps); 10-12 mostly gray, very compact, very dense, unoxidized
- Al-Pz-20 0-4 dark, black loam; 4-5 sudden color change to brown, some gray, no carbonates, oxidized (?); 5-7 brown, very dry, very loose; 7-12 brown turning lighter, more compact, dense, clay, some small cobbles; 12-16 gray/brown, more dense, unoxidized; 16-19 dark black, compact, some gravel
- Al-Pz-21 0-2 dark brown, moist, soft, medium plasticity, silty clay, some fine-coarse sand, traces of gravel; 2-3 yellow brown, some gray, low plasticity, moist, dense soil, silty clay, some fine-coarse sand, some fine-coarse gravel, oxidized; 3-4 yellow/brown, some gray, traces of orange, iron oxides, more carbonates, some gravel; 4-6 brown, orange, light gray, iron oxides, lots of carbonates, silty clay with fine-coarse gravel, sand seam, fine-coarse sand; 6-8 drier; 10 hit a rock
- Al-Pz-22 0-1 black, top soil, very wet, soft, silty, clay, some fine-coarse sand, some fine-coarse gravel; 1-2 brown, light gray, silty clay, some fine-coarse sand, oxidized; 4-5 dark gray, very tight, dry, silty clay, some sand, gravel, carbonates, transition zone; 5-6 dark gray, very hard, dry; 6-8 very dark gray, hard, dry, silty clay, some fine-coarse sand, some fine-coarse gravel, unoxidized; 8 hit a rock
- Al-Pz-23 Power auger- 8 oxidized, hit a rock
- Al-Pz-24 Power auger- 5 very wet, oxidized; 12 unoxidized
- Al-Pz-25 Power auger- 12 unoxidized
- Al-Pz-26 Power auger- 16 unoxidized
- Al-Pz-27 0-1 black, top soil; 1-2 yellow/brown, orange, traces of iron oxides, lots of gravel and sand, oxidized; 2-3 lots of carbonates; 3-4 some gray, some carbonates, small rocks; 4-7 yellow/brown, gray, very sandy; 7 hit a rock

- Al-Pz-28 0-2 black, top soil, very loose, semi-dry; 2-3 light brown, sandy, some gravel, oxidized; 3-4 light brown, orange, iron oxides, sandy, semi-dry, small gravel; 4-5 light brown, iron deposits, very sandy, dry; 5-6 traces of carbonates, sandy, wet; 6-7 very wet, sticky, very sandy, carbonates, lots of pebbles, gravel, rocks with 1" diameter; 7-8 very wet, more carbonates, lots of iron oxides, lots of gravel, very sandy
- Al-Pz-29 0-1 black, top soil; 2-4 light brown, sandy, sticky, some gravel and rocks, oxidized; 4-5 moist, very sandy, some rocks with 2" diameter; 5-6 sandy, lots of carbonates; 6-7 some gray, some iron oxides, lots of carbonates, loose soil, sandy, some 1/4" diameter rocks; 9-10 more gray, lots of iron oxides, lots of carbonates, dry, sandy, transition zone
- Al-Pz-30 0-1 black, top soil, very wet and sticky; 3-4 yellow, very wet and sticky, sandy, carbonates, rocks with diameter 1/4", oxidized; 4-5 light brown, orange traces, very wet, very sandy, iron oxides; 6-8 some gray, wet, transition zone; 8-9 gray, lots of carbonates, some iron oxides, drier, rocks with 1/2" diameter; 9-10 more gray, tighter soil, more iron oxides, gravel, sand; 10 unoxidized, hit a rock
- Al-Pz-31 0-2 black, top soil, very moist and sticky, sandy, some pebbles; 3-4 light brown, moist and sticky, some carbonates, sandy, small pebbles, oxidized; 4-5 light brown, orange, traces of iron oxides, some carbonates, sandy, rock with 1/4" diameter; 5-6 some gray, carbonates, iron oxides, small pebbles; 9 mostly gray, dark brown, very tight clay, dry, unoxidized
- Al-Pz-32 0-1 black, top soil, very sticky, sandy; 2-3 light brown, oxidized; 3-4 light brown, orange, traces of iron oxides, sandy, rock with diameter 1/2"; 5-7 light brown, some gray, lots of carbonates, sandy, pebbles, rocks with diameter 1/2"
- Al-Pz-33 0-0.5 black, top soil, very dry; 0.5 light brown/yellow, oxidized; 0.5-4 light brown/yellow, some gray, orange, lots of iron oxides, carbonates, pebbles, rocks with diameter 1", very dry; 4 hit a rock
- Al-Pz-34 0-1 black, top soil; 1 yellow/brown, oxidized; 7 yellow/brown, some gray, carbonates, lots of rocks with diameter 1"
- Al-Pz-35 0-1.5 black, top soil; 1.5-2 yellow/brown, lots of iron traces, small pebbles, oxidized, tried several well spots near this area and encountered lots of 2-3" rocks

- Al-Pz-36 0-1.5 black, top soil; 1.5 yellow/brown, lots of iron traces, carbonates, lots of small rocks, oxidized
- Al-Pz-37 0-1.5 black, top soil; 1.5 yellow/brown, lots of iron traces, carbonates, oxidized
- Al-Pz-38 0-1.5 sandy, very wet, soft, easy to push auger through soil, lots of water in the hole; 1.5 yellow/brown, very wet, oxidized

APPENDIX B

WATER TABLE ELEVATIONS OF MONITORING WELLS

Well Number AL-PZ	Ground elevation (mean sea level)	Top of well elevation (mean sea level)	Bottom of well elevation (mean sea level)	Elevation of water table (mean sea level)					
				Date					
				11/16/94	11/25/94	11/29/94	12/5/94	12/15/94	12/23/94
1	958.16	960.97	951.00	0	0	0	0	0	0
2	963.54	966.29	956.29	0	0	0	0	0	0
3	956.03	958.87	948.87	0	0	952.72	951.22	951.23	953.25
4	958.03	960.78	950.78	0	0	0	0	0	0
5	962.21	964.22	954.21	0	0	0	0	0	0
6	948.13	950.38	940.38	0	0	0	0	0	0
7	947.54	950.33	940.37	0	0	0	0	0	0
8	947.99	950.83	940.68	0	0	946.26	944.75	943.62	947.12
9	963.71	965.08	954.96	0	0	956.76	955.43	955.63	959.27
10	968.57	972.43	957.32	0	0	0	0	0	0
11	969.93	971.29	956.18	957.91	957.81	957.89	957.88	957.97	958.12
12	967.80	968.48	953.34	0	0	0	0	0	0
13	953.48	957.94	941.31	0	941.46	941.44	941.39	941.29	0
14	967.75	969.99	955.00	-	-	-	0	0	0
15	962.30	964.47	947.80	-	-	-	-	-	-
16	954.31	955.70	939.06	-	-	-	-	-	940.07
17	952.47	954.63	944.52	-	-	-	0	0	0
18	950.95	953.14	943.03	-	-	-	0	0	0
19	953.48	957.26	940.56	-	-	-	-	-	-
20	966.01	968.36	946.70	-	-	-	-	-	-
21	958.58	963.82	948.66	-	-	-	-	-	-
22	955.54	958.71	947.04	-	-	-	-	-	-
24	965.89	971.05	944.33	-	-	-	-	-	-
25	967.02	970.07	948.33	-	-	-	-	-	-
26	970.31	974.20	952.62	-	-	-	-	-	-

		Elevation of water table (mean sea level)									
Well Number	Date										
AL-PZ	12/31/94	1/6/95	1/13/95	1/18/95	1/25/95	2/1/95	2/8/95	2/17/95	2/20/95	2/22/95	3/1/95
1	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0
3	953.49	953.16	952.48	952.88	952.5	951.83	953.35	952.38	954.65	954.58	954.35
4	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	955.18
6	0	0	940.84	941.02	941.08	941.2	941.2	941.14	941.3	941.46	941.61
7	0	0	0	0	0	0	0	0	0	0	0
8	945.85	944.89	944.1	943.68	943.21	942.86	942.59	942.33	946.56	947.03	946.37
9	958.24	958.2	957.84	957.51	957.59	957.7	957.85	957.8	959.74	959.97	959.55
10	0	0	0	0	0	0	0	0	0	0	0
11	958.35	958.53	958.66	958.74	958.84	958.97	958.99	959.12	959.23	959.3	959.68
12	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0
15	-	-	-	-	-	-	-	-	-	-	-
16	940.17	940.47	940.65	940.72	940.77	940.93	940.89	940.94	941.02	941.04	940.94
17	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0
19	-	-	-	-	0	940.74	940.68	940.6	0	0	0
20	-	-	-	0	951.98	954.17	954.89	955.2	955.25	955.24	955.03
21	-	-	-	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	-	-	-	-

		Elevation of water table (mean sea level)									
Well Number AL-PZ	Date										
	3/10/95	3/15/95	3/23/95	3/24/95	3/30/95	4/4/95	4/13/95	4/19/95	4/27/95	5/4/95	5/10/95
1	0	0	0	0	0	0	955.25	954.91	955.95	955.21	956.67
2	0	0	0	0	0	957.34	961.29	961.01	962.2	962.03	962.41
3	953.99	954.96	954.91	954.94	955.06	955.01	955.25	955.27	955.43	955.4	955.59
4	0	0	0	0	951.2	951.15	955.78	955.95	956.62	956.3	957.03
5	955.8	959.71	959.47	959.4	959.74	959.22	960.63	960.31	961.07	960.6	961.45
6	941.91	942.43	943.99	943.61	945.48	943.33	946.64	946.42	947.02	946.62	947.35
7	0	0	0	0	944.51	943.81	945.85	945.77	946.26	945.66	946.46
8	944.35	947.29	946.97	946.92	947.1	946.76	947.31	947.23	947.34	947.22	947.39
9	959.27	963.1	962.99	962.97	963.44	963.06	963.77	963.63	963.99	963.91	964.19
10	0	958.18	959.79	960.08	961.47	961.19	964.58	964.13	966.42	966	967.9
11	960.22	963.37	964.42	964.47	965.48	965.01	966.74	966.63	968.4	967.71	968.87
12	0	0	0	0	0	0	0	0	0	958.52	964.2
13	0	0	0	0	0	0	0	0	0	0	0
14	0	955.04	956.6	956.64	957.64	957.71	959.01	959.31	961.57	961.45	966.25
15	-	-	-	-	-	-	-	-	-	-	-
16	941.06	941.07	941.19	941.21	941.22	941.28	941.7	942.22	942.98	944.09	945.34
17	0	0	0	0	0	0	950.35	950.19	951.03	950.41	951.29
18	0	0	945.76	945.65	948.55	947.97	949.42	949.25	949.93	949.24	950.64
19	0	0	0	0	0	0	0	0	0	0	0
20	955.02	954.9	954.81	954.76	954.6	954.48	954.52	954.57	954.56	954.64	954.84
21	-	-	-	-	-	0	949.12	949	949.01	949	949.28
22	-	-	-	-	-	-	0	949.53	948.76	948.54	948.56
24	-	-	-	-	-	-	-	-	-	-	0
25	-	-	-	-	-	-	-	-	-	-	0
26	-	-	-	-	-	-	-	-	-	-	0

		Elevation of water table (mean sea level)									
Well Number AL-PZ	Date										
	5/17/95	5/23/95	6/1/95	6/7/95	6/14/95	6/21/95	6/28/95	7/6/95	7/13/95	7/21/95	7/28/95
1	955.64	955.3	955.1	954.9	954.44	953.32	952.77	952.33	952.02	951.67	951.46
2	961.71	961.52	961.23	960.98	960.65	959.57	959.87	959.9	958.84	954.32	957.84
3	955.57	955.55	955.64	955.69	955.62	955.33	955.72	955.66	955.37	955.28	955.16
4	955.84	955.97	955.72	955.53	955.02	954.13	953.51	953.1	952.77	952.44	952.28
5	960.86	960.65	960.27	960.02	959.89	959.07	959.4	959.29	958.45	958.15	957.84
6	946.24	945.08	944.57	944.5	943.56	942.93	942.86	943.18	942.83	942.58	942.53
7	945.31	944.66	944.3	943.93	943.03	942.06	941.49	941.21	941.02	941.47	-
8	947.09	947.01	946.96	946.98	947.13	946.19	946.76	947.12	946.26	945.98	942.98
9	964.08	963.99	963.93	963.84	963.85	962.64	963.71	963.59	962.38	962.43	961.84
10	967.3	966.88	966.34	966.14	965.81	964.79	964.96	964.65	963.85	963.44	963
11	968.02	967.81	967.59	967.39	967.16	966.19	966.91	966.82	965.69	965.64	965.12
12	964.1	963.23	962.06	961.18	959.57	957.18	956.54	955.91	955.37	954.85	954.58
13	0	0	0	0	0	0	0	0	0	0	0
14	963.97	963.06	962.22	961.95	961.37	960.44	960.02	959.55	958.82	958.27	957.95
15	-	0	0	0	0	0	0	0	0	0	0
16	946.3	946.02	945.86	945.89	945.71	945.5	945.39	945.2	945.05	944.94	944.85
17	950.24	949.69	949.56	949.42	948.65	947.46	946.71	946.21	945.89	945.58	945.41
18	949.37	949.03	948.65	948.31	947.35	945.86	945.18	945.33	944.96	944.61	944.48
19	0	0	0	0	0	0	0	0	0	0	0
20	955.11	955.12	955.33	955.51	955.59	955.73	955.99	956.29	956.52	956.75	956.96
21	949.05	949.02	949.03	949.01	949	949	949	949	949.01	949.01	949
22	948.59	948.59	948.69	948.74	948.75	948.75	948.82	948.85	948.85	947.38	947.46
24	951.65	946.98	947.65	948	948.57	949.04	949.5	950.01	950.45	950.86	951.15
25	956.02	956.28	956.54	956.64	956.82	957.05	957.34	957.66	957.86	958.15	958.26
26	954.08	959.76	965.97	967.57	968.35	967.45	967.31	967.11	966.64	966.01	965.65

		Elevation of water table (mean sea level)							
Well Number	Date								
AL-PZ	8/2/95	8/8/95	8/16/95	8/23/95	8/29/95	9/8/95	9/23/95	10/17/95	11/9/95
1	951.19	950.99	0	0	0	0	0	0	0
2	956.69	956.63	956.7	956.64	956.64	956.65	956.64	956.64	956.61
3	954.53	953.62		953.77	952.98	951.74	950.27	949.57	949.27
4	952.12	952	952.84	952.49	952.23	951.89	951.31	951.16	951.13
5	957.12	956.57	956.87	955.89	955.22	954.95	954.76	954.57	954.42
6	942.2	942.23	942.11	941.86	941.68	941.01	940.72	940.7	940.71
7	-	-	-	-	-	-	-	-	-
8	943.27	943.36	943.49	943.44	943.38	943.22	942.79	0	942.82
9	961.36	960.73	961.38	960.38	959.6	958.05	955.51	955.46	955.45
10	962.05	960.56	961.12	960.62	959.77	958.33	957.76	957.71	957.7
11	964.41	964	964.1	963.35	962.38	961.16	959.96	958.93	958.42
12	954.01	953.73	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0
14	957.54	957.21	956.84	956.58	956.43	955.89	955.11	0	0
15	0	0	0	0	0	0	0	0	0
16	944.69	944.66	944.62	944.46	945.21	944.55	943.99	943.85	943.17
17	945.2	945.08	944.95	944.92	944.91	944.81	944.6	0	0
18	944.23	944.09	943.88	943.71	943.58	943.49	943.21	943.2	943.3
19	0	0	0	0	0	0	0	0	0
20	957.08	957.27	957.59	957.95	957.61	957.9	958.11	958.44	958.18
21	949.01	949	949	949	949	948.99	948.98	948.99	948.98
22	947.41	947.41	0	0	0	0	0	0	0
24	951.48	951.81	952.21	953.1	952.77	953.37	954.06	954.85	955.18
25	958.36	958.45	958.47	959.14	958.39	958.3	958.06	957.66	957.24
26	964.83	964.48	963.92	963.44	962.84	961.47	960.1	959.2	959.27

Well Number AL-PZ	Ground elevation (mean sea level)	Top of well elevation (mean sea level)	Bottom of well elevation (mean sea level)	Elevation of water table (mean sea level)					
				Date					
				5/17/95	5/23/95	6/1/95	6/7/95	6/14/95	6/21/95
27	954.67	957.70	947.67	0	948.67	948.82	948.73	948.76	948.66
28	962.65	965.70	955.65	-	0	956.23	956.05	956.03	956
29	963.51	968.55	953.51	-	0	0	0	0	0
30	961.84	964.06	952.51	-	0	961.39	960.43	960.33	960.15
31	961.45	963.32	951.78	-	-	0	957.09	957.2	957.27
32	960.93	964.01	954.01	-	-	0	959.11	959.3	958.26
33	954.44	958.03	950.44	-	-	-	-	-	-
34	953.07	956.18	946.15	-	-	-	-	-	-
35	952.20	955.28	945.28	-	-	-	-	-	-
36	951.00	953.92	943.92	-	-	-	-	-	-
37	946.37	948.61	938.54	-	-	-	-	-	-
38	943.96	947.56	938.46	-	-	-	-	-	-

Elevation of water table (mean sea level)											
Well Number	Date										
AL-PZ	6/28/95	7/6/95	7/13/95	7/21/95	7/28/95	8/2/95	8/8/95	8/16/95	8/23/95	8/29/95	9/8/95
27	948.54	948.43	948.39	948.2	948.11	948.04	948.05	948.05	948.01	948	948.02
28	956	956	956	956	956	956	956	956.01	956	956.01	955.99
29	0	0	0	0	0	0	0	0	0	0	0
30	960.1	960.09	960.81	959.92	959.84	959.64	959.41	959.32	959.11	958.85	958.25
31	957.34	957.44	957.53	957.55	957.57	957.52	957.47	957.36	957.27	961.02	959.26
32	958.98	959.01	958.12	958.12	957.55	956.51	956.2	955.9	955.47	955.31	954.98
33	-	0	953.56	952.92	952.57	951.74	951.38	0	0	0	0
34	-	0	948.15	946.66	946.53	946.49	946.46	0	0	0	0
35	-	0	945.91	946.81	947.39	947.6	947.89	945.92	946.41	946.56	946.71
36	-	0	0	947.84	945.45	945.46	945.44	945.09	945.07	944.88	944.31
37	-	0	0	943.16	940.27	940.86	941.16	940.92	941.27	941.34	941.33
38	-	0	942.98	943.35	942.58	943.02	942.08	943.51	942.34	941.74	940.93

		Elevation of water table (mean sea level)		
Well Number	Date			
AL-PZ	9/23/95	10/17/95	11/9/95	
27	948.02	948	948	
28	955.98	955.99	956.01	
29	0	0	0	
30	957.37	956.06	955.01	
31	958.12	956.65	955.42	
32	954.51	954.43	954.41	
33	0	0	0	
34	0	0	946.53	
35	946.69	946.41	945.93	
36	944.24	944.85	944.14	
37	941.05	940.07	939.67	
38	941.37	940.69	941.78	

APPENDIX C

DATA USED FOR SOIL CALCULATIONS

Table C1. Data used for calculations of gravimetric water content

Well #	Soil Type	Depth from the Surface feet	Date Sampled	Date Tested	$W_{(tin)}$ grams	$W_{(tin+wet\ soil)}$ grams	$W_{(tin+dry\ soil)}$ grams	$W_{(dry)}$ grams	θ_m gram/gram	Average θ_m gram/gram
MW-6	Wis. ox	0-5	-	4/27/95	35.18	85.33	77.28	42.10	0.19121	-
	Pre-Ill. ox	5-10	-	4/27/95	36.59	75.64	69.23	32.64	0.19638	-
	Pre-Ill. unox	10-15	-	4/27/95	33.18	91.10	84.14	50.96	0.13658	-
AI-21	oxidized	2.33-2.67	3/30/95	5/23/95	0.99	87.95	74.46	73.47	0.18361	0.17471
AI-21	oxidized	2.33-2.67	3/30/95	5/23/95	1.01	82.64	71.03	70.02	0.16581	
AI-21	oxidized	3.8-4.3	3/30/95	5/23/95	1.00	48.35	42.61	41.61	0.13795	0.14620
AI-21	oxidized	3.8-4.3	3/30/95	5/23/95	0.99	66.09	57.38	56.39	0.15446	
AI-22	oxidized	3.33	4/13/95	5/23/95	0.99	58.34	48.06	47.07	0.21840	0.22062
AI-22	oxidized	3.33	4/13/95	5/23/95	1.01	62.69	51.45	50.44	0.22284	
AI-22	oxidized	8.66	4/13/95	5/23/95	1.02	62.57	50.76	49.74	0.23743	0.24672
AI-22	oxidized	8.66	4/13/95	5/23/95	1.01	54.39	43.51	42.50	0.25600	
AI-15	oxidized	4.75-5.25	5/23/95	5/24/95	1.00	57.16	49.65	48.65	0.15437	0.14942
AI-15	oxidized	4.75-5.25	5/23/95	5/24/95	1.01	45.29	39.70	38.69	0.14448	
AI-27	oxidized	3.5-4.17	5/17/95	5/23/95	0.99	55.31	48.30	47.31	0.14817	0.14488
AI-27	oxidized	3.5-4.17	5/17/95	5/23/95	1.01	47.53	41.76	40.75	0.14160	
AI-29	top soil	2-3	5/25/95	5/30/95 ?	1.01	50.56	43.65	42.64	0.16205	0.16342
AI-29	top soil	2-3	5/25/95	5/30/95 ?	1.01	41.16	35.48	34.47	0.16478	
AI-29	oxidized	6.25-7.08	5/25/95	5/30/95 ?	0.99	19.92	17.37	16.38	0.15568	0.15595
AI-29	oxidized	6.25-7.08	5/25/95	5/30/95 ?	1.01	41.94	36.41	35.40	0.15621	
AI-29	oxidized	9.33	5/25/95	5/30/95 ?	1.01	30.70	26.76	25.75	0.15301	0.15378
AI-29	oxidized	9.33	5/25/95	5/30/95 ?	0.99	37.82	32.89	31.90	0.15455	

Table C1. Continued

Well #	Soil Type	Depth from the Surface feet	Date Sampled	Date Tested	W _(tin) grams	W _(tin+wet soil) grams	W _(tin+dry soil) grams	W _(dry) grams	θ_m gram/gram	Average θ_m gram/gram
Al-30	oxidized	5.08	5/30/95	5/30/95 ?	1.02	42.71	35.35	34.33	0.21439	0.22036
Al-30	oxidized	5.08	5/30/95	5/30/95 ?	0.98	52.02	42.6	41.62	0.22633	
Al-30	transition	10	5/30/95	5/30/95 ?	0.99	38.87	32.59	31.6	0.19873	0.19299
Al-30	transition	10	5/30/95	5/30/95 ?	0.99	54.38	45.96	44.97	0.18724	
Al-31	top soil	3.33	6/6/95	7/1/95	1.01	38.08	32.38	31.37	0.18170	0.18799
Al-31	top soil	3.33	6/6/95	7/1/95	1.01	39	32.82	31.81	0.19428	
Al-31	oxidized	5.67	6/6/95	7/1/95	1.01	29.09	24.53	23.52	0.19388	0.19675
Al-31	oxidized	5.67	6/6/95	7/1/95	1.01	50.59	42.34	41.33	0.19961	
sand					1	22.76	22.69	21.69	0.00323	-

Table C2. Data used for calculations of bulk density using clod method

Well #	Soil Type	Depth from the Surface feet	Date Tested	θ_m gram/gram	$W_{(a+t)}$ grams	$W_{(t+a+wax)}$ grams	$W_{(dry)}$ grams	$W_{(wax)}$ grams	$W_{(b+w)}$ grams	$W_{(bwat+wax)}$ grams
MW-6	Wis. ox	0-5	4/27/95	0.1912	47.43	51.17	39.8167	3.74	1070.7	1098.7
	Pre-III. ox	5-10	4/27/95	0.1964	56.43	59.88	47.1673	3.45	1070.4	1103.0
	Pre-III. unox	10-15	4/27/95	0.1366	44.67	46.53	39.3021	1.86	1070.3	1092.7
Al-21	oxidized	2.33-2.67	7/1/95	0.0264	75.29	77.62	73.3535	2.33	1168.4	1208.8
Al-21	oxidized	3.8-4.3	7/1/95	0.0237	42.65	44.51	41.6642	1.86	1168.1	1190.2
Al-22	oxidized	3.33	7/1/95	0.0228	51.67	54.03	50.5197	2.36	1168.0	1195.9
Al-22	oxidized	8.66	7/1/95	0.0203	43.40	45.02	42.5348	1.62	1167.9	1191.1
Al-15	oxidized	4.75-5.25	7/1/95	0.0149	48.75	51.02	48.0333	2.27	1167.7	1193.8
Al-27	oxidized	3.5-4.17	7/1/95	0.0099	47.86	50.43	47.3927	2.57	1167.1	1195.2
Al-29	top soil	2-3	7/1/95	0.0261	35.29	36.87	34.3927	1.58	1167.1	1185.8
Al-29	oxidized	6.25-7.08	7/1/95	0.0219	16.74	17.59	16.3808	0.85	1166.8	1175.9
Al-29	oxidized	9.33	7/1/95	0.0227	26.21	27.55	25.6275	1.34	1166.7	1180.9
Al-30	oxidized	5.08	7/1/95	0.0064	34.52	36.63	34.2995	2.11	1166.5	1188.4
Al-30	transition	10	7/1/95	0.0177	32.08	33.73	31.5214	1.65	1166.1	1183.6
Al-31	top soil	3.33	7/5/95	0.1817	31.46	33.21	26.6227	1.75	1298.2	1314.5
Al-31	oxidized	5.67	7/5/95	0.1939	23.64	24.72	19.8010	1.08	1296.9	1309.1

¹ density values for water from Handbook of Chemistry and Physics

² assume $\rho_{wax} = 0.9 \text{ g/cm}^3$ (Black et al., 1965)

³ correction factor accounts for the error in bulk densities as explained in the text

Table C2. Continued

$W_{(t+t+wax)}$ grams	$T_{(water)}$ C	ρ_w^1 g/cm ³	$V_{(wax+soil)}$ cm ³	V_{wax}^2 cm ³	ρ_b g/cm ³	θ_m gram/gram	θ_v cm ³ /cm ³	Correction Factor ³	Corrected ρ_b g/cm ³	Corrected θ_v cm ³ /cm ³
28.0	24.0	0.997296	28.0759	4.1556	1.6646	0.1912	0.3183	-	-	-
32.6	24.0	0.997296	32.6884	3.8333	1.6346	0.1964	0.3210	-	-	-
22.4	24.0	0.997296	22.4607	2.0667	1.9271	0.1366	0.2632	-	-	-
40.4	24.0	0.997296	40.5095	2.5889	1.9344	0.1836	0.3552	0.1450	1.7894	0.3286
22.1	24.0	0.997296	22.1599	2.0667	2.0735	0.1380	0.2860	0.1451	1.9285	0.2660
27.9	24.0	0.997296	27.9756	2.6222	1.9926	0.2228	0.4440	0.3400	1.6526	0.3683
23.2	24.0	0.997296	23.2629	1.8000	1.9818	0.2560	0.5073	0.3800	1.6018	0.4101
26.1	24.0	0.997296	26.1708	2.5222	2.0311	0.1544	0.3135	0.1550	1.8761	0.2896
28.1	24.0	0.997296	28.1762	2.8556	1.8717	0.1482	0.2773	-0.0340	1.8377	0.2723
18.7	24.0	0.997296	18.7507	1.7556	2.0237	0.1648	0.3335	0.1750	1.8487	0.3046
9.1	24.0	0.997296	9.1247	0.9444	2.0025	0.1557	0.3117	0.1200	1.8825	0.2931
14.2	24.0	0.997296	14.2385	1.4889	2.0101	0.1530	0.3076	0.0514	1.9587	0.2997
21.9	25.5	0.996783	21.9707	2.3444	1.7476	0.2144	0.3747	0.0837	1.6639	0.3567
17.5	25.0	0.997044	17.5519	1.8333	2.0054	0.1987	0.3985	0.2900	1.7154	0.3409
16.3	25.5	0.996783	16.3526	1.9444	1.8477	0.1817	0.3357	0.0880	1.7598	0.3198
12.2	26.0	0.996783	12.2394	1.2000	1.7937	0.1939	0.3478	0.0375	1.7562	0.3405
average =								0.1573		

Table C3. Data used for calculations of particle density using pycnometer method

Well #	Soil Type	Depth from the surface feet	Date Tested	W _p grams	W _(dry soil+p) grams	W _(dry soil) grams	W _(p+s+w) grams	W _(p+w) grams	T C	ρ_w^1 g/cm ³	ρ_s g/cm ³
MW-6	Wis. ox	0-5	7/5/95	17.950	29.08	11.130	73.68	66.80	31.0	0.9959616	2.6082
	Pre-III. ox	5-10	7/5/95	17.280	33.14	15.860	79.29	73.20	28.0	0.996232	1.6172 ²
	Pre-III. unox	10-15	7/5/95	18.130	29.32	11.190	74.72	67.74	29.0	0.995944	2.6472
AI-21	oxidized	2.33-2.67	7/4/95	16.620	26.92	10.300	73.48	66.97	26.0	0.996783	2.7089
AI-21	oxidized	3.8-4.3	7/4/95	22.720	32.34	9.620	78.61	72.56	26.0	0.996783	2.6860
AI-22	oxidized	3.33	7/4/95	34.070	43.48	9.410	89.85	83.97	25.5	0.996783	2.6571
AI-22	oxidized	8.66	7/5/95	33.560	43.42	9.860	89.50	83.20	26.0	0.996783	2.7608
AI-15	oxidized	4.75-5.25	7/4/95	31.860	40.93	9.070	87.36	81.70	25.3	0.997044	2.6520
AI-27	oxidized	3.5-4.17	7/4/95	30.520	41.56	11.040	87.21	80.35	25.0	0.997044	2.6333
AI-29	top soil	2-3	7/4/95	17.370	27.60	10.230	73.83	67.43	25.0	0.997044	2.6631
AI-29	oxidized	6.25-7.08	7/4/95	17.900	28.79	10.890	73.62	66.80	24.0	0.997296	2.6684
AI-29	oxidized	9.33	7/4/95	31.380	41.73	10.350	87.65	80.98	25.0	0.997044	2.8042
AI-30	oxidized	5.08	7/4/95	18.090	29.50	11.410	74.85	67.77	24.5	0.997044	2.6273
AI-30	transition	10	7/4/95	17.650	27.85	10.200	73.63	67.32	25.0	0.997044	2.6144
AI-31	top soil	3.33	7/5/95	31.940	42.45	10.510	88.24	81.71	28.5	0.995944	2.6300
AI-31	oxidized	5.67	7/5/95	30.590	40.71	10.120	86.69	80.33	25.0	0.997044	2.6835
sand	-	-	7/5/95	17.770	28.61	10.840	74.10	67.29	28.0	0.996232	2.6797

¹ density values for water from Handbook of Chemistry and Physics² this value is in error, assume average particle density for remaining calculations = 2.65 g/cm³

APPENDIX D

SLUG TEST DATA

Al-Pz-3

Test Date: 6/30/95-7/2/95

Test Type: Slug test with pressure transducer

Well Type: oxidized

Well Dimensions:

$r_c = 1.27$ cm
 $r_w = 3.4925$ cm
 $L_e = 177.698$ cm
 $L_w = 204.216$ cm
 $H = 914$ cm
 porosity = 0
 $r_c = 1.27$ cm

Bouwer Rice Results

$L_e/r_w = 50.88$
 $A = 2.957$
 $B = 0.454$
 $C = 2.656$
 $\ln(R_e/r_w) = 2.696$
 slope = $-8.92E-06$
 intercept = 3.35

Hydraulic Conductivity = $K = 1.08E-07$ cm/sec for time 0-14 hours

Al-Pz-6

Test Date: 9/1/95-9/5/95

Test Type: Slug test by bail down of 250 ml of water from the well (about 2 ft of head)

Well Type: oxidized

notes: Partial Penetration

Well Dimensions:

$r_c = 1.27$ cm

$r_w = 3.4925$ cm

$L_c = 33.8328$ cm

$L_w = 33.8328$ cm

$H = 914$ cm

porosity = 0.48

$r_e = 2.587$ cm

Bouwer Rice Results

$L_c/r_w = 9.687$

$A = 1.858$

$B = 0.236$

$C = 0.992$

$\ln(R_e/r_w) = 1.233$

slope = $-2.87E-05$

intercept = 2.51

Hydraulic Conductivity = $K = 3.5E-06$ cm/sec for time 0-6 hours

Al-Pz-9

Test Date: 8/25/95-9/1/95

Test Type: Slug test by bail down of 300 ml of water from the well (about 2 ft of head)

Well Type: oxidized

notes: Partial Penetration

Well Dimensions:

$r_c = 1.27$ cm

$r_w = 3.4925$ cm

$L_c = 157.276$ cm

$L_w = 157.276$ cm

$H = 914$ cm

porosity = 0.48

$r_c = 2.587$ cm

Bouwer Rice Results

$L_c/r_w = 43.601$

$A = 2.785$

$B = 0.418$

$C = 2.427$

$\ln(R_c/r_w) = 2.473$

slope = $-6.54E-05$

intercept = 3.34

Hydraulic Conductivity = $K = 3.55E-06$ cm/sec for time 0-3 hours

Al-Pz-16

Test Date: 9/23/95-9/26/95

Test Type: Slug test with pressure transducer

Well Type: unoxidized

Well Dimensions:

$r_c = 1.27$ cm

$r_w = 3.4925$ cm

$L_c = 99.06$ cm

$L_w = 150.2664$ cm

$H = 914$ cm

porosity = 0

$r_c = 1.27$ cm

Bouwer Rice Results

$L_c/r_w = 28.364$

$A = 2.374$

$B = 0.342$

$C = 1.919$

$\ln(R_c/r_w) = 2.267$

slope = $-2.4E-06$

intercept = 4.47

Hydraulic Conductivity = $K = 4.44E-08$ cm/sec for time 0-24 hours

Al-Pz-20

Test Date: 8/19/95-8/25/95

Test Type: Slug test with pressure transducer

Well Type: unoxidized

Well Dimensions:

$r_c = 1.27$ cm
 $r_w = 3.4925$ cm
 $L_c = 182.27$ cm
 $L_w = 333.45$ cm
 $H = 914$ cm
 porosity = 0
 $r_c = 1.27$ cm

Bouwer Rice Results

$L_c/r_w = 52.189$
 $A = 2.988$
 $B = 0.461$
 $C = 2.697$
 $\ln(R_c/r_w) = 2.909$
 slope = $-6.33E-06$
 intercept = 2.02

Hydraulic Conductivity = $K = 8.15E-08$ cm/sec for time 1-24 hrs

Al-Pz-25

Test Date: 8/19/95-8/25/95

Test Type: Slug test with pressure transducer

Well Type: unoxidized

Well Dimensions:

$r_c = 1.27$ cm
 $r_w = 2.54$ cm
 $L_e = 63.3984$ cm
 $L_w = 09.372$ cm
 $H = 914$ cm
 porosity = 0
 $r_c = 1.27$ cm

Bouwer Rice Results

$L_e/r_w = 24.96$
 $A = 2.279$
 $B = 0.325$
 $C = 1.75$
 $\ln(R_e/r_w) = 2.554$
 slope = $-1.27E-07$
 intercept = 3.46

Hydraulic Conductivity = $K = 4.14E-09$ cm/sec for time 2-28 hours

Al-Pz-26

Test Date: 6/19/95-6/20/95

Test Type: Slug test with pressure transducer

Well Type: unoxidized

Well Dimensions:

$r_e = 1.27$ cm

$r_w = 2.54$ cm

$L_e = 63.3984$ cm

$L_w = 465.43$ cm

$H = 914$ cm

porosity = 0

$r_e = 1.27$ cm

Bouwer Rice Results

$L_e/r_w = 24.96$

$A = 2.279$

$B = 0.325$

$C = 1.75$

$\ln(R_e/r_w) = 2.705$

slope = $-8.52E-06$

intercept = 3.48

Hydraulic Conductivity = $K = 2.93E-07$ cm/sec for time 0-23 hours

Al-Pz-30

Test Date: 8/8/95-8/10/95

Test Type: Slug test with pressure transducer

Well Type: transition

Well Dimensions:

$r_e = 1.27$ cm

$r_w = 4.1275$ cm

$L_e = 93.8784$ cm

$L_w = 210.6168$ cm

$H = 914$ cm

porosity = 0

$r_e = 1.27$ cm

Bouwer Rice Results

$L_e/r_w = 22.745$

$A = 2.217$

$B = 0.341$

$C = 1.64$

$\ln(R_e/r_w) = 2.232$

slope = $-8.59E-07$

intercept = 3.33

Hydraulic Conductivity = $K = 1.65E-08$ cm/sec for time 0-42 hours

Al-Pz-31

Test Date: 8/25/95-9/1/95

Test Type: Slug test by adding 650 ml of water into the well (4 feet of head)

Well Type: transition

Well Dimensions:

$r_c = 1.27$ cm

$r_w = 3.4925$ cm

$L_c = 68.58$ cm

$L_w = 164.90$ cm

$H = 914$ cm

porosity = 0

$r_c = 1.27$ cm

Bouwer Rice Results

$L_c/r_w = 18.535$

$A = 2.099$

$B = 0.291$

$C = 1.431$

$\ln(R_o/r_w) = 1.744$

slope = $-8.44E-06$

intercept = 4.81

Hydraulic Conductivity = $K = 8.68E-07$ cm/sec for time 0-13 hours

Al-Pz-37

Test Date: 9/23/95-9/26/95

Test Type: Slug test by bail down of 500 ml of water from the well (about 3.2 ft of head)

Well Type: oxidized

notes: Partial Penetration

Well Dimensions:

$r_c = 1.27$ cm
 $r_w = 4.1275$ cm
 $L_c = 76.5048$ cm
 $L_w = 76.5048$ cm
 $H = 914$ cm
 porosity = 0.48
 $r_c = 3.003$ cm

Bouwer Rice Results

$L_c/r_w = 18.535$
 $A = 2.099$
 $B = 0.291$
 $C = 1.431$
 $\ln(R_c/r_w) = 1.744$
 slope = $-6.56E-06$
 intercept = 2.92

Hydraulic Conductivity = $K = 6.74E-07$ cm/sec for time 0-7 hours

Al-Pz-38

Test Date: 9/1/95-9/5/95

Test Type: Slug test by bail down of 350 ml of water from the well (about 2.25 ft of head)

Well Type: oxidized

notes: Partial Penetration

Well Dimensions:

$r_c = 1.27$ cm
 $r_w = 4.1275$ cm
 $L_c = 93.8784$ cm
 $L_w = 93.8784$ cm
 $H = 914$ cm
 porosity = 0.48
 $r_c = 3.003$ cm

Bouwer Rice Results

$L_c/r_w = 22.745$
 $A = 2.217$
 $B = 0.314$
 $C = 1.64$
 $\ln(R_c/r_w) = 1.914$
 slope = $-3.63E-05$
 intercept = 4.2

Hydraulic Conductivity = $K = 3.34E-06$ cm/sec for time 0-6 hours