AN ABSTRACT OF THE THESIS OF

Justin Iverson for the degree of Master of Science in Geology presented on April 26, 2002.

Title: Investigation of the Hydraulic, Physical, and Chemical Buffering Capacity of Missoula Flood Deposits for Water Quality and Supply in the Willamette Valley of Oregon.

Abstract approved ______________________

Roy D. Haggerty

The Willamette Silt is a surficial geologic unit composed of successive Missoula Flood Deposits that underlies 3100 km^2 (1200 mi^2) of arable land in the Willamette Valley of Oregon. The Willamette Silt protects the underlying regionally important Willamette Aquifer from agricultural contamination while acting as a semi-confining unit and a diffuse recharge source. This primary study of the hydrogeologic and geochemical properties of the Willamette Silt incorporates extensive data collection, field work, laboratory analyses, and numerical modeling to provide a characterization of the hydraulic parameters, groundwater flow regime, agricultural leachate penetration, and buffering capacity of the unit.

Initial calculations of flow regimes show that groundwater in the Willamette Silt (WS) at the field area flows at approximately 5.6×10^{-7} m/s at a dip of 60 degrees downward toward deeply incised streams. At this rate, conservative agricultural species would be expected to reach the Willamette Aquifer approximately 23 years after fertilizer application to the surface. However, after more than 57 years of fertilizer application, the observed phosphorus and nitrate penetration fronts are located approximately half way through the

Willamette Silt. Phosphorus is a non-conservative solute that is retarded through sorption to clay and silt particles, which allow the WS to act as a phosphorus sink. The nitrate penetration front is coincident with a geochemical reduction-oxidation boundary, giving reason to believe that the WS is preventing nitrate (a highly soluble, non-sorbing tracer) transport through facilitation of autotrophic denitrification at this boundary. If this hypothesis proves true, the rate at which the reduction-oxidation boundary is propagating downward through the Willamette Silt is essential information for managing the water quality of the WA and streams bottoming in the WS. Further understanding of the rate of propagation of the reduction-oxidation boundary will require more study.

Numerical model analysis of a pump test conducted in the Willamette Aquifer shows that the Willamette Silt provides a source of diffuse recharge to the WA under stressing conditions. Further, the low hydraulic conductivity of the unit provides a hydraulic buffer to depletion of streams bottoming in the WS under pumping stress generated in the underlying WA. Volumetric balance analysis shows that less than 1% of the water removed from the aquifer at a pumping well near the river was recharged to the Willamette Silt from the Pudding River.

Investigation of the Hydraulic, Physical, and Chemical Buffering Capacity of Missoula Flood Deposits for Water Quality and Supply in the Willamette Valley of Oregon.

by

Justin Iverson

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of
Master of Science

Presented April 26, 2002

Commencement June 2002

Master of Science thesis of Justin Iverson presented on April 26, 2002.

APPROVED:

Major Professor, representing Geosciences

Head of the Department of Geosciences

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of the Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Justin Iverson, Author

ACKNOWLEDGEMENTS

Many state and federal government agencies supported this project and I had the pleasure of meeting and working with great people from all of these agencies. Funding for this work was provided by a grant from the Oregon Department of Agriculture. Well monitoring equipment and supporting instrumentation were provided by the Oregon Water Resources Department. Piezometer installation materials and equipment were provided by the U.S. Geological Survey.

Roy Haggerty provided support, guidance, and encouragement throughout the process of this research, as well as long before the project was conceived. Karl Wozniak introduced me to the world of field hydrogeology and provided a tremendous amount of assistance along the way. Chuck Eder was very gracious in allowing the use of his nursery as a field site. Of the many individuals who provided advise on the project, I would like to acknowledge my thesis committee, Roy Haggerty, Lew Semprini, Andrew Meigs, and Herbert Huddleston, for their comments and constructive criticism.

Finally, I would like to thank my close friends and family, especially Ang, who provided mental support and encouragement throughout this chapter in my life.

TABLE OF CONTENTS

TABLE OF CONTENTS CONT.

TABLE OF CONTENTS CONT.

LIST OF FIGURES

LIST OF FIGURES CONT.

LIST OF TABLES

LIST OF APPENDICES

LIST OF APPENDIX FIGURES

Figure Page

LIST OF APPENDIX FIGURES CONT.

LIST OF APPENDIX FIGURES CONT.

LIST OF APPENDIX FIGURES CONT.

LIST OF APPENDIX FIGURES CONT.

LIST OF APPENDIX TABLES

LIST OF APPENDIX WELL LOGS

Investigation of the Hydraulic, Physical, and Chemical Buffering Capacity of Missoula Flood Deposits for Water Quality and Supply in the Willamette Valley of Oregon.

1. Introduction

The Willamette Silt WS is the most extensive geologic unit exposed at the surface in the Willamette Valley of Oregon, underlying the majority of the Central and Southern Willamette Valley's arable land (see Figure 1). It covers an area of 3100 km^2 (1200 mi^2), virtually all of which are either currently under agricultural production, or suitable for agricultural production. Over its entire extent, the Willamette Silt immediately overlies an important regional aquifer, the Willamette Aquifer (WA) (Figure 2). The low hydraulic conductivity of the Willamette Silt forms a hydraulic barrier between streams bottoming in the silt and groundwater extraction from the Willamette Aquifer. The low hydraulic conductivity and reducing conditions of the Willamette Silt also provide a protective barrier to agricultural contamination of the underlying Willamette Aquifer.

The Willamette Silt underlies most of the Willamette Valley's streams. Within the Willamette Valley Lowland, only the Willamette River has eroded through the WS to underlying geologic units (the WA). All other streams in the Valley bottom within the WS. The thickness and low hydraulic conductivity of the WS provide a hydraulic buffer to groundwater flow between Willamette Valley streams and the Willamette Aquifer. As the WA becomes an increasingly utilized source for irrigation water in the Willamette Valley, the efficiency of this hydrologic buffer will be important to maintenance of stream stage in Willamette Valley rivers, particularly during summer low flows.

Figure 1: Extent and thickness of the Willamette Silt. Modified from Gannett and Caldwell (1998).

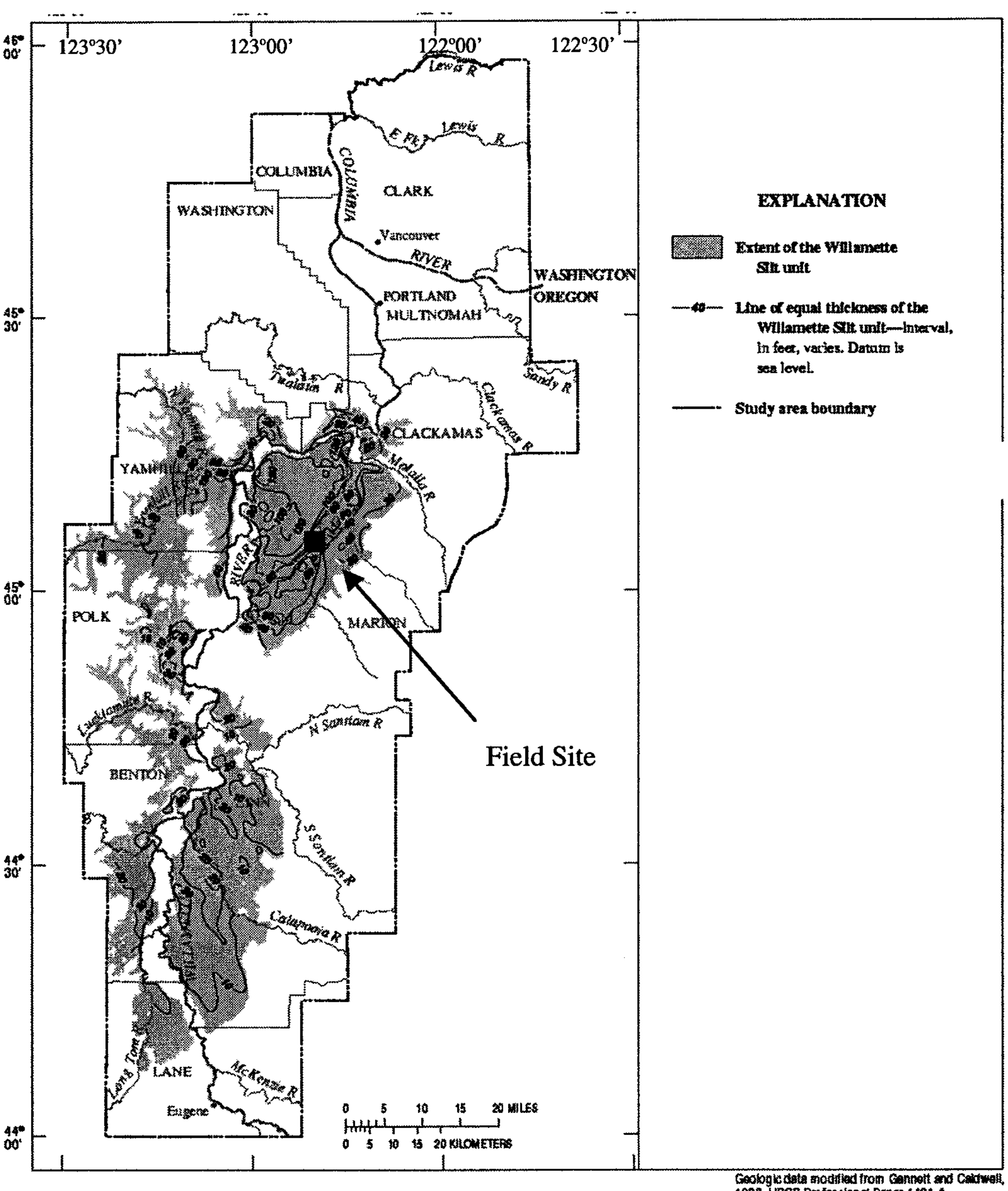
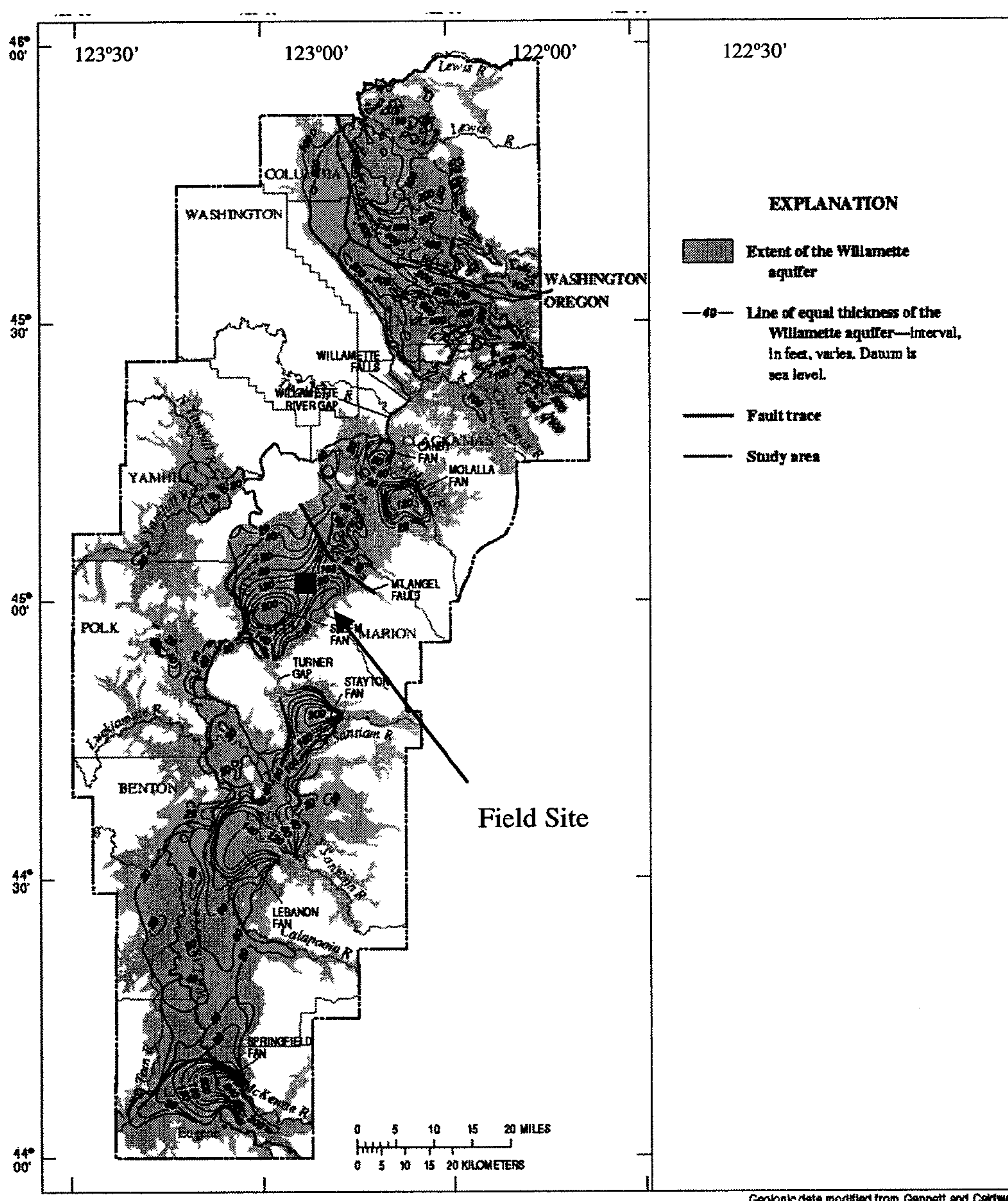


Figure 2: Extent and thickness of the Willamette Aquifer. Modified from Gannett and Caldwell (1998).



The Willamette Silt is the only geologic unit that protects the Willamette Aquifer from agricultural leachate contamination. Leachate from agricultural lands is a non-point source of contamination that contains high levels of nutrients, principally nitrate and phosphorus from fertilizers (*Rinella and Janet*, 1998). Since the WS is almost entirely composed of silt and clay with low hydraulic conductivity the unit acts as a critical hydraulic buffer between agricultural leachate and the WA. The WS is also an important biochemical and geochemical buffer to nitrate and phosphorous contamination of the WA. Reduced cations (such as Fe^{2+} and organic carbon) present in the WS act as electron donors in the biologically mediated process of autotrophic denitrification, which is hypothesized to create a reaction barrier to nitrate transport through the WS. Since phosphorus is strongly sorbed to clay particles through charge attraction, ligand exchange, and other mechanisms, the WS acts as a sink for phosphorus. If the WS were to cease being a geochemical buffer because the unit becomes saturated with fertilizer leachate, or because geochemical conditions change (e.g., the unit is oxidized), the water quality of the underlying WA could quickly degrade.

This thesis, jointly funded by the Oregon Department of Water Resources, the US Geological Survey, the Oregon Department of Agriculture, and Oregon State University, seeks to answer the following five questions:

1. What are the hydraulic gradients within the Willamette Silt and how do they change over the year? How important are the respective horizontal and vertical components of the hydraulic gradient?
2. What are typical transport times for water through the Willamette Silt (a) vertically to the underlying Willamette Aquifer; and (b) horizontally to adjacent streams?
3. How far into the Willamette Silt have nitrate and phosphate penetrated?

4. Is there a Reduction-Oxidation (RedOx) boundary within the Willamette Silt that effectively stops nitrate transport, and is this boundary moving downward? If so, how fast?
5. To what extent are streams bottoming in the Willamette Silt hydraulically connected to the Willamette Aquifer? How much of an influence do typical pumping rates from the Willamette Aquifer have on the flow rates in streams such as the Pudding River?

As the thesis progressed it became clear that current data were not sufficient to definitively answer questions pertaining to the RedOx boundary. Suggestions for future work focused on the RedOx boundary are presented in Section 6.2. It also became clear that the originally proposed two-dimensional groundwater model of the field site would not be sufficient to adequately describe the groundwater flow regime at the field site. A three-dimensional groundwater model was constructed for the purpose but will require more field data for satisfactory calibration.

This thesis describes the coupling of the local groundwater flow system and surface water system in the Willamette Valley. A groundwater flow model is constructed to describe general groundwater – surface water interaction in the shallow subsurface of the Willamette Valley (addressing question 5). The project provides the first set of nitrate and phosphate data across the Willamette Silt and identifies the presence of a RedOx barrier to nitrate transport (addressing questions 3 and 4). Through a quantitative understanding of the movement of groundwater across the WS based on field measurements, the transport directions for agricultural leachate are derived and first approximations to travel times are calculated (addressing questions 1 and 2).

2. Background

2.1 Hydrogeological Background

The Willamette Valley formed during late Miocene and Pliocene when tectonic activity resulting from the subduction of the Juan de Fuca Plate under North America caused uplift in the Coast Range and construction of the volcanic Cascades. This uplift resulted in broad subsidence of the forearc basin between the two ranges, deforming the previously flat-lying Columbia River Basalt (CRB) and creating the current Willamette Valley (*Niem and Niem*, 1984). The CRB forms a major confined aquifer in the Central Willamette Valley north of Salem. While basalt flows within the CRB typically have low hydraulic conductivity, highly fractured and rubblized interflow zones may have hydraulic conductivity as high as 2.5×10^{-3} m/s (750 ft/day) (*Woodward et al.*, 1998).

The generation of an extensive geographic lowland created a basin that received large volumes of sediment input from the Coast Range and the Cascades from the Pliocene to the early Pleistocene (*Hampton*, 1972). Early in the evolution of the Valley most of the sediments were fine-grained clays and silts, forming the low-conductivity Willamette Confining Unit (WCU) above the CRB.

Renewed tectonism and volcanism in the Pleistocene caused rapid construction in the Cascade Range and allowed glaciers and rivers to erode and deposit coarser sediment resulting in the deposition of alluvial fans on the east side of the Willamette Valley (*Glenn,* 1965). These alluvial fans comprise the Willamette Aquifer (WA), which varies greatly in both thickness and hydraulic conductivity. The unit exceeds 60 m (200 ft) in thickness at the centers of several alluvial fans along the eastern side of the Willamette Valley and thins to 0 m along the western side (*Gannett and Caldwell*, 1998; Figure 2). The hydraulic conductivity of the WA is locally higher than 3.5 x10^{-3} m/s (1000 ft/day), though it may be considerably less where there are clay or silt interbeds. The WA is a major source of water for irrigation, public supply, and domestic uses in the Willamette Valley. In addition, the WA discharges into the Willamette River along its length from Eugene to Portland, impacting river stage, temperature, and water quality.

In the late Pleistocene, near the end of the last glaciation, a series of catastrophic ice-dam-break floods (commonly called the Missoula Floods) surged down the Columbia River drainage and back-flooded up the Willamette Valley (*Glenn*, 1965; *Allison*, 1978; *O'Connor et al.*, 2001). As floodwaters ponded in the Willamette Valley, thick deposits of coarse grained material settled out at the head of the Valley near Portland, while progressively finer material settled out in successively thinner deposits up the Valley as far as Eugene, where the thinnest deposits of clay are found (3m, 10 ft thinning to 0 m). The layers of sediment deposited by successive flood events created a rhythmically bedded sequence in which individual beds range from 0.05 m to 1 m (2 in. to 3 ft) in thickness (*O'Conner* et al., 2001). These fine grained Missoula Flood deposits are known as the Willamette Silt (WS) in the Central and South Willamette Valley. The WS ranges from more than 30 m (100 ft) thick in the Central Willamette Valley to approximately 6 m (20 ft) thick in the Southern Willamette Valley, thinning to 0 m south of Eugene (*Gannett and Caldwell*, 1998; Figure 1). The WS has low hydraulic conductivity, typically less than 3.5 x10^{-6} m/s (1 ft/day) horizontally and 3.5 x10^{-8} m/s (0.01 ft/day) vertically, with the average hydraulic conductivity of the WS decreasing from north to south. The WS creates a semi-confining unit above the WA, and acts as a barrier to vertical flow from the surface into the aquifer.

2.2 Water Supply Issues

As the population of the Willamette Valley continues to grow rapidly, many surface water bodies have been fully allocated to industrial, municipal, and agricultural uses. Further allocation threatens aquatic habitat, water quality, and, in some cases, water supply to other users. Groundwater is in increasing demand to fulfill water resource needs in the Willamette Valley. However, allocation of groundwater is a complicated management task due to the dependence of summer river stage (base flow) on groundwater seepage to streams. Development of any aquifer in hydraulic connection with a gaining stream reach (a groundwater discharge area) reduces head in the aquifer, which results in either reduction or reversal of flow from the aquifer to the river. If the river is fully allocated the portion of groundwater that maintains base flow is already effectively allocated to surface water users who hold senior water rights to those wishing to develop the aquifer. Consequently, further development of an aquifer in hydraulic connection with a river will lead to over-allocation of the river and a drop in river stage below acceptable limits.

Further, a number of streams in Oregon are under total maximum daily load (TMDL) restrictions on heat and solutes in streams, to which agriculture is a major contributor. While streams such as the Pudding River are not currently under TMDL restrictions, they are likely to be in the coming years (e.g., 2007 in the case of the Pudding River). Groundwater recharge to streams often serves to dilute solutes and cool the waters of a stream. A significant reduction of direct groundwater recharge to a stream will affect the flow, temperature, and solute load concentration of the stream to some extent.

The drawdown effect of high volume pumping wells and the link between groundwater levels and base flow in streams is common knowledge and can be reviewed in standard groundwater texts (e.g., *Fetter*, 1988, *Dominico and Schwartz*, 1990). The interaction between groundwater and passive surface water bodies such as lakes and wetlands is an area of active research (e.g., *Townley and Trefty*, 2000). Further, groundwater flow models relating interaction with passive surface water bodies have been constructed and reported in the literature for numerous location specific studies (e.g., *Winter,* 1978). Research conducted on the interaction between groundwater and active surface water systems is generally restricted to groundwater – surface water exchange within the bounds of the hyporheic zone, not local and regional scale groundwater recharge to or from streams (e.g., *Wroblicky*, 1998). The effect of heterogeneous permeability on groundwater flow has been documented for numerous situations (for example, *Hemker*, 1999a, 1999b, *Wheatcraft and Winterberg*, 1985). However, despite the large volume of research on the broad topic of groundwater – surface water interaction, literature relating the effects of hydrogeologic permeability contrasts on local scale groundwater – surface water interaction is sparse.

Nield et al. (1994) describes a framework for quantitatively examining vertical groundwater – surface water interaction. Whereas this provides a good starting point, the study was based on lake – groundwater interaction and assumes homogeneity in hydraulic conductivity. *Meigs and Bahr* (1995) describe three-dimensional groundwater flow near drainage ditches in the context of pollution remediation. Their study approximates the geological situation we are investigating but assumes homogeneity and deals only with flow a few meters in the subsurface.

This thesis, then, addresses the interaction between groundwater and active surface water (i.e., a stream) at a representative field site in the central Willamette Valley. The effects of a permeability contrast due to a thick geologic unit, as opposed to a thin streambed sediment, are quantified and the transient flow system is described.

2.3 Water Quality Issues

Summaries of relevant water quality issues in the Willamette Valley, including those areas where the WS outcrops, are provided by *Wentz et al.* (1998), *Hinkle* (1998), and

Rinella and Janet (1998). Two water quality issues related to agricultural pollution are elevated nitrate and phosphate concentrations in both streams and groundwater. Whereas this study addresses the transport of both nitrate and phosphorus, a large fraction of the effort was concentrated on nitrate due the ease with which it is transported in groundwater.

Phosphorus is a water quality issue because elevated concentrations allow the growth of nuisance plants and algae blooms in water bodies. The US EPA has set 0.1 mg/L as a maximum contaminant level goal (MCLG) to prevent such growth. In parts of the Willamette Valley where streams drain predominantly agricultural land, 68% of streams have total phosphorus concentrations exceeding 0.1 mg/L (*Wentz et al.*, 1998).

Nitrate is a significant water quality issue, and is easily transported in groundwater. In drinking water, nitrate (NO_3^-) can cause blue baby syndrome (methemoglobinemia) above 10 mg/L, which is the EPA's Maximum Contaminant Level (MCL). Nitrogen is a major component of agricultural fertilizer. In addition to inorganic fertilizer application, other sources of nitrates on agricultural lands are manure and other organic fertilizers. Soil tillage is also an important factor in nitrate release from soils, with increased tillage generally resulting in increased nitrate release.

Nitrate is highly soluble in water and is easily transported. Therefore, in the absence of geochemical and/or biochemical constraints on transport, nitrate is transported with groundwater and in streams. The most important constraint on nitrate transport in groundwater systems is denitrification, the conversion of nitrate to nitrogen or nitrogen oxide gas. This reaction is biologically (microbially) mediated, and can happen along a number of different pathways (i.e., involving any one of a number of potential electron donors) (e.g. *Korom*, 1992; *Robertson et al.*, 1996). Therefore, developing an elementary understanding of denitrification conditions in the Willamette Silt is important to understanding its potential as a buffer against nitrate contamination of the Willamette Aquifer.

In a study of nitrate concentrations in wells, *Hinkle* (1998) found that approximately 9% of randomly sampled wells within the WA had nitrate concentrations in excess of the EPA's Maximum Contaminant Level (MCL) of 10 mg/L. Significantly, *Hinkle* (1998) noted that the cumulative thickness of clay above the sample location was a statistically significant predictor of nitrate concentration (and of pesticide contamination). Sample locations underlying a thick sequence of clay tended to have lower concentrations of nitrate, suggesting that the WS is currently a good buffer against nitrate contamination of the WA. However, *Hinkle* also noted that a large fraction (21%) of the water in the areas of the WA sampled predates 1953. Since such old water is unlikely to be significantly contaminated by nitrate, it is possible that nitrate concentrations in the WA may increase significantly in the coming years. Such dates on WA water testify to the capacity of the WS to buffer the WA from recent impulses of contamination. However, as older water also begins to become contaminated, the risk for significant contamination in the WA increases.

Clearly, the WS acts as a buffer to the WA, preventing short-term contamination of that aquifer. However, the capacity of the WS to buffer contamination is limited, and requires a very long lead time for management. This thesis provides data on the extent of agricultural leachate penetration into the WS. Theoretical conservative tracer transport times are estimated and compared to the actual nitrate penetration front observed at the field site to illustrate the effects of a RedOx boundary which governs the rate of nitrate transport in the WS.

2.4 Site History and Description

Since an agricultural field site irrigated from an existing high-volume pumping well was a requirement for this research, it was necessary to place an observation well transect on private property. The owner of a wholesale nursery operation adjacent to the

Pudding River, located approximately one mile SW of Mt. Angel, Oregon, agreed to allow the piezometer transect to be installed on his land (Figure 3a). The nursery is irrigated from a 0.25 m (10 in.) diameter well screened in the Willamette Aquifer between 20 and 32 m (65-105 ft.) bls and located approximately 25 m (100 ft.) from the Pudding River.

The field site was variously cropped in corn, clover and cereal grains from approximately 1945 to 1982. From 1983 until 1996 the field was used for rotating crops of onions, seed cabbage, wheat, bush beans, and flower seeds (see Appendix A for details). Since 1997, the field has been used to run a wholesale in-ground nursery operation. Soil amendments applied have been P (typically 120 lb/acre/yr), *K* (typically 60-90 lb/acre/yr), N (40-200 lb/acre/yr, depending on the crop), and lime (2 tons/acre in 1984 and 1991 and 3.5 tons/acre in 1996). Prior to 1982 the field was covered with large amounts of dairy manure. The area has been fertilized for a total of 57 years.

Figure 3a: *Location Map showing Piezometer (PZ) Nests, Irrigation Well (IR), and Surroundings. NE1/4, NE1/4, Section 8, T6S, R1W*

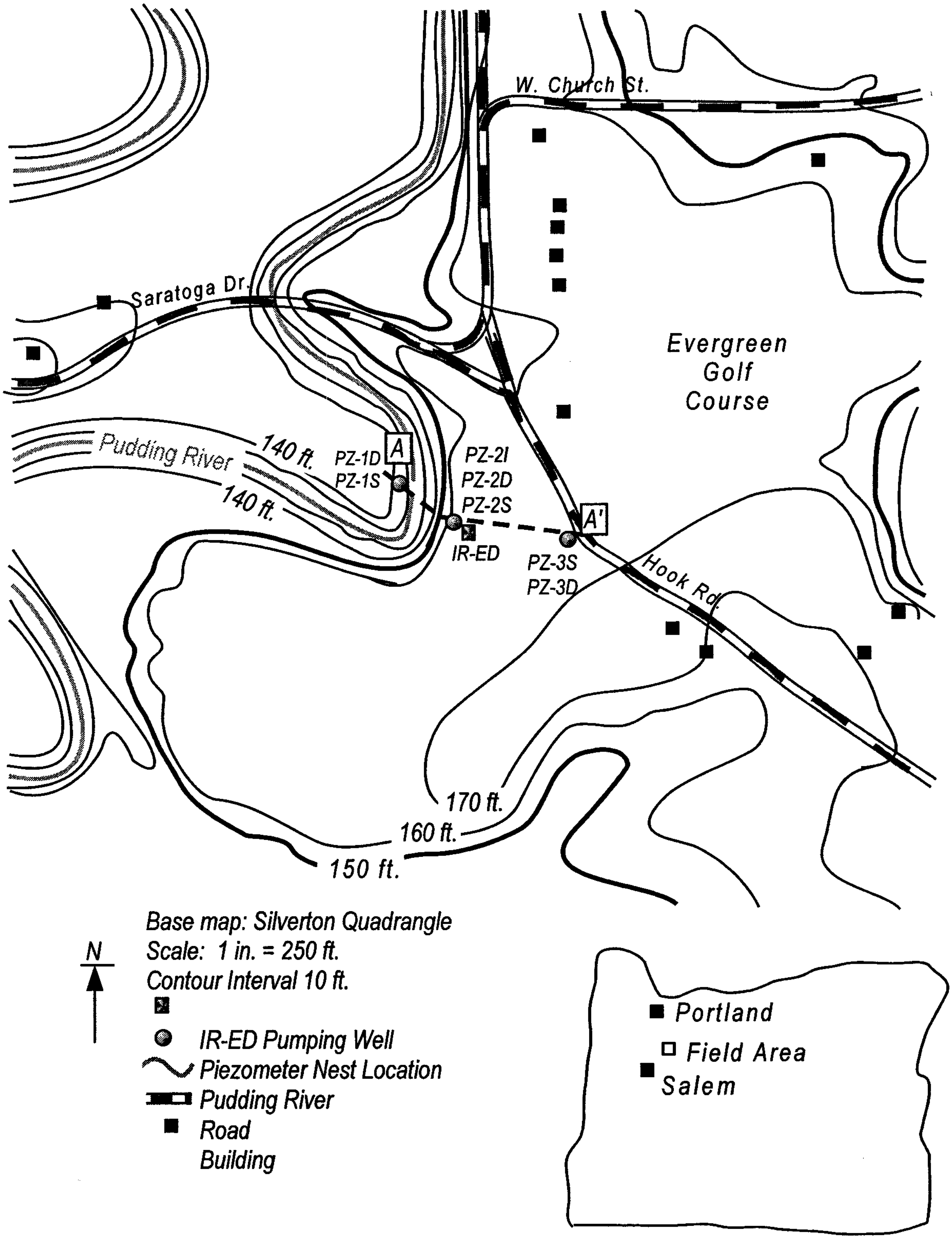
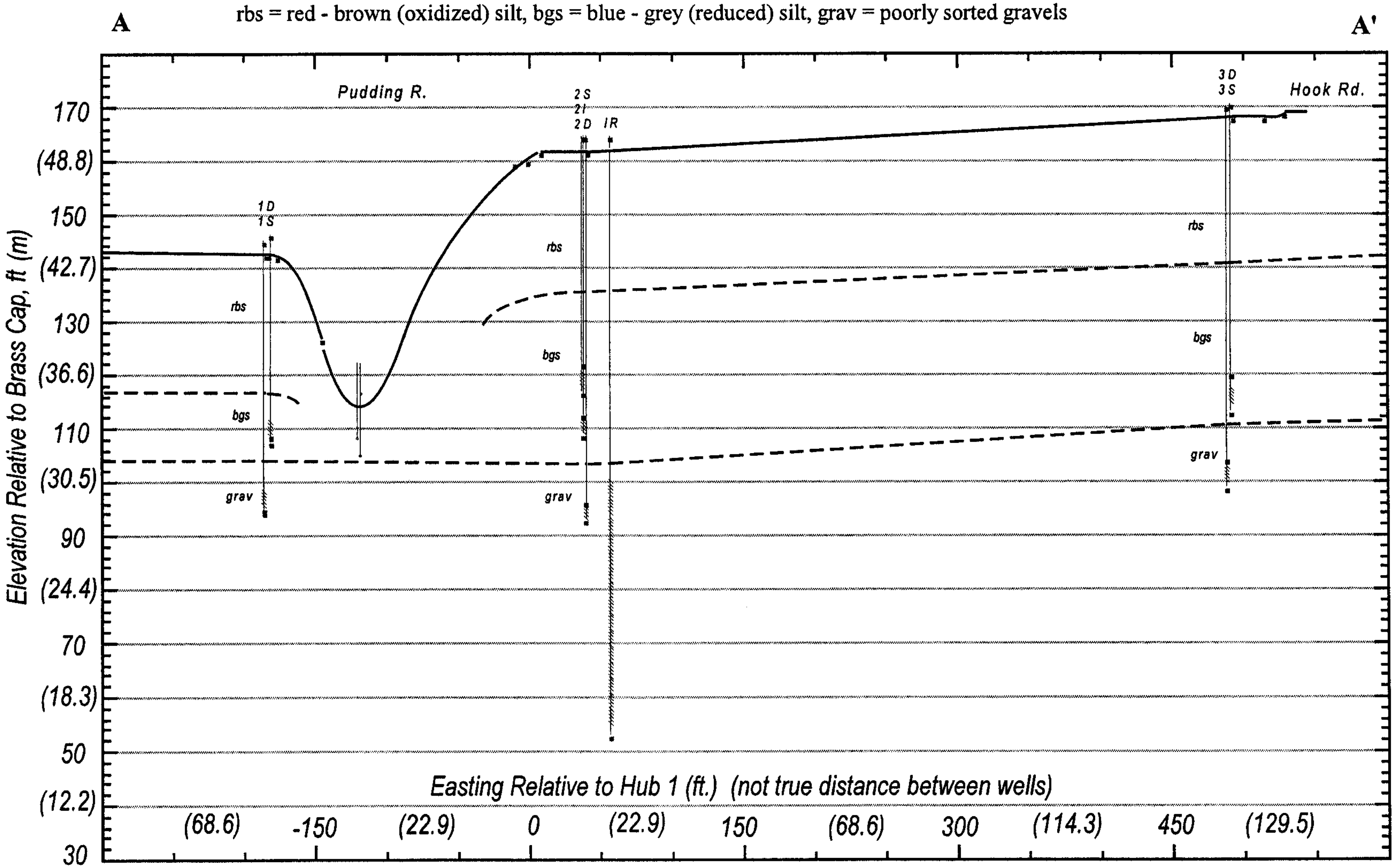


Figure 3b: Site Cross Section A - A'. Elevation in feet above mean sea level.

Small boxes represent survey data near the surface, calculated well depth and screened interval below the surface.
rbs = red - brown (oxidized) silt, bgs = blue - grey (reduced) silt, grav = poorly sorted gravels



3. Methods

3.1 Field Work

3.1.1 Piezometer Installation and Instrumentation

3.1.1.1 Piezometer Bore Drilling

Seven piezometer well bores were drilled using a SIMCO trailer-mounted hollow-stem auger owned and operated by the U.S. Geological Survey WRD based in Portland, OR (See Figures 3a and 3b for piezometer locations and relative depths). The auger flights were 1.52 m (5 ft) in length with an inside diameter of 0.080 m (3 in) and a blade diameter of 0.152 m (6 in) that created an average bore hole diameter of 0.17 m (6.625 in). The well was logged on site with well cuttings and examination of material samples. Piezometer well logs as well as nearby irrigation well logs are included in Appendix B.

Continuous core material samples were taken by driving a 0.06 m (2.5 in) diameter sample tube located inside the auger flights approximately 0.15 m (6 in) ahead of the drill bit. Continuous core samples were obtained as deep as possible, but abandoned in favor of discontinuous split spoon samples (between 6 to 9 m, 20 to 30 ft) when downward progress slowed substantially due to the force needed to drive the continuous core sampler.

Split spoon samples were taken every 1.5 or 3 m (5 or 10 ft) between periods of auger flight addition. Split spoon samples are 0.03 m (1.5 in) in diameter and up to 0.61 m (2 ft) in length depending on compaction of the sample and percent of material recovery. Split spoon samples were pounded before the auger head with a slide hammer (140 lbs., 30 inch length of travel) supported by the drill rig. The number of hammer blows necessary to pound the sampler 0.61 m (2 ft) in front of the drill head were recorded in the well logs in order to compare the relative competency of the underlying material.

All samples were collected into non-reactive clear acrylic butyrate tubes (Central Mine Equipment, St. Louis, Missouri). Samples were promptly separated into manageable lengths (split spoon samples are 0.15 m, 6 in and continuous core samples are approximately 0.38 m, 1.25 ft), capped, and frozen on site with dry ice in preparation for chemical analysis at a later date.

3.1.1.2 Piezometer Installation

Once the desired well depth was reached, PVC well casing was inserted into the hollow stem of the auger. From bottom to top, well casing consists of a bottom cone and sediment trap (not included in wells 2D, 2I, and 3S), a gravel pre-packed slotted well screen, and PVC well case piping. The well screen consists of two schedule 40 PVC tubes 0.91 m (3 ft) in length with 50 slots 0.001 m (0.05 in) wide spaced 0.003 m (1/8 in) apart along the central 0.79 m (2.6 ft) of the pipes. The volume between the two slotted pipes is filled with Lone Star MA (medium aquarium) sand estimated to be equivalent to 6-16 sand. The overall inside diameter of the pre-packed screen is 0.03 m (1.25 in) and the overall outside diameter is 0.07 m (2.85 in). The sediment trap and well casing are steam-cleaned schedule 40 PVC pipes with flush threaded ends. The casing has an inside diameter of 0.05 m (2 in) and an outside diameter of 0.06 m (2.4 in). The sediment traps are about 0.3 m (1 ft) in length, and the well casing was added to the screen in 3.05 m (10 ft) lengths, then cut to size about 1 m (3 ft) above ground surface.

Due to the small amount of space between well casing (o.d. 0.06 m, 2.4 in) and the auger stem (i.d. 0.07 m, 3 in) it was not possible to install loose gravel packing between the well and the bore hole before pulling the auger flights. The auger flights were pulled directly from around the well casing with a winch mounted to the drill rig. After the auger flights were removed, sounding of the bore hole with a weighted steal tape revealed that the holes had caved to some degree, filling the bottom 1.5 to 9.1 m (5 to 30 ft) of the well bore. Filling material seemed to have the equivalent density of mud slurry and the weighted tape was generally able to travel through the caved material to the bottom of the well bore. One to two 60 pound sacks of pea gravel (0.009 m, .375 inches in diameter) were poured into the bottom of each well and seemed to displace the caved material to some degree, raising the level of the bottom of the well bore above the level of the screened interval. The benefit of the loose gravel pack in regard to connection with the aquifer is unknown.

The majority of the well bore was back-filled with CETCO time release, non-coated, compressed, 0.009 m (0.375 in) diameter bentonite clay pellets. Once the bore holes were filled above the water level, CETCO bentonite chips (without time release) were used to fill the hole to within 2 ft of the surface. A metal well monument cover with a hinged locking cap was then grouted in over the top of the well casing stub. All well materials (casing, bentonite, etc.) were obtained from Western Well Supply, Aloha, Oregon.

3.1.1.3 Piezometer Development

Once wells were in place, they were developed with standard pumping and surging techniques. Wells were first pumped with a PVC hand pump, removing silt and clay bearing water from the well to the depth of the well screen. Wells were slow to recover and subsequent pumping (after a break of 1/2 to 1 hour) produced less than 5 additional gallons of silt and mud bearing water. Wells were pumped daily for a time period of one to two weeks.

Wells that did not respond significantly to pumping were also surged by hand with a PVC surge block over a period of weeks. Surging appeared to have some positive effect on well connection and resulted in quicker recovery of some surged wells.

3.1.1.4 Piezometer Instrumentation

Piezometers were instrumented with Druck 20 psi pressure transducers connected to Unidata Prologger data loggers (available from Unidata America, Lake Oswego, OR). Transducers were calibrated by averaging readings at 1.5 m (5 ft) water depth intervals and calculating a linear correlation equation. Final installation depth was just above the well screen. Loggers were programmed to record the water level above the transducer on 15 minute intervals, with shorter intervals programmed at times of interest such as pump and slug tests.

3.1.1.5 Stream Piezometer Installation and Instrumentation

Solinst self-contained pressure transducers were used to record Pudding River stream stage and the vertical hydraulic gradient directly below the stream. Two 0.05 m (2 in.) steel plumbing pipes with conical end plugs were pounded into the bed of the Pudding River with a fence-post tool. The piezometers were installed during low river stage near the middle of the stream to depths of 2.1 and 3.9 m (7 and 13 ft.) below river bottom. Once in place the conical end caps were driven out with a 0.0254 m (1 in.) diameter pipe inserted into the piezometer, creating hydraulic connection with the aquifer material below the stream. Water levels in both piezometers and relative stream stage were measured by hand during low flow to determine the vertical hydraulic gradient below the stream and to calibrate future transducer data. Three Solinst transducers were installed at the site, one in the deep stream piezometer, one on the side of the piezometer below water level (to record stream stage), and one above water level to independently record barometric pressure for calibration purposes. Once the stream stage began to rise in the autumn, the transducers were sealed at the top and allowed to submerge below stream level, open only to the aquifer below, and were recovered during the next low flow period.

3.1.1.6 Other Instrumentation

A Unidata tipping bucket rain gauge was connected to a Unidata Macrologger at Site 1. A Unidata Macro Logger collects pumping rate data from the site irrigation well (IR-ED) flow meter at Site 2. A Unidata barometer unit is attached to the Prologger located at Site 3. A SeaMetrix TX-81 flow meter connected to a Unidata Prologger was installed to measure drain tile out-flow rate for the field site. Unfortunately, the flow rate from the drain tile network was not sufficient to break the 0.069 L/s (1.1 gal/min) threshold of the instrument. Plots of transient head values with IR-ED pumping rate and local rainfall are presented in Figures 4 through 9.

3.1.2 Soil Sample Methods and Analyses

3.1.2.1 Test Holes

A transect for geochemical test holes was laid out between piezometer sites three and two. Twelve test holes (numbered 5-16) were cored at nine sites positioned every 15.24 m (50 ft) along the 152.4 m (500 ft) transect. Test Holes 12-15 were spaced on the corners of a 1.524 m (5 ft) square centered on a single coring site.

Soil samples were taken at the lower 0.15 m (6 in) of 0.31 m (1 ft) depth intervals for 3.05 m (10 ft), the maximum depth of recovery attainable with the hand sampling equipment. The test holes were dug to the top of each sampling depth with a 0.08 m (3.25 in) diameter barrel auger. Soil samples were collected with a 0.05 m (2 in) i.d. ring sampler driven with a slide hammer. Samples were collected into vinyl tubing, closed to the atmosphere with PVC caps, and kept in a cooler in the field.

Figure 4: Site 1 Head in Time with IR-ED Pumping Rate

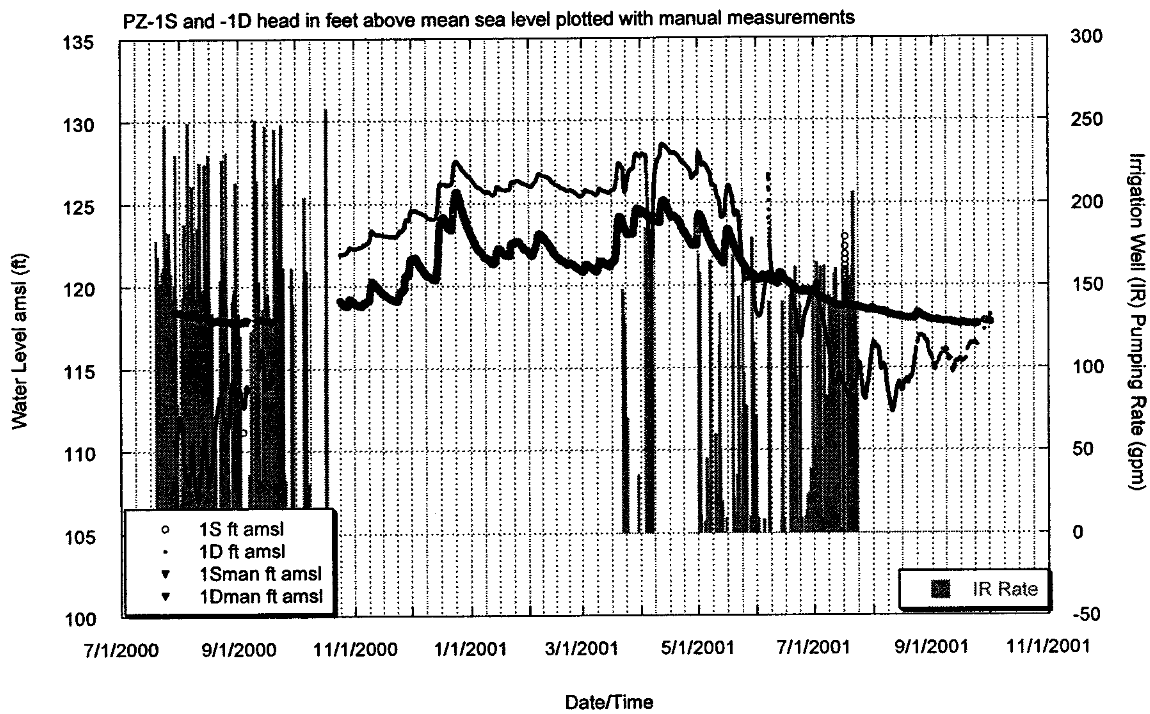


Figure 5: Site 1Head in Time with Local Rainfall

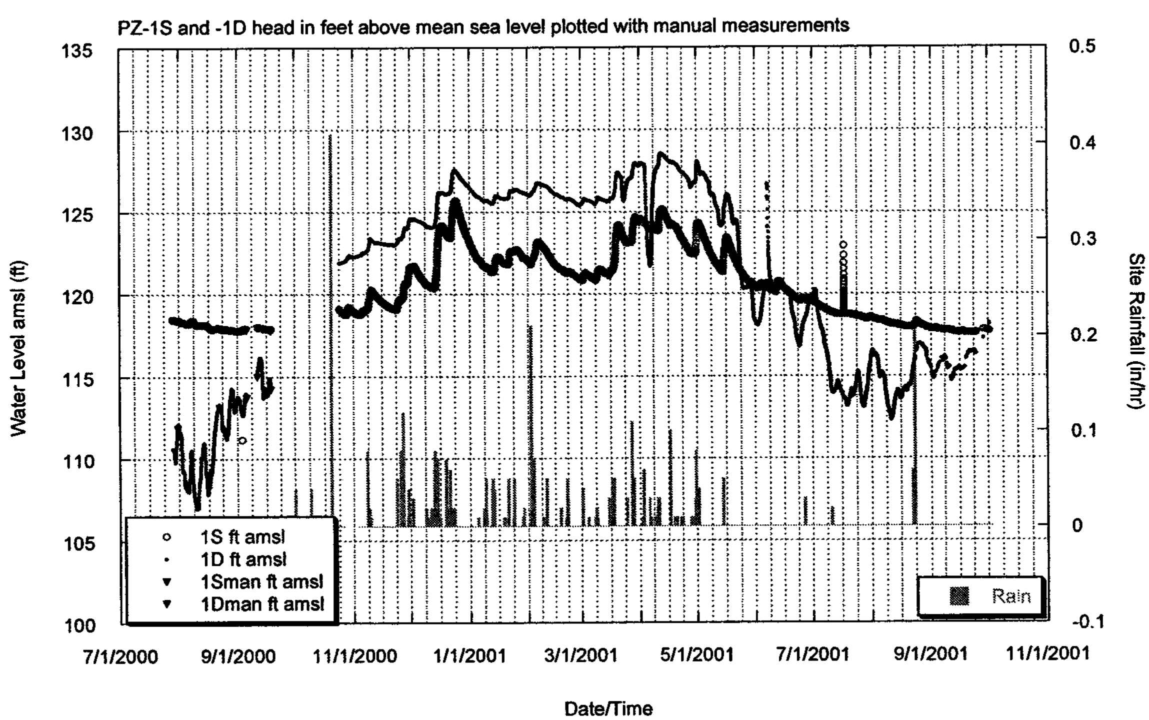


Figure 6: Site 2 Head in Time with Local Rainfall

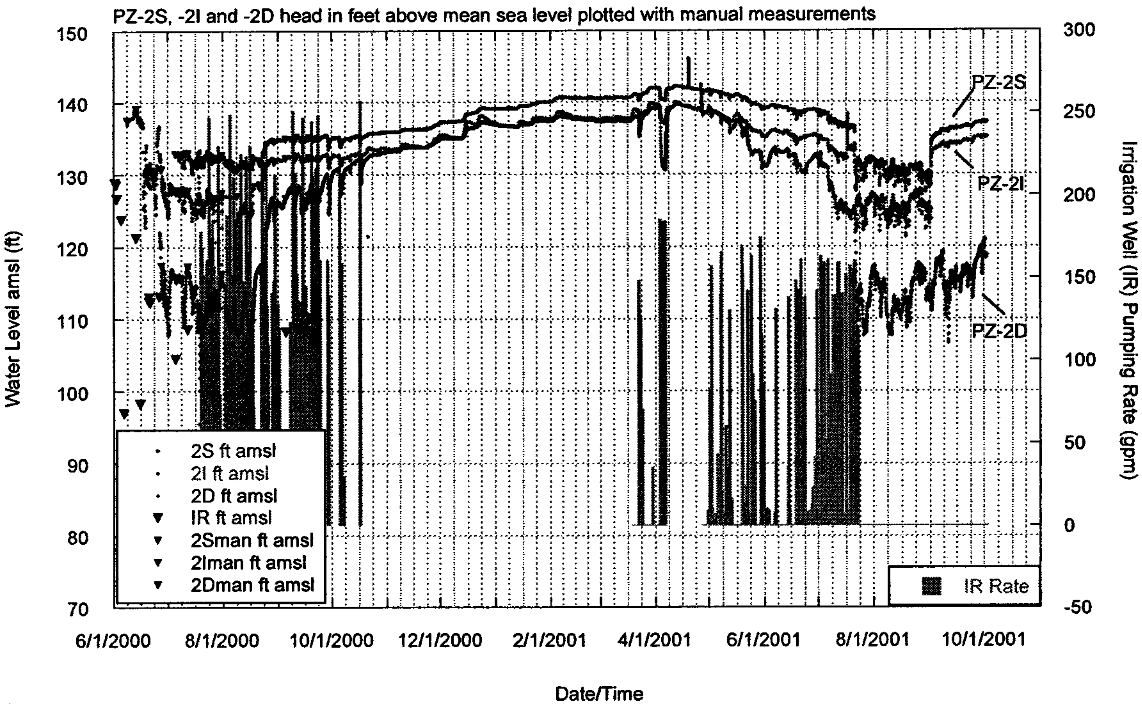


Figure 7: Site 2 Head in Time with IR-ED Pumping Rate

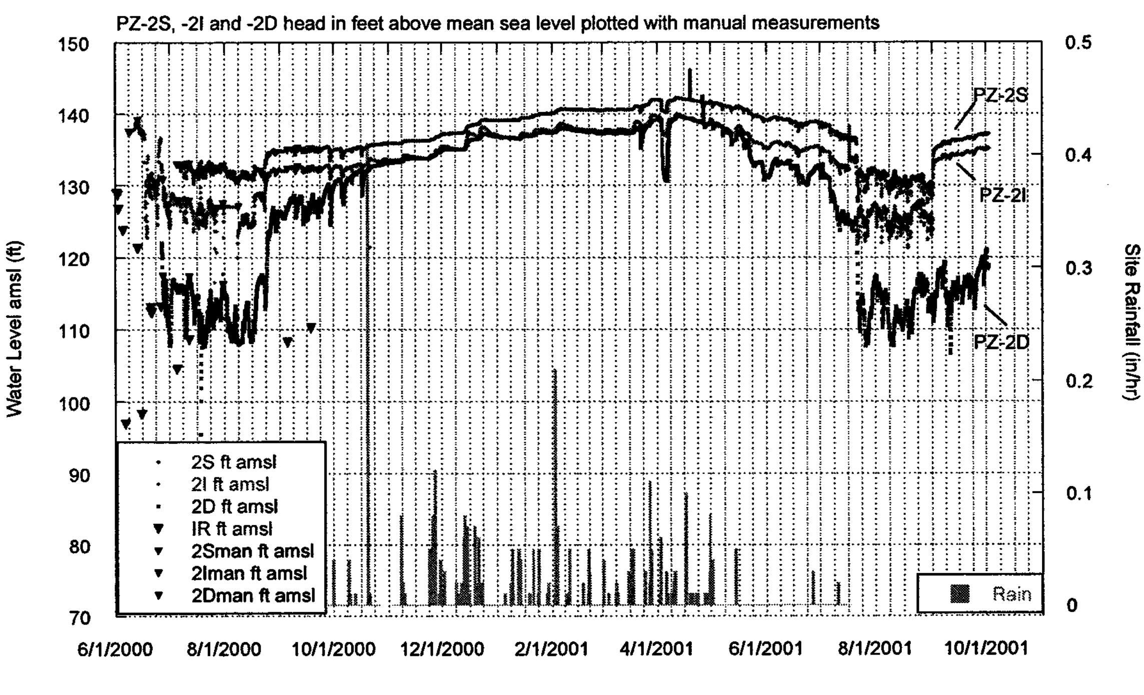


Figure 8: Site 3 Head in Time with IR-ED Pumping Rate

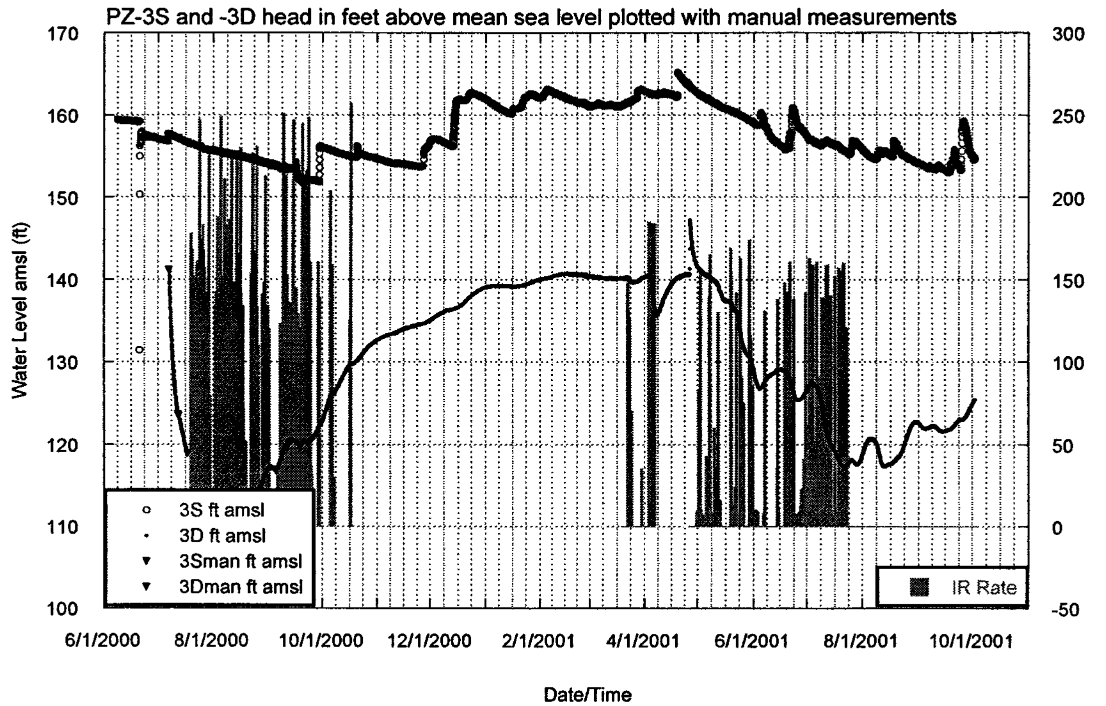
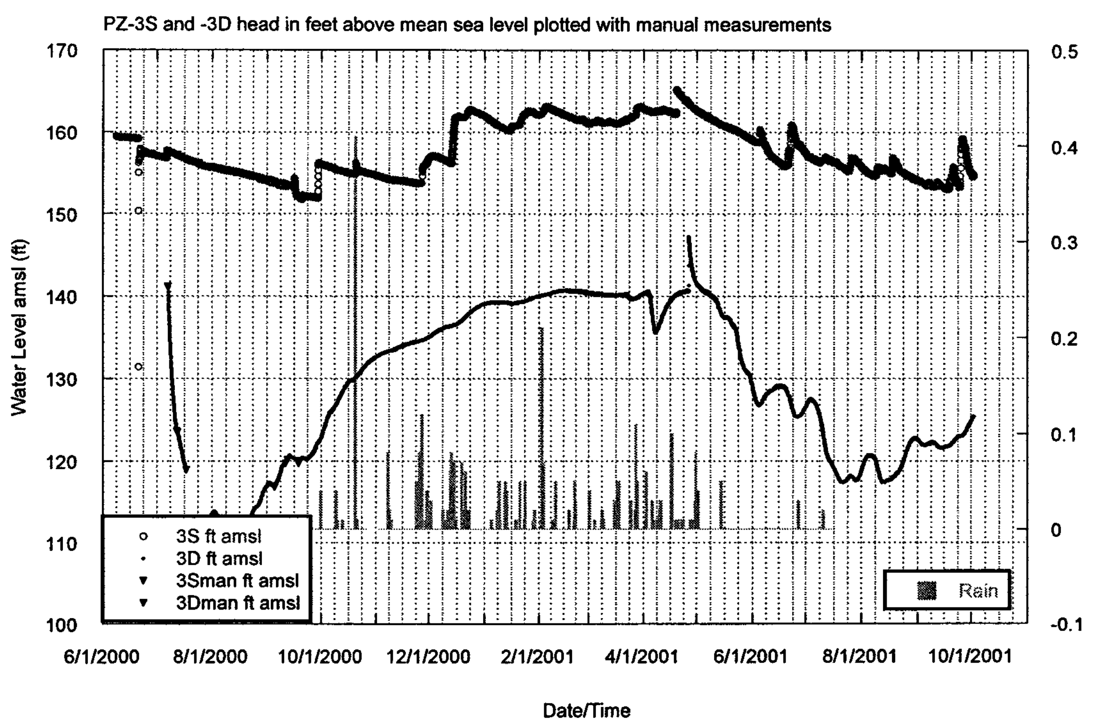


Figure 9: Site 3 Head in Time with Local Rainfall



3S wlbmp

3.1.2.2 Piezometer Bore Holes

Bore hole material sample collection methods are described with the piezometer drilling methods. Samples were split with a band saw while frozen. Half of the sample was archived at the OSU Department of Oceanography Core Lab for lithologic description purposes, the other half kept frozen while transported to the lab for chemical analysis.

3.1.2.3 Chemical Analysis

The Oregon State University Central Analytical Lab (CAL) performed the chemical analysis of the soil samples. Test hole samples were delivered shortly after returning from the field. Bore hole samples were delivered in a frozen state. In order to investigate the distribution of fertilizer leachate components and the reducing capacity of the Willamette Silt all samples were analyzed for pH and an agricultural leachate suite. The agricultural leachate suite consisted of phosphorous (P), ammonia (NH_4-H), nitrate ($N0_3$-N) and sulfate (SO_4-S). For completeness of the data set, select representative bore hole samples and test hole samples were analyzed for a general cation suite consisting of potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), zinc (Zn), manganese (Mn), copper (Cu), and iron (Fe). Analytical instruments used by the CAL to perform chemical analysis of field samples are briefly described in Appendix 3. Plots of constituent concentrations vs. depth for piezometer core samples are presented in Figures 10 through 15 and similar plots for test hole chemistry are included in Appendix C.

Figure 10: Site 2 Agricultural Lechate Products

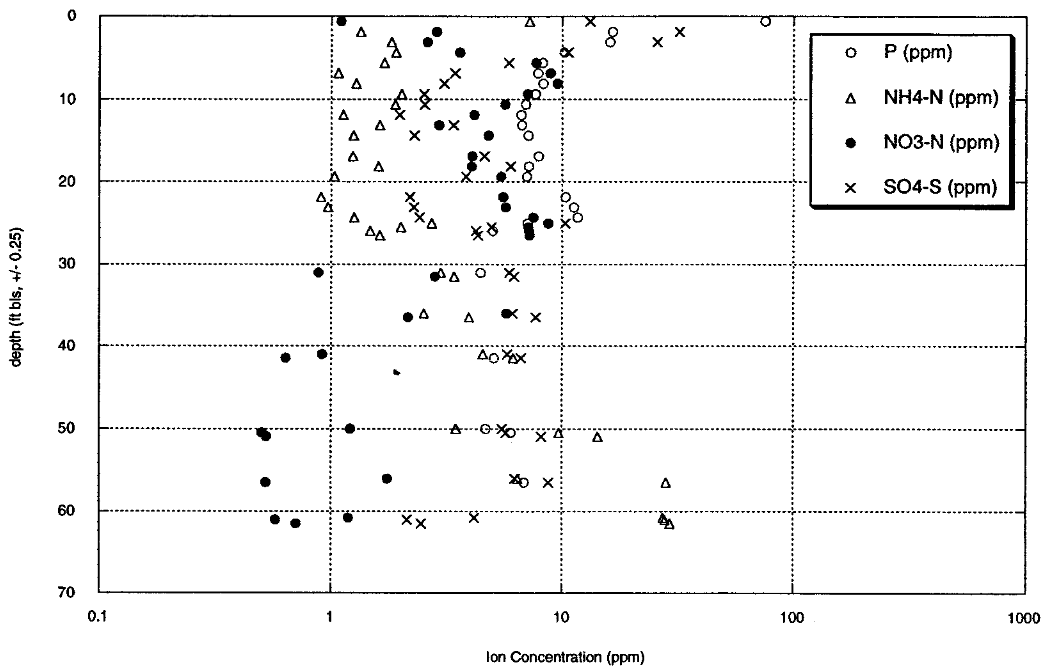


Figure 11: Site 2 Cations

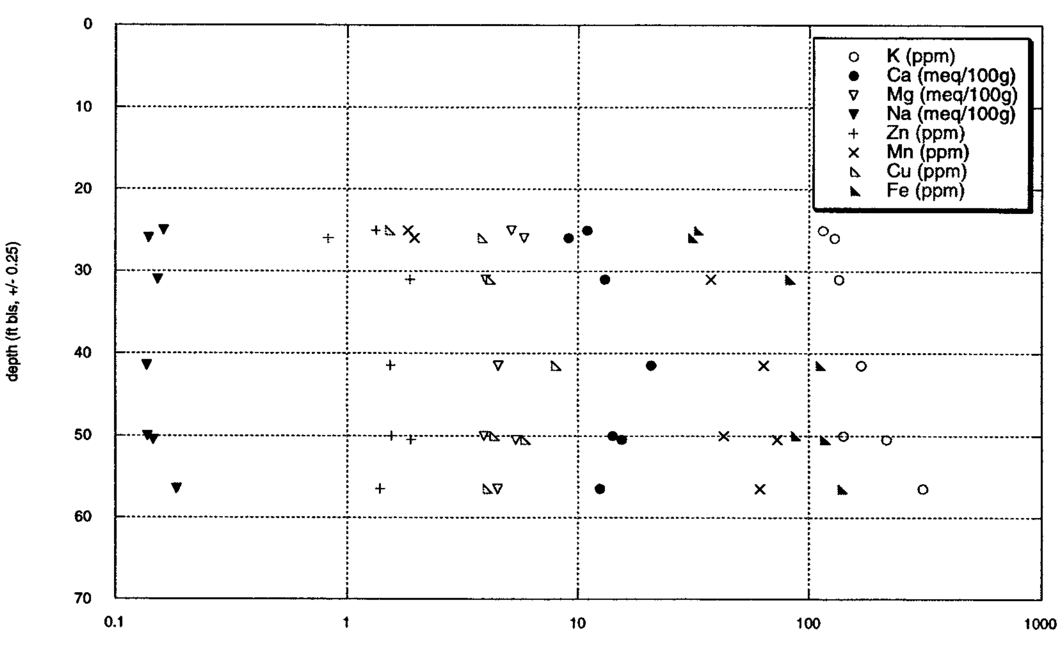


Figure 12: Site 3 Agricultural Lechate Products

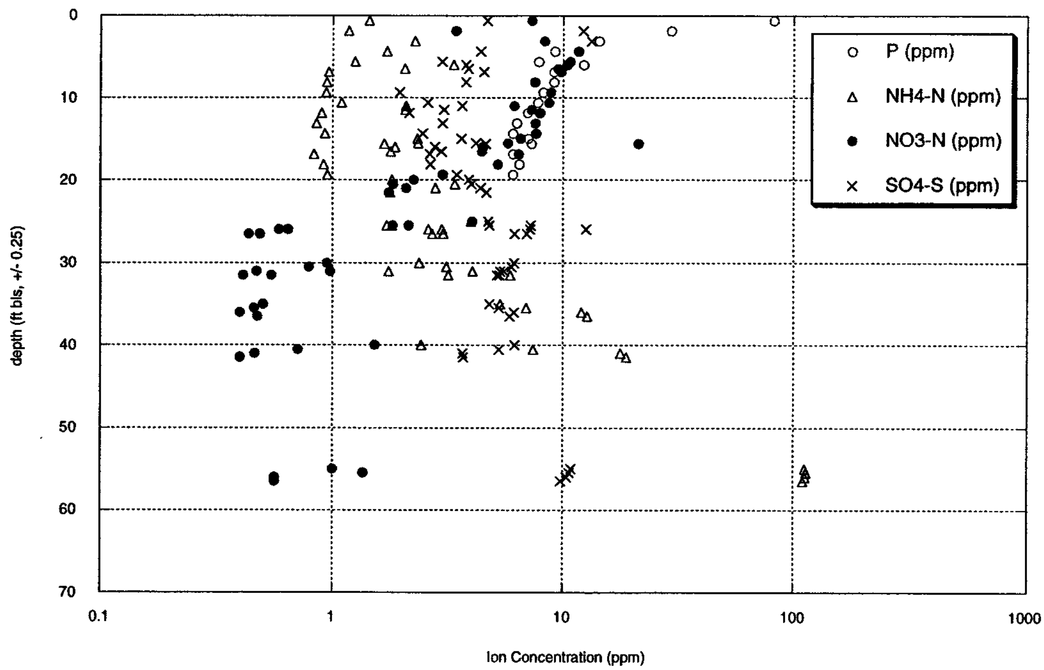


Figure 13: Site 3 Cations

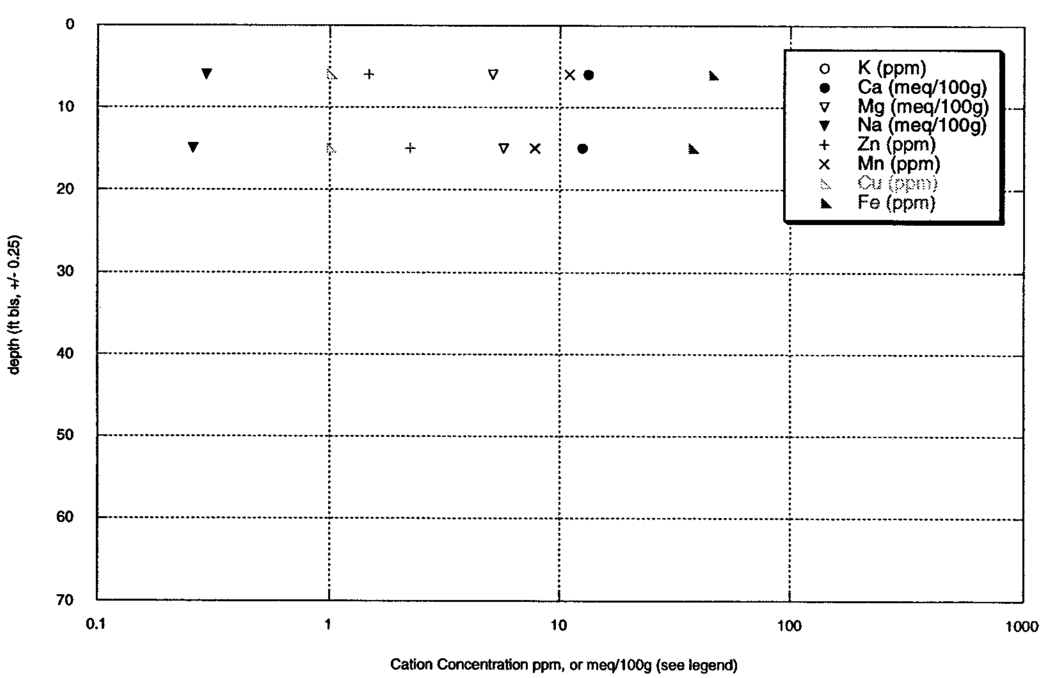


Figure 14: Site 2 pH

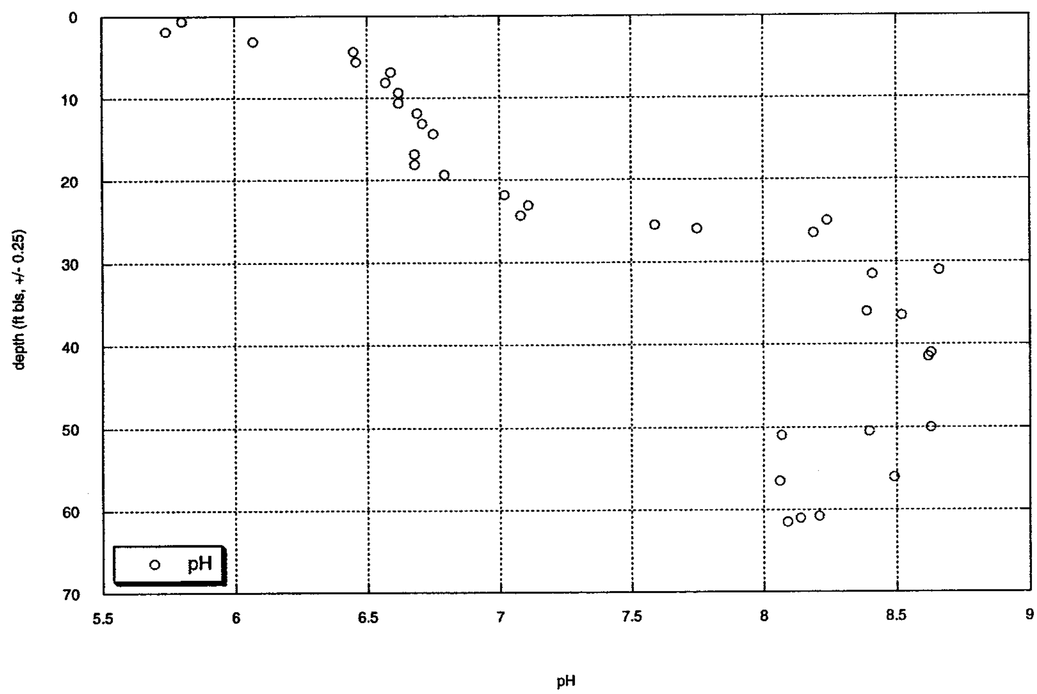
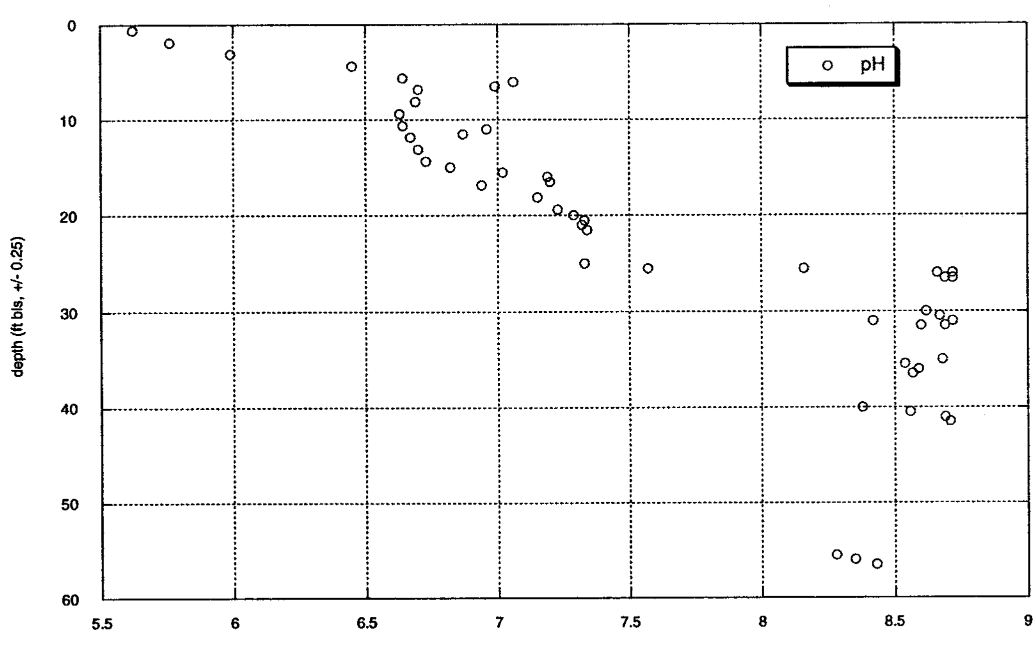


Figure 15: Site 3 pH



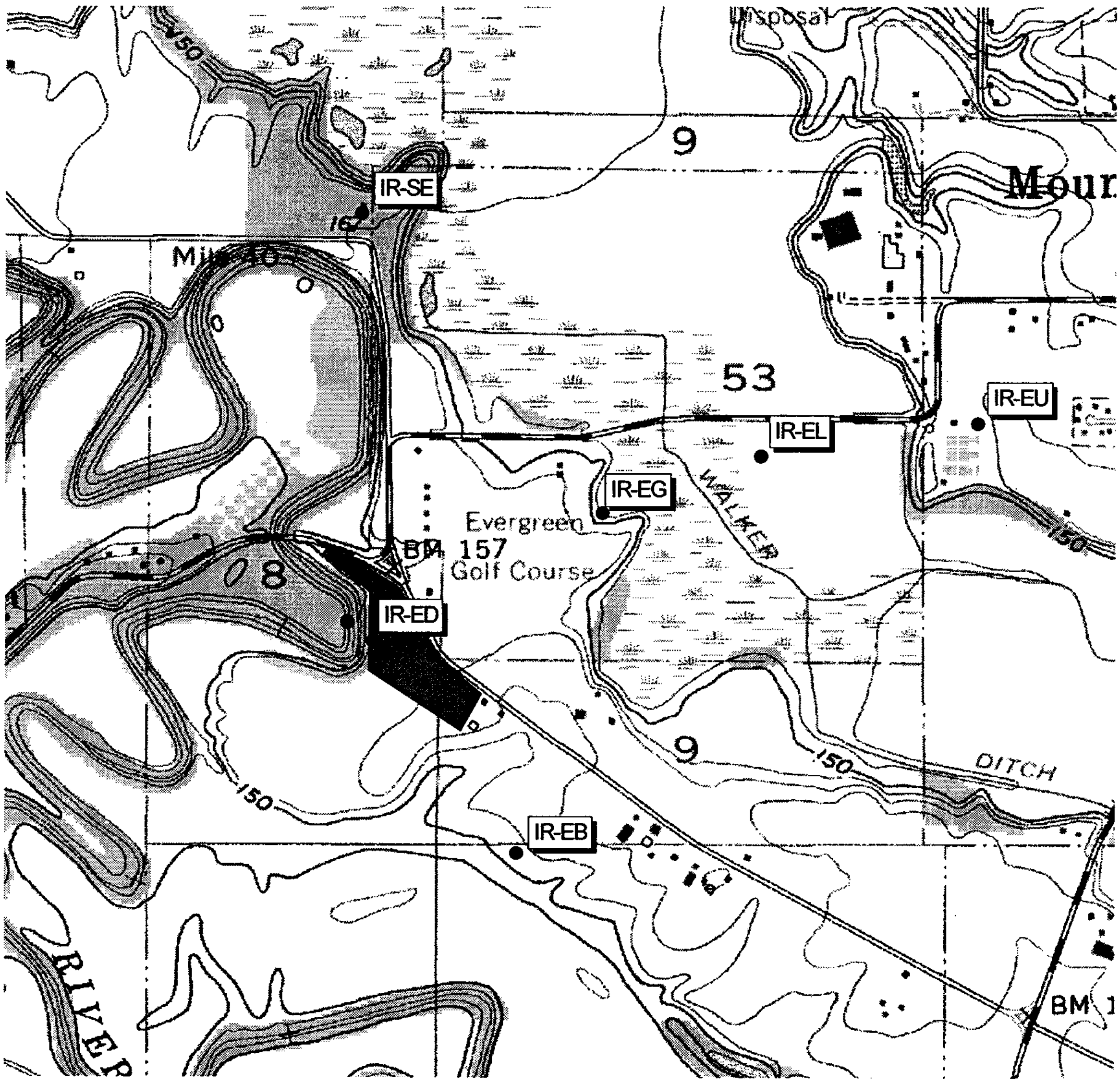
3.1.3 Pump Test Methods and Analyses

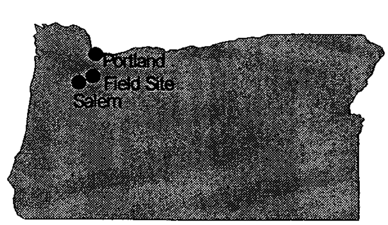
An aquifer pump test was conducted with the IR-ED irrigation well between April 3, 2001 and April 6, 2001. The early spring date was selected to perform the test at a time when the aquifer system was nearly static and when irrigation would not be occurring at adjacent farms. In addition to nearby farms not removing water from the system, five proximal irrigation wells were instrumented for the purposes of this test (Table 1, Figure 16). Additional monitored irrigation wells were instrumented with similar equipment and calibrated in the same manner as those installed in the site piezometers. Background head values were collected for roughly two weeks before the beginning of the pump test to assess the state of the aquifer (static, rising, or falling water levels) and to determine if any float was present in the transducers. Manual measurements of instrumented wells with a steel tape were made approximately every other day during these two weeks for head accuracy comparisons.

Table 1: Instrumented Irrigation Wells

Well Identification	Bearing from Pumping Well	Distance from Pumping Well (ft/m)	Screened Interval (estimated ft amsl)	OWRD Well ID MARI-
IR-EG	N 60 E	1837/559	111 to 41	3094
IR-EB	S 33 E	1959/597	45 to (-27)	3208
IR-SE	N 06 W	2999/914	13 to (-88)	53259
IR-EL	N 66 E	3025/922	95 to 44	3101
IR-EU	N 70 E	4560/1389	91 to (-21)	3090

Figure 16: Irrigation Wells Monitored During April Pump Test





400 0 400 800 Meters

Scale: 1:12,000
Base Map: Silverton Quadrangle, 1:24,000

● Irrigation WellsMonitored Irrigation Wells.shp
■ Field AreaDrained_area.shp

IR-ED irrigation well outflow was pumped directly into the Pudding River. The SeaMetrix TX-81 turbine flow meter normally installed at the drain tile output point was fitted to the pumping outflow pipe in order to ensure accuracy of the pumping rate measurement. The pump was briefly (~10 min.) turned on the day before the test in order to adjust the aperture of the outflow pipe valve to allow a constant flow rate of approximately 0.011 m^3/s (180 gpm)

During the test manual measurements were taken at all wells to ensure transducer calibration. The general results of the pump test are presented in Table 2, a more detailed summary of the analysis and accompanying graphs of drawdown (s), Theis analysis (t), and Cooper-Jacob analysis (cj) can be found in Appendix D. Equilibrium was not reached at monitored irrigation wells during the three day test, creating difficulty in obtaining the greatest possible amount of data from the test (eg., S_s in the WS). A longer pump test would be valuable in further characterizing the site.

Table 2: General Results of April Pump Test

Well ID	Theis *K* (m/s)	Theis *K* (ft/day)	Cooper Jacob *K* (m/s)	Cooper-Jacob *K* (ft/day)
PZ_1D	9.61×10^{-6}	2.72	1.22×10^{-5}	3.45
PZ_2D	3.84×10^{-7}	0.11	6.40×10^{-6}	1.81
PZ_3D	-	-	2.29×10^{-5}	6.49
IR_EG	4.23×10^{-5}	11.99	6.48×10^{-5}	18.38
IR_EB	3.84×10^{-5}	10.90	4.32×10^{-5}	12.25
IR_SE	4.23×10^{-5}	11.99	6.71×10^{-5}	19.02
IR_EL	2.11×10^{-5}	5.99	6.95×10^{-5}	19.70
IR_EU	3.84×10^{-5}	10.90	1.08×10^{-4}	30.64

3.1.4 Slug Test Methods and Analyses

Slug tests were performed at all piezometers by injecting approximately 4.16 L (1.1 gal) of water into a piezometer and recording the recovery of the water level with the piezometer pressure transducer. The amount of water used was sufficient to increase the head in the piezometers by 1.7 to 2.0 m (5.5 to 6.5 ft). Transducers were set to 1 second intervals for the first 5 to 10 minutes, 1 minute intervals for about 2 hours, and 15 minute intervals thereafter. Water was injected into the piezometers as close to instantaneously as possible by using a PVC pipe fitted with a valve and an outlet small enough to place inside the top of the piezometer well casing.

Results of Bouwer and Rice analyses (*Bouwer and Rice*, 1976 as described in *Dawson and Istok*, 1991) for the slug tests are presented in Table 3. Plots of slug test recovery curves are included in Appendix E.

Table 3: Piezometer Slug Test Results

Well ID	*K* (m/s)	*K* (ft/day)
PZ-1S	1.95×10^{-5}	5.53
PZ-1D	1.70×10^{-8}	4.8×10^{-3}
PZ-2S	8.86×10^{-6}	2.51
PZ-2I	7.07×10^{-7}	0.20
PZ-2D	2.93×10^{-8}	8.3×10^{-3}
PZ-3S	1.54×10^{-9}	4.0×10^{-4}
PZ-3D	6.43×10^{-9}	1.8×10^{-3}

3.2 Lab Work

Samples for lab analysis of the physical properties of the Willamette Silt were collected from Test Hole 17, located approximately 2 m SE of Piezometer Site 3 (see Figure 3a). Methods of soil sample extraction are detailed in Section 3.1.2, with the exception that samples were collected in brass sleeves. Samples from depths greater than 3 m (7 ft.) were unable to be recovered without significantly disturbing the sample due to upward pounding of the slide hammer.

3.2.1 Permeameter Analyses

Vertical hydraulic conductivity of WS samples was calculated in the lab using a constant head permeameter. A Marriott bottle was used to provide a constant head source for the apparatus. A Tempe cell (Soilmoisture Equipment Corp., Goleta, CA) was used to connect the sample to the permeameter without removing it from the sleeve in which it was collected. This method was used to keep the sample in contact with the sleeve wall and reduce potential sources of error due to water flowing between the sample and sleeve wall. The sample was flushed from the bottom with several pore volumes of CO_2 gas to eliminate any oxygen in the unsaturated pores. The core was then flushed from the top with several pore volumes of de-aired (boiled and cooled) water to allow CO_2 contained in the pores to dissolve into the water and provide for full saturation of the sample.

Flow rate and vertical head gradient (head above and below the sample) were recorded and used to calculate vertical conductivity (K_v) with Darcy's Law (see Table 4). The constant head test performed with this permeameter configuration provides a measure of the effective conductivity of the system (tubing, joints, Tempe cell, and screen mesh).

However, the component of K added by the equipment and screen mesh was small enough (undetectable when the experiment was run with an empty cell) to be assumed negligible.

The vertical conductivity of the samples was on the order of 10^{-7} m/s with the exception of the samples from 0.3 m (1 ft.) depth and from 1.3 m (4 ft.) depth (see Table 4). The shallow sample is expected to have a higher K_v due to disruption of soil layering by agricultural plowing. The 4 ft sample was noted to have macro-pores, considered responsible for the significantly higher (two orders of magnitude) vertical K. This brings to attention the fact that lab derived vertical K measurements are generally taken as valid only for small scales, not field scales that include heterogeneity in grain size, cracks, and macro-pores in varying abundance. However, as the WS is a fine-grained, layered unit (i.e., heterogeneity is known to be present in horizontal layers and average K_v calculated with the harmonic mean is dominated by the lowest K_v layers) and has not been observed to be fractured (or brittle), this lab determination of K_v is taken as representative of the WS (at least the upper portion, composed of the youngest Missoula Flood deposits). Neglecting the surface sample, results of this lab test are used to calculate an average K_v value for the WS at the field site with the harmonic mean of the results. It should be noted that tested core samples were taken from the upper-most portion of the WS near Site 3 with a grain size description of silty clay, an intermediate grain size classification (i.e. between the extremes of clay and silt) for the WS at the field site.

3.2.2 Grain Size Analyses

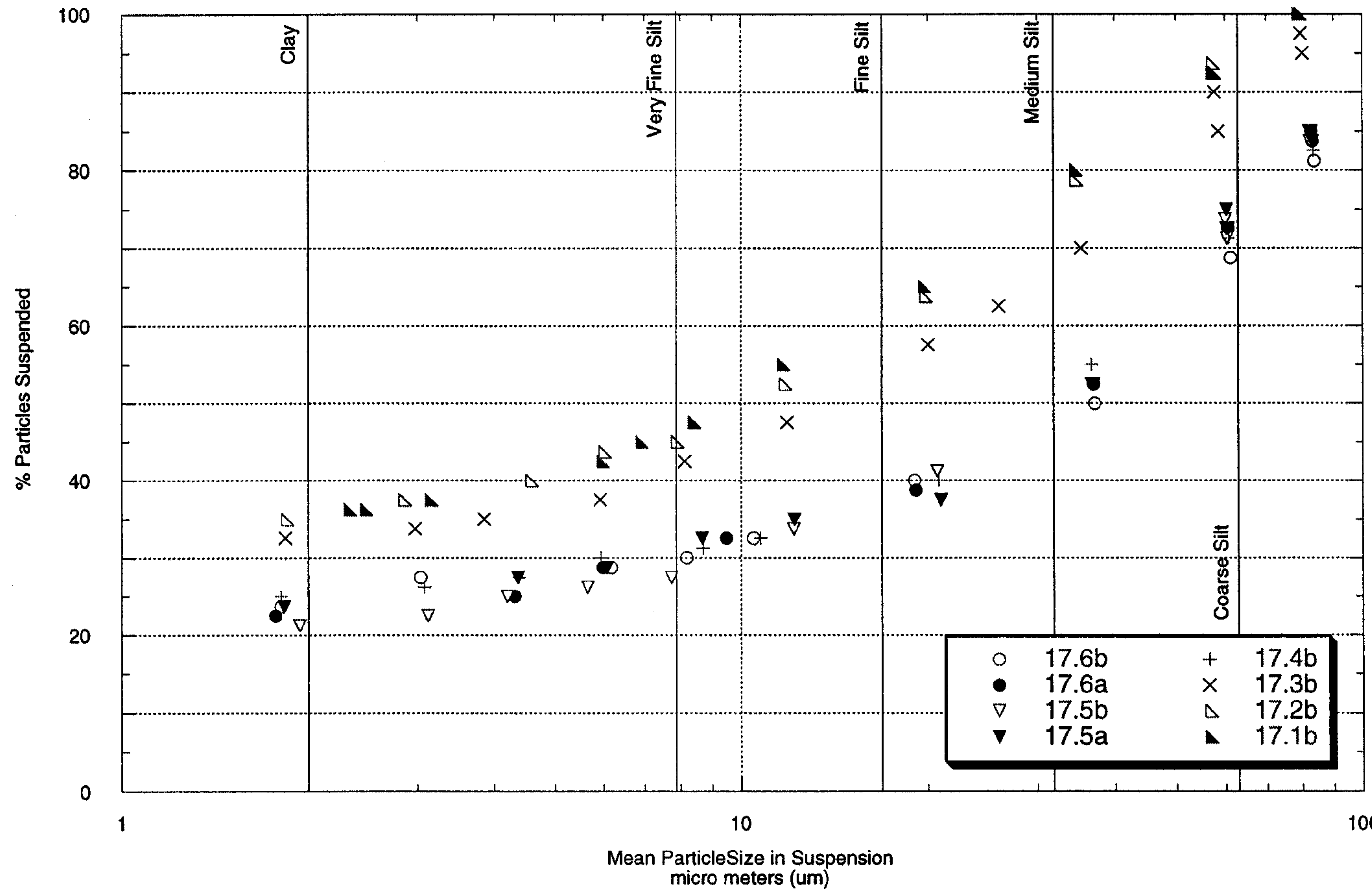
Particle size analysis was conducted on the eight samples used for the permeameter analysis in order to compare results of the two tests (see Table 4). After running the permeameter test, the saturated weight of the sample was recorded and the sample was placed in an oven at 104 °C (219°F) to dry. The samples were removed when completely dry and re-weighed to determine saturated porosity (see Table 4). The samples were then ground to eliminate soil aggregates and sieved to remove grains larger than fine sands from the sample, though no sample material was retained on the screen.

Forty grams of sample were added to a 250 ml solution of Sodium Hexametaphosphate (HPM) and water (20g/L) to further break down any remaining particle aggregation. Samples were allowed to soak for 24 hours or longer before testing occurred. The samples were transferred to a settling cylinder with 750 ml of additional water and standard hydrometer tests were performed (ASTM D421, D422, 2217). Results of the hydrometer analysis are presented in Figure 17. Note that overall grain size distribution coarsens with depth through the top 7 feet of the WS.

Table 4: Results of Permeameter and Grain Size Experiments

Sample ID	Depth m (ft)	K_v (m/s)	K_v (ft/day)	Porosity (-)
17.1b	0.15 (0.5)	2.14×10^{-4}	60.66	0.42
17.2b	0.45 (1.5)	2.22×10^{-7}	0.06	0.38
17.3b	0.76 (2.5)	7.69×10^{-7}	0.22	0.41
17.4b	1.06(3.5)	2.35×10^{-5}	6.66	0.40
17.5a	1.22 (4.0)	1.17×10^{-7}	0.03	0.41
17.5b	1.37 (4.5)	1.07×10^{-7}	0.03	0.39
17.6a	1.52 (5.0)	2.98×10^{-7}	0.08	0.39
17.6b	1.68 (5.5)	3.02×10^{-7}	0.09	0.40
Average		-	-	0.40
Harmonic Mean (neglecting 0.5 ft sample)		2.30×10^{-7}	6.53×10^{-2}	
Geometric Mean (neglecting 0.5 ft sample)		4.62×10^{-7}	1.31×10^{-1}	

Figure 17: Borehole Sample Particle Size Distributions



4. Analyses

4.1 Head Gradients

4.1.1 Vertical Head Gradients

Vertical head gradients in the Willamette Silt (WS) and between the WS and Willamette Aquifer (WA) are seasonally dependent. Vertical hydraulic gradients are relatively small and downward (except under streams, which are typically groundwater discharge zones) in the winter due to the absence of agricultural pumping from the WA and recharge of the system from rainfall infiltration. In the summer vertical head gradients in the WS are significantly larger in the downward direction than winter gradients due to pumping and lack of recharge. Under the influence of these summer conditions, upward vertical gradients in discharge zones (under streams) are smaller, and at some points reversed from, winter gradients. The amount of change in vertical gradient increases with proximity to the pumping well: Site 3 gradients are up to 3 times larger in the presence of pumping while Site 2 gradients are up to 10 times larger. The reversed gradient observed at Site 1 is related to its proximity to the Pudding River (as well as to the pumping well) where the "normal" gradient is presumably upward to the river all year in the absence of pumping (*Woodward et al.*, 1998). Plots of transient vertical head gradients with IR-ED pumping rate and local rainfall are presented in Figures 18 to 23.

Absolute values of vertical head gradients in the WS at Site 2 (between PZ-2S and PZ-2I) range between 0.1 and 10 over the period of record. The calculation of vertical head gradients at Site 3 (WS) and Site 1 (Pudding River flood plain deposits) are estimates of gradients for the upper units because the lower piezometers (PZ-1D and PZ-3D) are

Figure 18: Site 1 Vertical Head Gradient with IR-ED Pumping Rate

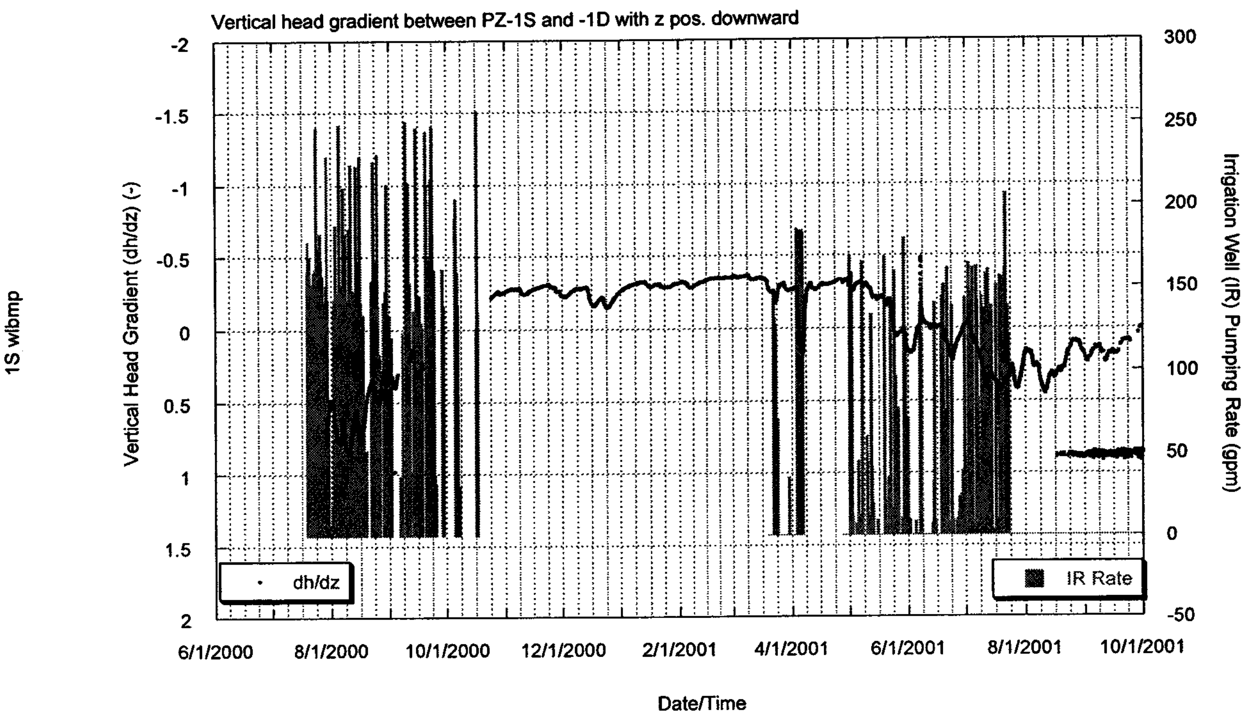


Figure 19: Site 1 Vertical Head Gradient with Local Rainfall

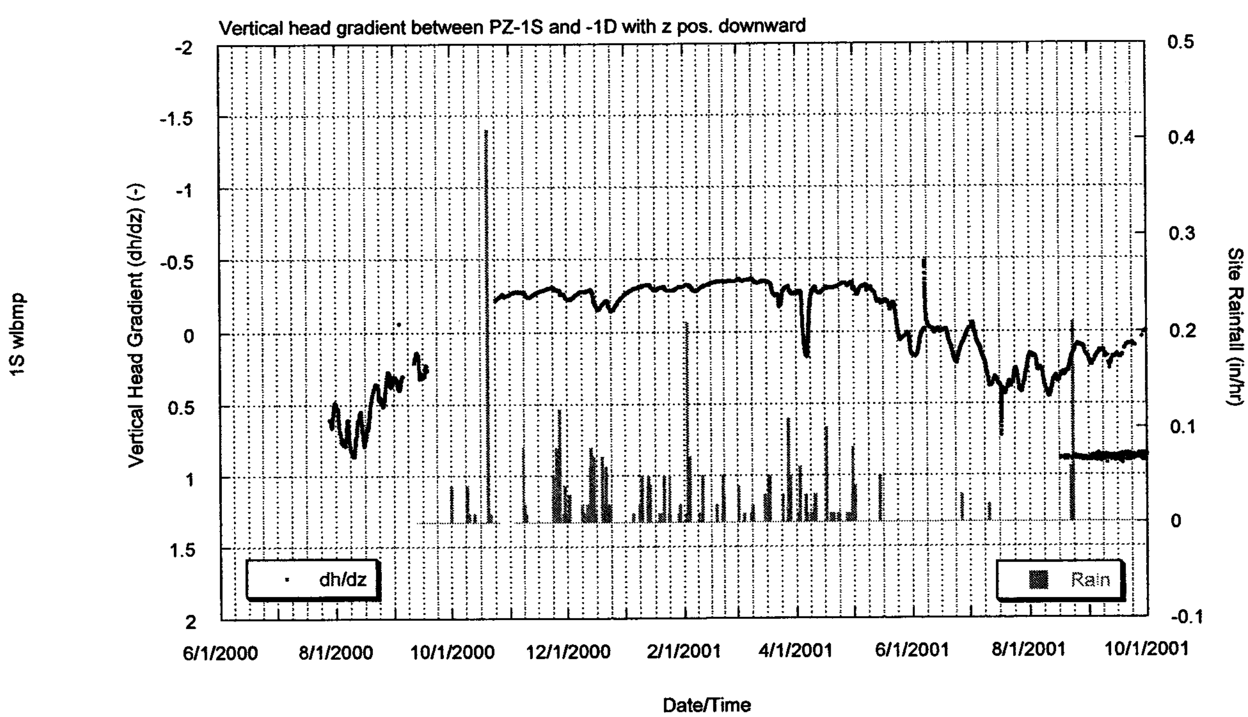


Figure 22: Site 3 Vertical Head Gradient with IR-ED Pumping Rate

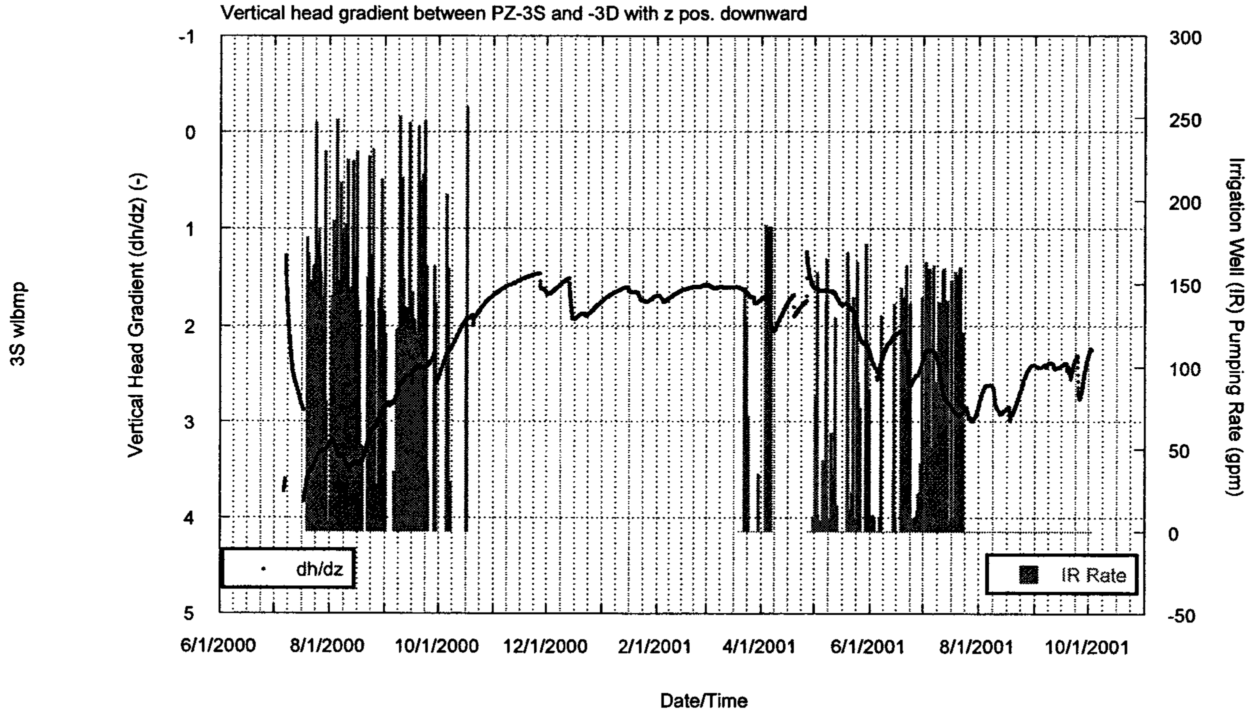


Figure 23: Site 3 Vertical Head Gradient

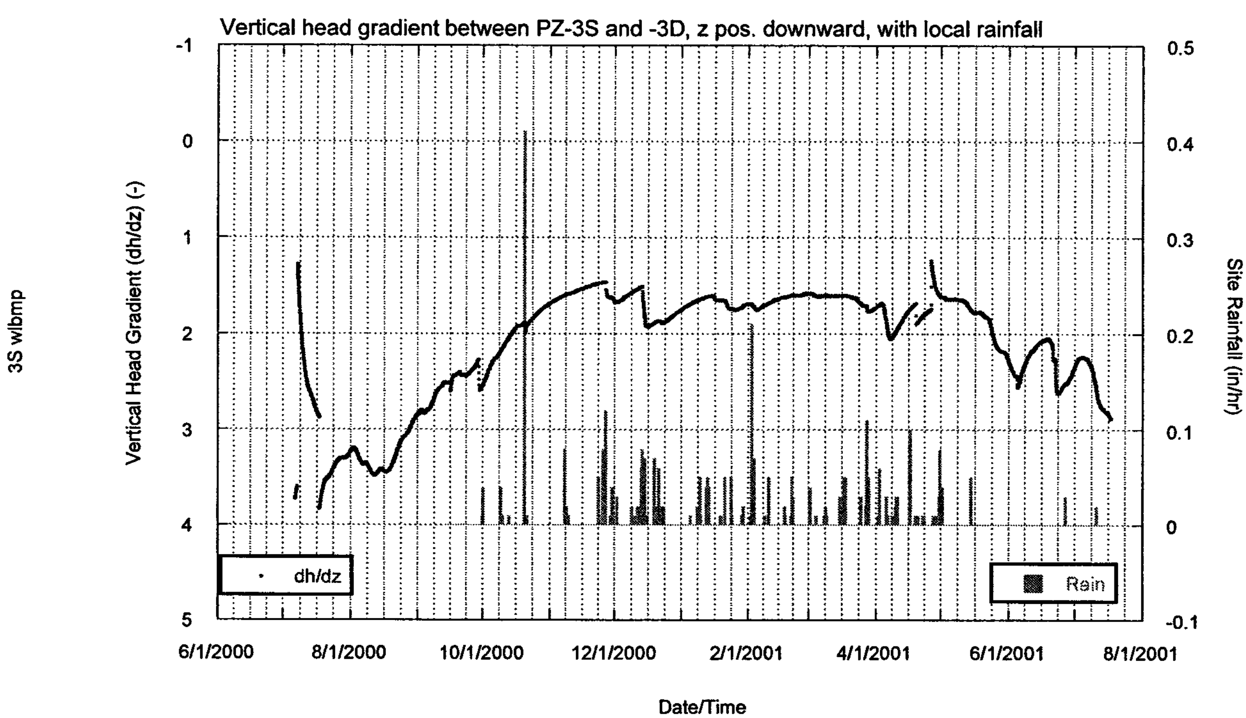


Figure 20: Site 2 Vertical Head Gradient with IR-ED Pumping Rate

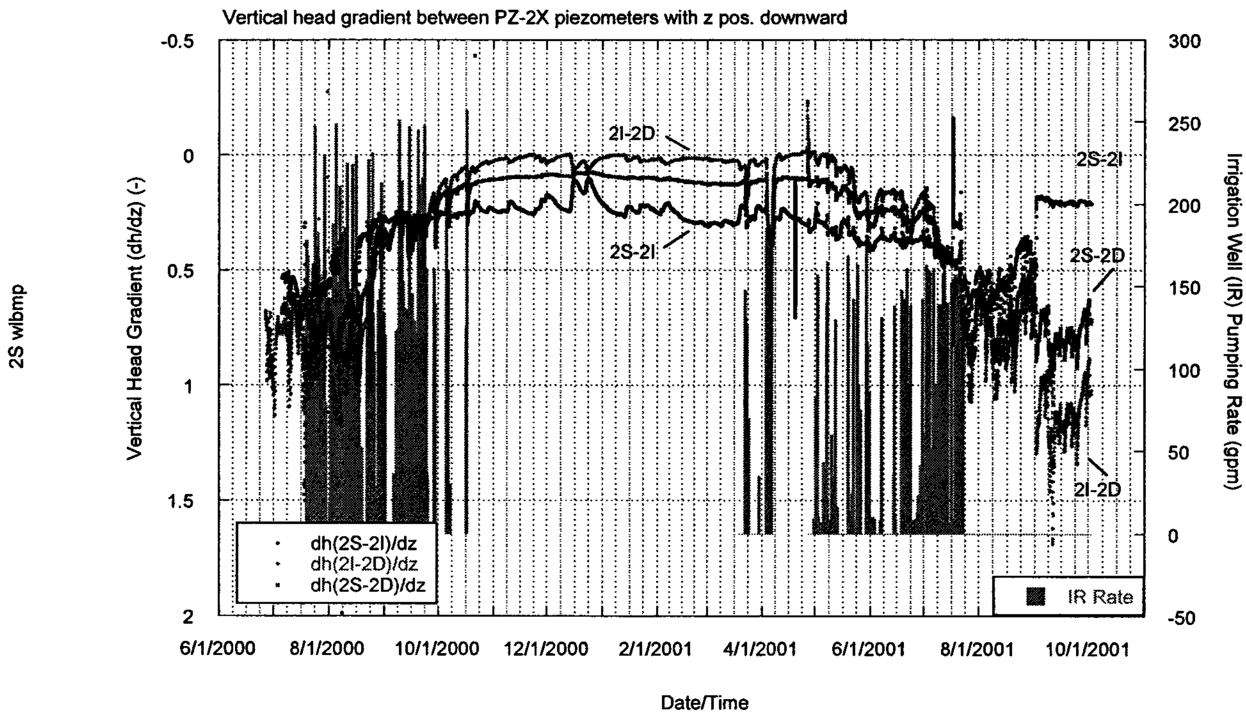
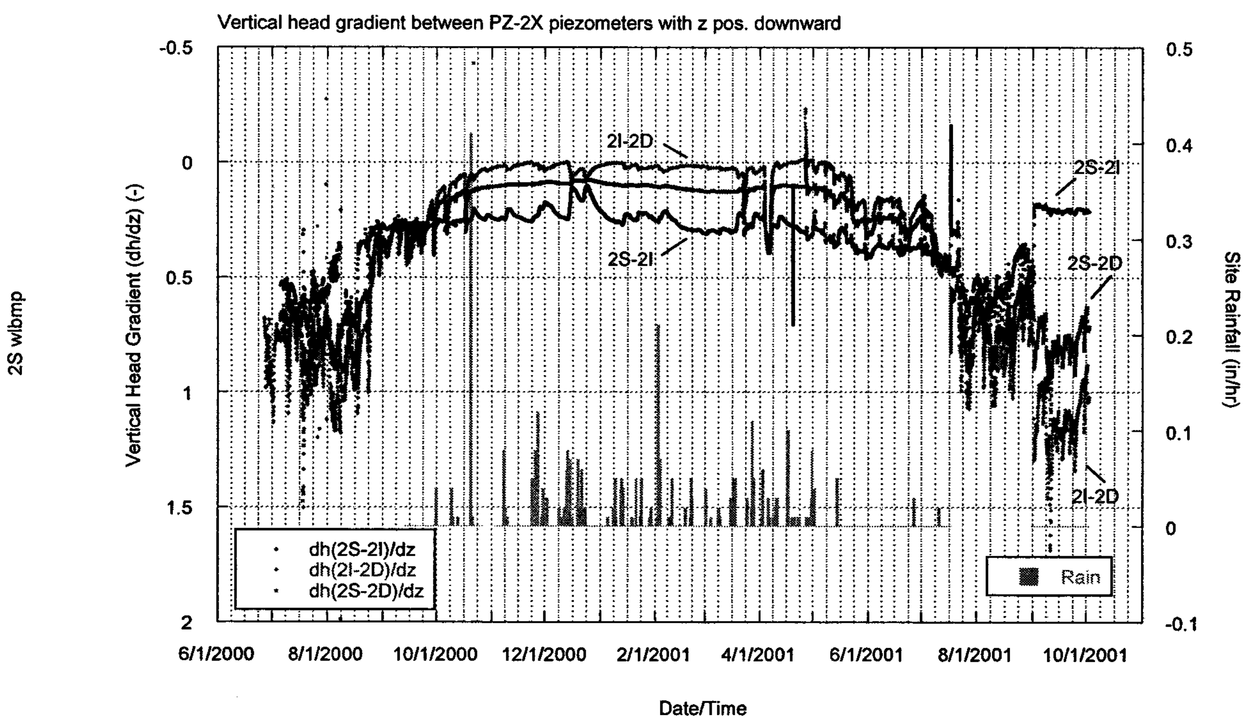


Figure 21: Site 2 Vertical Head Gradient with Local Rainfall



located approximately 3 m (10 ft) below the contact between the WA and the upper units (the WS at Site 3 and the flood plain deposits at Site 1). This geometry will result in overestimated gradients during times of pumping, when the head in the WA is significantly reduced, creating a greater total difference in head between the two wells than would be observed in the upper units alone. The gradients will be underestimated in the absence of pumping when the vertical gradient in the aquifer is very small compared to the upper units, creating a smaller total change in head over the total distance between the two wells than would be observed in the upper units alone. The vertical head gradient between the WS and the WA measured at Site 2 (PZ-2S to PZ-2D) averages about 25% greater or smaller (depending on whether or not pumping is occurring) than vertical gradients in the WS measured at Site 2 over the period of record. Therefore the estimated vertical head gradient in the WS at Site 3 is between 1.5 and 3.5 +/- 25%. The vertical head gradient in the Pudding River flood plain deposits at Site 1 is –0.4 to 0.9 with an error smaller than +/- 25% as the hydraulic conductivity of the flood plain deposits is similar to that of the WA.

4.1.2 Horizontal Head Gradients

Horizontal hydraulic gradients in the WS and between the WS and Pudding River in the vicinity of the field site are controlled by proximity to the Pudding River and are moderately seasonally dependent (Figures 24 and 25). To compare head measurements at approximately equal elevations, head measurements at piezometers with differing screened intervals had to be averaged or compared across non-equal intervals. Horizontal head gradients in the WS were calculated with head measurements at PZ-3S and the average head of PZ-2S and PZ-2I (averaging the screened intervals of PZ-2S and PZ-2I produces nearly the same screened interval as PZ-3S). Horizontal head gradients between the WS and Pudding River were measured between PZ-2S and Pudding River stream stage.

Figure 24: Horizontal Hydraulic Gradients (dh/dx) in the WS with IR-ED Pumping Rate

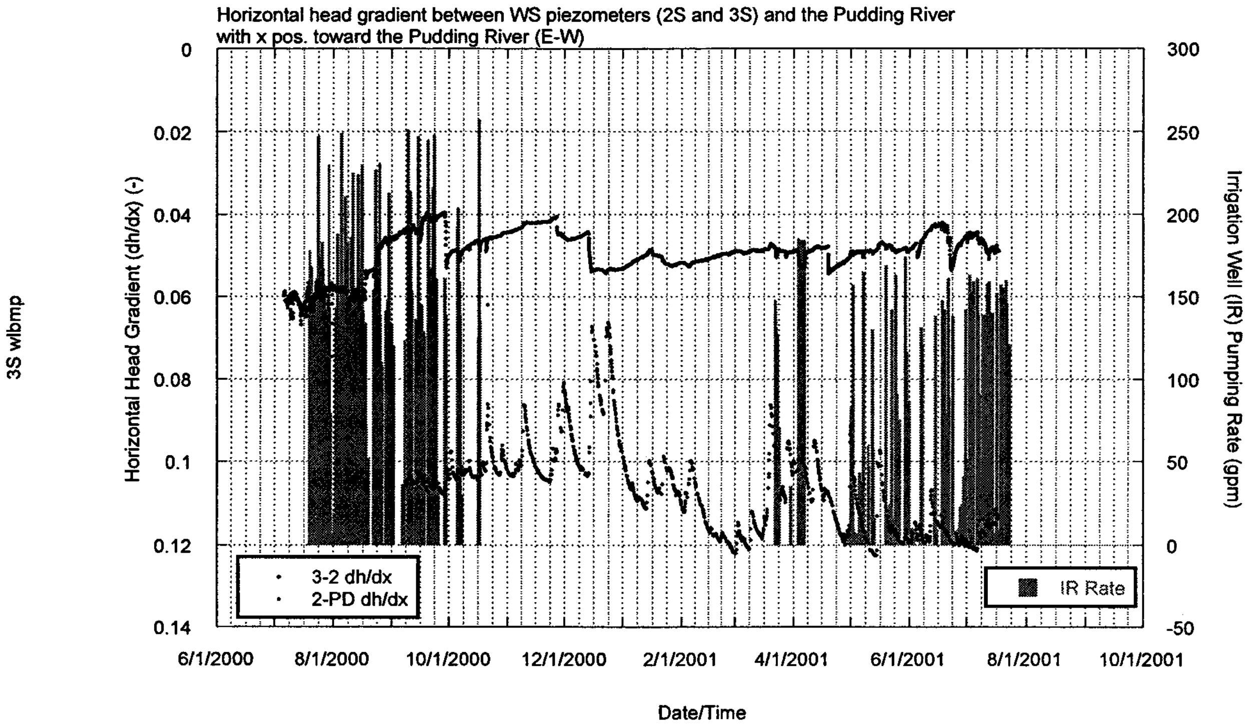
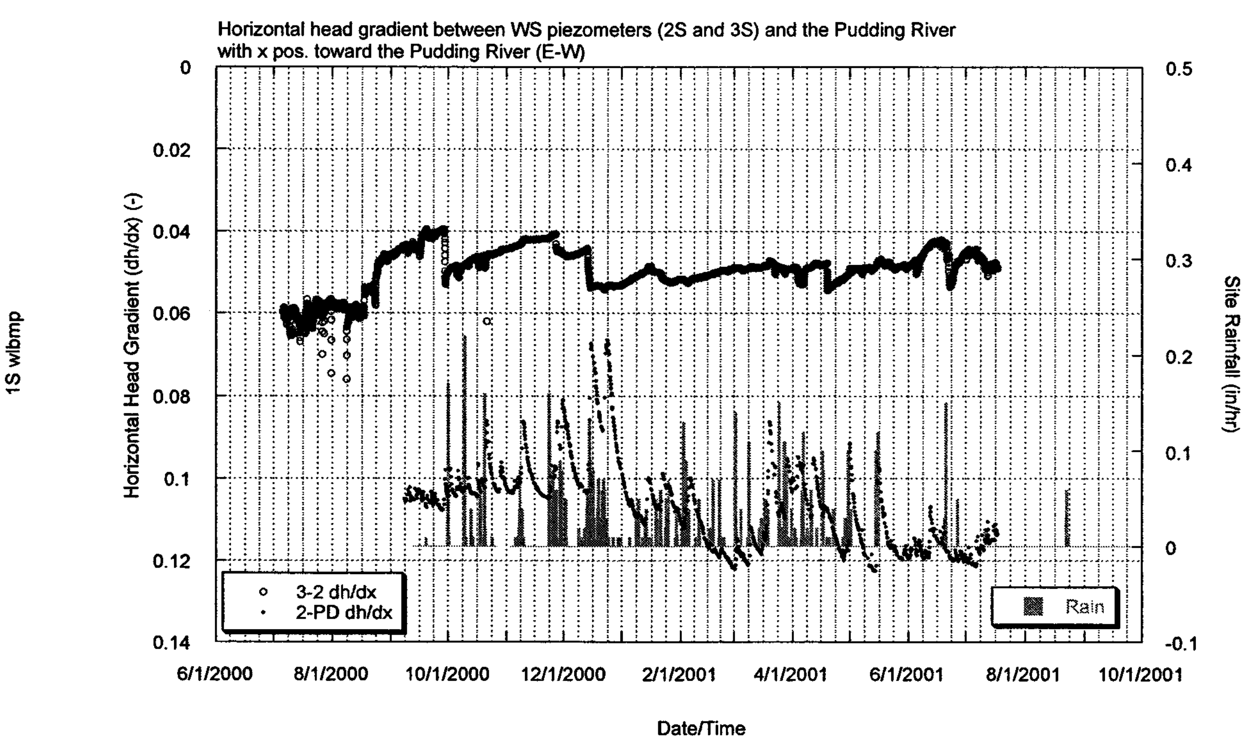


Figure 25 : Horizontal Hydraulic Gradients (dh/dx) in the WS with Local Rainfall



Pudding River stage is approximately the head between the bottom of the Pudding River, 1 m (3 ft.) below the bottom of the PZ-2S screened interval, and the stage of the Pudding River, with average stage being roughly equal to the top of the PZ-2S screened interval. The flashy appearance of the head gradient between PZ-2S and the Pudding River is due to the faster response time and larger precipitation capture zone of the river compared to the WS at Site 2. Further, due to the shorter data set available for the Pudding River, seasonal trends are based on visual extrapolation of data. The absolute 0.02 (unitless) seasonal change in horizontal head gradients in the WS and between the WS and Pudding River are approximately equal. This change relates roughly to a 1.6-fold increase in horizontal gradient in the WS and a 1.2 fold increase in horizontal gradient between the WS and the Pudding River during the winter months. Increase in horizontal hydraulic gradient is due to winter recharge of the WS from precipitation and the lack of depletion by leakage to the WA under the effects of pumping (see Vertical Head Gradient section above). These effects create a greater increase in head in the WA than rise in Pudding River stage.

Horizontal hydraulic gradients increase with proximity to the Pudding River, and to deeply incised streams in general. Horizontal hydraulic gradients are approximately twice as large between Site 2 and the Pudding River as horizontal gradients between Site 3 and Site 2. Without more control on heads in the WS it is difficult to speculate on the function describing this increase in gradient with proximity to deeply incised streams (i.e., logarithmic vs. linear). The horizontal head gradient in the WS (between Sites 2 and 3) is approximately an order of magnitude less than the vertical gradient at Site 2 and two orders of magnitude less than the vertical gradient at Site 3. The horizontal head gradient between Site 2 and the Pudding river is one the same order of magnitude (though consistently half of) the vertical gradient in the WS at Site 2.

Whereas the vertical head gradients are 2 times to 2 orders of magnitude greater than horizontal head gradients, the anisotropic nature of the WS ($K_h > K_v$, due to its origin as a series of layered flood deposits) makes the horizontal flow present at the field site significant to the overall groundwater flow description (Darcy's Law).

4.2 Conservative Tracer Travel Time

4.2.1 Vertical Travel Time

The amount of time it would take for a conservative tracer (i.e., a tracer that does not chemically react with the porous medium) to travel vertically across the Willamette Silt (WS) is complicated by the transient nature of the head gradients at the field site. Both a minimum time (using the maximum observed gradient) and an average time (using the harmonic mean of the gradient over the period of a year) are shown in Table 5. The vertical gradient observed between PZ-2S and PZ-2I is used in this calculation.

The value of vertical hydraulic conductivity (K_v) at the field site is also a source of uncertainty in the calculation. The hydraulic conductivity (K) values calculated from slug tests in the WS are hypothesized to be influenced to some degree by bore skin effects (See Table 3 for results, and Section 3.1.4 for discussion). Further, slug tests are not able to discretely measure K in a specific direction and (if valid) most likely over-predict the vertical K of the silt due to the inherent anisotropy of the medium (horizontal K is likely greater than vertical K due to preferential horizontal deposition of the silt). Permeameter tests of WS core samples do provide a direction-specific K_v of the silt (harmonic mean 2.30 x 10^{-7} m/s neglecting the disturbed surface sample). As discussed earlier, the test is performed on small discrete samples of WS and may under-predict the K_v of the silt as a whole if the unit contains significant preferential paths (a hypothesis that is rejected for the field site in Section 3.2.1) or over-predict the K_v of the silt as a whole if the upper layers of the silt are less compact and/or have an overall coarser grainsize than lower layers.

However, despite uncertainties, permeameter results provide the best available estimation of vertical hydraulic conductivity and are used for K_v in this calculation.

Porosity, the remaining component of the calculation, is more easily defined. Porosity (n_e) was experimentally measured from 8 test hole samples extracted from the top 2 m (6 ft) of the WS and is assumed representative of bulk WS porosity.

Table 5: Min. and Avg. Travel Times of a Conservative Tracer Across the WS

Parameters:	K_v (m/s)	n_e (-)	dh/dz (-)	$v=K_v n_e dh/dz$ (m/s)	WS thickness (m)	$t=d/v$ (years)
Min. Time	2.3×10^{-7}	0.40	0.80	7.36×10^{-8}	18	8
Avg. Time	2.3×10^{-7}	0.40	0.267	2.45×10^{-8}	18	23

The results of these estimates show that if nitrate was conservative in the Willamette Silt, nitrate contamination of the Willamette Aquifer would be expected within approximately 23 years of fertilizer application to the surface. Since analysis of WS bore-hole samples show the nitrate penetration front to be located approximately 8 m (25 ft) below land surface after 57 years of fertilizer application, these estimates give reason to believe that the WS is retarding nitrate transport through biogeochemical reactions (hypothesized to be autotrophic denitrification). This phenomenon will be expanded on in the discussion (Section 6.1).

4.2.2 Horizontal Travel Times

Calculation of the rate at which a conservative tracer can travel horizontally within the WS is complicated by the spatially variable nature of the horizontal head gradients at the field site and, to a lesser degree, the transient variability of the horizontal gradients. Since the function with which horizontal head gradient increases toward the Pudding River is unknown, two horizontal travel rates will be calculated (Table 6). One will relate a maximal horizontal rate of travel valid near (within 50m, 150ft.) the Pudding River (or generally near a deeply incised stream) with the horizontal gradient between Site 2 and the Pudding River. The second will relate a slower travel rate (approaching minimal) valid between 50 and 200 m (150 and 650 ft.) from the Pudding River with the horizontal gradient between Site 3 and Site 2. Temporal variation in horizontal gradients is small (approximately 0.02) and is therefore neglected in these calculations.

Horizontal hydraulic conductivity (K_h) for the WS will be conservatively estimated with the slug test results of PZ-2S (9 x 10^{-6}, see discussion in the previous section). Porosity (n_e) will be taken from lab tests.

Table 6: Horizontal Travel Times of a Conservative Tracer Through the WS

Parameters:	K_h (m/s)	n_e (-)	dh/dx (-)	$v=K_h n_e dh/dx$ (m/s)	distance (m)	$t=d/v$ (years)
Near River	9 x 10^{-6}	0.40	0.10	3.60 x 10^{-7}	50	4
Far-from River	9 x 10^{-6}	0.40	0.05	1.80 x 10^{-7}	150	27

4.2.3 Transport Velocity Vectors in the Willamette Silt

Considering the horizontal and average vertical transport velocities above, conservative solute transport in the WS occurs approximately at a 60 degree downward angle toward the Pudding River (or generally toward a deeply incised stream) at a rate of approximately 5.6×10^{-7} m/s. Note that this vector relates groundwater flow within 200 meters of a deeply incised stream, and flow directions likely become more vertical with greater distance from these streams. Very near the Pudding River (within 50 m) groundwater flow becomes more horizontal and travels more quickly, approximately at a 30 degree downward angle toward the river at approximately 6.4×10^{-7} m/s. While groundwater flow in the WS near the Pudding River is not vertical, as is generally assumed in confining and semi-confining units, the distance vertically across the WS as a whole is much shorter than the distance horizontally through it, yielding shorter travel times (for conservative tracers) in the vertical direction.

4.3 Nitrate and Phosphorous Penetration Fronts

Under the assumption that nitrate and phosphorus have not penetrated completely through the Willamette Silt, nitrate and phosphorus concentrations in samples collected from the bottom of the Willamette Silt (~ 18 m, 60 ft.) are used as background values to judge the vertical progression of the anions. Background levels of phosphorus and nitrate for the field site are approximately 5 ppm and less than 1 ppm respectively. Published background values for dissolved nitrate concentrations in the Willamette Valley fall between 0 and 4 ppm, while background dissolved phosphorus concentrations are between .01 and 0.02 ppm (*Hinkle*, 1997). Note that published background ranges are for dissolved constituents, while field site values were obtained from soil samples. The assumed background nitrate concentration at the field site falls within published values because of the conservative nature of nitrate. The assumed phosphorous background concentration at the field site is much (approximately an order of magnitude) larger than published valued because of the strongly sorbing nature of phosphorus, causing it to concentrate on soil particles.

Figures 10 and 13 show that the phosphorus penetration front is approximately 7 m (23 ft.) below land surface (bls) at Site 2 and approximately 6 m (20 ft.) bls at Site 3. The strongly sorbing nature of phosphorus due to charged attraction and ligand exchange (i.e., phosphorus does not travel conservatively with groundwater flow) is assumed to be responsible for these retarded penetration fronts. Figures 10 and 13 show that the Nitrate penetration front is approximately 8.2 m (27 ft.) bls at Site 2 and 8 m (26 ft.) bls at Site 3. The retardation of the nitrate penetration front is noted in section 4.2.1 and discussed in section 6.1.

4.4 Site Recharge Rate

Recharge to the WS at the field site can be estimated as the fraction of local rainfall passing the root systems of the nursery plants (Plant Evapotranspiration, ET) and the site drain tile system into the Willamette Silt. A tipping bucket rain gauge collected rainfall data at the field site from September of 2000 through the time at which this thesis was prepared. Local rainfall values are plotted with piezometer head values in Figures 5, 7, and 9. The tipping bucket rain gauge recorded 0.46 m (18.14 in) of rainfall at the field site over the 2000 – 2001 water year, 0.097 m (3.84 in.) less than the amount of rainfall NOAA recorded in Salem, OR, approximately 24 km (15 mi.) SW of the field site. As discussed in section 3.1.1, drain tile outflow was less than the instrument recording threshold of 0.069 L/s (1.1 gal/min) year round and estimated to be approximately 0.045 L/s (0.714 gal/min). Roughly estimating that 10% of water applied to the surface of the field site is transported out of the WS by the drain tile network and that ET processes in the rainy season return approximately 30% of rainfall to the atmosphere, recharge to the field site is on the order of 0.28 m (10.8 in.) for the 2000 – 2001 water year. Note that the 2000 – 2001 water year was the second-driest water year for this part of Oregon, so this value is not a good estimate of average yearly recharge rate at the field site.

5. Modeling

5.1 Field Scale Groundwater Flow Model

5.1.1 Model Purpose and Objectives

An interpretive three-dimensional groundwater flow model was constructed for the purpose of addressing the extent to which streams bottoming in the Willamette Silt are hydraulically connected to the Willamette Aquifer. The model was also used to determine the influence that typical pumping rates from the Willamette Aquifer have on groundwater – surface water interaction between deeply incised streams such as the Pudding River and the underlying WS and WA.

The first objective of the modeling effort was to build and calibrate a model to accurately simulate the field pump test conducted between April 3 and April 6, 2001. The second objective was to use the calibrated model to estimate the extent of interaction between the Pudding River and the Willamette Aquifer through the Willamette Silt with mass balance analysis. Note that the model was not constructed for the purpose of estimating heads in the WS or WA, but to quantify the volumetric balance of groundwater flowing through the WS between the WA and the Pudding River.

5.1.2 Conceptual Model Boundary Conditions

Construction of the conceptual model was complicated by the lack of physical and hydraulic boundaries near the field site. Mt. Angel, a basaltic highland upthrust by the Mt. Angel Fault, forms a small physical no-flow boundary on the east side of the model. Other than this feature, no geologic boundaries occur within the model domain.

According to the USGS Regional Aquifer System Analysis (RASA) study of the Willamette Lowland Aquifer System (*Woodward et al.,* 1998) streams in the area bottoming in the WS form groundwater discharge zones under natural (non-pumping) conditions, and are therefore hydraulic barriers to horizontal groundwater flow. However, the effects of pumping can alter the position and effect of these barriers (by reversing the hydraulic gradient). Since it is our goal to study this phenomenon these potential hydraulic barriers are unsuitable for use in the model.

In the absence of physical and hydraulic boundary conditions, non-physically based boundaries were placed at the edges of the model. The Theis drawdown equation, based on pump test results, was used to calculate the distance at which pumping of IR-ED had little (approx. 2 mm) effect on the head field. Constant head boundaries were placed around the model in layers representing the WA at this distance (4 km, 2.5 mi), assumed to be outside the hydrologic influence of the well. No-flow boundaries were placed around the model in layers representing the WS to ensure vertical flow in the unit at the boundaries. The effects of pumping (drawdown) in the numerical model did not extend beyond approximately 1 km (0.6 mi.), validating the assumption that the boundary conditions did not affect the outcome of the model.

5.1.3 Model Design and Results

The numerical model employed MODFLOW, the USGS modular three-dimensional finite-difference groundwater flow model (*McDonald and Harbaugh,* 1996). The model was initially constructed with the aid of GMS 3.1, a MODFLOW pre- and post- processing program developed by Boss Intl. Using GMS, ESRI Arc/view GIS coverages containing registered locations of wells, rivers, and other features were used to define the conceptual model. Transient data gathered at the field site (pumping rate, rainfall, river stage, etc.) were used in the model whenever possible. Hydraulic parameters from field (pump and slug test) and lab (grain-size analysis and permeameter test) experiments were used in the model as initial parameters.

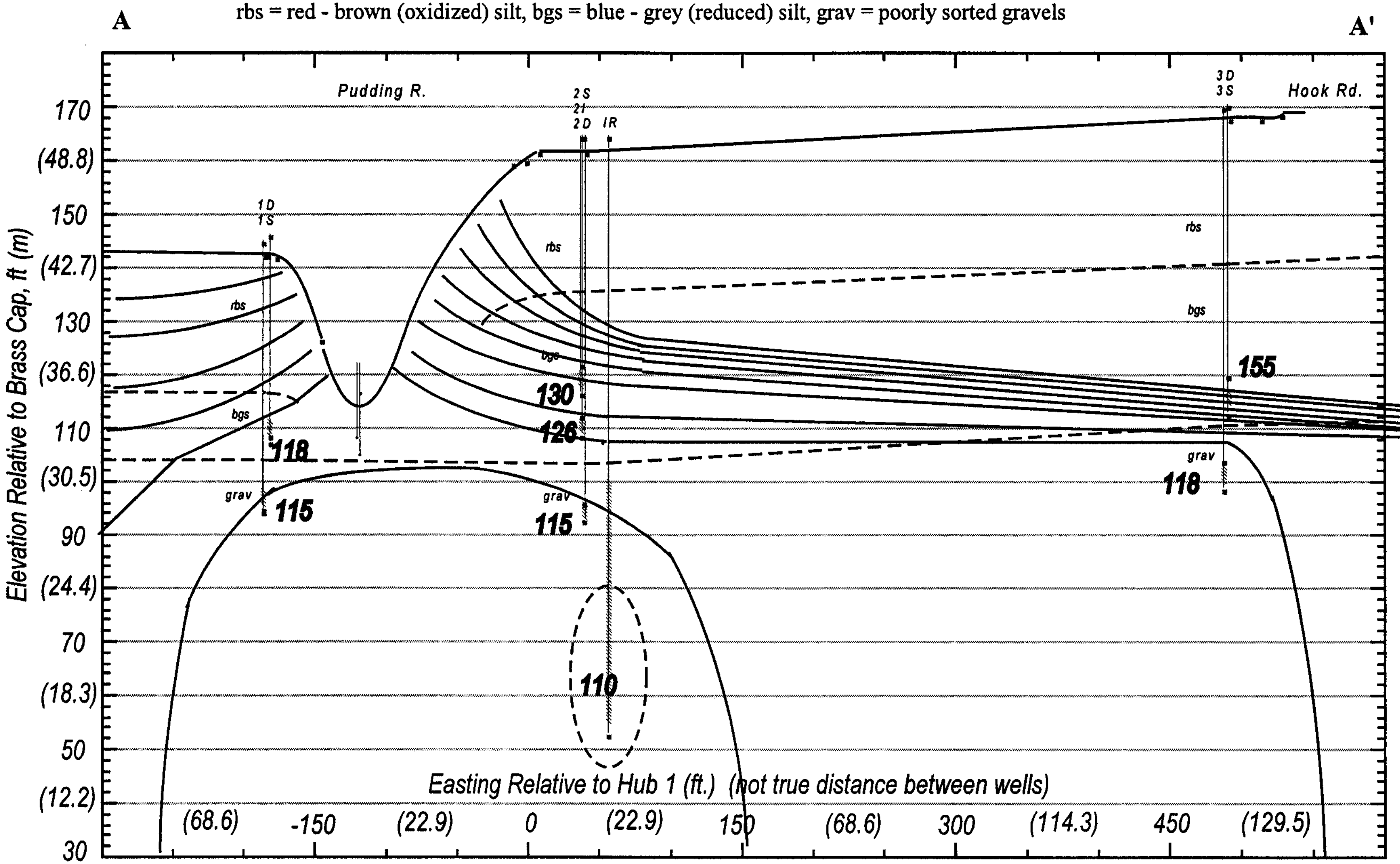
Semi-quantitative vertical head maps of the field site sketched along the A-A' cross section (Figure 26) showed that the largest vertical head drop at the field site was in a relatively small vertical range just above the WS/WA contact. This observation is interpreted to be due to the low *K* poorly sorted gravel in matrix support noted later in the discussion (Section 6.1). In order to capture this vertical head change in the model, 11 layers were used, 9 to model the WS and 2 to model the WA. The surface (top of layer 1) is constructed from the USGS 10m DEM file for the Silverton Quadrangle. The WS/WA contact (bottom of layer 9) and the WA/Willamette Confining Unit contact (bottom of layer 11) are interpolated from contact elevation data compiled for the USGS RASA study of the Willamette Lowland Aquifer System (*Woodward et al.*, 1998). The bottom of layer 10 is placed 18 m (60 ft.) below the WS/WA contact, corresponding to the screened interval of well IR-ED. The bottom elevation of layers 1-8 are distributed between the land surface and the WS/WA contact with layers thinner near the contact in order to capture the large vertical head gradient predicted to be in that area.

An irregular grid was used in the model due to the large areal extent of the model necessitated by the choice of boundary conditions. The grid is based on a 1 m^2 cell centered on IR-ED, with the grid expanding by a factor of 1.3 in the x-direction (E-W) and 1.4 in the y-direction (N-S) to a maximum size of 300 m^2. The grid is finer in the x direction to better refine model output relating interaction between the WA and the Pudding River (which runs predominantly from S to N across the model).

The initial head array and constant head boundary conditions for the model were based on the generalized USGS RASA head map presented by Woodward et al. (1998). The generalized head values presented in the report were similar to the early spring (pre- pump test) heads in the WA observed near the field site and were used for layers 10 and 11.

Figure 3b: Site Cross Section A - A'. Elevation in feet above mean sea level.

Semi-analytical vertical head map based on August 2001 water levels (bold, in feet amsl), 5 foot contours
rbs = red - brown (oxidized) silt, bgs = blue - grey (reduced) silt, grav = poorly sorted gravels



Initial head conditions in the Willamette Silt were constructed by adding head to the RASA contours according to observed vertical head gradients in the WS at the field site. The model was roughly calibrated at steady state without pumping to let the MODFLOW model construct a head field congruent with river stage and constant head boundary conditions. This steady state solution was then used as the initial head field in the transient model. Updated initial head fields were created during the calibration process as the parameter values evolved. Figures 27a and 27b show plan and cross section views of the model through the layer or row at which the pumping well is located and demonstrate grid spacing, layer spacing, and initial head fields, as well as river, observation well and other attribute locations.

5.1.4 Model Sensitivity Analysis

Once the model was run with field test hydraulic parameters (and after changes to parameters were made during manual calibration), parameter sensitivity analyses were performed with UCODE, an inverse modeling program developed by the USGS (Potter and Hill, 1998). Results of sensitivity analyses indicated that the vertical hydraulic conductivity of the WS was the most sensitive parameter with respect to its ability to influence the fit of observed vs. modeled drawdown at observation wells under the effects of pumping. The horizontal conductivity and specific storage of the WA were moderately sensitive parameters. The value of streambed conductance was the least sensitive parameter. Relative parameter sensitivities are given in Table 7.

Figure 27a: Plan View of Three Dimensional Numerical Flow Model

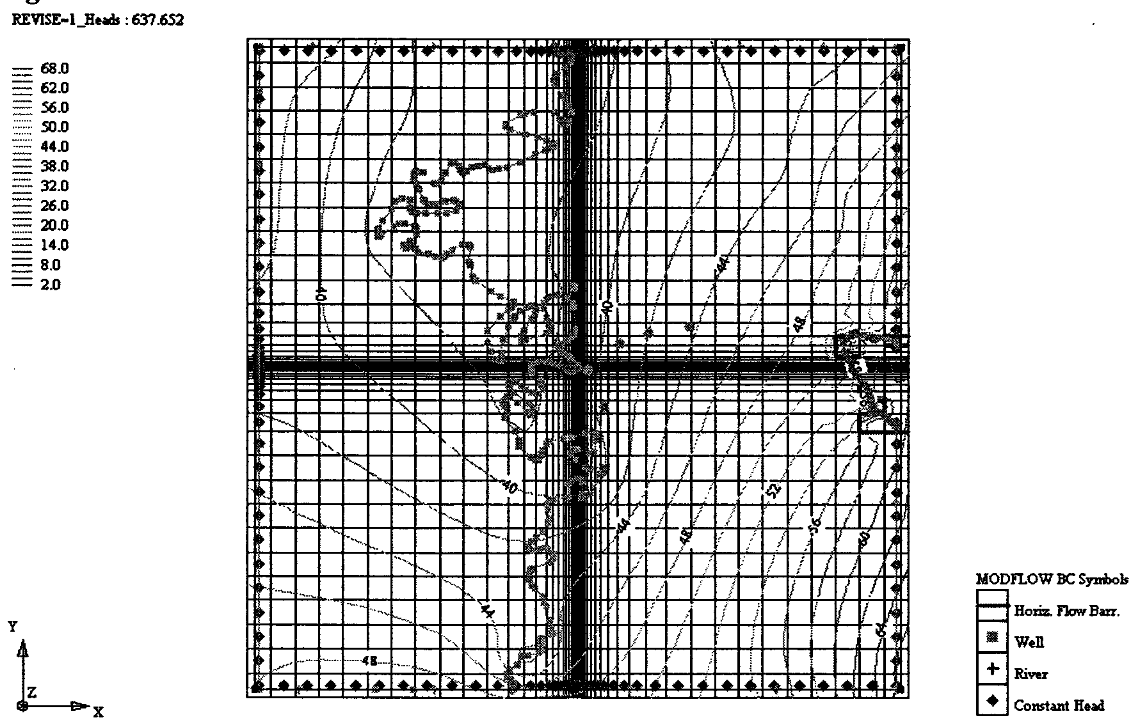


Figure 27b: Cross Section of Three Dimensional Numerical Flow Model

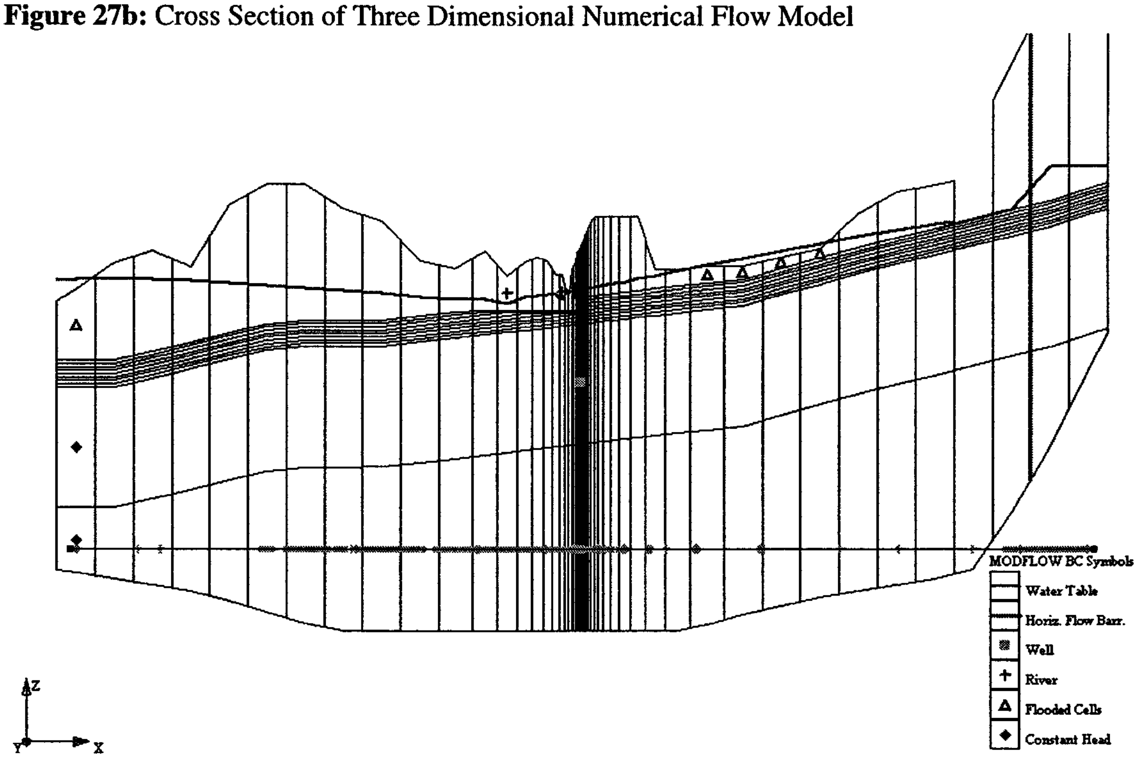


Table 7: Relative Sensitivity of Model Parameters to Modeled vs. Observed Drawdown. Sensitivities calculated with UCODE and normalized to a scale from 0-1.

Parameter	WS K_v	WA S_s	WA K_h	WS S_s	WA K_v	WS K_h	Riv Cond
Norm. Sens.	0.725	0.437	0.422	0.220	0.002	0.001	0.0003

5.1.5 Model Calibration

The transient model (simulating the April 2001 pump test) was calibrated with drawdown values observed during the April 2001 pump test at site piezometers and the five additional instrumented irrigation wells. Modeling this time period provided the best time sequence for calibration of the model as no other groundwater users were active and the largest and most diverse data set was recorded.

As stated above hydraulic parameters computed for the WS and WA with pump and slug test analysis were used as initial parameters in the model. The bottom of the Pudding River is composed mostly of sand except where it scours to bedrock (Willamette Aquifer Material), which is hypothesized to be the controlling factor on leakage to and from the Pudding River. As riverbed conductance plays little role in the conceptual model and is a low sensitivity parameter in the numerical model (see Table 7) it was set to a commonly published value of hydraulic conductivity for sand (1×10^{-3} m/s) multiplied by the stream bed dimensions of the Pudding River.

These initial parameters produced calculated drawdown curves that matched observed data for the first 24 hours of the pump test at wells IR-ED and IR-EU. After manual calibration to roughly match modeled and observed drawdown at observation wells over the three day time period of the test, hydraulic parameters were optimized with UCODE to obtain the best possible fit (See Appendix F for plots of observed vs. modeled drawdowns). The UCODE parameter optimization code returned values for hydraulic parameters which agreed well with all field and lab determined hydraulic parameter values except for the K_v of the WS. Table 8 displays the model optimized and field and lab measured values.

Table 8: Model Optimized and Observed Parameters

	Willamette Aquifer			Willamette Silt		
Parameter	K_h (m/s)	K_v (m/s)	S_s (1/m)	K_h (m/s)	K_v (m/s)	S_s (1/m)
Model Opt.	2.4×10^{-5}	2.4×10^{-5}	3.2×10^{-6}	1×10^{-7}	1.5×10^{-9}	8×10^{-4}
Observed	7.0×10^{-5}	2.4×10^{-5}	3.8×10^{-6}	7×10^{-6}	3×10^{-7}	-
Obs. Pt. or Method	Avg. WA pump test result	Avg. WA pump test result	Avg. WA pump test result	Avg. WS slug test result	Avg. WS permeameter result	-

The modeled drawdown at IR-EG is more than the observed drawdown due to the presence of a holding pond adjacent to the well that was unmonitored and not modeled but assumed to leak to the aquifer during the pump test. Model fit to observed drawdown at site piezometers was poor. The greater observed than modeled drawdown at PZ-2S may be the result of its proximity (same layer, 6 cells away) to the Pudding River in the model.

5.1.6 Model Results

Simulated drawdown due to pumping from the Willamette Aquifer appears to reach a recharge boundary (form a suitably large capture area) approximately 3.5 days after pumping begins. Mass balance analysis shows that diffuse leakage from storage in the Willamette Silt is the dominant source of the recharge to the WA and the limiting factor for drawdown in the Willamette Aquifer. Comparison of the volumetric budget output from the groundwater flow model run under pumping and non-pumping conditions (Table 9, Scenario 1) shows the transient model mass balance over the duration of the pump test.

Table 9: Groundwater Flow Model Mass Balance

	Scenario 1. Optimized	Scenario 2. WS K_v * 100	Scenario 3. WS S_s /100	Scenario 4. Pumping 5 mo.
% Storage	99.8	87.8	91.8	70.1
% Const. Head	0.1	0	3.7	21.4
% Riv. Leakage	0.1	12.2	3.5	6.6

The volumetric budget shows that less than 1% of the total water pumped from the aquifer during the 3 day pump test was drawn into the model domain from the Pudding River and more than 99% came from storage in the WS. Table 9 shows the contribution of the three sources of water in the model (as percent of pumped volume) for three other parameter scenarios. The three alternate scenarios kept all but one parameter optimized, in Scenario 2 the harmonic mean of vertical conductivity values calculated from permeameter analysis (assumed to be the maximum K_v of the unit, approximately 100x the optimized value) was modeled, in Scenario 3 a value of specific storage 100x less than optimum was modeled (an unrealistically small S_s), and in Scenario 4 the pumping rate observed at the field site averaged over the summer pumping season was modeled.

The parameters modified in scenarios 2 and 3 were chosen for modification based on targeted sensitivity analyses performed to determine which parameters had the greatest influence on the conclusions drawn from the model (i.e., the difference in the volumetric balance of flow between the Pudding River and WS under the influence of pumping). The sensitivity of the model conclusion was calculated as:

$$S_c = \left| C_{p_i} \frac{dQ_{PR}}{dp_i} \right|$$

where S_c is the sensitivity of the conclusion, C_{pi} is the confidence interval for the parameter, p_I is the parameter tested, and Q_{PR} is the volumetric flow between the Pudding River and the WS. The induced change in parameter input values were calculated by multiplying the optimized values by one tenth of a log interval. The sensitivity of the conclusion was normalized by multiplying the derivative by the confidence interval of the parameter in log space. The value and source of the confidence intervals are presented with the results of the sensitivity analyses in Table 10.

Results of sensitivity analyses indicated that the specific storage (S_s) of the WS was the most sensitive parameter in the model with respect to its ability to influence the volumetric balance of flow between the Pudding River and the WS under the influence of pumping. The horizontal and vertical hydraulic conductivity of the WS were moderately influential parameters. The conclusions of the model were least sensitive to the values of streambed conductance, horizontal and vertical hydraulic conductivity of the WA , and specific storage of the WA.

Table 10: Model Conclusion Sensitivity Analysis.
Parameters are listed in order of their influence on the conclusion of the model.

Parameter	**Log Confidence** (i.e. +/- 10^{-x})	**Source**	**Sensitivity** (m^3)
WS S_s	1	Domenico and Schwartz, 1990	32.18
WS K_v	2	Permeameter Test	1.62
WS K_h	2	Slug Tests	1.14
PR Spec. Cond.	2	Value for WS K_v	0.26
WA K_v	0.5	Pump Test	0.065
WA K_h	0.5	Pump Test	0.035
WA S_s	0.05	Pump Test	0.0125

Scenario 2, inputting the maximum reasonable value of K_v for the WS, produced the most dramatic change in the distribution of water sources (Table 9). The 100x greater vertical hydraulic conductivity allowed 12% of the total amount water pumped from the WA to be recharged from river leakage. With this large vertical conductivity scenario the WS wells were computed to be drawdown much further than observed while the WA wells received a large amount of water and had much smaller drawdowns than observed during the pump test (Appendix F). Altering the specific storage by a factor of 100 had a moderate effect on the outcome of the distribution of recharge sources, increasing the amount of water from river and constant head leakage to 3.5% each. With this small specific storage scenario all computed drawdowns were greater than observed drawdowns, except in the case of PZ-2S which did not seem to be affected (Appendix F). As the model was not meant to allow boundary condition interaction, results produced by scenario 4 over a five-month time period in which the cone of depression reached the model boundary can not be validated.

Note that though WS S_s was found to be the parameter most important to the model conclusions (i.e., the volumetric balance of flow between the Pudding River and WS under the influence of pumping), the percentage of water removed from the Pudding River in Scenario 3 was less than that in Scenario 2. This discrepancy exists because the sensitivity was calculated as a derivative with a change in parameter values of 1/10 of a log cycle beyond the optimized value, whereas the three "worst case" scenarios were run with changes in parameter values of 2 log cycles. As the influence of individual parameters is not linear, the large change in WS S_s was not substantially more significant than a small change in the parameter. In fact, the same percentage of water from the Pudding River under pumping conditions would have been calculated whether the WS S_s was decreased by 1 or by 2 log units.

6. Discussion

6.1 Nitrate Transport in the Willamette Silt

As stated in section 4.2.1, a discrepancy exists between the observed nitrate penetration front and the calculated vertical travel time for a conservative tracer, leading to the conclusion that transport of nitrate in the WS is being retarded through denitrification reactions. Figures 28 and 29 show plots of nitrate and pH from bore hole split spoon and continuous core samples verses depth below land surface (bls). A general trend of increasing pH (more reducing conditions) and decreasing nitrate with depth can be seen at both Site 2 and Site 3. This trend presumably exists because autotrophic denitrification can be a H^+ consuming reaction (e.g. *Korom*, 1992; *Robertson et al.*, 1996). (Nitrate concentrations increase with depth for approximately the first meter (3 ft) because plant roots assimilate nitrate near the surface).

Further, the depth at which the trends stabilize at background conditions (nitrate ~ 0-2 ppm, pH ~ 8.5), between 6 m and 9 m (20 ft and 30 ft) bls, is coincident with the reduction – oxidation (RedOx) boundary identified visually in core samples at Sites 2 and 3. This visual boundary is also noted in a majority of OWRD well logs for proximal irrigation and domestic wells (Appendix B). The RedOx boundary is visible in core as a sharp contact between oxidized red-brown silt and reduced blue-gray silt. Lind (1983) reported a similar RedOx boundary in a clay aquitard in Denmark. The boundary was identified visually by a distinct transition between oxidized red-brown material and reducing blue-gray material and corresponded with the stabilization of a decreasing nitrate trend and an increasing iron (II) trend with depth.

Figure 29: Site 2 Split Spoon Sample Chemical Analysis

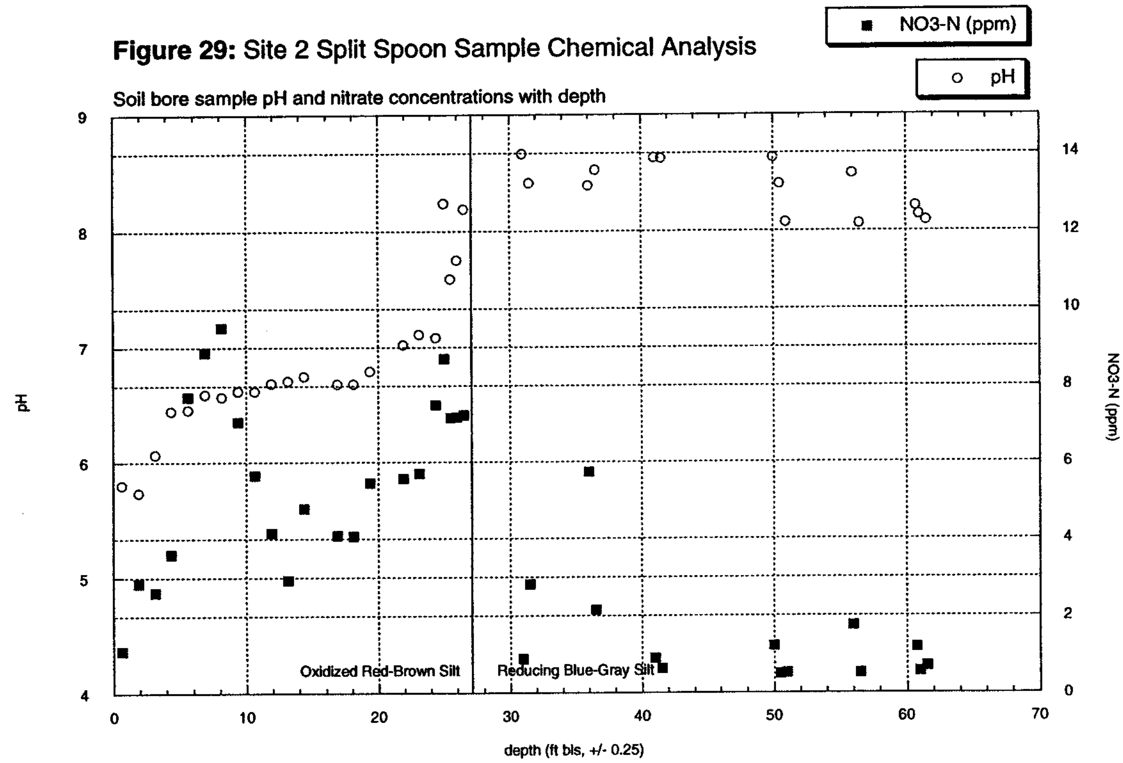
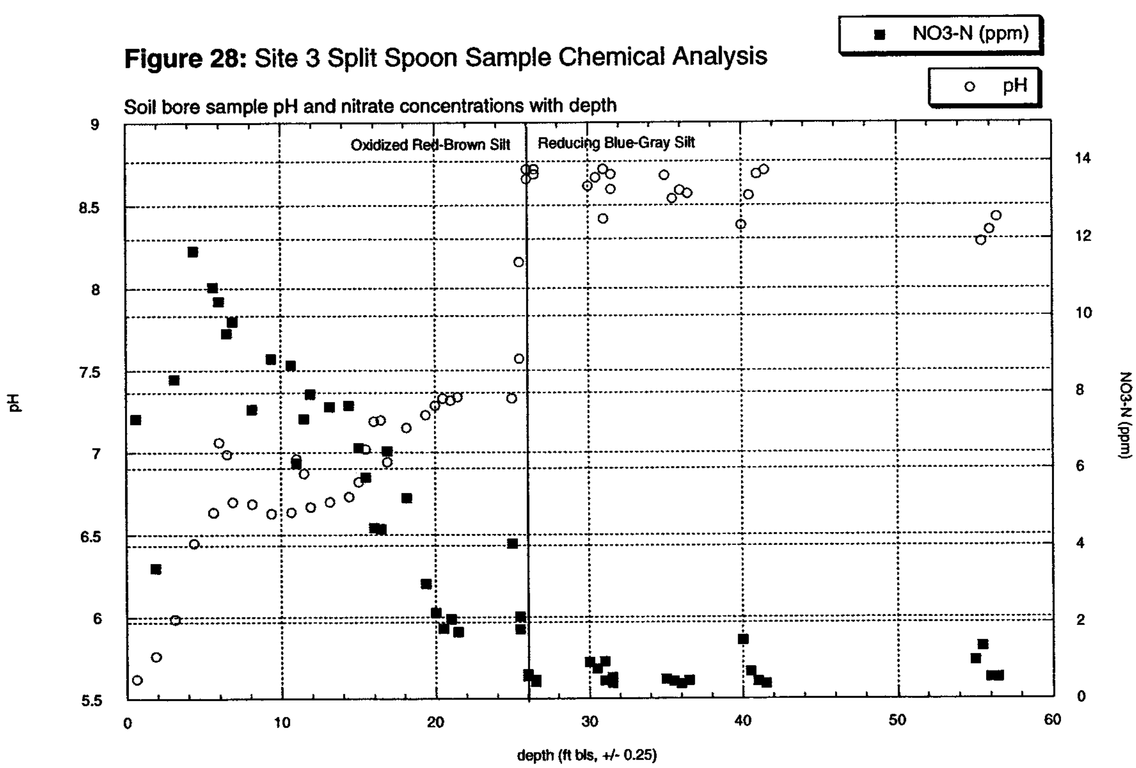


Figure 28: Site 3 Split Spoon Sample Chemical Analysis



Autotrophic denitrification is hypothesized to be the dominant control on nitrate transport in the WS and may be dependent on the RedOx condition of the WS. In the absence of organic carbon (OC), nitrate is relatively stable (and therefore conservative) under oxidized conditions (i.e., lack of reduced compounds acting as electron donors). However, nitrate is thermodynamically unstable under reducing conditions and, in the presence of appropriate denitrifying bacteria, converted to nitrous oxide (N_20) or nitrogen (N_2) gas (*Korom*, 1992). As this reaction takes place, the WS becomes oxidized at the reaction front, loosing the ability to further aid the denitrification process.

If this hypothesis is correct, nitrate will act as a conservative tracer in the oxidized zone and may have implications for water quality in streams bottoming in the WS. First, the RedOx boundary has propagated below the level of conventional drain tile networks, offering no denitrification buffering potential to captured water that is commonly routed directly into nearby streams. Further, as the (approximately horizontal) RedOx boundary moves downward, nitrate passing below the drain tile network may travel further horizontally without encountering the boundary. This process will effectively increase the amount of un-buffered (nitrate rich) water that seeps from the WS directly to streams.

The presence of a RedOx front (with oxidized conditions above and reducing conditions below) will indicate the location of the nitrate front under equilibrium conditions. If this hypothesis proves true, the rate at which the RedOx boundary is propagating downward through the silt will be essential information for managing the water quality of the WA and streams bottoming in the WS. Further documentation of this hypothesis, including the nature and rate of the reaction and the rate of propagation of the RedOx boundary will necessitate further study.

6.2 Key Parameters Controlling Groundwater / Surface Water Interaction

The vertical hydraulic conductivity of the Willamette Silt (WS K_v), the parameter most important to the quality of the groundwater flow model (i.e., the fit of modeled to observed drawdown at observation wells) is the parameter with the greatest factor of uncertainty. The specific storage of the Willamette Silt (WS S_s), the parameter most important to the outcome of model conclusions (i.e., the difference in the volumetric balance of flow between the Pudding River and WS under the influence of pumping) is the parameter with the second greatest factor of uncertainty. While the exact value of WS S_s is most important only in the immediate numerical vicinity of the optimized parameters (see Section 5.1.6), the value of WS K_v is important over many orders of magnitude. Many factors, including difficulty in piezometer installation, uncertainty in the quality of piezometer connection, inability to collect intact and/or uncompressed core samples from depth for lab analysis, and the lack of a longer term pump test have lead to large confidence intervals on WS S_s and WS K_v.

The physical properties of the WS and WA materials proved problematic for installation of piezometer bore holes with a hollow stemmed auger. The fine grained Missoula Flood Deposits, which make up the WS, smeared extensively when exposed to the blades of the auger. Further, with the inability to insert gravel down the hollow stem of the auger flights during well emplacement, a large amount of material (below the water table) caved into the open bore during removal of auger flights. This fine grained material surrounded the well screen with in an chaotic mass, as opposed to the laminated structure of the surrounding WS. The auger did not have enough torque or mass to drill through the poorly sorted gravel in matrix support (PSGMS) assumed to constitute the top of the WA. This resulted in deep piezometers placed with screened intervals high in the WA in a "tight" portion of the formation. Wells placed in the WA were also susceptible to filling with caved WS materials during auger flight removal.

Due to these difficulties, the effectiveness of the hydraulic connection of piezometers to the surrounding material is uncertain, though a large effort was made to fully develop the wells (See Section 3.1.1). Qualitatively, Site 3 piezometers were installed with more difficulty (more bore hole disturbance and caving) than Site 2 piezometers, which were in turn installed with more difficulty than Site 1 piezometers (installed in shallow materials more accommodating to the use of a hollow stem auger). Analysis of well test results was complicated by the unknown effects of the difficulty experienced in completion of the piezometers and the uncertainty in their connection to the surrounding media.

Slug test results from piezometers screened in similar materials (i.e. WA piezometers screened in gravel in matrix support and WS piezometers at Sites 2 and 3 screened in clayey silt) have hydraulic conductivity values varying over orders of magnitude (Table 3, Section 3.1.4), resulting in large confidence intervals. Since slug tests give local hydraulic conductivity near the well screen, the results of the slug tests are interpreted to be significantly affected by the quality of hydraulic connection between piezometers and the surrounding material (WS or WA). For example, Piezometer 3S, which shows the lowest hydraulic conductivity, was the well at which the most difficulty in drilling was experienced (loss of drill head due to shearing of head bolts, auger removal in the middle of drilling and re-drilling).

Despite this uncertainty however, it is also notable that (neglecting PZ-3S) the hydraulic conductivity of the WS decreases with depth, which may be due in part to greater compaction of the Missoula Flood Deposits that make up the unit at depth. Also, though assumed to be part of the WA, the poorly sorted (perhaps somewhat cemented) gravel in matrix support (PSGMS) present at the top of the unit has a smaller hydraulic conductivity than the overlying silt. The inability to bring an intact sample of the material to the surface necessitates some assumption as to the physical properties of the upper portion of the WA, which could conceivably have been weathered and/or cemented to some extent before deposition of Missoula Flood Deposits. The unit is recognized as a hard to drill "cemented conglomerate" in OWRD logs for nearby wells, indicating that the unit is somewhat spatially continuous and well consolidated. Though the exact difference in K_v is uncertain, the hydraulic conductivity of the PSGMS is interpreted by all estimates to be less than that of the overlying silt.

As can be seen in the model sensitivity analysis (Section 5.1.4), the value of vertical hydraulic conductivity (K_v) in the Willamette Silt was the dominant controlling factor for model fit to observed drawdown values. A K_v value of 1.5 x 10^{-9} in the WS (a value near the minimum K_v calculated from field slug tests at PZ-3D) produced the most satisfactory fit of model drawdown to observed drawdown at monitored irrigation wells. This value is lower than all observed slug test and permeameter test results but is not considered to be an unreasonable value for the parameter in the model.

As discussed above, slug tests measure dominantly horizontal hydraulic conductivity and permeameter tests were performed on near-surface samples. The optimized parameter is interpreted to represent the bulk vertical hydraulic conductivity of the WS and the PSGMS, or the harmonic mean of the vertical conductivity of each successive Missoula Flood Deposit and the low conductivity top portion of the WA. A low conductivity layer near the WS/WA contact such as the horizon of poorly sorted gravel in matrix support is also predicted by head map analysis (discussed in section 5.1.3) and may reasonably be responsible for this low average K_v.

There is a strong need for an effective K_v at the scale of the WS, obtainable with descrete measurements of WS K_v through the entire thickness of the WS and into the uppermost portion of the WA. Further, if the upper portion of the WA does prove to control the effective WS K_v, a study of the spatial extent of the consolidated portion of the unit needs to be made to determine the breadth of influence of the unit. These measurements are the most important future piece of information needed to augment this project and to help form water use policy in the future.

7. Conclusions

7.1 Chemical Transport in the Willamette Silt

Through a quantitative understanding of the movement of groundwater across the Willamette Silt (WS) based on field measurements, transport vectors of agricultural leachate are derived and first approximations to travel times are calculated. Conservative (non-reactive) solutes traveling with the dominant groundwater flow regime are estimated to follow at a 60-degree downward angle in the Willamette Silt toward local deeply incised streams. Though transport direction is angular, the distance vertically across the WS is much shorter than the distance horizontally through it, yielding much shorter travel times (for conservative tracers) in the vertical direction. The time required for a conservative tracer (i.e., a tracer that does not chemically react with the porous medium) to travel vertically across the Willamette Silt (WS) is complicated by the transient nature of the head gradients at the field site. Minimum vertical travel times across the WS for conservative tracers (given maximum winter hydraulic gradient) are calculated to be approximately 8 years, though average travel times are more likely near 23 years. Thus, a conservative solute would be expected to travel from the surface to the boundary between the WS and Willamette Aquifer (WA) in approximately 23 years. We emphasize here that the aquatic pollutants of concern are **not** transported conservatively through the entirety of the WS, and so this is certainly an underestimate of the transport time. The magnitude of the underestimate, however, is unknown.

The large combined surface area of small matrix particles (silt and clay) that make up the Willamette Silt (WS) form a sink for phosphorus and other sorbing solutes. This physical property of the WS is a controlling factor on the rate of propagation of non-conservative (sorbing) solutes. Assuming background concentrations of phosphorus at the field site are approximately 5 ppm, Figures 10 and 13 show that the phosphorus penetration front is approximately 7 m (23 ft.) bls at Site 2 and approximately 6 m (20 ft.) bls at Site 3.

Field observations of retarded nitrate (a conservative, non-sorbing solute in the absence of denitrification) penetration fronts give reason to believe that the WS is retarding nitrate transport through biologically mediated denitrification reactions. A general trend of increasing pH and decreasing nitrate with depth can be seen at both Site 2 and Site 3 in Figures 28 and 29. Further, the point at which the trends stabilize at background levels, between 6 and 9 m (20 and 30 ft) bls, is coincident with the reduction – oxidation (RedOx) boundary visually observed in the core samples to occur between oxidized red-brown silt and the reducing blue-gray silt. We hypothesize that autotrophic denitrification is the dominant control on nitrate transport in the WS and is dependent on the RedOx condition of the WS. The rate of movement of the RedOx boundary, therefore, may control the time at which nitrate reaches the Willamette Aquifer over much of the Willamette Valley. Further documentation of this hypothesis exploring the nature and rate of the reaction as well as the rate of propagation of the RedOx boundary will necessitate further study.

7.2 Effects of Pumping in the WA on Streams Bottoming in the WS

Numerical model analysis of a 3-day pump test conducted in the Willamette Aquifer shows that the Willamette Silt provides a source of diffuse recharge to the WA under stressing conditions that accounts for more than 98% of the total water removed from the Willamette Aquifer. Volumetric balance analysis shows that less than 1% of the water removed from the aquifer at a pumping well near the river was recharged to the Willamette Silt from the Pudding River. Using alternate values of vertical hydraulic conductivity and specific storage for the Willamette Silt (maximum and minimum values respectively) model analysis shows that the Pudding River could contribute a maximum 12% of the water pumped from the Willamette Aquifer.

Uncertainty in the physical structure responsible for the low effective vertical conductivity necessary for a good numerical model fit to observed conditions needs to be rectified in order to validate the range of applicability of the model. If compacted silt near the WS/WA contact is responsible, the model will be valid over most of the central and south Willamette Valley. If the poorly sorted gravel in matrix support (PSGMS) which forms the top of the WA is the responsible structure, it's areal extent will determine the spatial applicability of the model.

References

Allen, I. S., 1978, Late Pleistocene sediments and floods in the Willamette Valley: The Ore Bin, v. 40, no. 11, p. 177-191, and no. 12, p. 193-202.

Anderson, M.P., and W.W. Woessner, 1992. Applied Groundwater Modeling: Simulation of Flow and Advective Transport. Academic Press, 381p.

Bredehoeft, J.D., C.E. Neuzil, and P.C.D. Milly, 1983, Regional flow in the Dakota Aquifer: a study of the role of confining layers: USGS, Water Supply Paper 2237, 45p.

Dawson, *K*.J. and Istok, J.D. 1991. Aquifer testing: design and analysis of pumping and slug tests. Lewis Publishers, Inc., 344p.

Domenico, P.A., and F.W. Schwartz, 1990, Physical and Chemical Hydrogeology, John Wiley and Sons, N.T., 824p.

Fetter, C.W., 1994, Applied Hydrogeology (3rd edition), Merrill Publishing Co., Columbus, Ohio, 592p.

Friedman, R., C. Ansell, S. Diamond, and Y.Y Haimes, 1984, The use of models for water resources management, planning and policy. Water Resources Research, v. 20, no. 7, pp. 793-802.

Gannett, M.W., and R.R. Caldwell, 1998, Geologic Framework of the Willamette Lowland Aquifer System, Oregon and Washington: U.S. Geological Survey Professional Paper 1424-A, 32p., 8pl.

Glenn, J.L., 1965, Late Quaternary sedimentation and geologic history of the north Willamette Valley, Oregon: Corvallis, Oregon State University, Ph.D. dissertation, 231p.

Hemker, C.J., 1999a, Transient well flow in vertically heterogeneous aquifers: Journal of Hydrology, v. 225, pp. 1-18

Hemker, C.J., 1999b, Transient well flow in layered aquifer systems: the uniform well-face drawdown solution: Journal of Hydrology, v. 225, pp. 19-44.

Hinkle, S.R., 1997. Quality of Shallow Ground Water in Alluvial Aquifers of the Willamette Basin, Oregon, 1993-95. : U.S. Geological Survey Water-Resources Investigations Report 97-4082-B, 48p.

Korom, S., 1992, Natural Denitrification in the Saturated Zone: A review. Water Resources Research, v. 28, no. 6, pp. 1657-1668.

Lind, A. –M., 1983, Nitrate reduction in the subsoil, *in* Denitrification in the Nitrogen Cycle, edited by H.L. Golterman, pp. 145-156, Plenum, New York, 294p.

McDonald, M.G., and A.W. Harbaugh, 1988, A modular three dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 14 chapters.

Meigs, L.C., and J.M. Bahr, 1995, Three-dimensional groundwater flow near narrow surface water bodies. Water Resources Research, v. 31, no. 12, pp. 3299-3307.

Nield, S.P., L.R. Townley, and A.D. Barr. 1994, A framework for quantitative analysis of surface water – groundwater interaction: Flow geometry in a vertical section. Water Resources Research, v. 30, no. 8, pp. 2461-2475.

Niem, A.R. and W.A. Niem, 1984, Cenozoic geology and geologic history of western Oregon, *in* Atlas of the ocean margin drilling program, western Oregon-Washington, continental margin and adjacent ocean floor, Region B, Kulm, L.D., and others, eds.: Ocean Margin Drilling Program Regional Atlas Series, Atlas 1, Marine Science International, Woods Hole, Massachusetts, sheets 17 and 18.

O'Conner, J.E., A. Sarna-Wojcicki, K.C. Wozniak, D.J.Polette, and R.J. Fleck. 2001. Origin, extent, and thickness of quaternary geologic units in the Willamette Valley, Oregon: U.S. Geological Survey Professional Paper 1620, 52p., 1plate.

Rinella, F.A., and M.L. Janet. 1997. Seasonal and Spatial Variability of Nutrients and Pesticides in Streams of the Willamette Basin, Oregon, 1993-95: U.S. Geological Survey Water-Resources Investigations Report 97-4082-C, 59p

Robertson, W.D., B.M. Russell, and J.A. Cherry. 1996. Attenuation of nitrate in aquitard sediments of southern Ontario. Journal of Hydrology, v. 180, pp. 267-281.

Townley, L.R. and M.G.Tefry. 2000. Surface water – groundwater interaction near shallow circular lakes: Flow geometry in three dimensions. Water Resources Research, v. 36 no. 4, pp. 935-949.

Wheatcraft, S.W. and F. Winterburg. 1985. Steady state flow passing through a cylinder of permeability different from the surrounding medium. Water Resources Research, v. 21, no. 12, pp.1923-1929.

Woodward, D.G., M.W. Gannett, and J.J. Vaccaro, 1998, Hydrogeologic Framework of the Willamette Lowland Aquifer System, Oregon and Washington: U.S. Geological Survey Professional Paper 1424-B, 82p., 1pl.

Wroblicky, G.J., M.E. Campana, H.M. Ballett, and C.N. Dahm, 1998, Seasonal-variation in surface-subsurface water exchange and lateral hyporheic area of two stream-aquifer systems, Water Resources Research, v.34, no. 3, p. 317-328.

APPENDICES

APPENDIX A:

Crops Grown at the Field Site Since 1983

Table A1: Crops grown at field site since 1983. Information based on interview with landowner.

Years	Crop	N (lb/acre)	P (lb/acre)[1]	K (lb/acre)	Other Ammends.
1983	Catnip	100	120	60-90	
1984	Onions	200	120	60-90	2 ton/acre lime
1985	Seed cabbage	140	120	60-90	
1986-87	Wheat	100	120	60-90	
1988	Bush beans	100	120	60-90	
1989-90	Wheat	100	120	60-90	
1991-92	Strawberries	60	120	60-90	2 ton/acre lime, 1991
1993-96	Flower seeds	70	120	60-90	3.5 ton/acre lime, 1996
1997-Present	Nursery plants[2]	40-140[3]	120	60-90	

[1] Landowner bases P and K application rates to soil tests. Landowner does not recall significant variability from these levels.
[2] Ruby glow daphne, Carol Mackie daphne, Sommerset daphne, Boxwood and Arbor vitae.
[3] N usage depends on size of nursery plants, with larger plants using more N.

APPENDIX B:

Piezometer Bore Logs

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-1S	Page: 1/3

Location:	County:	OWRD Log ID:
T6S, R1W, S8, NE1/4 of SE 1/4	Marion	MARI 55416

Drilled by:	Drilling Method:	Logged by:	OWRD Well ID:
Kevin Knutson	Hollow Stem Auger	Justin Iverson	L39906
Start Date:	**Ending Date:**	**Total Depth:**	**USGS Site ID:**
6/22/2000	6/22/2000	35 ft.	

Depth	Sample: Blow Count	% Rec	Type	Sample #	Lith Log Strip	Lithologic Description
1–5		75	Continuous Core	Blank 1S-1 1S-2 1S-3		Brown Sandy Silt Silt > Fine Sand Moderately Sorted Lithic Fragments > quartz grains Forms short (1/2 in) ribbon
6–10		55	Continuous Core	Blank 1S-4 1S-5 1S-6		Brown Sandy Silt Silt ~ Fine Sand Moderately Sorted Lithic Fragments > quartz grains Forms v. Short (<1/4 in) ribbon
11–15		80	Continuous Core	Blank 1S-7 1S-8 1S-9		Brown Sandy Silt Silt ~ Fine Sand Moderately Sorted lithic frags > qtz grns > mica Forms v. Short (<1/4 in) ribbon

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-1S	Page: 2/3
Location: T6S, R1W, S8, NE1/4 of SE 1/4	County: Marion	OWRD Log ID: MARI 55416	
Drilled by: Kevin Knutson	Drilling Method: Hollow Stem Auger	Logged by: Justin Iverson	OWRD Well ID: L39906
Start Date: 6/22/2000	Ending Date: 6/22/2000	Total Depth: 35 ft.	USGS Site ID:

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
16 17 18 19 20		60	Continuous Core	Blank 1S-10 1S-11 1S-12		Brown Silty Sand Med and Fine Grained Sand > Silt Moderately Sorted lithic frags > qtz grns > mica No Ribbon ~1% black organic material
21 22 23 24 25		60	Continuous Core	Blank 1S-13 1S-14 1S-15		1st Water blue-gray micacious sandy silt silt ~ sand, <1in. ribbon
26 27 28 29 30		60	Continuous Core	Blank 1S-16 1S-17 1S-18		Fine Grained Sand Sand > Silt, coarsening downwards Lithic fragments > quartz grains 28 ft – silty clay 28.5 ft – paleosol 28.7 ft – quartz rich medium sand with carbonized wood

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-1S	Page: 3/3
Location: T6S, R1W, S8, NE1/4 of SE 1/4	County: Marion	OWRD Log ID: MARI 55416	
Drilled by: Kevin Knutson	Drilling Method: Hollow Stem Auger	Logged by: Justin Iverson	OWRD Well ID: L39906
Start Date: 6/22/2000	Ending Date: 6/22/2000	Total Depth: 35 ft.	USGS Site ID:

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
31 32 33 34 35		0	Continuous Core	Blank		Auger Stem filled in with sediment while recovering 25 to 30' sample. No sample possible, assume blue-gray silty sand.
36 37 38 39 40						
41 42 43 44 45						

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-1D	Page: 1/4

Location: T6S, R1W, S8, NE1/4 of SE 1/4		County: Marion	OWRD Log ID: MARI 55014
Drilled by: Kevin Knutson	Drilling Method: Hollow Stem Auger	Logged by: Justin Iverson	OWRD Well ID: L39905
Start Date: 6/27/2000	Ending Date: 6/28/2000	Total Depth: 48.6 ft.	USGS Site ID:

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
1						
2						Brown Sandy Silt Silt > Fine Sand Moderately Sorted Lithic Fragments > quartz grains Forms short (1/2 in) ribbon
3						
4						
5						
6						
7						Brown Sandy Silt Silt ~ Fine Sand Moderately Sorted Lithic Fragments > quartz grains Forms v. Short (<1/4 in) ribbon
8						
9						
10						
11						
12						Brown Sandy Silt Silt ~ Fine Sand Moderately Sorted lithic frags > qtz grns > mica Forms v. Short (<1/4 in) ribbon
13						
14						
15						

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-1D	Page: 2/4
Location: T6S, R1W, S8, NE1/4 of SE 1/4	**County:** Marion	**OWRD Log ID:** MARI 55014	
Drilled by: Kevin Knutson	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39905
Start Date: 6/27/2000	**Ending Date:** 6/28/2000	**Total Depth:** 48.6 ft.	**USGS Site ID:**

Depth	Sample: Blow Count	Sample: % Rec	Sample: Type	Sample: Sample #	Lith Log Strip	Lithologic Description
16–20						Brown Silty Sand Med and Fine Grained Sand > Silt Moderately Sorted lithic frags > qtz grns > mica No Ribbon ~1% black organic material
21–25						1st Water blue-gray micacious sandy silt silt ~ sand, <1in. ribbon
26–30						Fine Grained Sand Sand > Silt, coarsening downwards Lithic fragments > quartz grains 28 ft – silty clay 28.5 ft – paleosol 28.7 ft – quartz rich medium sand with carbonized wood

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-1D	Page: 3/4

Location:	County:	OWRD Log ID:
T6S, R1W, S8, NE1/4 of SE 1/4	Marion	MARI 55014

Drilled by:	Drilling Method:	Logged by:	OWRD Well ID:
Kevin Knutson	Hollow Stem Auger	Justin Iverson	L39905
Start Date:	**Ending Date:**	**Total Depth:**	**USGS Site ID:**
6/27/2000	6/28/2000	48.6 ft.	

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
31–35						Assume blue-gray silty sand.
36–40	37	50	Split Spoon Sample	1D-1 1D-2		Blue-gray silty clay Encountered hard drilling indicative of gravel at 39'
41–45	98	75	Split Spoon Sample	1D-3 1D-4 1D-5		Andisitic gravel in blue-gray silty clay matrix support

Boring Well Log	Project: Pudding River GW-SW		Well Number: PZ-1D	Page: 4/4
Location: T6S, R1W, S8, NE1/4 of SE 1/4		County: Marion	OWRD Log ID: MARI 55014	
Drilled by: Kevin Knutson	Drilling Method: Hollow Stem Auger	Logged by: Justin Iverson	OWRD Well ID: L39905	
Start Date: 6/27/2000	Ending Date: 6/28/2000	Total Depth: 48.6 ft.	USGS Site ID:	

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
46 47 48 49 50	100 (R)	0	Split Spoon Sample	Blank		Andisitic gravel in blue-gray silty clay matrix support Auger refused at 48' End Hole
51 52 53 54 55						
56 57 58 59 60						

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-2S	Page: 1/3
Location: T6S, R1W, S8, NE1/4 of SE 1/4		**County:** Marion	**OWRD Log ID:** MARI 55417
Drilled by: Kevin Knutson	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39902
Start Date: 6/19/2000	**Ending Date:** 6/20/2000	**Total Depth:** 45.2 ft.	**USGS Site ID:**

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
1			Continuous Core			Brown Top Soil Silt content increasing downward
2						
3		25		2S-1		
4						
5						Gray-Brown Silt (Soil)
6			Continuous Core			
7				2S-2		Gray-Brown Silty Clay Silt content decreasing downward
8		100		2S-3		
9				2S-4		
10				2S-5		Gray-Brown Clay w/ micatious flakes
11			Continuous Core			
12				2S-6		
13		90		2S-7		Gray-Brown Clay w/ micatious flakes
14				2S-8		
15				2S-9		1st Water

Boring Well Log	**Project:** Pudding River GW-SW	**Well Number:** PZ-2S	**Page:** 2 / 3
Location: T6S, R1W, S8, NE1/4 of SE 1/4	**County:** Marion	**OWRD Log ID:** MARI 55417	
Drilled by: Kevin Knutson	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39902
Start Date: 6/19/2000	**Ending Date:** 6/20/2000	**Total Depth:** 45.2 ft.	**USGS Site ID:**

Depth	**Sample**				**Lith Log Strip**	**Lithologic Description**
	Blow Count	**% Rec**	**Type**	**Sample #**		
16						
17			Continuous Core	2S-10		Brown Silty Clay w/ micatious flakes
18		60		2S-11		
19				2S-12		
20						
21						
22						
23						
24						
25						Brown-Gray Silt
26						
27			Split Spoon Sample	2S-13 2S-14 2S-15 2S-16		
28	19	90				
29						Blue-Gray Clay
30						

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-2S	Page: 3/3
Location: T6S, R1W, S8, NE1/4 of SE 1/4		County: Marion	OWRD Log ID: MARI 55417
Drilled by: Kevin Knutson	Drilling Method: Hollow Stem Auger	Logged by: Justin Iverson	OWRD Well ID: L39902
Start Date: 6/19/2000	Ending Date: 6/20/2000	Total Depth: 45.2 ft.	USGS Site ID:

Depth	Sample: Blow Count	% Rec	Type	Sample #	Lith Log Strip	Lithologic Description
31 32 33 34 35						Blue-Gray Silt w/ Mica Flakes
36 37 38 39 40	29	45	Split Spoon Sample	2S-17 2S-18		Blue-Gray Silt w/ Mica Flakes
41 42 43 44 45						Blue-Gray Clayey-Silt w/ Mica Flakes End Hole

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-2I	Page: 1 / 4
Location: T6S, R1W, S8, NE1/4 of SE 1/4	**County:** Marion	**OWRD Log ID:** MARI 54951	
Drilled by: Rodney Weick	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39900
Start Date: 5/25/2000	**Ending Date:** 5/25/2000	**Total Depth:** 53.6	**USGS Site ID:**

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
1						Brown Top Soil Silt content increasing downward
2						
3						
4						
5						Gray-Brown Silt (Soil)
6						Gray-Brown Silty Clay
7						Silt content decreasing downward
8						
9						Gray-Brown Clay
10						w/ micatious flakes
11						
12						
13						Gray-Brown Clay
14						w/ micatious flakes
15						1st Water

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-2I	Page: 2/4
Location: T6S, R1W, S8, NE1/4 of SE 1/4	**County:** Marion	**OWRD Log ID:** MARI 54951	
Drilled by: Rodney Weick	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39900
Start Date: 5/25/2000	**Ending Date:** 5/25/2000	**Total Depth:** 53.6	**USGS Site ID:**

Depth	Sample: Blow Count	% Rec	Type	Sample #	Lith Log Strip	Lithologic Description
16						
17						Brown Silty Clay w/ micatious flakes
18						
19						
20						
21						
22						
23						
24						Brown-Gray Silt
25						
26						
27						
28						
29						Blue-Gray Clay
30						

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-2I	Page: 3 / 4
Location: T6S, R1W, S8, NE1/4 of SE 1/4	County: Marion	OWRD Log ID: MARI 54951	
Drilled by: Rodney Weick	Drilling Method: Hollow Stem Auger	Logged by: Justin Iverson	OWRD Well ID: L39900
Start Date: 5/25/2000	Ending Date: 5/25/2000	Total Depth: 53.6	USGS Site ID:

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
31 32 33 34 35						Blue-Gray Silt w/ Mica Flakes
36 37 38 39 40						Blue-Gray Silt w/ Mica Flakes
41 42 43 44 45						Blue-Gray Clayey-Silt w/ Mica Flakes

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-2I	Page: 4/4
Location: T6S, R1W, S8, NE1/4 of SE 1/4	County: Marion	OWRD Log ID: MARI 54951	
Drilled by: Rodney Weick	Drilling Method: Hollow Stem Auger	Logged by: Justin Iverson	OWRD Well ID: L39900
Start Date: 5/25/2000	Ending Date: 5/25/2000	Total Depth: 53.6	USGS Site ID:

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
46						
47						Blue-Gray Clayey-Silt w/ Mica Flakes
48						
49						
50						
51						
52						Blue-Gray Clayey-Silt w/ Mica Flakes
53						
54						End Hole
55						
56						
57						
58						
59						
60						

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-2D	Page: 1/5
Location: T6S, R1W, S8, NE1/4 of SE 1/4	**County:** Marion	**OWRD Log ID:** MARI 54952	
Drilled by: Rodney Weick / **Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39888	
Start Date: 5/23/2000 / **Ending Date:** 5/25/2000	**Total Depth:** 69.5 ft.	**USGS Site ID:**	

Depth	Sample: Blow Count	% Rec	Type	Sample #	Lith Log Strip	Lithologic Description
1						Brown Top Soil Silt content increasing downward
2			Continuous Core	2D-1		
3		100		2D-2		
4				2D-3		Gray-Brown Silt (Soil)
5				2D-4		
6						Gray-Brown Silty Clay Silt content decreasing downward
7			Continuous Core	2D-5		
8		100		2D-6		
9				2D-7		Gray-Brown Clay w/ micatious flakes
10				2D-8		
11						
12			Continuous Core	2D-9		
13		90		2D-10		Gray-Brown Clay w/ micatious flakes
14				2D-11		
15				2D-12		1st Water

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-2D	Page: 2/5
Location: T6S, R1W, S8, NE1/4 of SE 1/4		County: Marion	OWRD Log ID: MARI 54952
Drilled by: Rodney Weick	Drilling Method: Hollow Stem Auger	Logged by: Justin Iverson	OWRD Well ID: L39888
Start Date: 5/23/2000	Ending Date: 5/25/2000	Total Depth: 69.5 ft.	USGS Site ID:

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
16						
17			Continuous Core	2D-14		Brown Silty Clay w/ micatious flakes
18		75		2D-15		
19				2D-16		
20						
21						
22			Continuous Core	2D-18		
23		75		2D-19		
24				2D-20		Brown-Gray Silt
25						
26						
27			Continuous Core			
28		0				
29						Blue-Gray Clay
30						

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-2D	Page: 3/5

Location: T6S, R1W, S8, NE1/4 of SE 1/4		County: Marion	OWRD Log ID: MARI 54952
Drilled by: Rodney Weick	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39888
Start Date: 5/23/2000	**Ending Date:** 5/25/2000	**Total Depth:** 69.5 ft.	**USGS Site ID:**

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
31 32 33 34 35	26	50	Split Spoon Sample	2D-23 2S-24		Blue-Gray Silt w/ Mica Flakes
36 37 38 39 40						Blue-Gray Silt w/ Mica Flakes
41 42 43 44 45	28	50	Split Spoon Sample	2D-27 2S-28		Blue-Gray Clayey-Silt w/ Mica Flakes

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-2D	Page: 4/5
Location: T6S, R1W, S8, NE1/4 of SE 1/4	County: Marion	OWRD Log ID: MARI 54952	
Drilled by: Rodney Weick	Drilling Method: Hollow Stem Auger	Logged by: Justin Iverson	OWRD Well ID: L39888
Start Date: 5/23/2000	Ending Date: 5/25/2000	Total Depth: 69.5 ft.	USGS Site ID:

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
46 47 48 49 50						Blue-Gray Clayey-Silt w/ Mica Flakes
51 52 53 54 55	17	75	Split Spoon Sample	2D-29 2D-30 2D-31		Blue-Gray Clayey-Silt w/ Mica Flakes
56 57 58 59 60	33	50	Split Spoon Sample	2D-34 2D-35		Blue-Gray Clayey-Silt w/ Mica Flakes

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-2D	Page: 5/5
Location: T6S, R1W, S8, NE1/4 of SE 1/4	**County:** Marion	**OWRD Log ID:** MARI 54952	
Drilled by: Rodney Weick	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39888
Start Date: 5/23/2000	**Ending Date:** 5/25/2000	**Total Depth:** 69.5 ft.	**USGS Site ID:**

Depth	Sample: Blow Count	% Rec	Type	Sample #	Lith Log Strip	Lithologic Description
61						Blue-Gray Clayey-Silt w/ Mica Flakes
62			Split Spoon Sample	2D-38		Red-Brown Paleosol
63	28	66		2D-39 2D-40		Gravelly Sand (WA)
64						Gravel up to 1/2 in. in diameter in a coarse sand/sand silt matrix
65						grav~30%, sand~50%, silt~20%
66						
67			Split Spoon Sample	2D-41 2D-42		Gravelly Sand (WA) as above
68	100 (R)	50?				
69						(poor sample from drill head)
70						v. poorly sorted cobbley gravel in framework support? w/ silt and sand matrix
71						
72						
73						
74						
75						

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-3S	Page: 1/4
Location: T6S, R1W, S8, NE1/4 of SE 1/4	**County:** Marion	**OWRD Log ID:** MARI 54953	
Drilled by: Rodney Weick	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39904
Start Date: 5/25/2000	**Ending Date:** 5/26/2000	**Total Depth:** 55.1 ft.	**USGS Site ID:**

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
1						
2						Brown Top Soil Silt content increasing downward
3						
4						Brown Clayey Silt w/ small mica flakes
5						
6						
7			Split Spoon Sample	3S-1 3S-2		Brown Clayey Silt
8	28	50				
9						Brown Silty Clay
10						
11						
12			Split Spoon Sample	3S-3 3S-4		
13	15	50				Brown Silty Clay w/ mica flakes
14						
15						

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-3S	Page: 2/4

Location:	County:	OWRD Log ID:
T6S, R1W, S8, NE1/4 of SE 1/4	Marion	MARI 54953

Drilled by:	Drilling Method:	Logged by:	OWRD Well ID:
Rodney Weick	Hollow Stem Auger	Justin Iverson	L39904
Start Date:	**Ending Date:**	**Total Depth:**	**USGS Site ID:**
5/25/2000	5/26/2000	55.1 ft.	

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
16 17 18 19 20	12	100	Split Spoon Sample	3S-5 3S-6 3S-7 3S-8		Brown Clayey Silt w/ mica flakes
21 22 23 24 25	20	100	Split Spoon Sample	3S-9 3S-10 3S-11 3S-12		Brown Clayey Silt w/ mica flakes 1st Water Brown Silty Clay w/ mica flakes
26 27 28 29 30	31	75	Split Spoon Sample	3S-13 3S-14 3S-15		Brown Silty Clay w/ mica flakes Blue-Gray Clayey Silt w/ mica flakes

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-3S	Page: 3/4
Location: T6S, R1W, S8, NE1/4 of SE 1/4	**County:** Marion	**OWRD Log ID:** MARI 54953	
Drilled by: Rodney Weick	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39904
Start Date: 5/25/2000	**Ending Date:** 5/26/2000	**Total Depth:** 55.1 ft.	**USGS Site ID:**

Depth	Sample: Blow Count	Sample: % Rec	Sample: Type	Sample: Sample #	Lith Log Strip	Lithologic Description
31–35	23	100	Split Spoon Sample	3S-16 3S-17 3S-18 3S-19		Blue-Gray Silty Clay w/ mica flakes
36–40	18	100	Split Spoon Sample	3S-20 3S-21 3S-22 3S-23		Blue-Gray Silty Clay w/ mica flakes
41–45						Blue-Gray Silty Clay w/ mica flakes

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-3S	Page: 4/4

Location: T6S, R1W, S8, NE1/4 of SE 1/4	County: Marion	OWRD Log ID: MARI 54953

Drilled by:	Drilling Method:	Logged by:	OWRD Well ID:
Rodney Weick	Hollow Stem Auger	Justin Iverson	L39904
Start Date:	**Ending Date:**	**Total Depth:**	**USGS Site ID:**
5/25/2000	5/26/2000	55.1 ft.	

Depth	Sample: Blow Count	% Rec	Type	Sample #	Lith Log Strip	Lithologic Description
46 47 48 49 50	35	0	Split Spoon Sample			Blue-Gray Silty Clay w/ mica flakes
51 52 53 54 55						Blue-Gray Silty Clay w/ mica flakes
56 57 58 59 60	40	100	Split Spoon Sample	3S-25 3S-26 3S-27 3S-28		Blue-Gray Silty Clay NO mica flakes

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-3D	Page: 1 / 5
Location: T6S, R1W, S8, NE1/4 of SE 1/4	**County:** Marion	**OWRD Log ID:** MARI 55051	
Drilled by: Kevin Knutson	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39903
Start Date: 6/20/2000	**Ending Date:** 6/27/2000	**Total Depth:** 68.9 ft.	**USGS Site ID:**

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
1			Continuous Core			
2				3D-1		Brown Top Soil Silt content increasing downward
3		90		3D-2		
4				3D-3		Brown Clayey Silt w/ small mica flakes
5				3D-4		
6			Continuous Core			
7				3D-5		Brown Clayey Silt
8		95		3D-6		
9				3D-7		Brown Silty Clay
10				3D-8		
11			Continuous Core			
12				3D-9		
13		90		3D-10		Brown Silty Clay w/ mica flakes
14				3D-11		
15				3D-12		

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-3D	Page: 2/5
Location: T6S, R1W, S8, NE1/4 of SE 1/4	County: Marion	OWRD Log ID: MARI 55051	
Drilled by: Kevin Knutson	Drilling Method: Hollow Stem Auger	Logged by: Justin Iverson	OWRD Well ID: L39903
Start Date: 6/20/2000	Ending Date: 6/27/2000	Total Depth: 68.9 ft.	USGS Site ID:

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
16						
17			Continuous Core	3D-13		Brown Clayey Silt w/ mica flakes
18		85		3D-14		
19				3D-15		
20				3D-16		
21						Brown Clayey Silt w/ mica flakes
22						1st Water
23						
24						Brown Silty Clay w/ mica flakes
25						
26			Split Spoon Sample			Brown Silty Clay w/ mica flakes
27				3D-17 3D-18		
28	45	90		3D-19 3D-20		Blue-Gray Clayey Silt w/ mica flakes
29						
30						

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-3D	Page: 3/5
Location: T6S, R1W, S8, NE1/4 of SE 1/4	**County:** Marion	**OWRD Log ID:** MARI 55051	
Drilled by: Kevin Knutson	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39903
Start Date: 6/20/2000	**Ending Date:** 6/27/2000	**Total Depth:** 68.9 ft.	**USGS Site ID:**

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
31 32 33 34 35	30	45	Split Spoon Sample	3D-21 3D-22		Blue-Gray Silty Clay w/ mica flakes
36 37 38 39 40						Blue-Gray Silty Clay w/ mica flakes
41 42 43 44 45	29	75	Split Spoon Sample	3D-24 3D-25 3D-26		Blue-Gray Silty Clay w/ mica flakes

Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-3D	Page: 4 / 5
Location: T6S, R1W, S8, NE1/4 of SE 1/4	**County:** Marion	**OWRD Log ID:** MARI 55051	
Drilled by: Kevin Knutson	**Drilling Method:** Hollow Stem Auger	**Logged by:** Justin Iverson	**OWRD Well ID:** L39903
Start Date: 6/20/2000	**Ending Date:** 6/27/2000	**Total Depth:** 68.9 ft.	**USGS Site ID:**

Depth	Sample: Blow Count	% Rec	Type	Sample #	Lith Log Strip	Lithologic Description
46						Blue-Gray Silty Clay w/ mica flakes
47						
48						
49						
50						
51						Blue-Gray Silty Clay w/ mica flakes
52						
53						
54						
55						
56						Blue-Gray Silty Clay w/ mica flakes
57						
58						
59						
60						

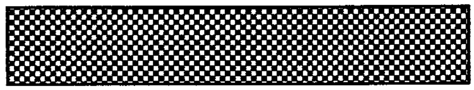
Boring Well Log	Project: Pudding River GW-SW	Well Number: PZ-3D	Page: 5/5

Location: T6S, R1W, S8, NE1/4 of SE 1/4		County: Marion	OWRD Log ID: MARI 55051
Drilled by: Kevin Knutson	Drilling Method: Hollow Stem Auger	Logged by: Justin Iverson	OWRD Well ID: L39903
Start Date: 6/20/2000	Ending Date: 6/27/2000	Total Depth: 68.9 ft.	USGS Site ID:

Depth	Sample				Lith Log Strip	Lithologic Description
	Blow Count	% Rec	Type	Sample #		
61						
62			Split Spoon Sample	3D-27		Blue-Gray v. poorly sorted gravel in matrix support matrix is sand – silt – clay
63	200 (R)	25				
64						
65						
66						
67						
68						
69						End Hole
70						
71						
72						
73						
74						
75						

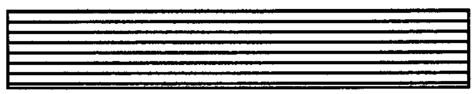
Pattern Scheme for Lithology Logs

Soil



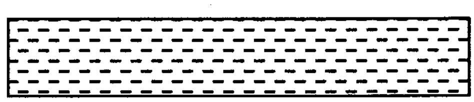
Clay

Silty Clay

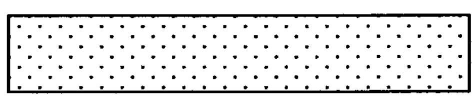


Silt

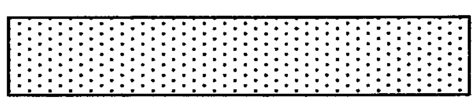
Sandy Silt



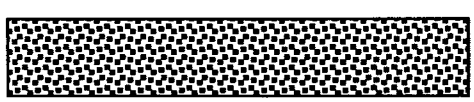
Fine Sand



Med. Sand



Gravel



IR-ED: OWRD MARI 53920 Well Log

✓

MARI 53920

STATE OF OREGON
WATER SUPPLY WELL REPORT
(as required by ORS 537.765)
Instructions for completing this report are on the last page of this form.

WELL I.D. # L 28937
START CARD # 105314

(1) OWNER: Well Number 1
Name Chuck Eder
Address 11580 Hook Rd
City Mt. Angel State Or Zip 97362

(2) TYPE OF WORK
[x] New Well [ ] Deepening [ ] Alteration (repair/recondition) [ ] Abandonment

(3) DRILL METHOD:
[x] Rotary Air [ ] Rotary Mud [ ] Cable [ ] Auger
[ ] Other

(4) PROPOSED USE:
[ ] Domestic [ ] Community [x] Industrial [x] Irrigation
[ ] Thermal [ ] Injection [ ] Livestock [ ] Other

(5) BORE HOLE CONSTRUCTION:
Special Construction approval [ ] Yes [x] No Depth of Completed Well 109 ft.
Explosives used [ ] Yes [x] No Type Amount

HOLE Diameter	From	To	SEAL Material	From	To	Sacks or pounds
16"	0	20	Bent Ch	0	20	24 sacks

How was seal placed: Method [ ] A [ ] B [ ] C [ ] D [ ] E
[x] Other Poured & Hydrated
Backfill placed from 109 ft. to 115 ft. Material Native
Gravel placed from ft. to ft. Size of gravel

(6) CASING/LINER:

	Diameter	From	To	Gauge	Steel	Plastic	Welded	Threaded
Casing:	12"	+1	77	.250	[x]	[ ]	[x]	[ ]
	10"	60	65	.250	[x]	[ ]	[x]	[ ]
	10"	105	109	.250	[x]	[ ]	[x]	[ ]
Liner:					[ ]	[ ]	[ ]	[ ]

Final location of shoe(s) 77

(7) PERFORATIONS/SCREENS:
[ ] Perforations Method
[x] Screens Type wire wrap Material SS

From	To	Slot size	Number	Diameter	Tele/pipe size	Casing	Liner
65	105	.50		11	11	[ ]	[ ]

(8) WELL TESTS: Minimum testing time is 1 hour
[ ] Pump [ ] Bailer [x] Air [ ] Flowing Artesian

Yield gal/min	Drawdown	Drill stem at	Time
120		100	1 hr.

Temperature of water 50 Depth Artesian Flow Found
Was a water analysis done? [ ] Yes By whom
Did any strata contain water not suitable for intended use? [ ] Too little
[ ] Salty [ ] Muddy [ ] Odor [ ] Colored [ ] Other
Depth of strata:

(9) LOCATION OF WELL by legal description:
County Marion Latitude Longitude
Township 6 S N or S Range 1 W E or W. WM.
Section 9 SW 1/4 SW 1/4
Tax Lot N/A Lot Block Subdivision
Street Address of Well (or nearest address) 11580 Hook Rd
Mt. Angel, OR 97362

(10) STATIC WATER LEVEL:
28 ft. below land surface. Date 3/25/99
Artesian pressure lb. per square inch. Date

(11) WATER BEARING ZONES:
Depth at which water was first found 58

From	To	Estimated Flow Rate	SWL
58	112	100 gpm	28

(12) WELL LOG:
Ground Elevation Unknown

Material	From	To	SWL
Brown Clay Silt	0	20	
Gray Sandy Silt	20	58	
Course Gravel & Sand	58	112	28
Gray Sandy Silt	112	115	

RECEIVED APR 9 1999 WATER RESOURCES DEPT SALEM, OREGON

RECEIVED JUL 19 1999 WATER RESOURCES DEPT. SALEM, OREGON

Date started 3/12/99 Completed 3/25/99

(unbonded) Water Well Constructor Certification:
I certify that the work I performed on the construction, alteration, or abandonment of this well is in compliance with Oregon water supply well construction standards. Materials used and information reported above are true to the best of my knowledge and belief.
WWC Number
Signed [signature] Date 3/26/99

(bonded) Water Well Constructor Certification:
I accept responsibility for the construction, alteration, or abandonment work performed on this well during the construction dates reported above. All work performed during this time is in compliance with Oregon water supply well construction standards. This report is true to the best of my knowledge and belief.
WWC Number 723
Signed [signature] Date 3-25-99

ORIGINAL - WATER RESOURCES DEPARTMENT FIRST COPY - CONSTRUCTOR SECOND COPY - CUSTOMER

IR-EG: OWRD MARI 3094 Well Log

BILL SCHAFER OWNER

3094 MARI

NOTICE TO WATER WELL CONTRACTOR
The original and first copy of this report are to be filed with the STATE ENGINEER, SALEM 10, OREGON within 30 days from the date of well completion.

RECEIVED NOV 29 1962 STATE ENGINEER SALEM, OREGON

WATER WELL REPORT
STATE OF OREGON
(Please type or print)

State Well No. 6/1W-9M
State Permit No.

(1) OWNER:
Name EVERGREEN GOLF CLUB
Address RT 1 BOX . MT. ANGEL ORE

(2) LOCATION OF WELL:
County MARION Driller's well number
¼ ¼ Section 9 T. 6S R. 1W W.M.
Bearing and distance from section or subdivision corner

(3) TYPE OF WORK (check):
New Well ☒ Deepening ☐ Reconditioning ☐ Abandon ☐
If abandonment, describe material and procedure in Item 12.

(4) PROPOSED USE (check):
Domestic ☐ Industrial ☐ Municipal ☐
Irrigation ☒ Test Well ☐ Other ☐

(5) TYPE OF WELL:
Rotary ☐ Driven ☐
Cable ☒ Jetted ☐
Dug ☐ Bored ☐

(6) CASING INSTALLED: Threaded ☐ Welded ☒
10" Diam. from 0 ft. to 103 ft. Gage 3/8"
" Diam. from ft. to ft. Gage
" Diam. from ft. to ft. Gage

(7) PERFORATIONS: Perforated? ☒ Yes ☐ No
Type of perforator used MILLS
Size of perforations 3/4 in. by 3" in.
800 perforations from 30 ft. to 100 ft.
perforations from ft. to ft.
perforations from ft. to ft.
perforations from ft. to ft.
perforations from ft. to ft.

(8) SCREENS: Well screen installed ☐ Yes ☒ No
Manufacturer's Name
Type Model No.
Diam. Slot size Set from ft. to ft.
Diam. Slot size Set from ft. to ft.

(9) CONSTRUCTION:
Well seal—Material used in seal BENTONITE
Depth of seal 20 ft. Was a packer used? YES
Diameter of well bore to bottom of seal 14" in.
Were any loose strata cemented off? ☐ Yes ☒ No Depth
Was a drive shoe used? ☒ Yes ☐ No
Was well gravel packed? ☐ Yes ☒ No Size of gravel:
Gravel placed from ft. to ft.
Did any strata contain unusable water? ☐ Yes ☒ No
Type of water? Depth of strata
Method of sealing strata off

(10) WATER LEVELS:
Static level 7 ft. below land surface Date 8-9-62
Artesian pressure lbs. per square inch Date

(11) WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? ☒ Yes ☐ No If yes, by whom? STETTLER SUPPLY
Yield: 400 gal./min. with 52 ft. drawdown after 1 hrs.
" 500 " 64 " 1 "
" 620 " 90 " 1 "
Bailer test gal./min. with ft. drawdown after hrs.
Artesian flow g.p.m. Date
Temperature of water 55 Was a chemical analysis made? ☐ Yes ☒ No

(12) WELL LOG: Diameter of well below casing 10"
Depth drilled 103 ft. Depth of completed well 103 ft.
Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of formation.

MATERIAL	FROM	TO
TOPSOIL	0	2
CLAY YELLOW COLOR	2	6
CLAY GRAY COLOR	6	8
CLAY BLUE COLOR	8	19
CONGLOMERATE 3" -	19	70
GRAVEL W.B. COARSE	70	71
CONGLOMERATE 3" -	71	91
GRAVEL W.B. COARSE	91	92
CONGLOMERATE 3" -	92	103
ALL CONGLOMERATE W.B WITH SMALL INTERMITTENT FLOWS		

Work started 8-1 1962 Completed 8-9 1962
Date well drilling machine moved off of well 8-9 1962

(13) PUMP: BEEHLEY
Manufacturer's Name
Type: TURBINE H.P. 15

Water Well Contractor's Certification:
This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.
NAME J.A. SNEED & SONS (Person, firm or corporation) (Type or print)
Address 3910 SILVERTON RD. N.E. SALEM O.
Drilling Machine Operator's License No. 187
[Signed] R.T. Sneed (Water Well Contractor)
Contractor's License No. 6 Date 8-9- 1962

(USE ADDITIONAL SHEETS IF NECESSARY)

IR-EB: OWRD MARI 3208 Well Log

NOTICE TO WATER WELL CONTRACTOR
The original and first copy of this report are to be filed with the
STATE ENGINEER, SALEM, OREGON 97310
within 30 days from the date of well completion.

3208 MARI

WATER WELL REPORT
STATE OF OREGON
(Please type or print)
(Do not write above this line)

RECEIVED
MAY 30 1978
WATER RESOURCES DEPT.
SALEM, OREGON

State Well No. 6S/1W-16bb
State Permit No.

(1) OWNER:
Name ~~XXXX~~ J.B.M. Farm Co.
Address Rt. 1 Box 160
Mt. Angel, Oregon 97362

(2) TYPE OF WORK (check):
New Well ☒ Deepening ☐ Reconditioning ☐ Abandon ☐
If abandonment, describe material and procedure in Item 12.

(3) TYPE OF WELL:
Rotary ☒ Driven ☐
Cable ☒ Jetted ☐
Dug ☐ Bored ☐

(4) PROPOSED USE (check):
Domestic ☐ Industrial ☐ Municipal ☐
Irrigation ☒ Test Well ☐ Other ☐

(5) CASING INSTALLED: Threaded ☐ Welded ☒
12" Diam. from +2 ft. to 210 ft. Gage 250
" Diam. from ft. to ft. Gage
" Diam. from ft. to ft. Gage

(6) PERFORATIONS: Perforated? ☒ Yes ☐ No.
Type of perforator used Mills
Size of perforations 1/2 in. by 3 in.
710 perforations from 96 ft. to 168 ft.
perforations from ft. to ft.
perforations from ft. to ft.

(7) SCREENS: Well screen installed? ☐ Yes ☒ No
Manufacturer's Name
Type Model No.
Diam. Slot size Set from ft. to ft.
Diam. Slot size Set from ft. to ft.

(8) WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? ☒ Yes ☐ No If yes, by whom?
Yield: 600 gal./min. with 142 ft. drawdown after 4 hrs.
Bailer test gal./min. with ft. drawdown after hrs.
Artesian flow g.p.m.
Temperature of water Depth artesian flow encountered ft.

(9) CONSTRUCTION:
Well seal—Material used Bentionite
Well sealed from land surface to 30 ft.
Diameter of well bore to bottom of seal 16 in.
Diameter of well bore below seal 12 in.
Number of sacks of cement used in well seal sacks
Number of sacks of bentonite used in well seal 2½ sacks
Brand name of bentonite National
Number of pounds of bentonite per 100 gallons of water 200 lbs./100 gals.
Was a drive shoe used? ☒ Yes ☐ No Plugs Size: location ft.
Did any strata contain unusable water? ☐ Yes ☒ No
Type of water? depth of strata
Method of sealing strata off
Was well gravel packed? ☐ Yes ☒ No Size of gravel:
Gravel placed from ft. to ft.

(10) LOCATION OF WELL:
County Marion Driller's well number
NW ¼ NW ¼ Section 16 T. 6S R. 1W W.M.
Bearing and distance from section or subdivision corner

(11) WATER LEVEL: Completed well.
Depth at which water was first found 78 ft.
Static level 23 ft. below land surface. Date 5-26-77
Artesian pressure lbs. per square inch. Date

(12) WELL LOG: Diameter of well below casing 0
Depth drilled 210 ft. Depth of completed well 210 ft.

Formation: Describe color, texture, grain size and structure of materials; and show thickness and nature of each stratum and aquifer penetrated, with at least one entry for each change of formation. *Report each change in position of Static Water Level and indicate principal water-bearing strata.*

MATERIAL	From	To	SWL
Soil	0	2	
Clay (Brown)	2	29	
Clay (Blue)	29	40	
Conglomarent (Brown-Med.)	40	75	
Clay (Gray)	75	78	
Gravel -Med-	78	90	
Clay (green)	90	95	
Gravel - Med -	95	173	
Sand (fine Brown)	173	175	
Gravel - Med. -	175	182	
Sand (fine Black)	182	184	
Clay (Gray Sandy)	184	205	
Clay (Brown)	205	210	

Work started 4-25-77 19 Completed 5-26 1977
Date well drilling machine moved off of well 5-28 1977

Drilling Machine Operator's Certification:
This well was constructed under my direct supervision. Materials used and information reported above are true to my best knowledge and belief.
[Signed] W.A. Bombello (Drilling Machine Operator) Date 6-9, 1977
Drilling Machine Operator's License No. 491

Water Well Contractor's Certification:
This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.
Name BUD'S WELL DRILLING (Person, firm or corporation) (Type or print)
Address 1257 N. E. CLOVER RIDGE RD. ALBANY, OREGON 97321
[Signed] W.A. Bombello (Water Well Contractor)
Contractor's License No. 621 Date 6-9, 1977

(USE ADDITIONAL SHEETS IF NECESSARY)

IR-SE: OWRD MARI 53259 Well Log

MARI 53259

RECEIVED

AUG 2 0 1998

WATER RESOURCES DEPT. SALEM, OREGON

STATE OF OREGON
WATER SUPPLY WELL REPORT
(as required by ORS 537.765)
Instructions for completing this report are on the last page of this form.

WELL I.D. # L 22679
START CARD # 111436

(1) OWNER: Well Number
Name STAN SEIFER
Address 11045 WAYPARK DR. NE
City SALEM State OR Zip 97305

(2) TYPE OF WORK
[X] New Well [ ] Deepening [ ] Alteration (repair/recondition) [ ] Abandonment

(3) DRILL METHOD:
[ ] Rotary Air [ ] Rotary Mud [X] Cable [ ] Auger
[ ] Other

(4) PROPOSED USE:
[ ] Domestic [ ] Community [ ] Industrial [X] Irrigation
[ ] Thermal [ ] Injection [ ] Livestock [ ] Other

(5) BORE HOLE CONSTRUCTION:
Special Construction approval [ ] Yes [X] No Depth of Completed Well 260 ft.
Explosives used [ ] Yes [X] No Type Amount

HOLE Diameter	From	To	SEAL Material	From	To	Sacks or pounds
16	0	120	BENTONITE	0	37	43 SACKS
12	120	261	CEMENT	37	120	76 sacks

How was seal placed: Method [ ] A [ ] B [X] C [ ] D [ ] E
[X] Other BENTONITE POURED DRY
Backfill placed from ft. to ft. Material
Gravel placed from 120 ft. to 133 ft. Size of gravel 3/4 round

(6) CASING/LINER:

	Diameter	From	To	Gauge	Steel	Plastic	Welded	Threaded
Casing:	12"	+2.0	237	250	[X]	[ ]	[X]	[ ]
					[ ]	[ ]	[ ]	[ ]
					[ ]	[ ]	[ ]	[ ]
					[ ]	[ ]	[ ]	[ ]
Liner:					[ ]	[ ]	[ ]	[ ]
					[ ]	[ ]	[ ]	[ ]

Final location of shoe(s) 237

(7) PERFORATIONS/SCREENS:
[X] Perforations Method MILLS KNIFE
[ ] Screens Type Material

From	To	Slot size	Number	Diameter	Tele/pipe size	Casing	Liner
						[ ]	[ ]
128	161	3"x38	594			[X]	[ ]
168	229	3"x78	1098			[X]	[ ]
						[ ]	[ ]
						[ ]	[ ]

(8) WELL TESTS: Minimum testing time is 1 hour

[X] Pump [ ] Bailer [ ] Air [ ] Flowing Artesian

Yield gal/min	Drawdown	Drill stem at	Time
			1 hr.
1050	31		6hr.

Temperature of water 55° Depth Artesian Flow Found
Was a water analysis done? [ ] Yes By whom NO
Did any strata contain water not suitable for intended use? [ ] Too little
[ ] Salty [ ] Muddy [ ] Odor [ ] Colored [ ] Other
Depth of strata:

(9) LOCATION OF WELL by legal description:
County MARION Latitude Longitude
Township 6S N or S Range 1W E or W. WM.
Section 8 NE 1/4 NE 1/4
Tax Lot 200 Lot Block Subdivision
Street Address of Well (or nearest address) SAME

(10) STATIC WATER LEVEL:
53 ft. below land surface. Date 7-24-98
Artesian pressure lb. per square inch. Date

(11) WATER BEARING ZONES:

Depth at which water was first found 78'

From	To	Estimated Flow Rate	SWL
129	229	1050+	53

(12) WELL LOG:
Ground Elevation

Material	From	To	SWL
SILT BROWN	18	41	
SILT GREY SANDY	41	47	
CLAY GREY STICKY	47	69	
CLAY GREY SANDY	69	78	
GRAVEL & CLAY	78	84	
CLAY GREY SANDY	84	87	
CEMENTED GRAVEL & SAND	87	98	
CLAY GREY	98	113	
CLAY GREY W/ GRAVEL	113	129	
GRAVEL & SAND COARSE GREY	129	141	
CLAY GREY	141	142	
GRAVEL & SAND MED COARSE GREEN GREY	142	148	
CEMENTED GRAVEL GREY	148	161	
CLAY GREY	161	168	
CLAY W/ GRAVEL GREY	168	174	
CEMENTED GRAVEL GREY BRN	174	185	
SAND & GRAVEL GREY BROWN MEDIUM LOOSE	185	187	
CONT'D PAGE 2			

Date started 6-3-98 Completed 7-24-98

(unbonded) Water Well Constructor Certification:
I certify that the work I performed on the construction, alteration, or abandonment of this well is in compliance with Oregon water supply well construction standards. Materials used and information reported above are true to the best of my knowledge and belief.
WWC Number
Signed Date

(bonded) Water Well Constructor Certification:
I accept responsibility for the construction, alteration, or abandonment work performed on this well during the construction dates reported above. All work performed during this time is in compliance with Oregon water supply well construction standards. This report is true to the best of my knowledge and belief.
WWC Number 688
Signed Steven N. Stadeli Date 8-3-98

ORIGINAL & FIRST COPY-WATER RESOURCES DEPARTMENT SECOND COPY-CONSTRUCTOR THIRD COPY-CUSTOMER

IR-EL: OWRD MARI 3101 Well Log

RECEIVED NOV 29 1962 STATE ENGINEER SALEM, OREGON

NOTICE TO WATER WELL CONTRACTOR
The original and first copy of this report are to be filed with the STATE ENGINEER, SALEM 10, OREGON within 30 days from the date of well completion.

WATER WELL REPORT
STATE OF OREGON
(Please type or print)

3101 MARI

State Well No. 6/1W-9E1
State Permit No.

(1) OWNER:
Name DR. C. J. EBNER
Address Rt. 1 BOX 164
MT. ANGEL ORE

(2) LOCATION OF WELL:
County MARION Driller's well number
¼ ¼ Section 9 T. 6 S R. 1W W.M.
Bearing and distance from section or subdivision corner

(3) TYPE OF WORK (check):
New Well ☒ Deepening ☐ Reconditioning ☐ Abandon ☐
If abandonment, describe material and procedure in Item 12.

(4) PROPOSED USE (check):
Domestic ☐ Industrial ☐ Municipal ☐
Irrigation ☒ Test Well ☐ Other ☐

(5) TYPE OF WELL:
Rotary ☐ Driven ☐
Cable ☒ Jetted ☐
Dug ☐ Bored ☐

(6) CASING INSTALLED: Threaded ☐ Welded ☒
8" Diam. from 0 ft. to 100 ft. Gage .250
" Diam. from ft. to ft. Gage
" Diam. from ft. to ft. Gage

(7) PERFORATIONS: Perforated? ☒ Yes ☐ No
Type of perforator used MILLS
Size of perforations 5/16 in. by 2½ in.
610 perforations from 46 ft. to 97 ft.
perforations from ft. to ft.
perforations from ft. to ft.
perforations from ft. to ft.
perforations from ft. to ft.

(8) SCREENS: Well screen installed ☐ Yes ☒ No
Manufacturer's Name
Type Model No.
Diam. Slot size Set from ft. to ft.
Diam. Slot size Set from ft. to ft.

(9) CONSTRUCTION:
Well seal—Material used in seal CEMENT
Depth of seal 44' ft. Was a packer used? YES
Diameter of well bore to bottom of seal 12 in.
Were any loose strata cemented off? ☐ Yes ☒ No Depth
Was a drive shoe used? ☒ Yes ☐ No
Was well gravel packed? ☐ Yes ☒ No Size of gravel:
Gravel placed from ft. to ft.
Did any strata contain unusable water? ☐ Yes ☒ No
Type of water? Depth of strata
Method of sealing strata off

(10) WATER LEVELS:
Static level 1' + ft. below land surface Date 5-10-61
Artesian pressure 2 lbs. per square inch Date 5-10-61

(11) WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? ☒ Yes ☐ No If yes, by whom? STETTLER SUPPLY
Yield: 300 gal./min. with 30 ft. drawdown after 1 hrs.
" 500 " 33 " 1 "
" 700 " 38 " 1 "
Bailer test gal./min. with ft. drawdown after hrs.
Artesian flow g.p.m. Date
Temperature of water 55 Was a chemical analysis made? ☐ Yes ☒ No

(12) WELL LOG: Diameter of well below casing 8"
Depth drilled 100' ft. Depth of completed well 100' ft.

Formation: *Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of formation.*

MATERIAL	FROM	TO
TOPSOIL	0	2
CLAY YELLOW COLOR	2	7
CONGLOMERATE BOULDERS	7	51
GRAVEL COARSE	51	52'6"
CONGLOMERATE BOULDERS	52'6	67'
GRAVEL + SAND 1"-	67'	68'
CONGLOMERATE BOULDERS	68	94
GRAVEL LOOSE 3"- W. B	94	95
CONGLOMERATE 3"-	95	100'
ARTESIAN AT 67' TO 68'		
2# HEAD PRESSURE		
ARTESIAN AT 94' TO 95'		
2# HEAD PRESSURE		
ALL CONGLOMERATES AS LISTED ABOVE		
SEEMS TO BE WATER BEARING		

Work started 5-2- 1961 Completed 5-10 1961
Date well drilling machine moved off of well 5-10- 1961

(13) PUMP:
Manufacturer's Name
Type: TURBINE H.P. 10

Water Well Contractor's Certification:
This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.

NAME J.A. SHEED & SONS
(Person, firm or corporation) (Type or print)
Address 3910 SILVERTON RD NE SALEM O.

Drilling Machine Operator's License No. 187

[Signed] B.J. Sheed
(Water Well Contractor)
Contractor's License No. 6 Date 5-10- 1961

(USE ADDITIONAL SHEETS IF NECESSARY)

IR-EU: OWRD MARI 3090 Well Log

NOTICE TO WATER WELL CONTRACTOR
The original and first copy of this report are to be filed with the WATER RESOURCES DEPARTMENT, SALEM, OREGON 97310 within 30 days from the date of well completion.

RECEIVED AUG 2 1978 WATER RESOURCES DEPT. SALEM, OREGON

WATER WELL REPORT
STATE OF OREGON
(Please type or print)
(Do not write above this line)

3090 MAR.

State Well No. 6S/1W-9ac
State Permit No.

RECEIVED JUN 28 1978 WATER RESOURCES DEPT. SALEM, OREGON

(1) OWNER:
Name D.T.S. Partnership
Address 2350 Barnes Circle
Reno, Nevada 89509

(2) TYPE OF WORK (check):
New Well ☒ Deepening ☐ Reconditioning ☐ Abandon ☐
If abandonment, describe material and procedure in Item 12.

(3) TYPE OF WELL:
Rotary ☐ Driven ☐
Cable ☒ Jetted ☐
Dug ☐ Bored ☐

(4) PROPOSED USE (check):
Domestic ☐ Industrial ☐ Municipal ☐
Irrigation ☒ Test Well ☐ Other ☐

(5) CASING INSTALLED: Threaded ☐ Welded ☒
8" Diam. from 1½ + ft. to 172 ft. Gage .250
" Diam. from ft. to ft. Gage
" Diam. from ft. to ft. Gage

(6) PERFORATIONS: Perforated? ☒ Yes ☐ No.
Type of perforator used Mills Knife
Size of perforations ¼ in. by 3 in.
1180 perforations from 50 ft. to 170 ft.
perforations from ft. to ft.
perforations from ft. to ft.

(7) SCREENS: Well screen installed? ☐ Yes ☒ No
Manufacturer's Name
Type Model No.
Diam. Slot size Set from ft. to ft.
Diam. Slot size Set from ft. to ft.

(8) WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? ☒ Yes ☐ No If yes, by whom? Stettler Supply Co.
Yield: 545 gal./min. with 72 ft. drawdown after ½ hrs.
400 " 46 " 3/4 "
250 " 30 " 40 mins.
Bailer test gal./min. with ft. drawdown after hrs.
Artesian flow g.p.m.
Temperature of water XX Depth artesian flow encountered ft.

(9) CONSTRUCTION:
Well seal—Material used Cement
Well sealed from land surface to 25 ft.
Diameter of well bore to bottom of seal 12 in.
Diameter of well bore below seal 8 in.
Number of sacks of cement used in well seal 28 sacks
How was cement grout placed? Gravity Pressure

Was a drive shoe used? ☒ Yes ☐ No Plugs Size: location ft.
Did any strata contain unusable water? ☐ Yes ☒ No
Type of water? depth of strata
Method of sealing strata off
Was well gravel packed? ☒ Yes ☐ No Size of gravel: 3/4 crushed
Gravel placed from 25 ft. to 35 ft.

(10) LOCATION OF WELL:
County Marion Driller's well number
S.W. ¼ N.E. ¼ Section 9 T. 6 S. R. 1 W. W.M.
Bearing and distance from section or subdivision corner

(11) WATER LEVEL: Completed well.
Depth at which water was first found approx. 40 ft.
Static level 35 ft. below land surface. Date 5/23/78
Artesian pressure XX lbs. per square inch. Date

(12) WELL LOG: Diameter of well below casing 0
Depth drilled 190 ft. Depth of completed well 172 ft.

Formation: Describe color, texture, grain size and structure of materials; and show thickness and nature of each stratum and aquifer penetrated, with at least one entry for each change of formation. Report each change in position of Static Water Level and indicate principal water-bearing strata.

MATERIAL	From	To	SWL
Top soil-brn.-	0	1	
Clay-brn.-	1	27	
Clay-blue-	27	42	
Course-conglom.-brn.-	42	75	(W.B.)
Med.-conglom.-greyish-green(hd.)	75	90	"
Med.conglom.-grey- softer-	90	100	"
Med.conglom.grey- med.hd.-	100	130	"
Med.conglom.grey- hd.-	130	172	"
Clay-blue-soft-	172	190	

The well was pumped for a total of 10½ hrs. in two different days & these readings were taken at the end of the second day.

Work started 4/19/78 19 Completed 5/19/78 19
Date well drilling machine moved off of well 5/19/78 19

Drilling Machine Operator's Certification:
This well was constructed under my direct supervision. Materials used and information reported above are true to my best knowledge and belief.
[Signed] [signature] (Drilling Machine Operator) Date 6/27, 1978
Drilling Machine Operator's License No. 1071

Water Well Contractor's Certification:
This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.
Name R.Stadeli & Sons,Inc. (Person, firm or corporation) (Type or print)
Address 11364 Evergrn.Rd.N.E.,Silvrtn.Or.97381
[Signed] Paul R. Stadeli (Water Well Contractor)
Contractor's License No. 296 Date 6/26/78, 19

(USE ADDITIONAL SHEETS IF NECESSARY)

SP*45656-119

APPENDIX C:

Analytical Instruments Used by the Central Analytical Laboratory

1. The Perkin Elmer Optima 3000DV is an inductively-coupled plasma optical emission spectrometer with a diode array detector. The dual view is capable of viewing the plasma axially for improved detection limits, or radially to provide lower matrix effects and fewer spectral interferences. Routine analysis includes P, K, Ca, Mg, Mn, Fe, Cu, B and Zn and this instrument is capable of running any ICP analyte.

2. The Leco CNS-2000 Macro Analyzer simultaneously determines carbon, nitrogen and sulfur in solid samples. No digestion or extraction is required. Up to 2g of ground sample can be used for maximum accuracy in heterogeneous samples.

3. The Alpkem Flow Solution with digital and monochromater detectors provides automated analysis of Total Kjeldahl N, NH4, NO3, Total P, or ortho-P in soil, plant and water samples. The Random Access Sampler allows simultaneous analysis of 2 analytes and automatic dilution of off-scale samples. This instrument is used primarily for low level detection in water samples.

4. The Alpkem RFA 300 provides automated analysis of Total Kjeldahl N, NH4, NO3, Total P, or ortho-P in soil, plant and water samples. This instrument is used primarily for higher concentration levels in soil and plant samples.

5. Waters Capillary Ion Analysis System performs separations by applying an electrical field to the sample in a capillary filled with an electrolyte.

Further information regarding CAL can be found on their web site (www.css.orst.edu/Services/Plntanal/CAL/calhome.htm).

APPENDIX D:

Soil Test Hole Chemical Results

Fig. D1: Test Hole 5 Agricultural Lechate Products

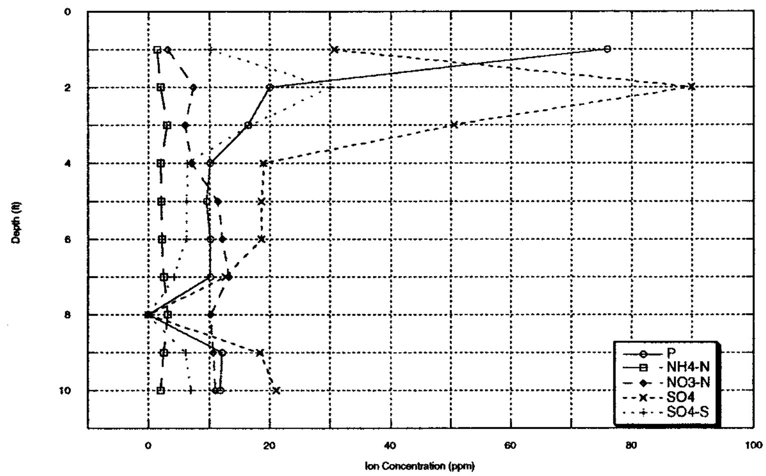


Figure D2: Test Hole 6 Agricultural Lechate Products

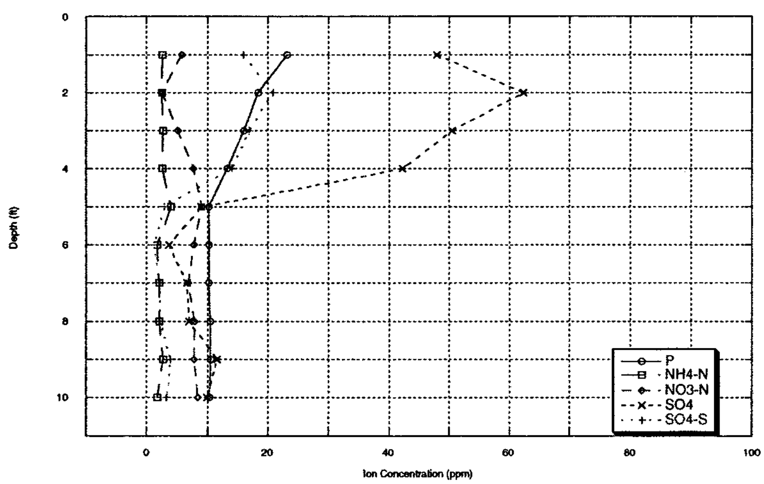


Figure D3: Test Hole 7 Agricultural Lechate Products

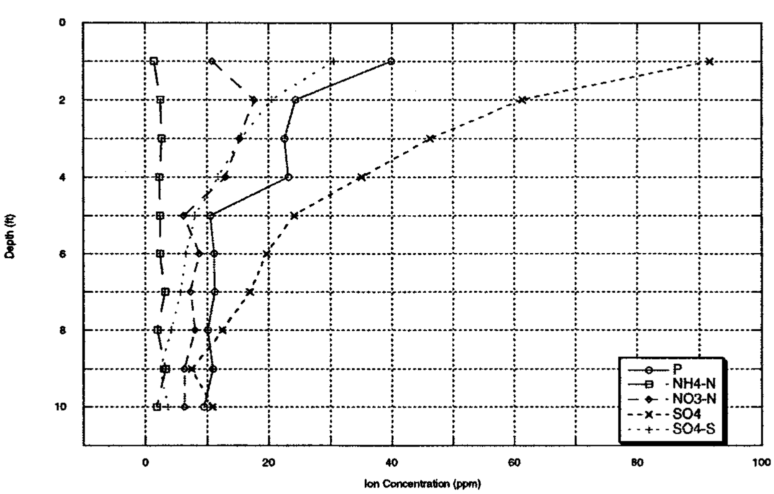


Figure D4: Test Hole 8 Agricultural Lechate Products

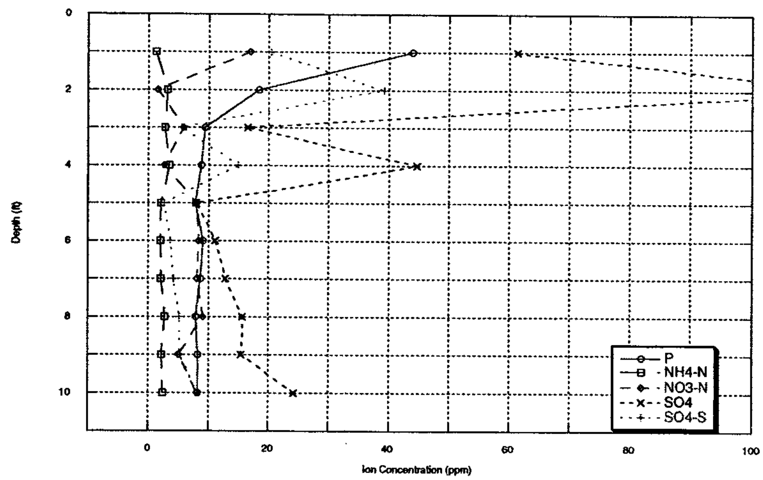


Figure D5: Test Hole 9 Agricultural Lechate Products

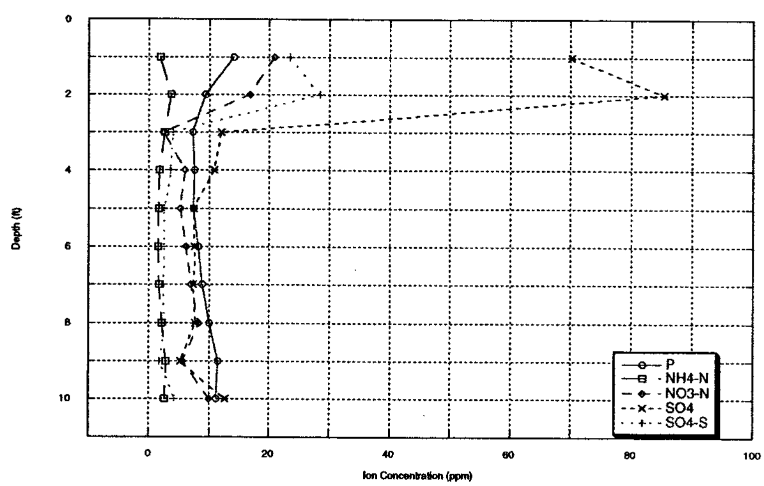


Figure D6: Test Hole 10 Agricultural Lechate Products

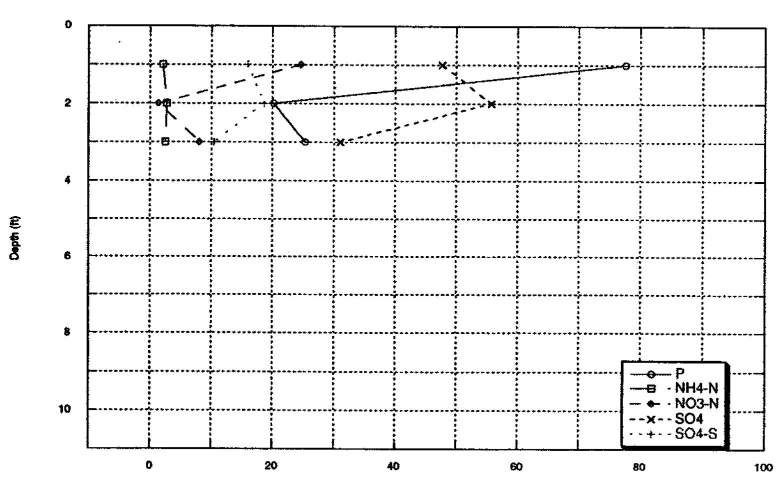


Figure D7: Test Hole 11 Agricultural Lechate Products

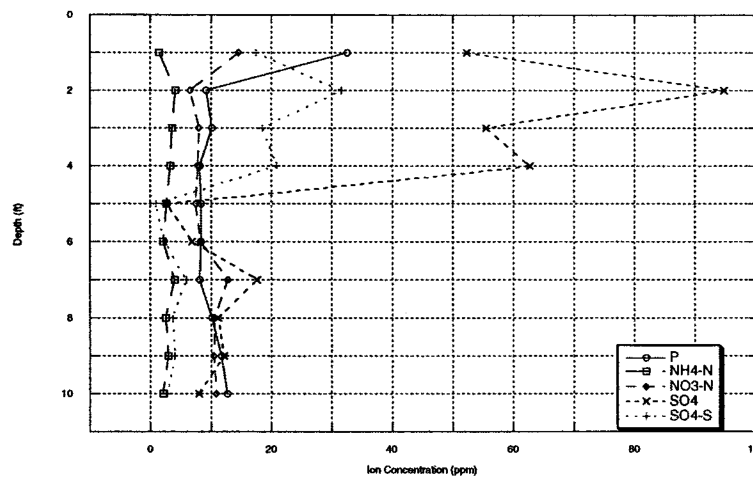


Figure D8: Test Hole 12 Agricultural Lechate Products

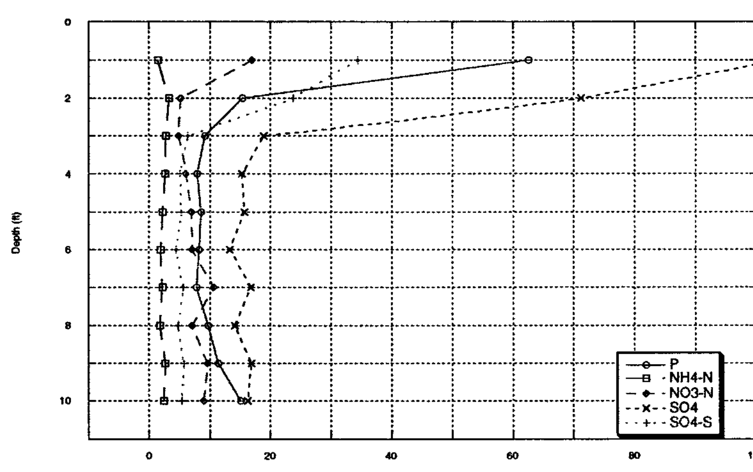


Figure D9: Test Hole 12 Cation Plot

Pudding_Project/Chem_Data/TestHole_Chem/12cation.qpw

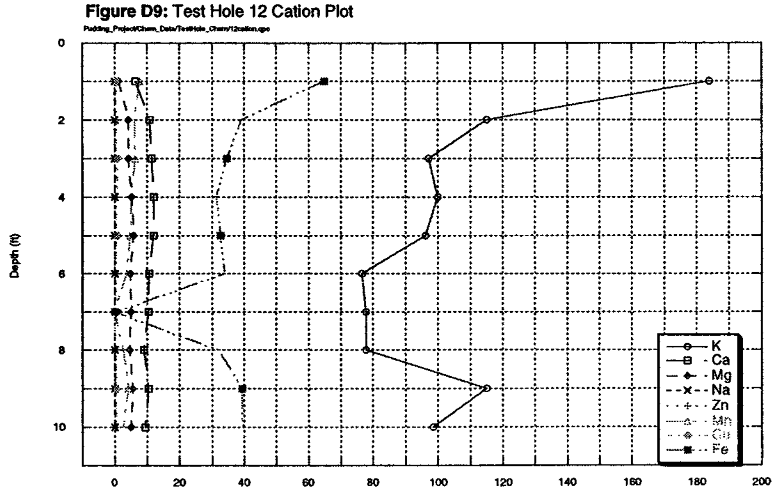


Figure D10: Test Hole 13 Agricultural Lechate Products

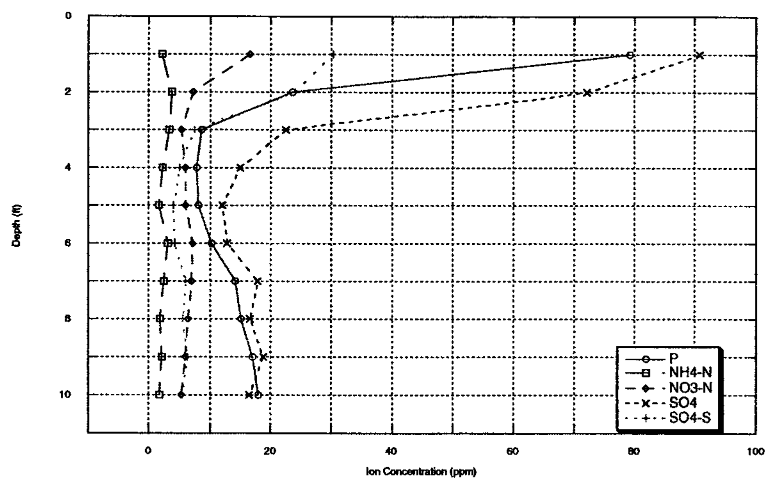


Figure D11: Test Hole 13 Cation Plot

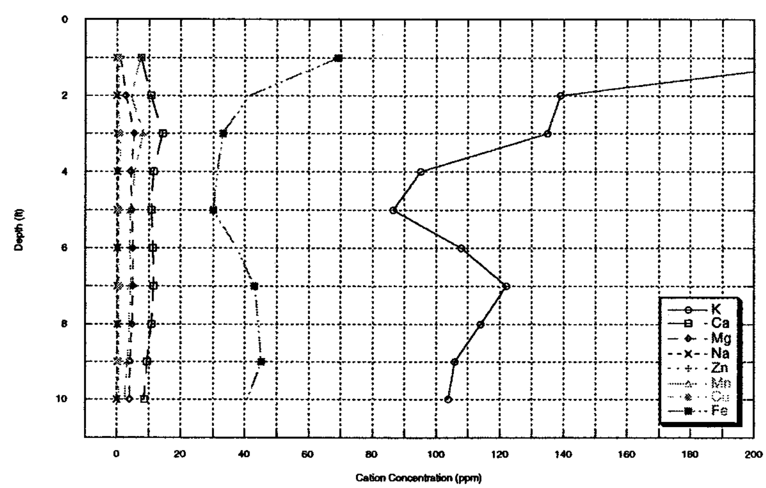


Figure D12: Test Hole 14 Agricultural Lechate Products

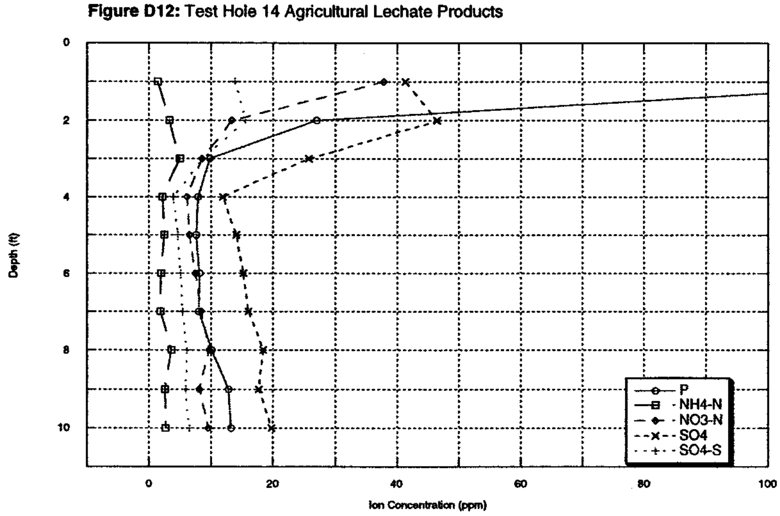


Figure D13: Test Hole 14 Cation Plot

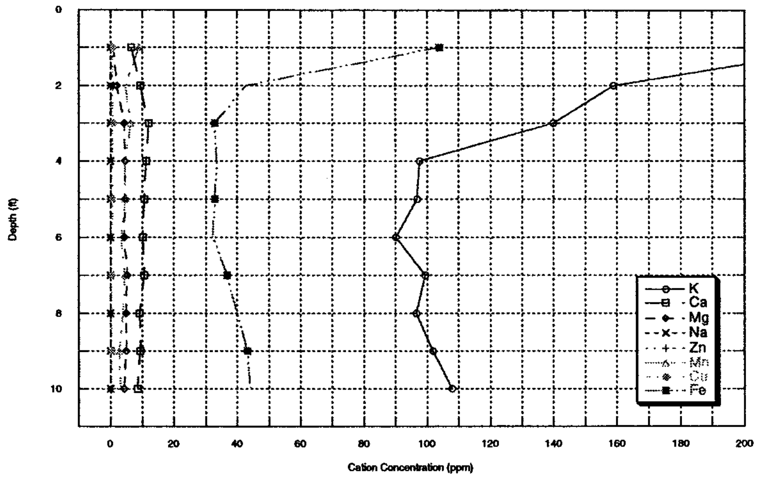


Figure D14: Test Hole 15 Agricultural Lechate Products

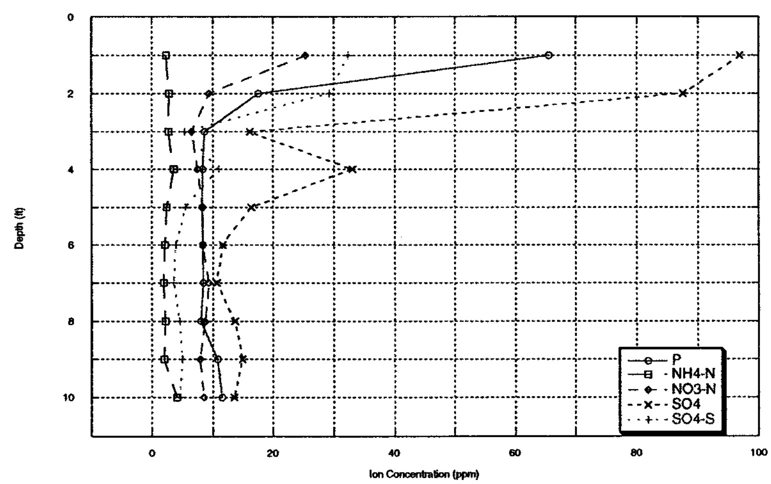


Figure D15: Test Hole 15 Cation Plot

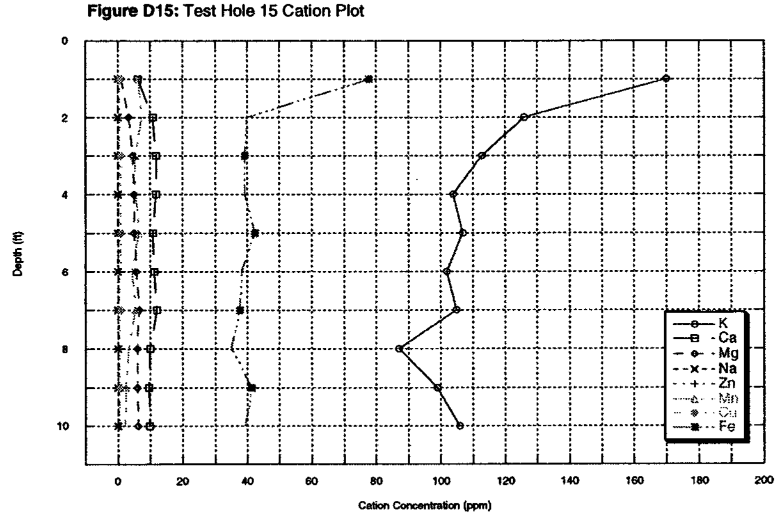


Figure D16: Test Hole 16 Agricultural Lechate Products

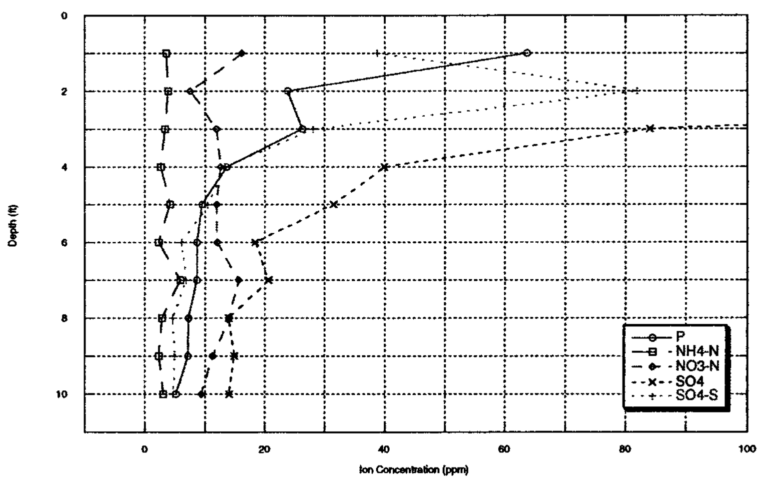


Figure D17: Test Hole 16 Cation Plot

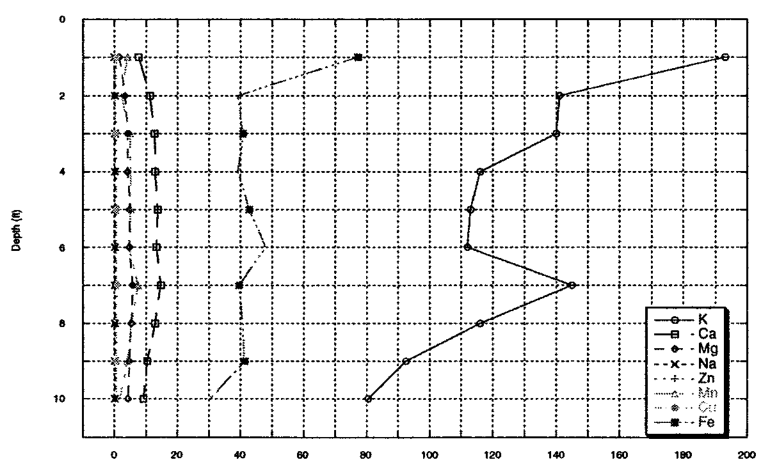
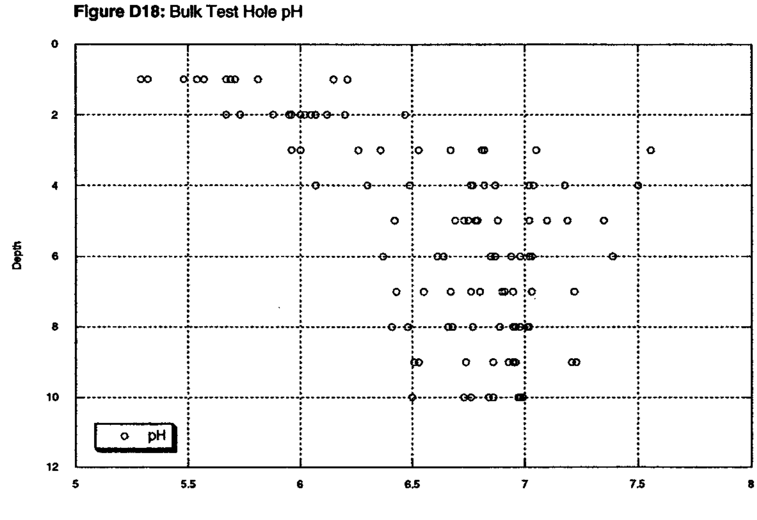


Figure D18: Bulk Test Hole pH



APPENDIX E:
Pump Test Drawdown and Analysis Plots

Figure E1: Site 1 Drawdown During April Pump Test

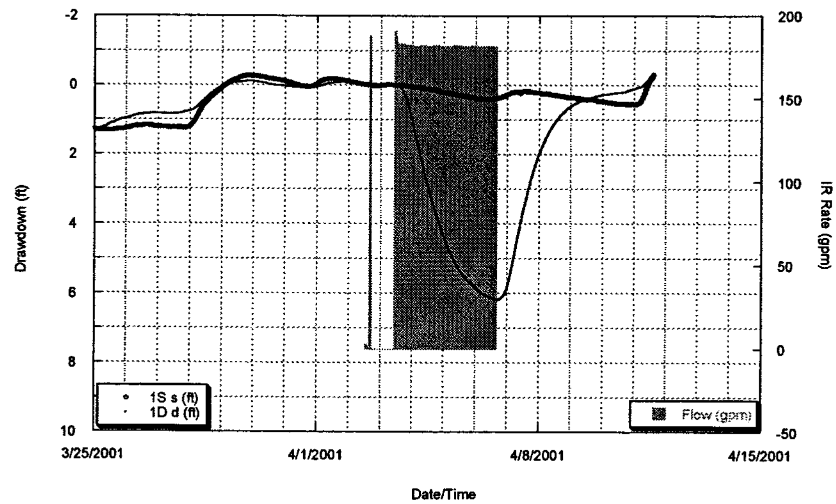


Figure E2: Site 1D Theis Analysis

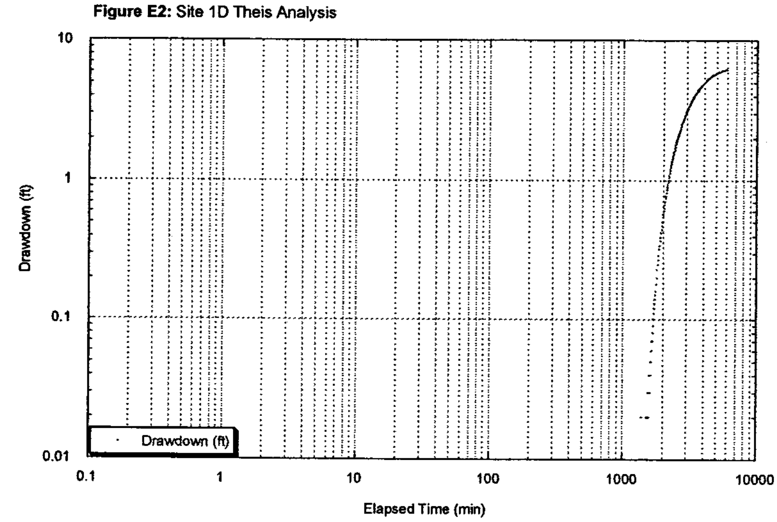


Figure E3: Site 1D CooperJacob Analysis

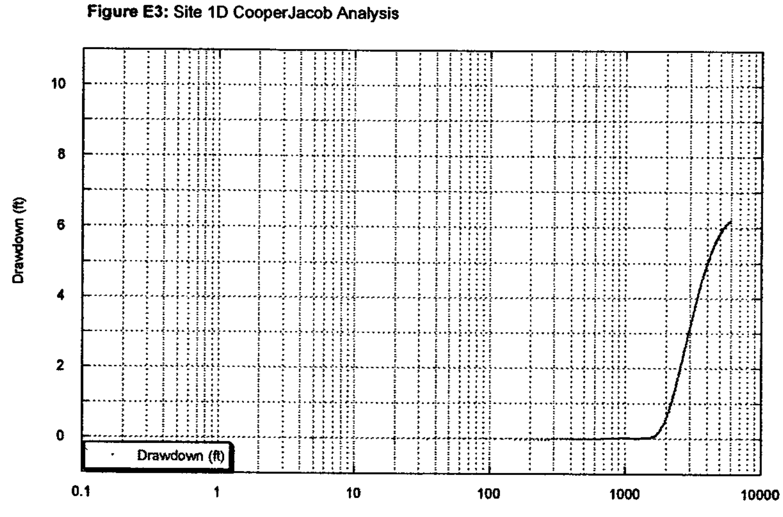


Figure E4: Site 2 Drawdown During April Pump Test

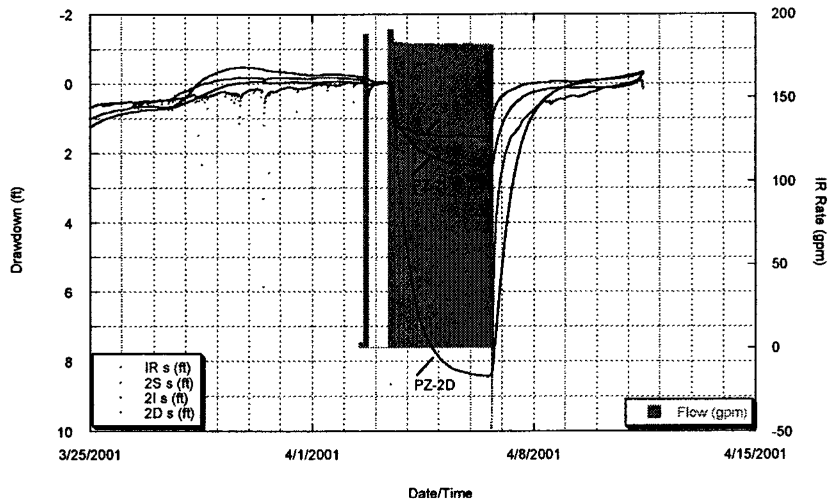


Figure E5: Site 2D Theis Analysis

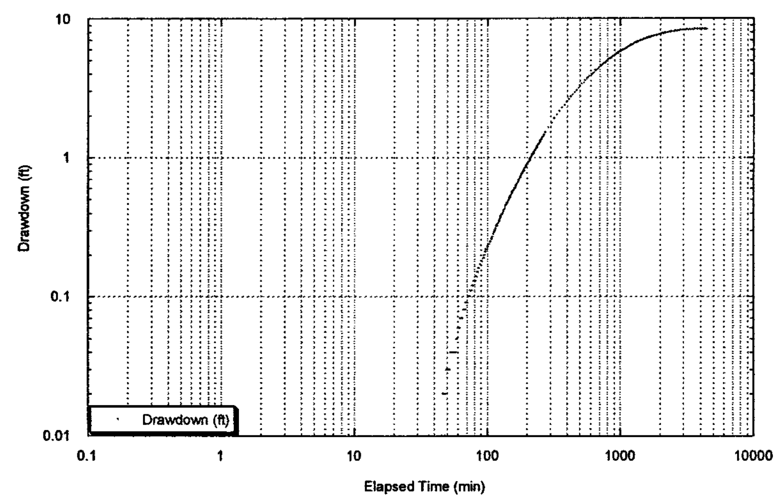


Figure E6: Site 2D CooperJacob Analysis

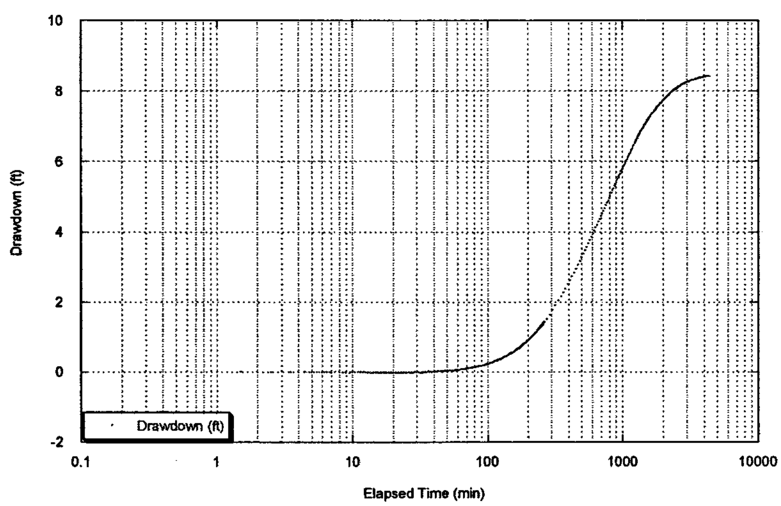


Figure E7: Eder 3 Drawdown During April Pump Test

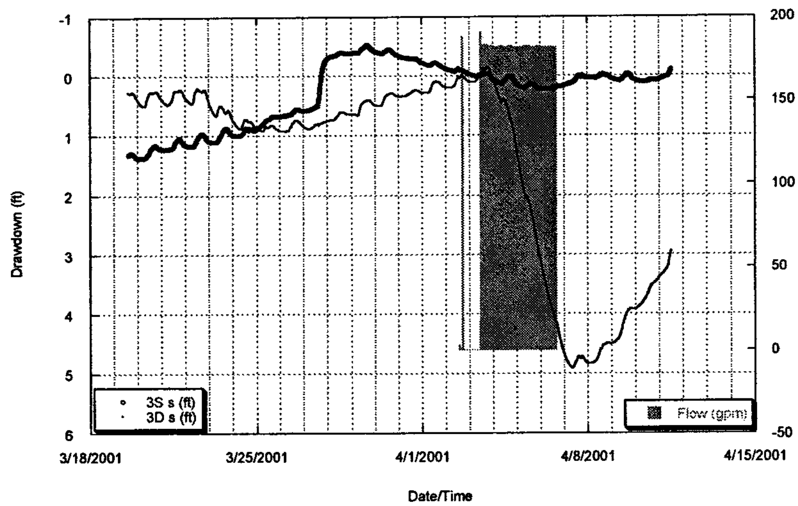


Figure E8: Site 3D Theis Analysis

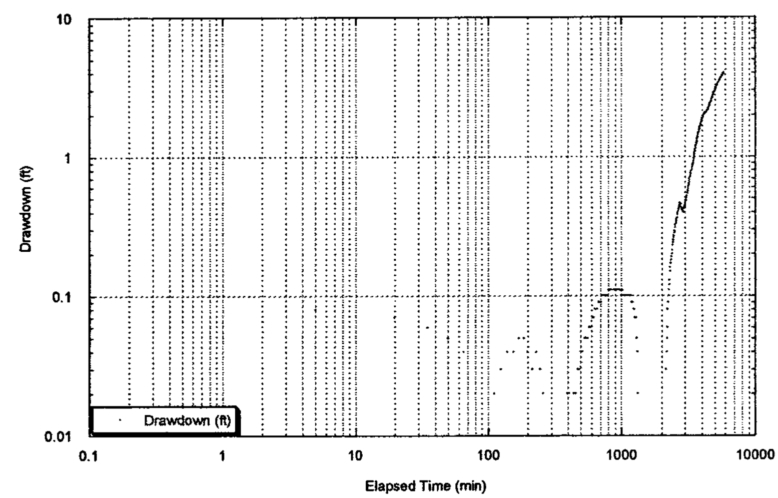


Figure E9: Site 3D CooperJacob Analysis

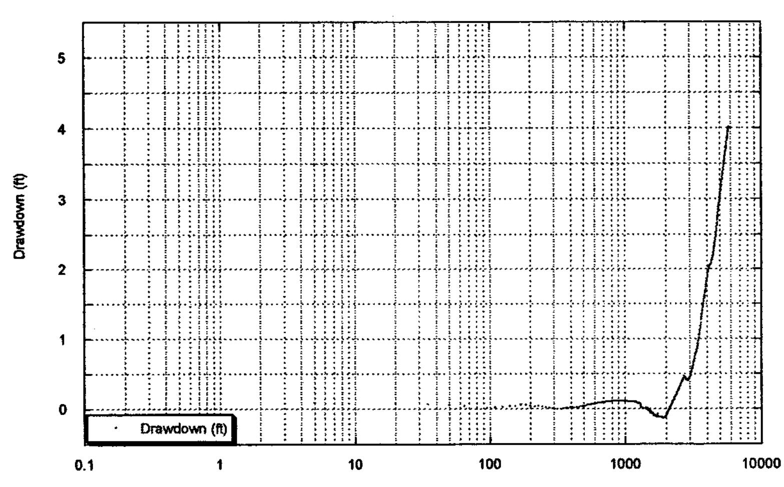


Figure E10: IR-EG Drawdown During April Pump Test

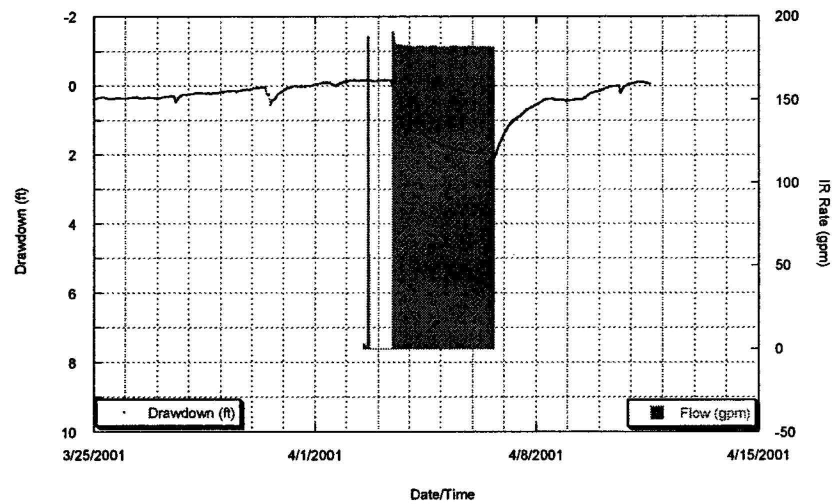


Figure E11: IR-EG Theis Analysis

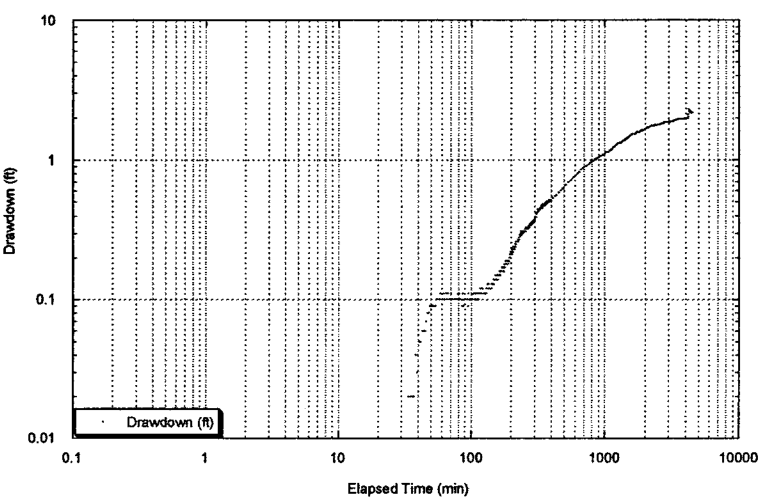


Figure E12: IR-EG CooperJacob Analysis

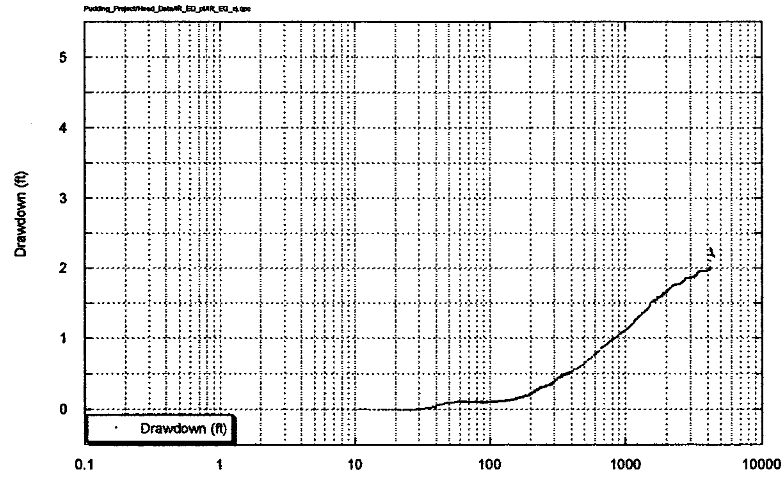


Figure E13: IR-EB Drawdown During April Pump Test

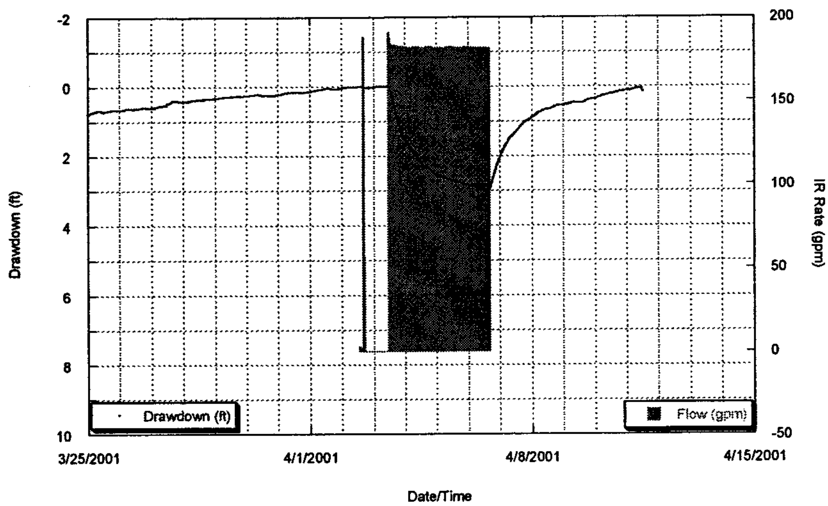


Figure E14: IR-EB Theis Analysis

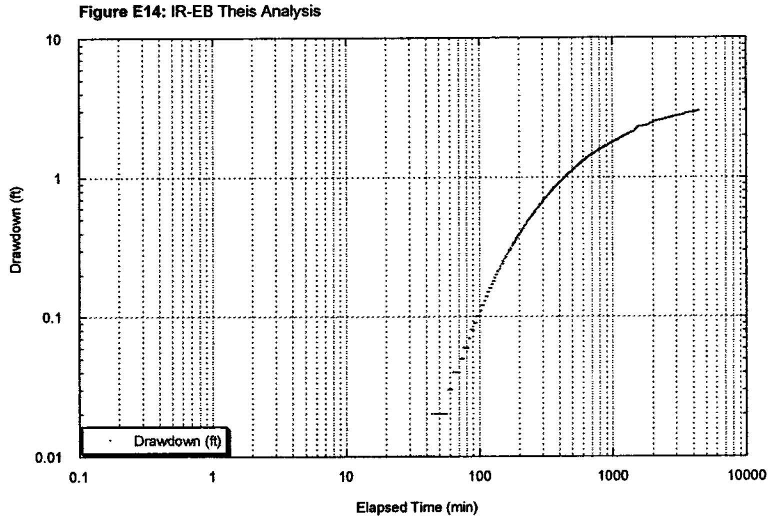


Figure E15: IR-EB CooperJacob Analysis

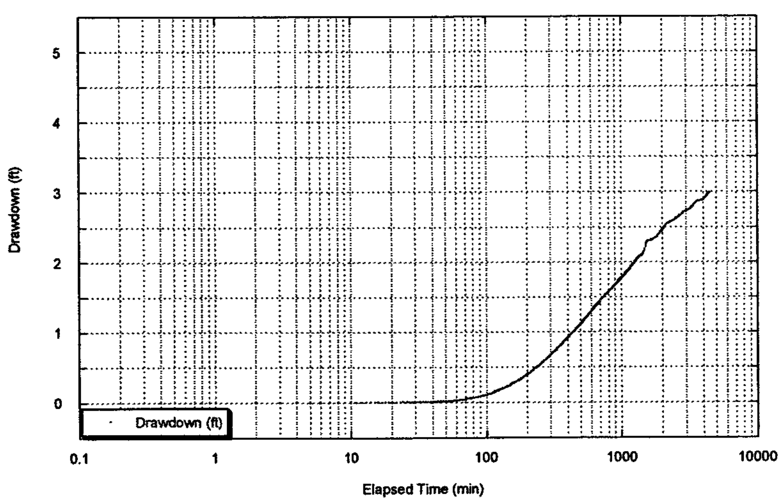


Figure E16: IR-SE Drawdown During April Pump Test

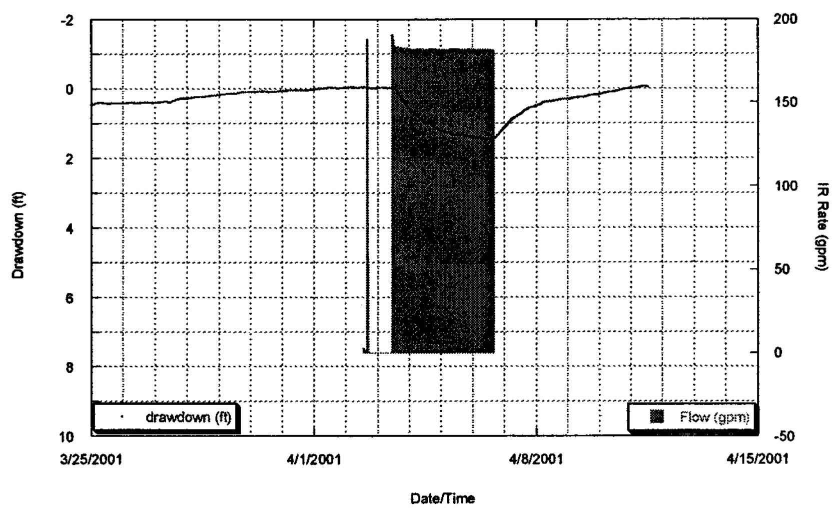


Figure E17: IR-SE Theis Analysis

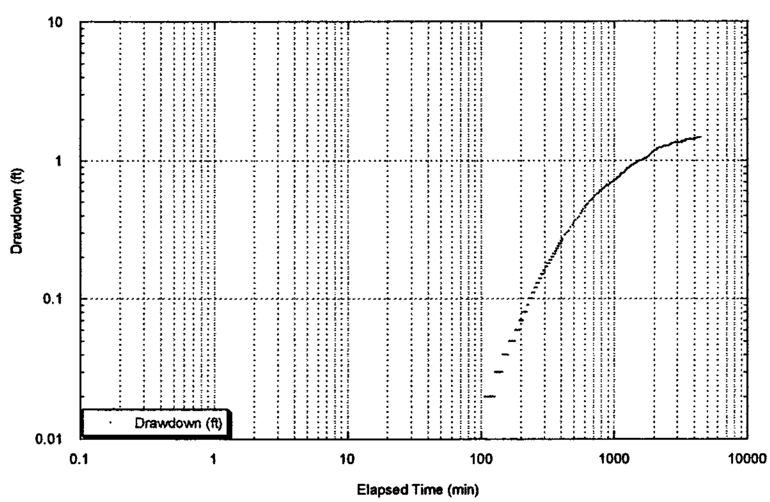


Figure E18: IR-SE CooperJacob Analysis

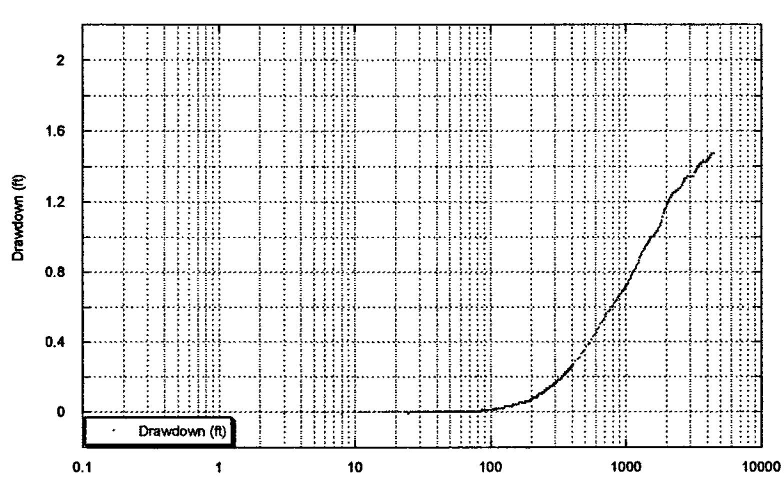


Figure E19: IR-EL Drawdown During April Pump Test

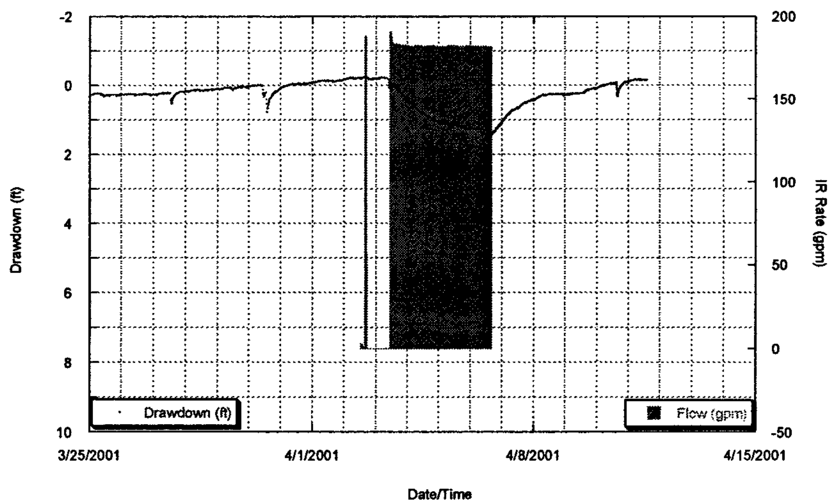


Figure E20: IR-EL Theis Analysis

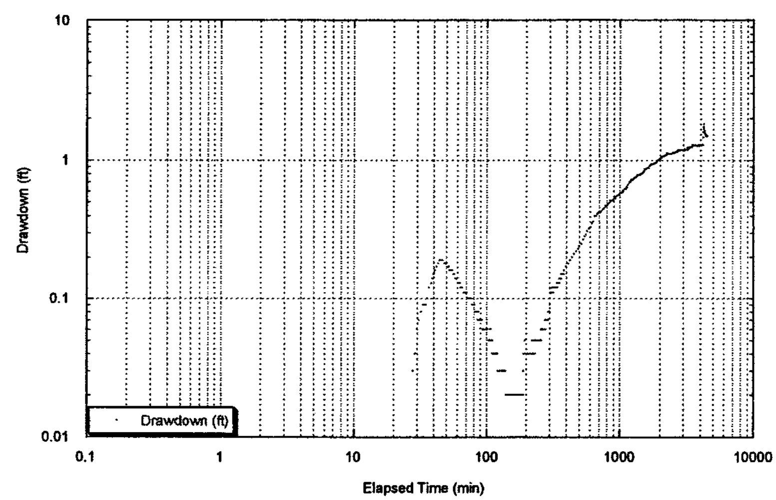


Figure E21: IR-EL CooperJacob Analysis

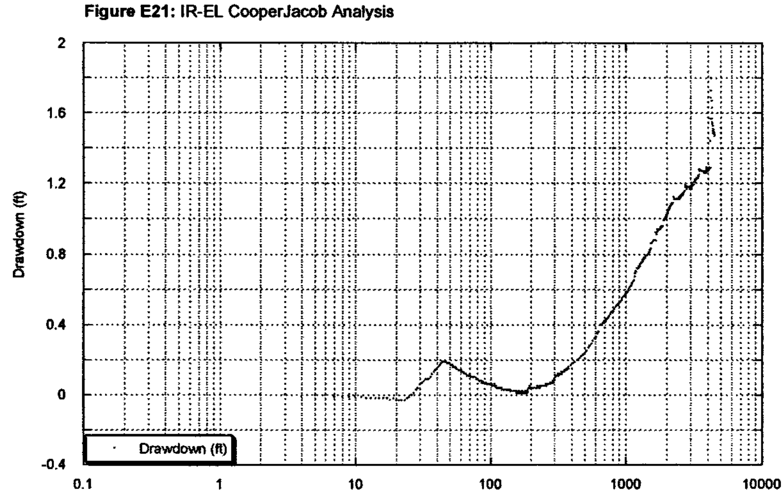


Figure E22: IR-EU Drawdown During April Pump Test

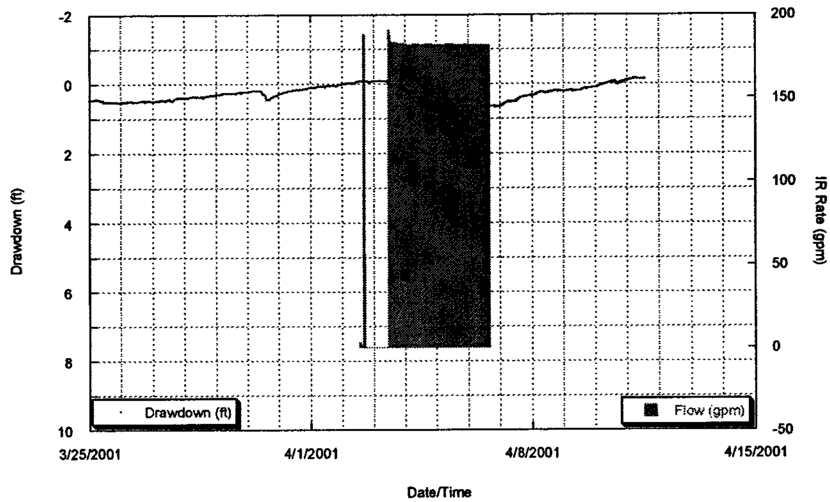


Figure E23: IR-EU Theis Analysis

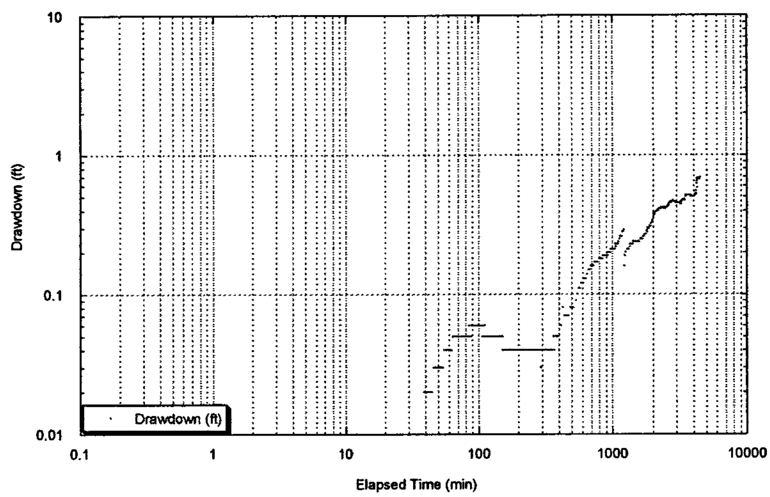


Figure E24: IR-EU CooperJacob Analysis

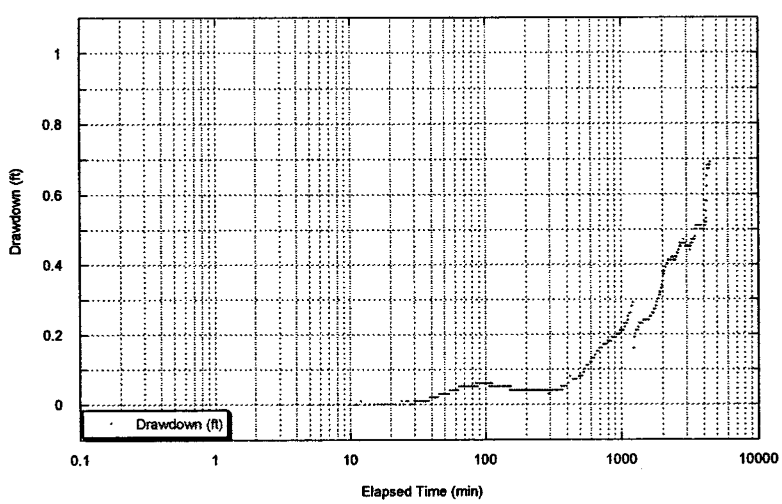
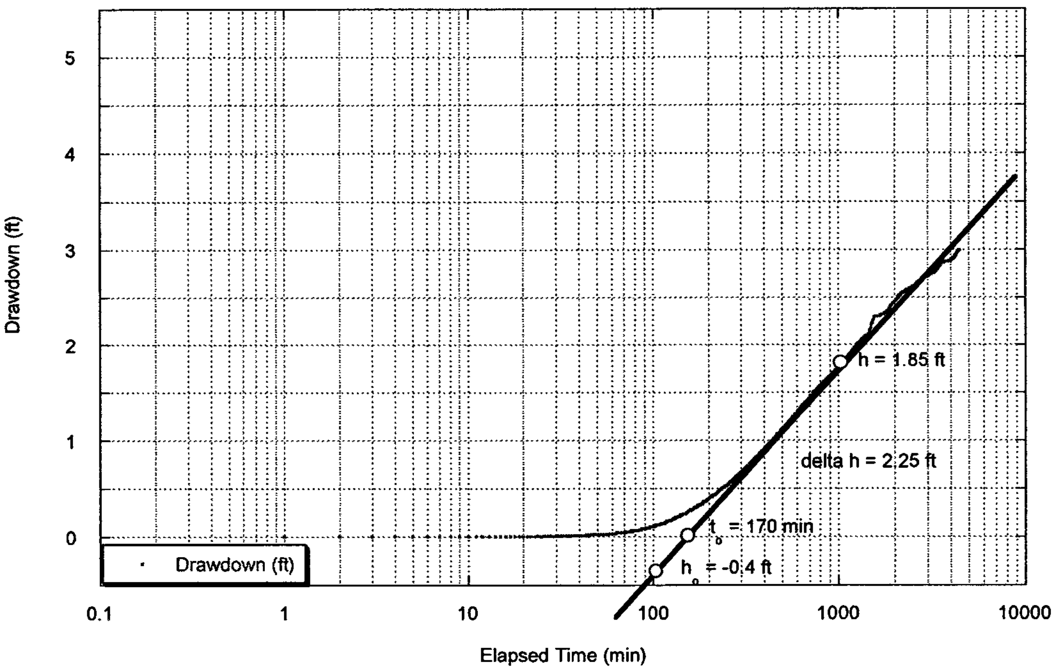


Figure E25: IR-EB CooperJacob Analysis Calculation Example



Example Cooper-Jacob analysis and calculation. See Table E1 for all pump test analyses.

$$h_0 = -0.5,\ h = 1.75,\ \Delta h = 2.25,\ t_o = 170\,\text{min}$$

$$T = \frac{2.3Q}{4\pi\Delta h} = \frac{2.3(24.0625 ft^3 \min^{-1})}{4\pi(2.25 ft)} = 1.96 ft^2 \min^{-1}$$

$$K = \frac{T}{b}, b \approx 200 ft$$

$$K = \frac{1.96 ft^2 \min^{-1}}{200 ft}\left(\frac{1m}{3.28 ft}\right)\left(\frac{1\min}{60s}\right) = 4.32x10^{-5}\frac{m}{s}$$

$$S = \frac{2.25Tt_o}{r^2} = \frac{2.25(1.96 ft^2 \min^{-1})(170\min)}{(1959 ft)^2} = 1.95x10^{-4}$$

Table E1: Detailed Analysis of April Pump Test

See Dawson and Istok, 1991 chapter 12 for further description of variables and conceptual model description and schematic

Note: site piezometers penetrate only the top few feet of the Willamette Aquifer and are screened over a much shorter interval than IR wells

Site	rad from IR (ft)	rad from IR (m)	theis matchpoints confidence in fit (arbitrary 1-10)	1/u (-)	W(u) (-)	s (ft)	t (min)	cooper-jacob values delta s (ft)	t0 (min)
PZ-2D	16.5	5.03	7	1	1	4.4	200	8	200
PZ-1D	257.5	78.49	4	0.1	0.01	1.1	700	15.2	2000
PZ-3D	435.7	132.80	1					4.25	2000
IR-EG	1837	559.92	6	1	1	1	200	1.5	170
IR-EB	1959	597.10	9	1	1	1.1	170	2.25	170
IR-SE	2999	914.10	8	1	1	1	350	1.45	300
IR-EL	3025	922.02	4	1	1	2	610	1.4	400
IR-EU	4560	1389.89	2	1	1	1.1	900	0.9	530

flowrate (Q)

Q(gpm)=	180
Q(ft^3/min)=	24.0624
Q(m^3/sec)=	0.011355

Theis

	T (ft^2/day)	T (m^2/s)	K (ft/day)	K (m/s)	S	Ss (1/ft)	Ss (1/m)
PZ-2D	6.27E+02	6.74E-04	2.72E+00	9.61E-06	1.28E+00	5.56E-03	1.83E-02
PZ-1D	2.51E+01	2.70E-05	1.09E-01	3.84E-07	7.35E-03	3.20E-05	1.05E-04
PZ-3D							
IR-EG	2.76E+03	2.96E-03	1.20E+01	4.23E-05	4.54E-04	1.97E-06	6.48E-06
IR-EB	2.51E+03	2.70E-03	1.09E+01	3.84E-05	3.08E-04	1.34E-06	4.41E-06
IR-SE	2.76E+03	2.96E-03	1.20E+01	4.23E-05	2.98E-04	1.30E-06	4.26E-06
IR-EL	1.38E+03	1.48E-03	5.99E+00	2.11E-05	2.55E-04	1.11E-06	3.65E-06
IR-EU	2.51E+03	2.70E-03	1.09E+01	3.84E-05	3.01E-04	1.31E-06	4.31E-06

Cooper-Jacob

	T (ft^2/day)	T (m^2/s)	K (ft/day)	K (m/s)	S	Ss (1/ft)	Ss (1/m)
PZ-2D	7.93E+02	8.52E-04	3.45E+00	1.22E-05	9.10E-01	3.96E-03	1.30E-02
PZ-1D	4.17E+02	4.49E-04	1.81E+00	6.40E-06	1.97E-02	8.55E-05	2.81E-04
PZ-3D	1.49E+03	1.60E-03	6.49E+00	2.29E-05	2.46E-02	1.07E-04	3.51E-04
IR-EG	4.23E+03	4.55E-03	1.84E+01	6.48E-05	3.33E-04	1.45E-06	4.75E-06
IR-EB	2.82E+03	3.03E-03	1.23E+01	4.32E-05	1.95E-04	8.48E-07	2.79E-06
IR-SE	4.37E+03	4.70E-03	1.90E+01	6.71E-05	2.28E-04	9.91E-07	3.26E-06
IR-EL	4.53E+03	4.87E-03	1.97E+01	6.95E-05	3.09E-04	1.35E-06	4.42E-06
IR-EU	7.05E+03	7.58E-03	3.06E+01	1.08E-04	2.81E-04	1.22E-06	4.01E-06

APPENDIX F:

Slug Test Recovery and Analysis Plots

Figure F1 : Site 1S Slug Test Bouwer and Rice Analysis

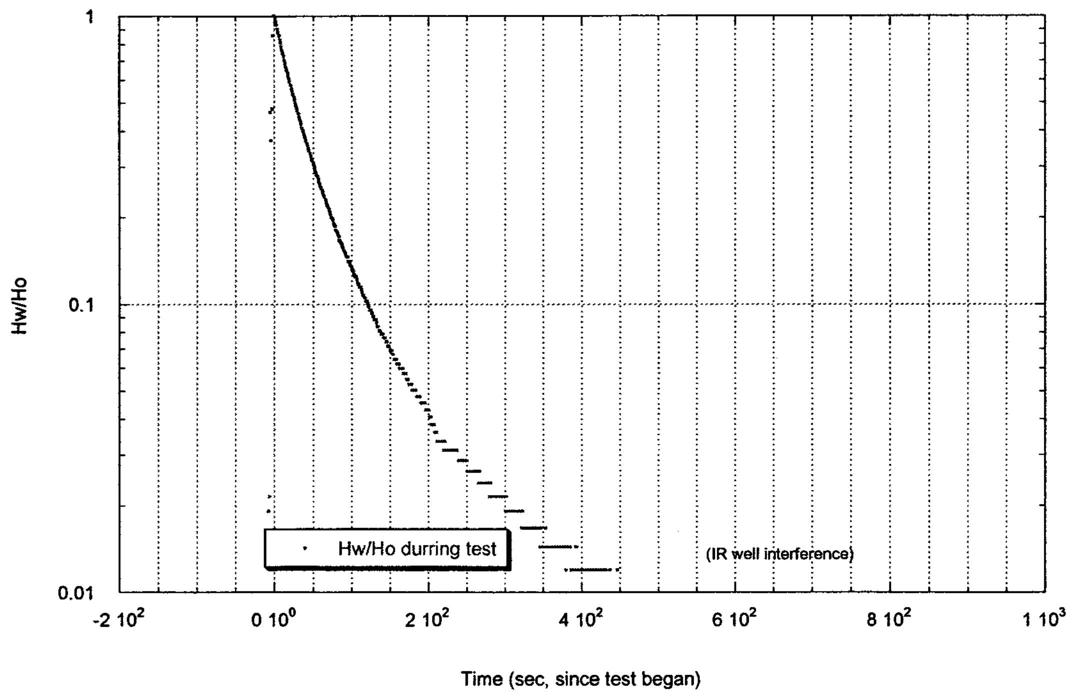


Figure F2: Site 1D Slug Test Bouwer and Rice Analysis

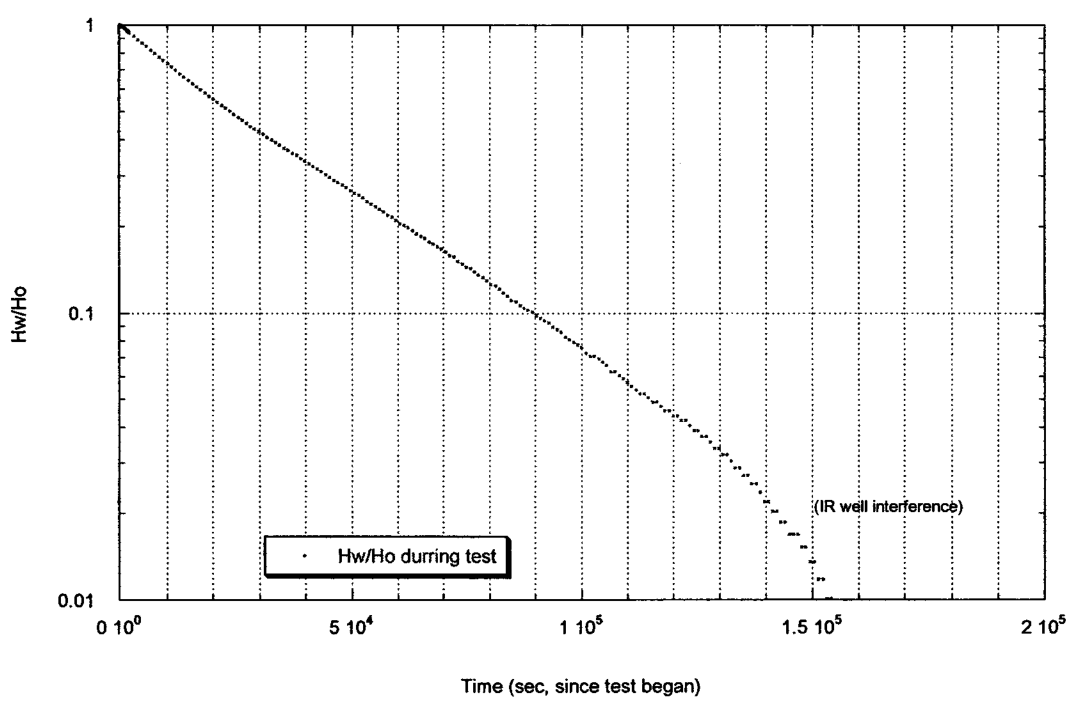


Figure F3: Site 2S Slug Test Bouwer and Rice Analysis

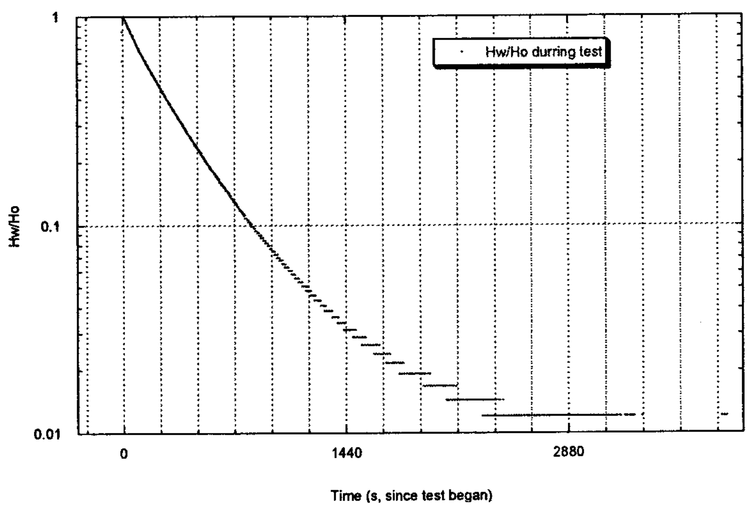


Figure F4: Site 2I Slug Test Bouwer and Rice Analysis

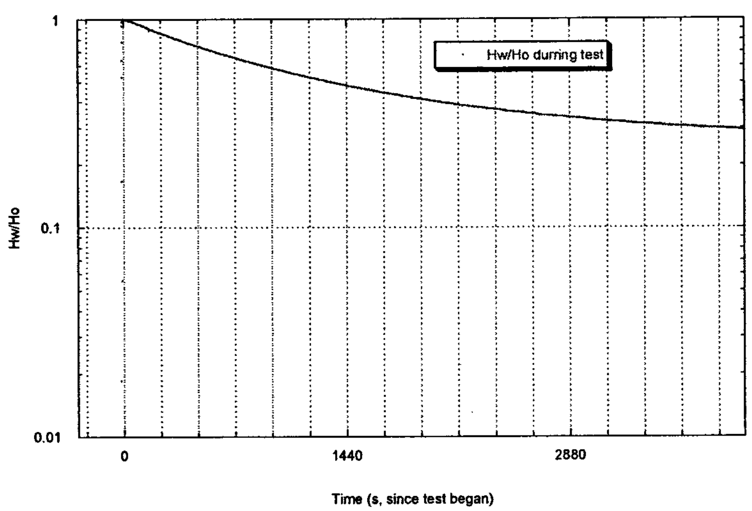


Figure F5: Site 2D Slug Test Bouwer and Rice Analysis

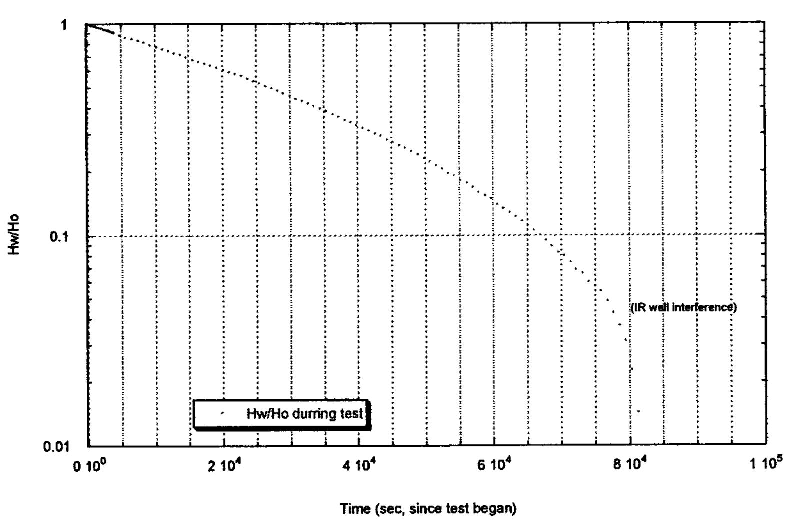


Figure F6: Site 3S Slug Test Bouwer and Rice Analysis

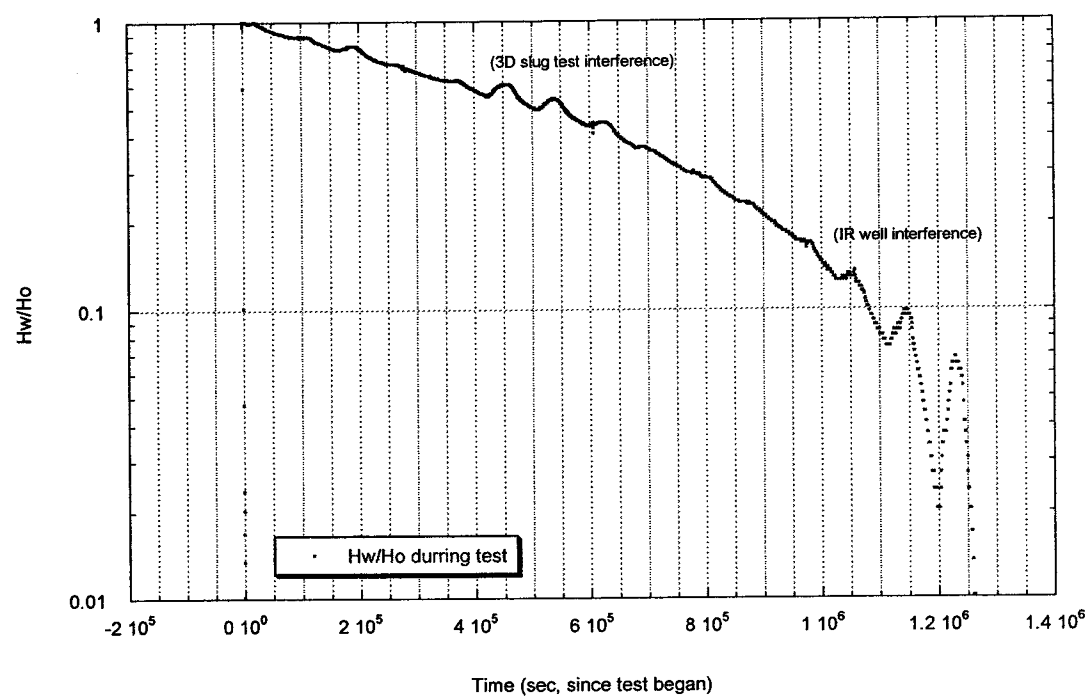


Figure F7: Site 3D Slug Test Bouwer and Rice Analysis

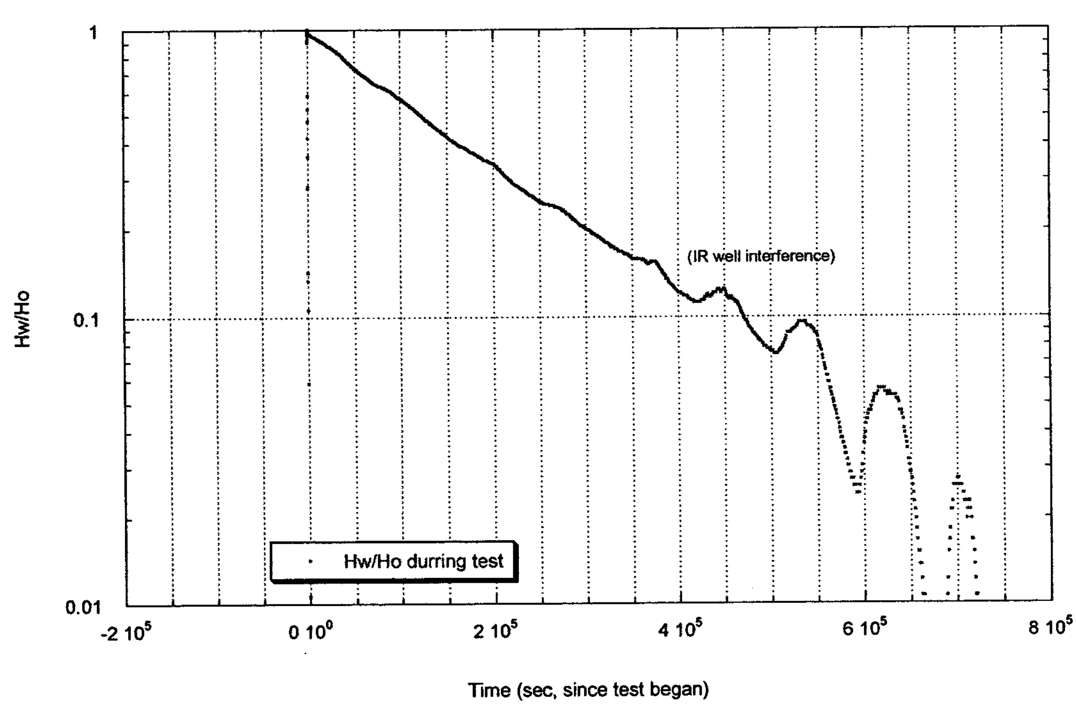
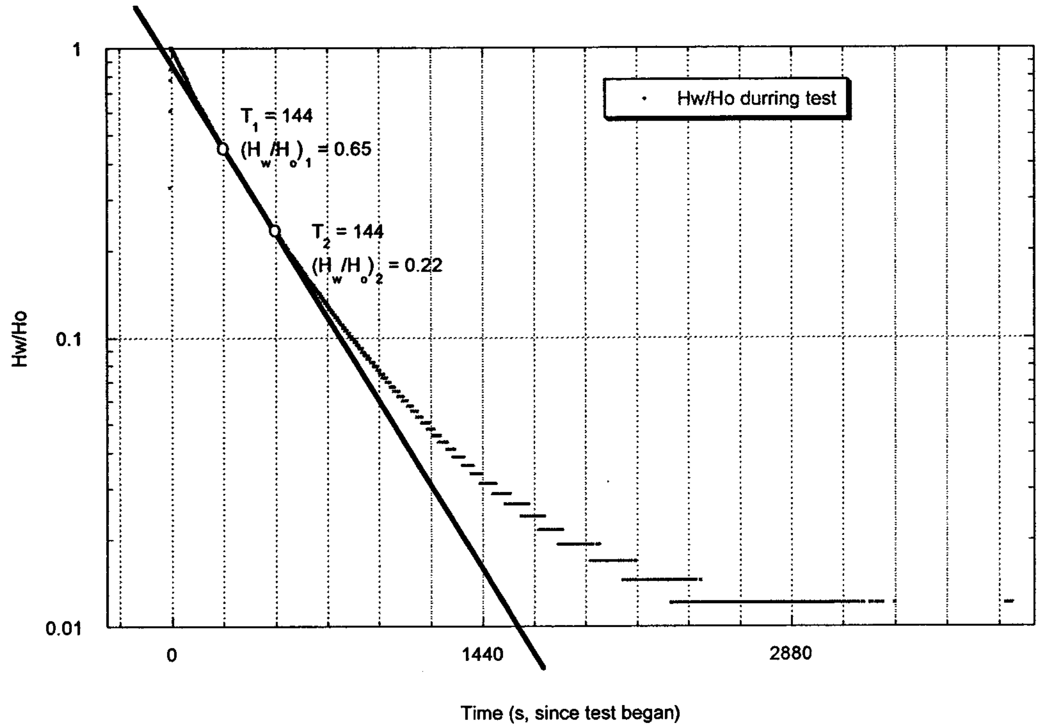


Figure F8: Site 2S Slug Test Bouwer and Rice Analysis Calculation Example



Example Bouwer and Rice Analysis. See Table F1 for full analyses.

$$t_1 = 144s,\ \ln(H/H_w)_1 = 0.65,\ t_2 = 288s,\ \ln(H/H_w)_2 = 0.21$$

$$K = \frac{r_c^2 \ln(R/r_w)}{2(l-d)t_l} \text{ (for aspect ratio of WS piezometers)}$$

$$t_l = \frac{t_2 - t_1}{\ln(H/H_w)_2 - \ln(H/H_w)_1} = \frac{288s - 144s}{\ln(0.21) - \ln(0.65)} = 127.5s$$

$$K = \frac{(0.025m)^2(4.696)}{2(0.792m)127.5s} = 8.86\frac{m}{s}$$

Figure F1: Slug Test Results using Bouwer and Rice Method
See Dawson and Istok, 1991 chapter 23 for further description of variables and conceptual model description and schematic

Site Param.	Bottom Silt (ft amsl)	Bottom Aqifer (ft amsl)	Bottom Well (ft amsl)	Head Before Slug Test (ft amsl)	Lithologic Description of Material at Screen Depth
PZ-1S	103		107	118.79	sandy silt
PZ-1D		-69	94	126.71	gravel in matrix support
PZ-2S	103		116	141.95	clayey silt
PZ-2I	103		108	132.39	clayey silt
PZ-2D		-69	92	138.91	gravel in matrix support
PZ-3S	110		112	162.17	clayey silt
PZ-3D		-69	98	140.61	gravel in matrix support

English Units

Site	casing rad.	grav. pack rad.	wt above screen	screen length	sat. thickness		aspect ratio			$\ln[(m-l)/r_w]<6$	$\ln[(m-l)/r_w]>6$
	r_c	r_w	l	l-d	m	$\ln[(m-l)/r_w]$	$(l-d)/r_w$	A	B	$\ln(R/r_w)$	$\ln(R/r_w)$
	(ft)	(ft)	(ft)	(ft)	(ft)	(-)	(-)	(-)	(-)	(-)	(-)
PZ-1S	0.08333	0.11875	11.79	2.6	15.79	3.5170292	21.894737	2.25	0.25	2.616719021	
PZ-1D	0.08333	0.11875	32.71	2.6	195.71	7.224485	21.894737	2.25	0.25		2.724359378
PZ-2S	0.08333	0.11875	25.95	2.6	38.95	4.6956842	21.894737	2.25	0.25	2.773310894	
PZ-2I	0.08333	0.11875	24.39	2.6	29.39	3.7401727	21.894737	2.25	0.25	2.840529335	
PZ-2D	0.08333	0.11875	46.91	2.6	207.91	7.2121392	21.894737	2.25	0.25		2.814900471
PZ-3S	0.08333	0.11875	50.17	2.6	52.17	2.823882	21.894737	2.25	0.25	3.155149785	
PZ-3D	0.08333	0.11875	42.61	2.6	209.61	7.2487286	21.894737	2.25	0.25		2.791276149

Site	t_1	$(Hw/Ho)_1$	$\ln(Hw/Ho)_1$	t_2	$(Hw/Ho)_2$	$\ln(Hw/Ho)_2$	t_L	K	K
	(day)	(-)	(-)	(day)	(-)	(-)	(day)	(ft/day)	(ft/day)
PZ-1S	0.0005787	0.03	-3.506557897	0.0011574	0.012	-4.4228486	0.0006316	5.532654408	
PZ-1D	0.5787037	0.17	-1.771956842	1.1574074	0.079	-2.5383074	0.7551422		0.004817648
PZ-2S	0.0016667	0.65	-0.430782916	0.0033333	0.21	-1.5606477	0.0014751	2.510589563	
PZ-2I	0.0166667	0.41	-0.891598119	0.0333333	0.17	-1.7719568	0.0189317	0.200359353	
PZ-2D	0.2314815	0.6	-0.510825624	0.462963	0.36	-1.0216512	0.4531517		0.008295048
PZ-3S	2.3148148	0.75	-0.287682072	4.6296296	0.59	-0.5276327	9.6470446	0.000436742	
PZ-3D	2.3148148	0.31	-1.171182982	4.6296296	0.1	-2.3025851	2.04597		0.001821809

SI Units

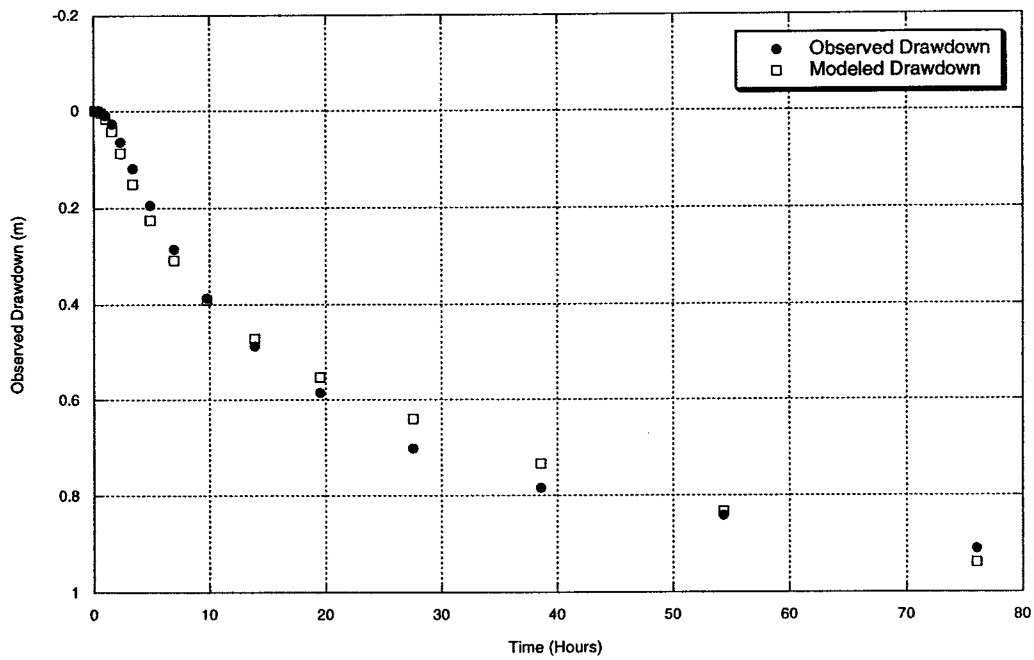
Site	casing rad.	grav. pack rad.	wt above screen	screen length	sat. thickness		aspect ratio			$\ln[(m-l)/r_w]<6$	$\ln[(m-l)/r_w]>6$
	r_c	r_w	l	l-d	m	$\ln[(m-l)/r_w]$	$(l-d)/r_w$	A	B	$\ln(R/r_w)$	$\ln(R/r_w)$
	(m)	(m)	(m)	(m)	(m)	(-)	(-)	(-)	(-)	(-)	(-)
PZ-1S	0.025399	0.036195	3.593592	0.79248	4.812792	3.5170292	21.894737	2.25	0.25	2.616719021	
PZ-1D	0.025399	0.036195	9.970008	0.79248	59.652408	7.224485	21.894737	2.25	0.25		2.724359378
PZ-2S	0.025399	0.036195	7.90956	0.79248	11.87196	4.6956842	21.894737	2.25	0.25	2.773310894	
PZ-2I	0.025399	0.036195	7.434072	0.79248	8.958072	3.7401727	21.894737	2.25	0.25	2.840529335	
PZ-2D	0.025399	0.036195	14.298168	0.79248	63.370968	7.2121392	21.894737	2.25	0.25		2.814900471
PZ-3S	0.025399	0.036195	15.291816	0.79248	15.901416	2.823882	21.894737	2.25	0.25	3.155149785	
PZ-3D	0.025399	0.036195	12.987528	0.79248	63.889128	7.2487286	21.894737	2.25	0.25		2.791276149

Site	t_1	$(Hw/Ho)_1$	$\ln(Hw/Ho)_1$	t_2	$(Hw/Ho)_2$	$\ln(Hw/Ho)_2$	t_L	K	K
	(s)	(-)	(-)	(s)	(-)	(-)	(s)	(m/s)	(m/s)
PZ-1S	50	0.03	-3.506557897	100	0.012	-4.4228486	54.567833	1.9518E-05	
PZ-1D	5.00E+04	0.17	-1.771956842	1.00E+05	0.079	-2.5383074	65244.29		1.69956E-08
PZ-2S	144	0.65	-0.430782916	288	0.21	-1.5606477	127.44887	8.8568E-06	
PZ-2I	1440	0.41	-0.891598119	2880	0.17	-1.7719568	1635.6969	7.06823E-07	
PZ-2D	2.00E+04	0.6	-0.510825624	4.00E+04	0.36	-1.0216512	39152.304		2.92631E-08
PZ-3S	2.00E+05	0.75	-0.287682072	4.00E+05	0.59	-0.5276327	833504.65	1.54073E-09	
PZ-3D	2.00E+05	0.31	-1.171182982	4.00E+05	0.1	-2.3025851	176771.81		6.42694E-09

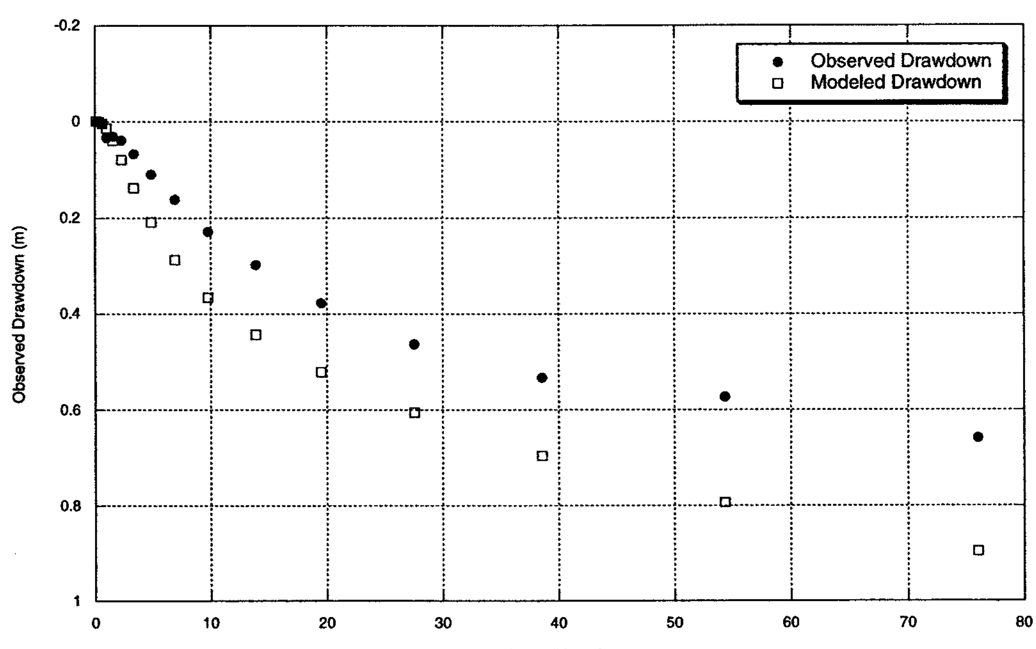
APPENDIX G:

Modflow Modeled vs. Observed Drawdowns at IR Wells

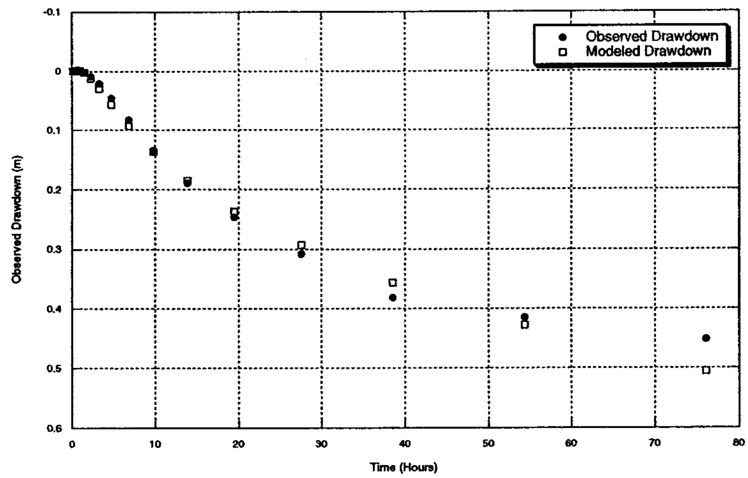
S1_EB: IR-EB Modeled vs. Observed Drawdown During April Pump Test



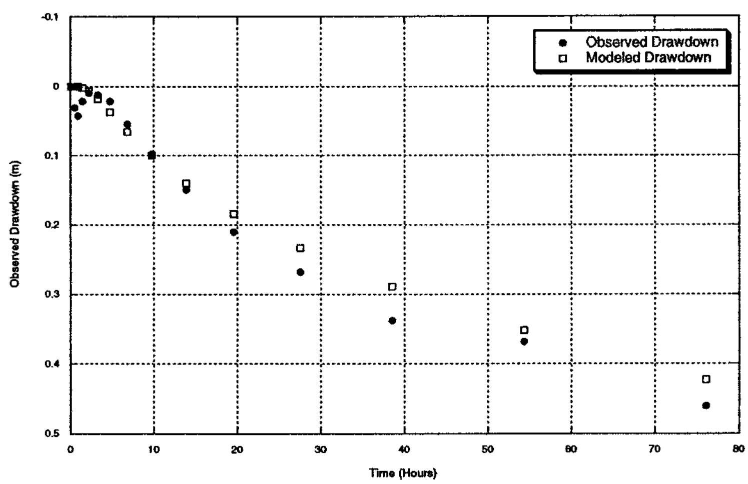
S1_EG: IR-EG Modeled vs. Observed Drawdown During April Pump Test



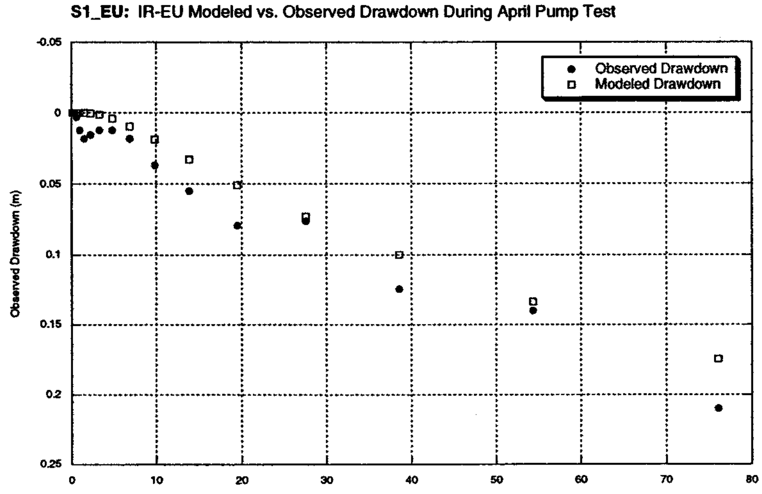
S1_SE: IR-SE Modeled vs. Observed Drawdown During April Pump Test



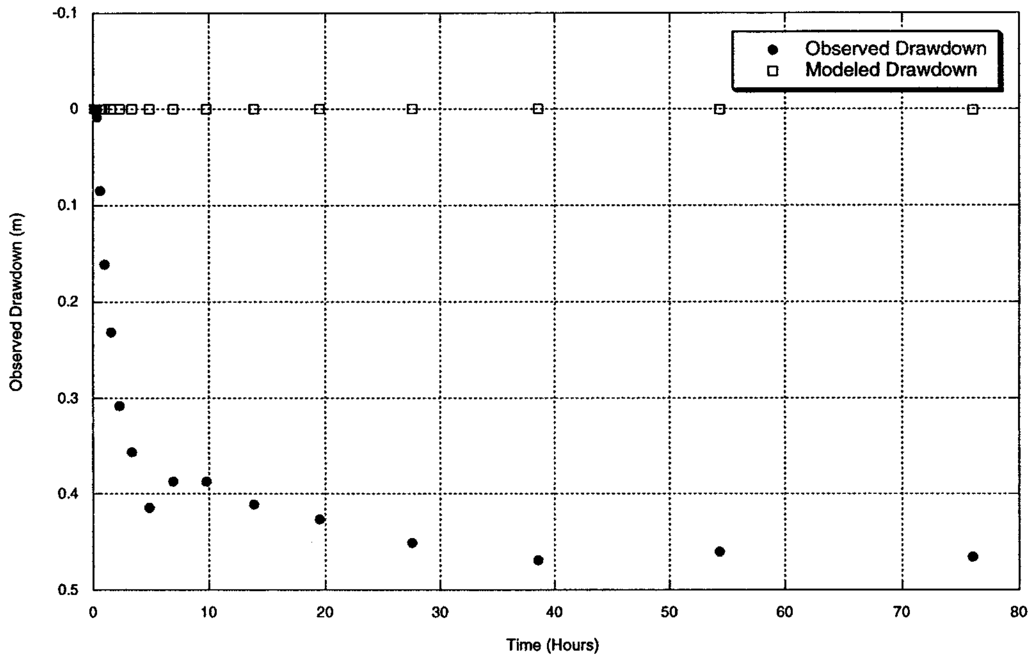
S1_EL: IR-EL Modeled vs. Observed Drawdown During April Pump Test



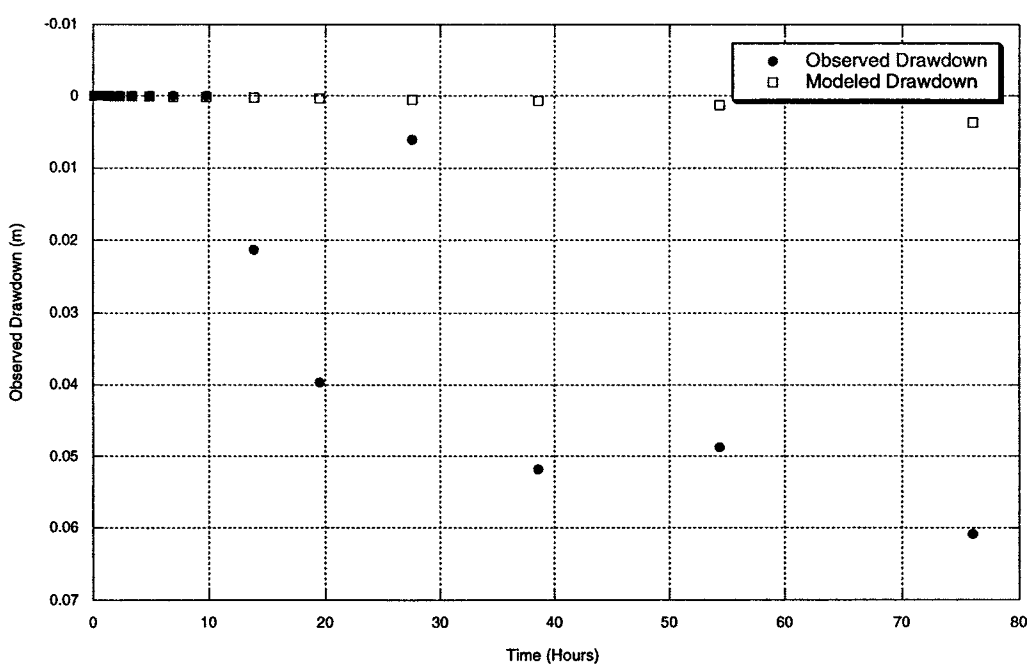
S1_EU: IR-EU Modeled vs. Observed Drawdown During April Pump Test



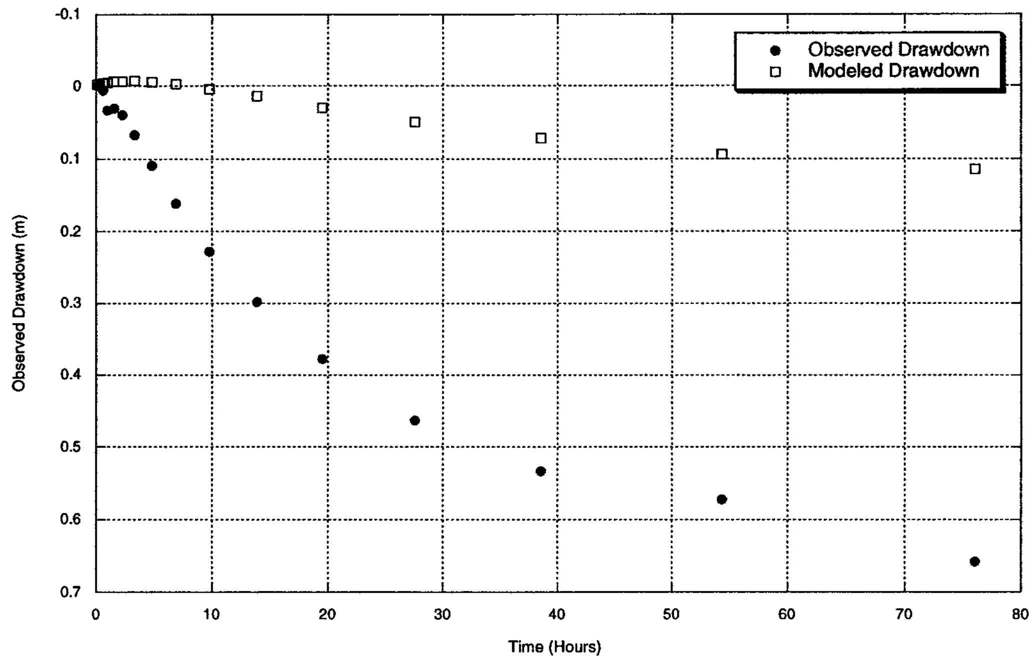
S1_2S: PZ-2S Modeled vs. Observed Drawdown During April Pump Test



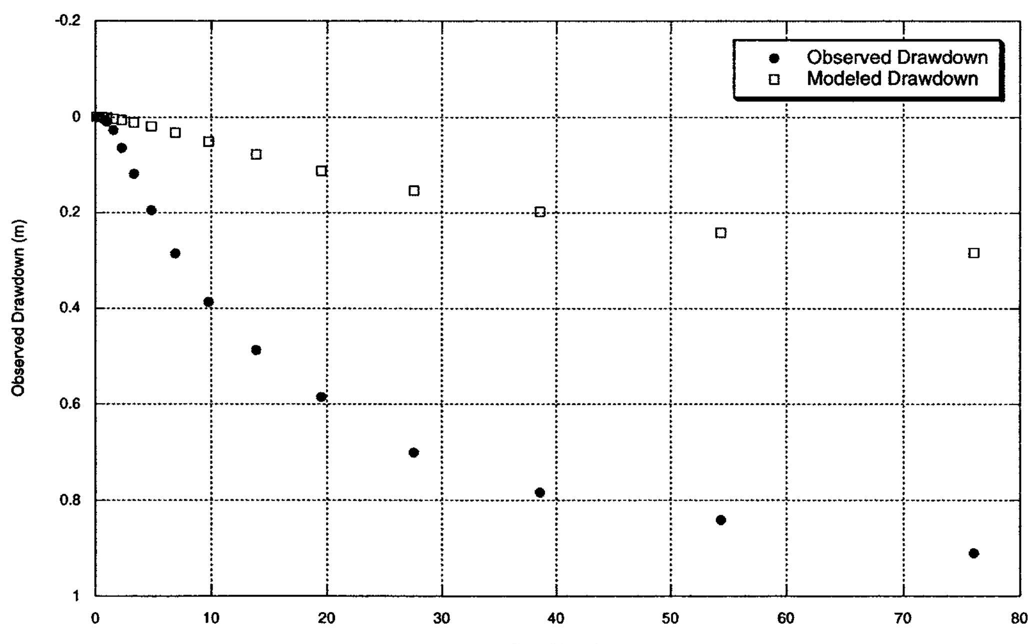
S1_3S: PZ-3S Modeled vs. Observed Drawdown During April Pump Test



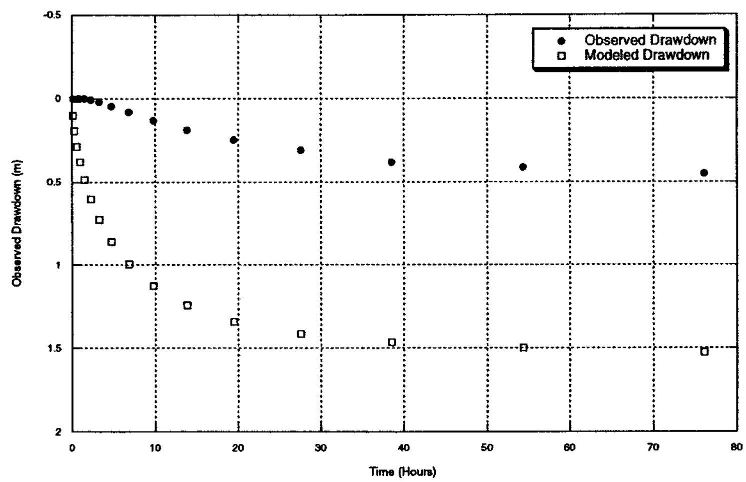
S2_EG: IR-EG Modeled vs. Observed Drawdown During April Pump Test



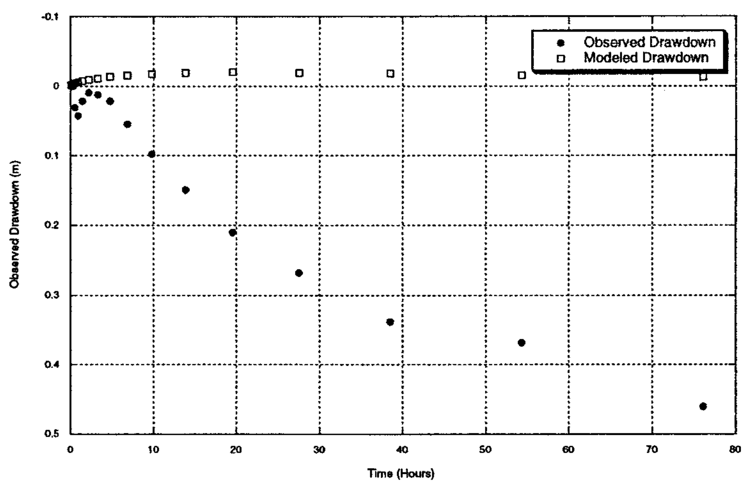
S2_EB: IR-EB Modeled vs. Observed Drawdown During April Pump Test



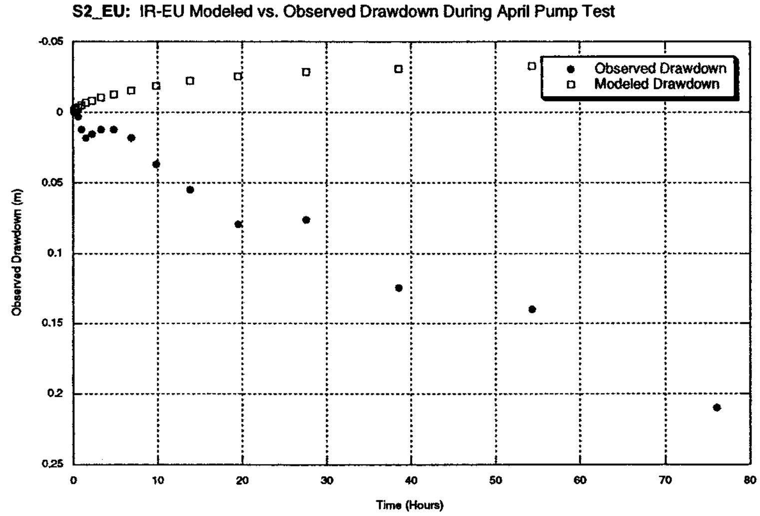
S2_SE: IR-SE Modeled vs. Observed Drawdown During April Pump Test

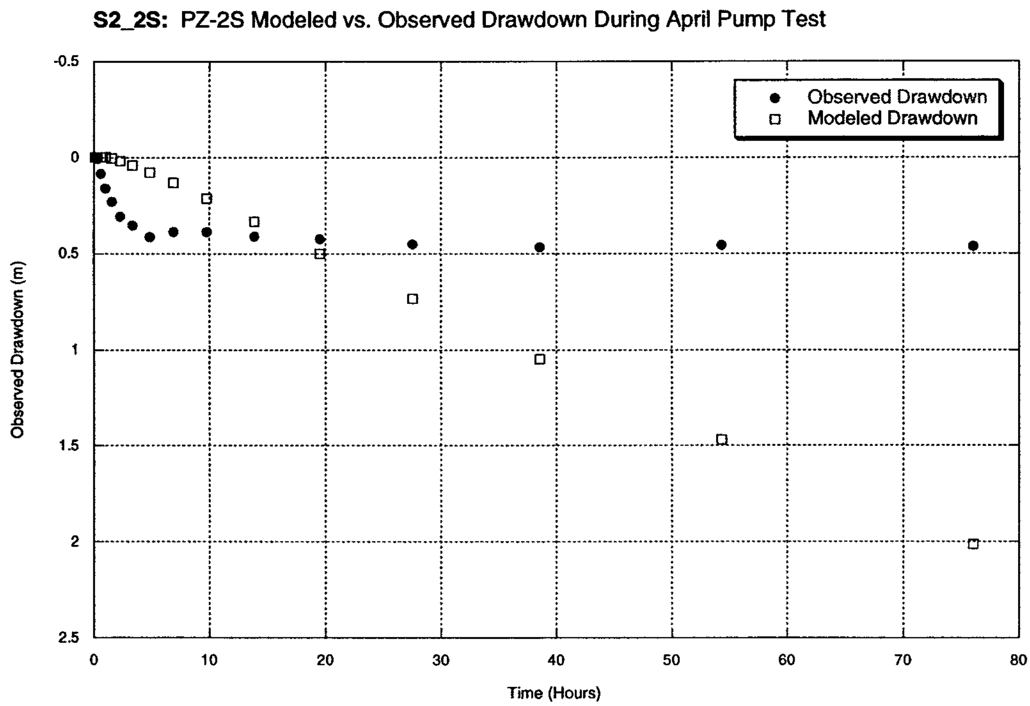


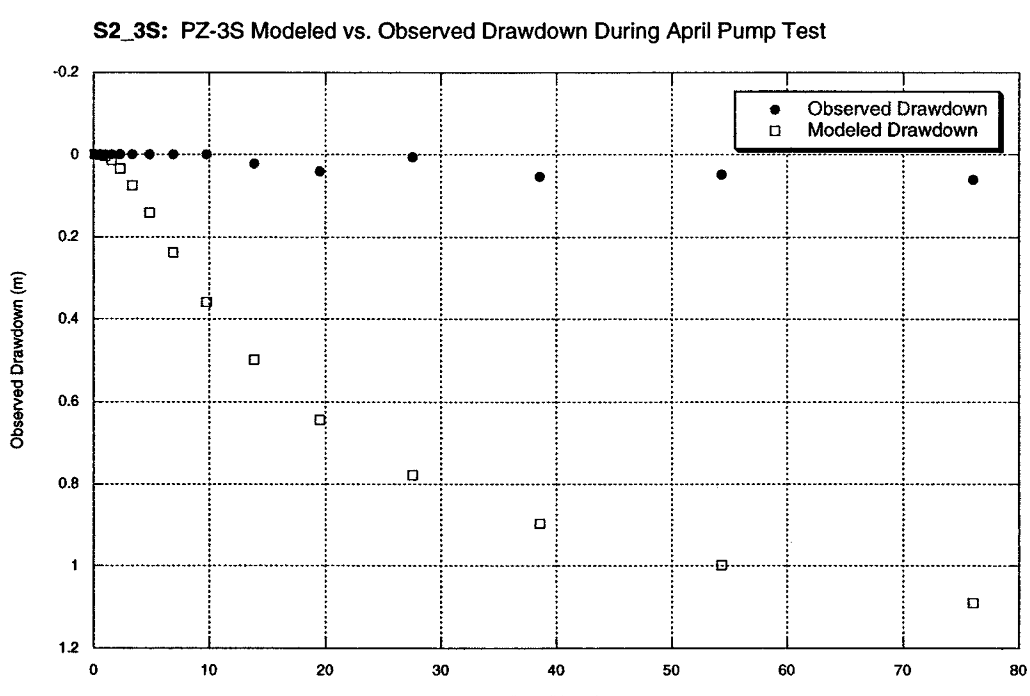
S2_EL: IR-EL Modeled vs. Observed Drawdown During April Pump Test



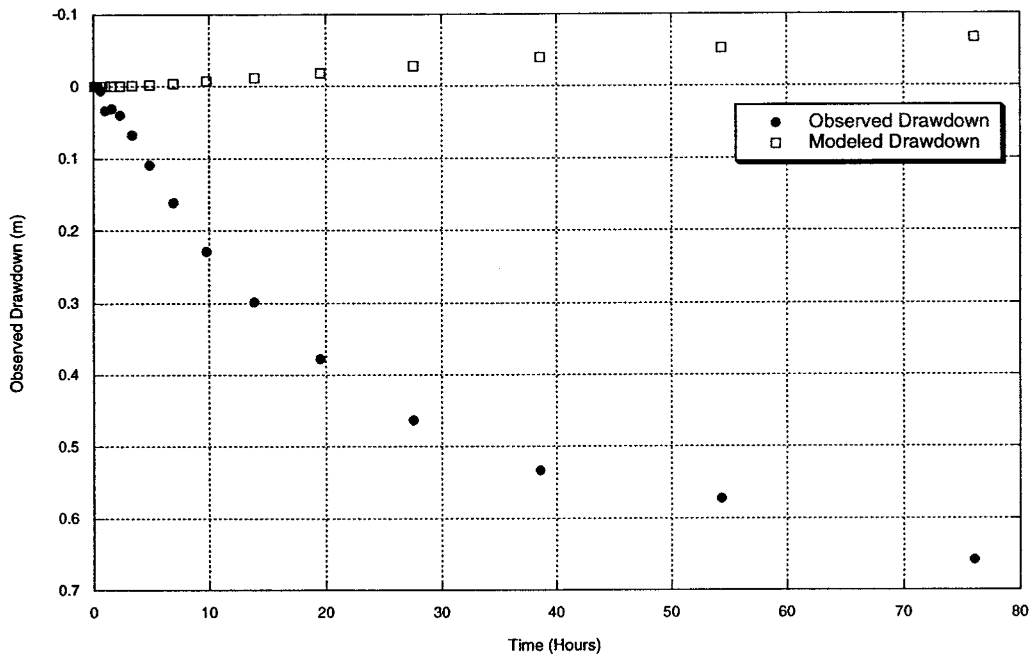
S2_EU: IR-EU Modeled vs. Observed Drawdown During April Pump Test



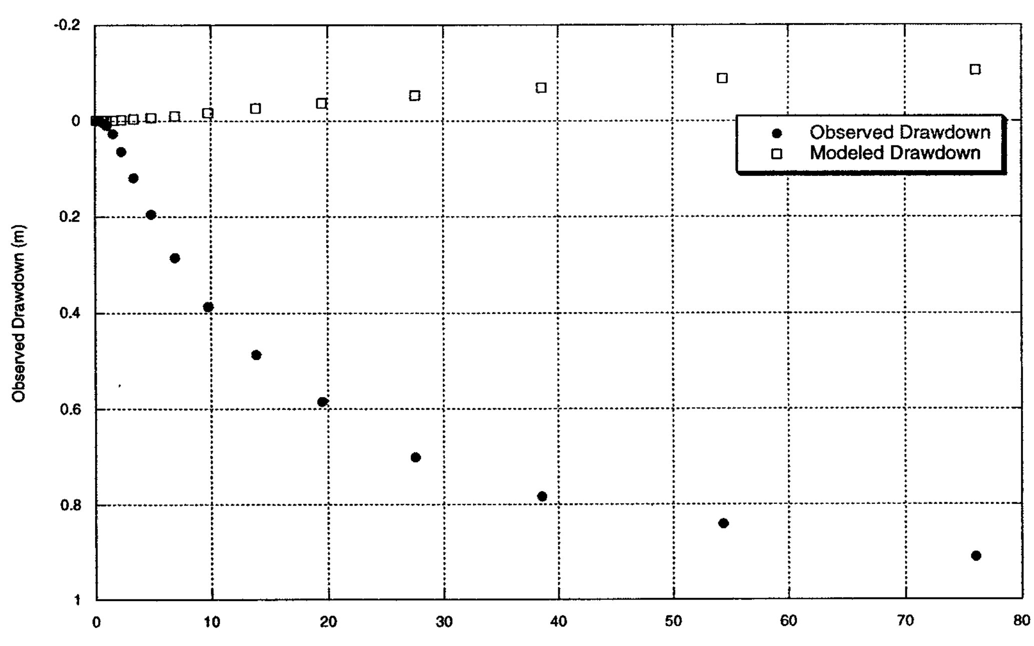

S2_2S: PZ-2S Modeled vs. Observed Drawdown During April Pump Test
Observed Drawdown
Modeled Drawdown
Observed Drawdown (m)
-0.5
0
0.5
1
1.5
2
2.5
0
10
20
30
40
50
60
70
80
Time (Hours)


S2_3S: PZ-3S Modeled vs. Observed Drawdown During April Pump Test
Observed Drawdown
Modeled Drawdown
Observed Drawdown (m)
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
0
10
20
30
40
50
60
70
80
Time (Hours)

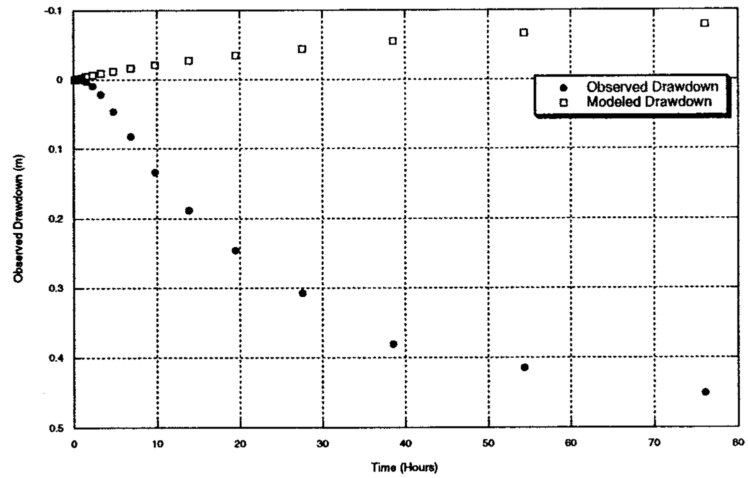
S3_EG: IR-EG Modeled vs. Observed Drawdown During April Pump Test



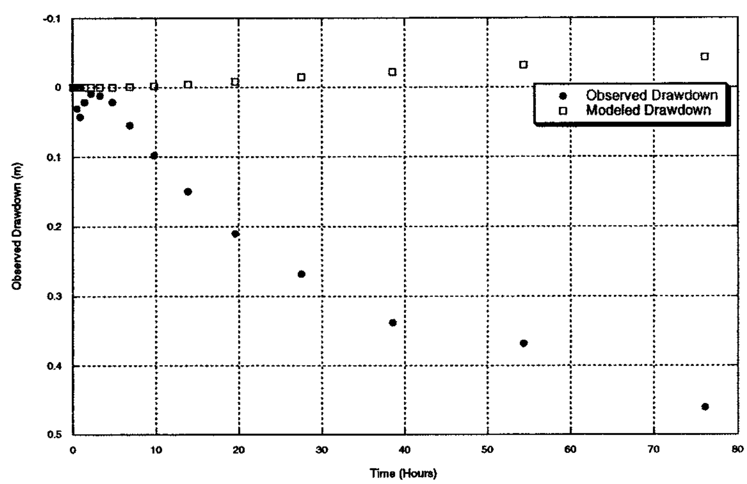
S3_EB: IR-EB Modeled vs. Observed Drawdown During April Pump Test



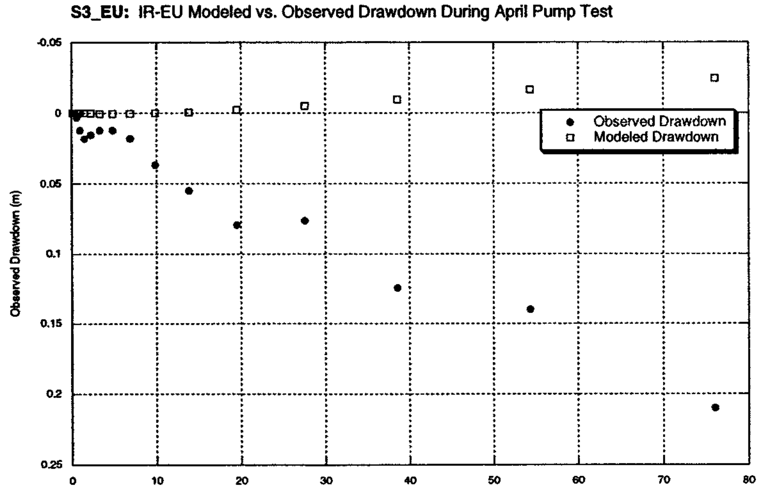
S3_SE: IR-SE Modeled vs. Observed Drawdown During April Pump Test



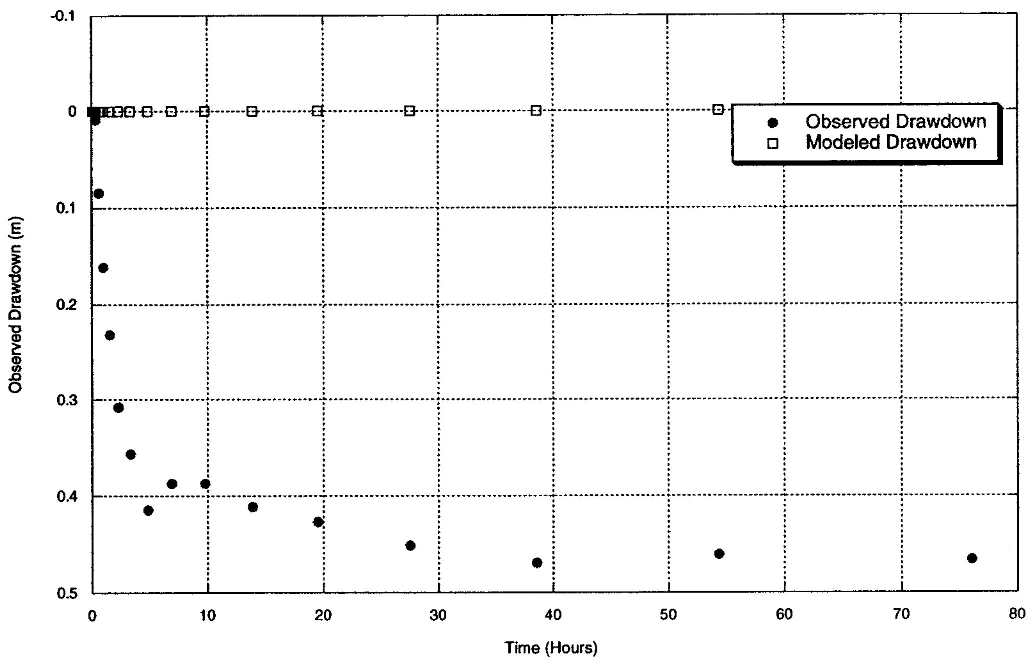
S3_EL: IR-EL Modeled vs. Observed Drawdown During April Pump Test



S3_EU: IR-EU Modeled vs. Observed Drawdown During April Pump Test



S3_2S: PZ-2S Modeled vs. Observed Drawdown During April Pump Test



S3_3S: PZ-3S Modeled vs. Observed Drawdown During April Pump Test