1992

Assessing vertical groundwater flow in clay tills above high permeability zones.

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ASSESSING VERTICAL GROUNDWATER FLOW IN CLAY TILLS

ABOVE HIGH PERMEABILITY ZONES

by

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A Thesis
Submitted to the Faculty of Graduate Studies and Research
through the Department of Geological Engineering
in Partial Fulfillment of the Requirements for the
Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada
1992

ISBN 0-315-78891-7

ABSTRACT

This study examined and evaluated methods of assessing vertical groundwater flow in clay tills above high permeability zones (HPZs). The primary objective was to develop a series of rapid tests which can be employed to determine if an HPZ within otherwise low permeability soil could facilitate the spread of groundwater contamination.

Given the difficulties in determining hydraulic properties of clay soils, this study focussed on examining some non-conventional techniques for determining hydraulic connection of an HPZ to the ground surface. These techniques were: (1) physical, (2) geochemical, (3) isotopic, and (4) bacteriological. These techniques were employed at two sites with differing hydrogeologic environments. The results were compared to results obtained from conventional field permeability testing.

The results of this study demonstrated that the conventional method of estimating vertical groundwater flow velocity using the Darcy equation is questionable in low permeability media. Uncertainties exist in obtaining accurate values for all Darcy parameters.

The most favourable techniques were the isotopic techniques. The distribution of oxygen-18 and tritium in groundwater yielded the most conservative estimate of penetration of recently recharged waters. Their distribution could be used to estimate groundwater age. Their use was also practical because of their low cost and relative ease of measurement.

Bacteriological techniques, namely the bacterial counting tests, agreed with the

isotopic techniques in estimating the depth of active groundwater flow. The use of bacterial tracers may also give some insight into the maximum depth penetration of relatively larger-sized particles.

The physical techniques were also effective. Pulse interference testing of an HPZ was used to determine its storativity and infer that it was confined. This test was also used to infer hydraulic connection/disconnection to other units by checking for drawdown responses. Induced infiltration testing was used to infer hydraulic connection of an HPZ to the surface when the HPZ was shallow. Monitoring seasonal water level fluctuations in piezometers was effective in determining the depth of active groundwater flow.

Geochemical techniques were not effective. Groundwater geochemistry appears to be influenced more by weathering of the tills rather than by vertical transport of constituents from the weathered zone by groundwater flow.

This work is dedicated to my parents -

J. Omer and Jessie Chiasson.

ACKNOWLEDGEMENTS

This thesis would not have been possible without the contributions of several people. To all of these people, I wish to express my gratitude.

First and foremost, I wish to thank my thesis advisor, Dr. Michael Sklash. Certainly, without his guidance and funding, this project would never have gotten off the ground. I wish to thank him for proposing this project and for providing support along the course of this work. His coordination of the many people and activities that were involved in this project allowed the study to proceed successfully.

The critical review and contributions to this thesis by Dr. Jatinder Bewtra and Dr. Peter Hudec are recognized.

The co-operation of personnel at the Maidstone Township Roads Department, the Maidstone Municipal Office, and Agriculture Canada is greatly appreciated. I wish to thank them for permitting us to study their respective sites.

The involvement of the Department of Biological Sciences in this study proved to be a valuable learning experience. Thanks are extended to Dr. Maxine Holder-Franklin, Kelly Favrin, and Samira Georges for their contributions to the project and for letting me use their facilities and equipment.

I also wish to thank Dr. Ihsan Al-Aasm for his help with the oxygen-18 extraction process, and Mrs. Ingrid Churchill and Mr. Greg Kuhun for their help with the major ion analyses.

Last, but certainly not least, special thanks are extended to my friends and colleagues Andrew Ainslie, Osman Ibrahim, Jag Krishnamurthy, and Randy Sherman for their field and laboratory assistance.

Funding for this project from Imperial Oil is gratefully acknowledged.

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1.0 INTRODUCTION

1.1 Background

High permeability zones (HPZs), such as sand lenses, commonly occur at various depths in otherwise low permeability clayey soils in southern Ontario and in similarly glaciated terrains. Because of their low permeability, clay deposits are often targets for surface waste disposal sites (i.e. landfills, landfarms, and sludge lagoons). Therefore, HPZs merit special hydrogeological attention as potential conduits for migration of contaminants from such sites. Figure 1.1 depicts a hypothetical scenario, typical of glaciated terrains, where buried sand lenses in clayey deposits may facilitate the spread of groundwater contamination.

The normal approach in dealing with HPZs at potentially or existing contaminated sites is to monitor them over time by installing monitoring wells and analyzing groundwater quality. Active approaches involve excavating the HPZ and backfilling with lower permeability material or isolating the HPZ by means of cutoff or slurry walls. These procedures are often extremely expensive and unnecessary if it can be demonstrated that contamination from the surface will not reach the HPZ. This requires a knowledge of whether or not the HPZ is hydraulically connected to the ground surface.

In assessing the degree of hydraulic connection of an HPZ to the surface, the critical question is, "How quickly does water move from the surface to the HPZ?". The key difficulty in answering this question is in accurately determining the representative bulk permeability of the clay overlying the HPZ. Clayey deposits in

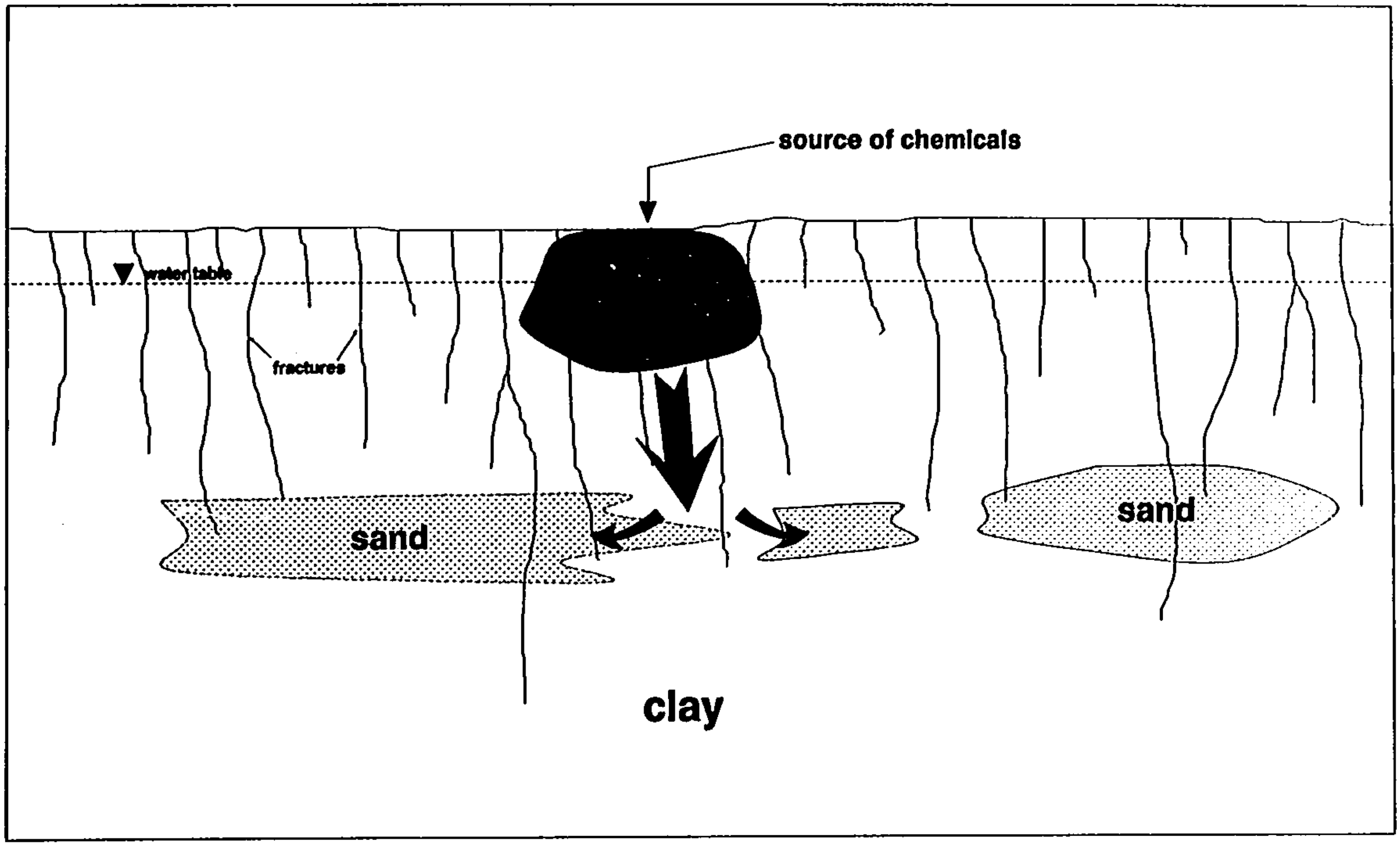


Figure 1.1. Scenario where high permeability zones may facilitate the spread of groundwater contamination.

southern Ontario and similarly glaciated terrains are fractured and weathered from the surface to a depth of several metres.

Obtaining an accurate value for bulk hydraulic conductivity in fractured clay deposits has, over the past two decades, proven to be fraught with difficulties and uncertainties (Grisak and Cherry, 1975; Day, 1977; Desaulniers et al., 1981; Prudic, 1982; Hendry, 1982; Sharp, 1984; Keller et al., 1986; Cravens and Ruedisili, 1987; Lafleur et al., 1987; Hendry, 1988; Keller et al., 1988; D'Astous et al., 1989; Keller et al., 1989). These problems are due mainly to time and size scale limitations on the ability to directly observe flow behaviour in low permeability media. Consequently, many small scale approaches to the problem have resulted (e.g. laboratory permeability testing of soil cores and single-well permeability testing in the field). These conventional laboratory and field methods for determining hydraulic conductivity may yield values up to three orders of magnitude lower than the actual value (Keller et al., 1986 and D'Astous et al., 1989). This short-coming is due to the fact that boreholes can miss fractures and consequently not be representative of the most conductive zones. Furthermore, conventional augering can possibly smear the borehole walls and close fractures, resulting in apparent permeabilities lower than actual values (D'Astous et al., 1989).

In short, problems and uncertainties arise in extrapolating information from the small size and time scale to the large size and time scale. As pointed out by Keller et al. (1989), this extrapolation is fundamentally weak to the extent that the following questions may not have been answered:

1. Have the major conductors in the unit been intercepted?

2. Is it valid to extrapolate the results of short-term, high gradient tests to long-term, low-gradient conditions?

To deal effectively with the problem of obtaining reliable bulk permeability values for clayey soils, hydrogeologists need at their disposal a diverse complement of techniques so as to be able to exploit whatever opportunities are offered by a particular setting.

In southern Ontario, groundwater behaviour in clay deposits is fairly well documented (Desaulniers et al., 1981, D'Astous et al., 1989, and Ruland et al., 1991). The upper weathered and fractured clay till is the most active zone of groundwater flow; the underlying grey, unweathered and visually unfractured clay is believed to be fissured to depths of approximately 12 m (Soderman and Kim, 1970 and Ruland et al., 1991). However, little attention has been given to groundwater behaviour in fractured clays with high permeability zones. These HPZ's will further alter groundwater flow patterns in both fractured and unfractured clay deposits.

Brathwaite (1988) examined hydraulic connection of sand lenses in Maidstone Township, Essex County, Ontario. Here, the HPZs are approximately 8 m below ground surface in unweathered grey clay till. The study confirmed that the upper 4 m or so of weathered, fractured clay is the zone of most active groundwater flow and concluded that hydraulic connection of the HPZ to the ground surface is poor. However, an evaluation of methods for determining hydraulic connection of the HPZ to the surface was not conducted.

1.2 Objectives and Scope

The primary objective of this study is to develop a series of rapid tests which can be employed to determine whether or not an HPZ (i.e. sand lenses) within otherwise low permeability soil could facilitate the spread of groundwater contamination. To develop these tests, methods for determining hydraulic connection/disconnection of an HPZ to the ground surface were examined and evaluated. Four major techniques for evaluating hydraulic connection of HPZs to the ground surface were the focus of this study. These four techniques are: (1) physical (hydraulic) techniques, (2) geochemical techniques, (3) isotopic techniques, and (4) bacteriological techniques. The results of these techniques are compared to results obtained from conventional field permeability testing.

These techniques were employed at two sites characterized by different hydrogeologic environments (i.e. with sand lenses at different depths). The two field test sites were the Maidstone Municipal Office and Agriculture Canada Substation, Eugene F. Whelan Experimental Farm. Both sites are located in Maidstone Township, Essex County, Ontario. At the Maidstone Municipal Office, Brathwaite (1988) concluded that there is a poor hydraulic connection between the ground surface and HPZs occurring at a depth of about 8 m. This study involved re-testing of this site using additional hydraulic, isotopic, and bacteriological techniques. At the Whelan Farm site, sand lenses are shallow (less than 3 m deep) and hydraulic connection is suspected to be good. The relative effectiveness of each technique in determining hydraulic connection was evaluated by comparing the results at both sites.

The significance of the development of a suite of tests to determine whether high permeability zones are important in contaminant transport will improve the site selection process for waste disposal activities and reduce the costs of monitoring existing waste facilities. A suite of tests will also aid in implementing remedial action plans at contaminated sites.

1.3 Structure of the Thesis

This thesis is divided into six chapters. Chapter 1 discusses background, objectives, and reasons for conducting this study. Chapter 2 deals with a description of the study areas, focussing on physiography, geology, and hydrogeology. Chapter 3 is devoted to outlining methods of determining hydraulic connection of HPZ's in low permeability media. This chapter describes methods and procedures used in this study, briefly discusses previous studies, and describes other potential techniques that were not employed in this study. Chapter 4 covers the results for each technique analysed in this study and Chapter 5 discusses the results and evaluates the methods studied. Finally, Chapter 6 presents conclusions and recommendations revealed from this study.

2.0 THE STUDY AREAS

2.1 Introduction

The study areas are located in north central Essex County, Ontario in the Township of Maidstone, approximately 17 km east of the City of Windsor (Figure 2.1). The test sites are referred to as:

Test Site #1 - Puce Road Site

Test Site #2 - Whelan Farm Site.

The Puce Road site is located on the properties occupied by the Maidstone Municipal Office and the Maidstone Township Roads Department. The properties are situated on the west side of East Puce Road (Essex County Road No. 25) approximately 3.5 km south of the Town of Puce and 0.6 km north of Highway 401. The property is rectangular, approximately 98 m by 158 m in plan area. The site is about 1 km south of Essex County Landfill No. 3.

The Whelan Farm site refers to the Eugene Whelan Experimental Farm, a substation of the Harrow Research Station, owned and operated by Agriculture Canada. The property is located on the southwest corner of Essex County Road No. 46 and Maidstone Township Concession Road 18-19, slightly less than 2 km west of the Town of Woodslee. The property is rectangular, approximately 600 m by 650 m in plan area.

2.2 Regional Setting

The test sites are located on the Essex Clay Plain which is a subregion of the

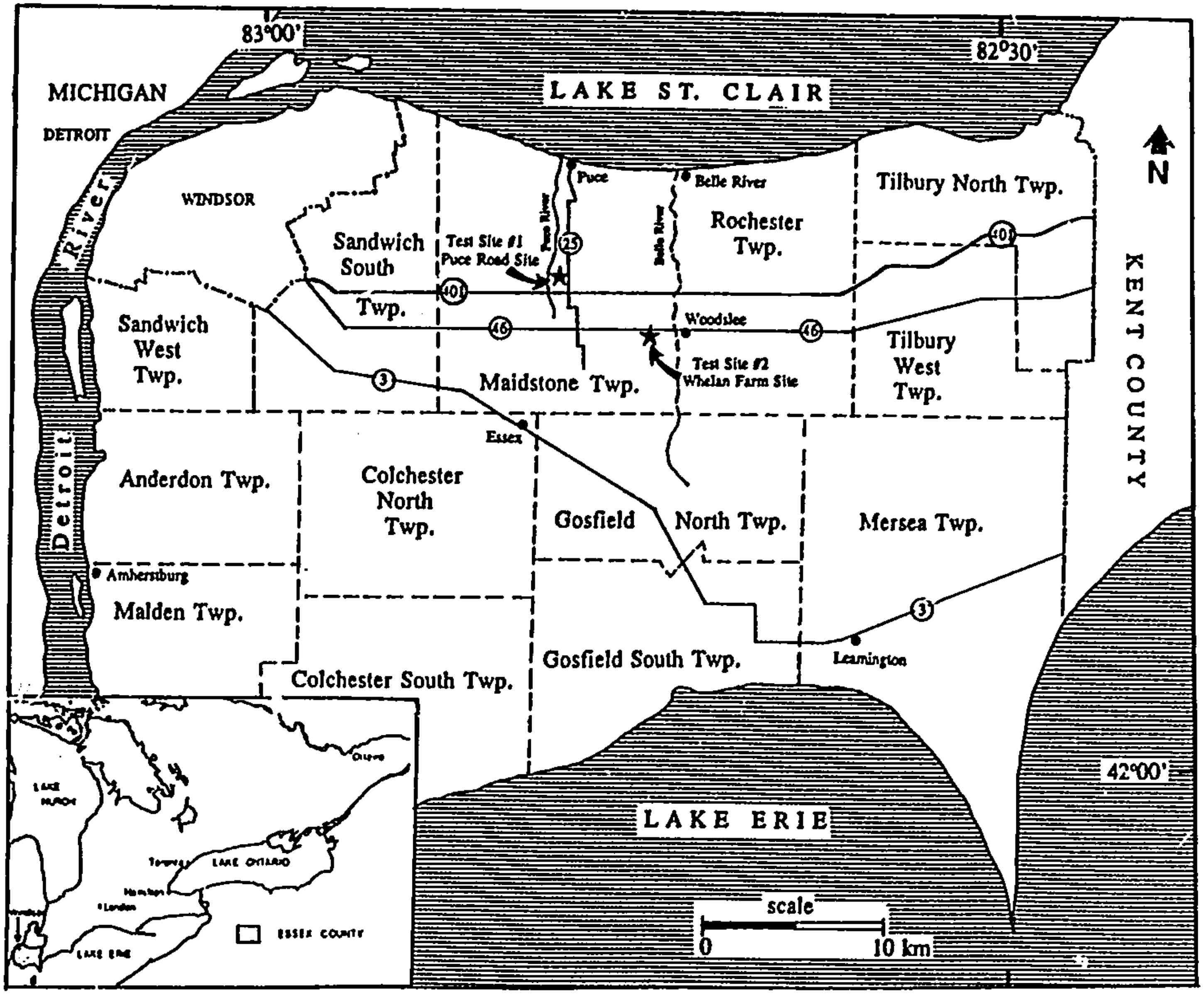


Figure 2.1. Map of Essex County showing test site locations.

more extensive St. Clair Clay Plain (Chapman and Putnam, 1984) (Figure 2.2). The Essex Clay Plain lies between Lake St. Clair and Lake Erie, covering most of Essex County and the southwestern part of Kent County. The region exhibits very little relief, varying from 175 to 213 metres above sea level (masl). The slope and surface drainage are predominantly northward toward Lake St. Clair under an extremely low gradient (approximately 0.1%). Coupled with very poor drainage and the low permeability of the heavy clay soil, dredged ditches and tile underdrains have had to be installed throughout the Essex Clay Plain to provide satisfactory conditions for crop growth (Chapman and Putnam, 1984). Such is the case at the Whelan Farm site.

The region exhibits a humid climate with cold winters (Hunt, 1974). Annual temperatures range from -7.8°C (January) to 27.8°C (July) with a mean of approximately 9.[illegible]. The total number of frost free days in the region is 160 to 170 days. Mean annual precipitaion is about 825 mm (Ontario Ministry of Natural Resources, 1975).

2.3 Geology

2.3.1 Bedrock Geology

Essex County is underlain by the eastern fringe of the bowl-shaped Michigan Basin whose centre is located in central Michigan. The basin consists of sequences of Paleozoic carbonate, shale, sandstone and evaporite deposits. Grey shales and argillaceous limestones of the Middle Devonian Hamilton Group lie directly below the

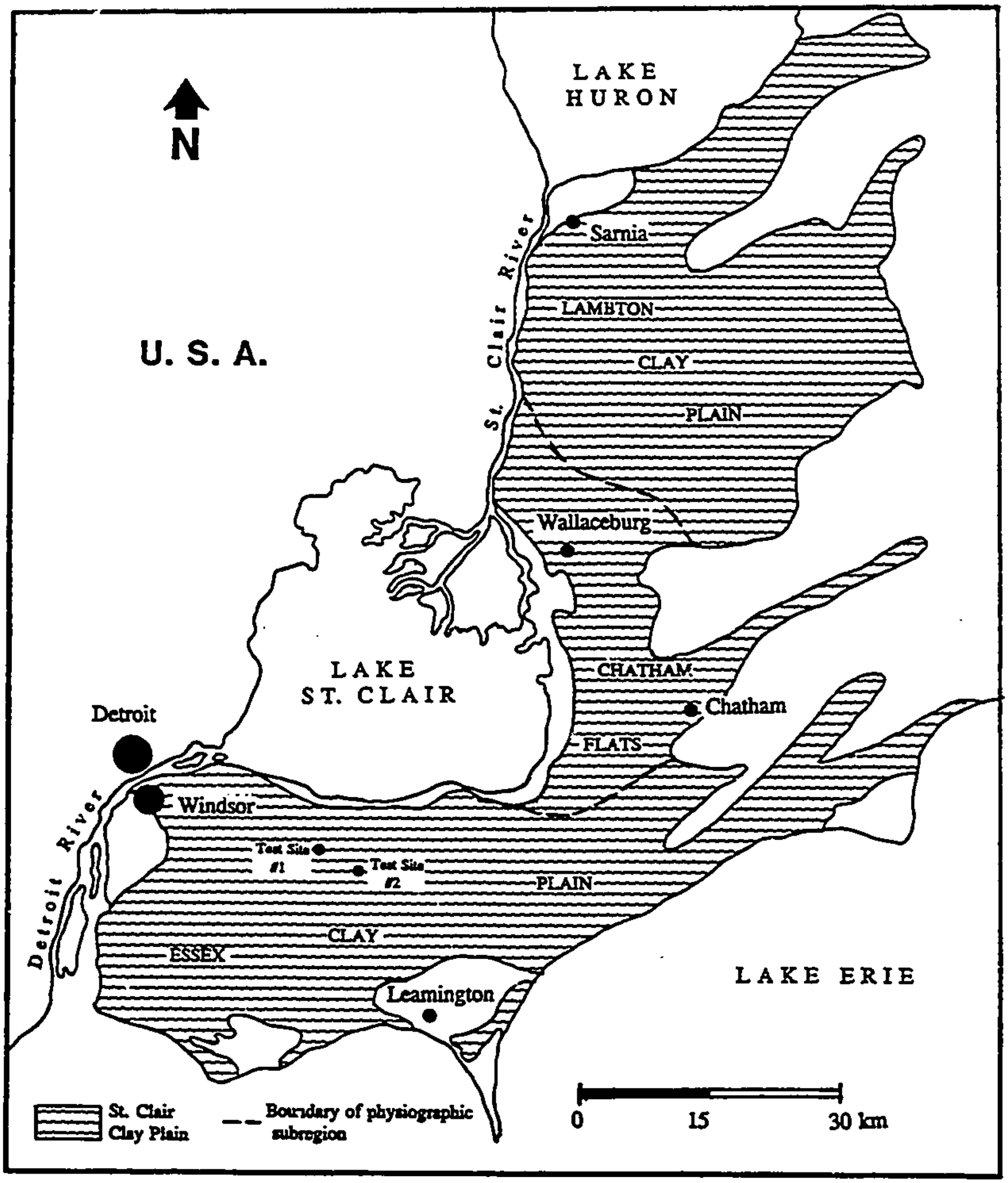


Figure 2.2. St. Clair Clay Plain with physiographic subregions (after Chapman and Putnam, 1984).

glacial overburden in the study areas (Telford and Russell, 1981).

2.3.2 Quaternary Geology

The overburden in the St. Clair Clay Plain, including the study sites, exceeds 30 m of Quaternary glacial drift which has been described as a clayey silt till (Vagners, 1972), silty clay till (Desaulniers et al., 1981) and glaciolacustrine clay (Chapman and Putman, 1984). Agricultural soil surveys denote the prevailing soil type as the Brookston clay loam, a dark-surfaced gleysolic soil developed under a swamp forest of moisture-loving trees (Chapman and Putman, 1984).

The exact origin of the till comprising the Essex Clay Plain is somewhat ambiguous. Lack of stratification tends to exclude a lacustrine origin and a normally consolidated state below a surface crust excludes a lodgement till origin (Vorauer et al., 1986). Chapman and Putman (1984) believe the tills were deposited by glacial Lake Whittlesey and subsequently by Lake Warren. Dreimanis (1961) attributes the extreme thickness of the till and its high clay content to more recent glacial reworking of older lacustrine deposits. Generally, the clay plain is referred to as a "water-laid till" (Dusseault and Vorauer, 1986), formed by glacial advance during the most recent (Wisconsin) Ice Age.

The tills throughout the St. Clair Clay Plain typically consist of 40-60% clay, 30-40% silt, 5-10% sand and less than 5% gravel (M.M Dillon Limited, 1988). They contain carbonate and shale fragments from underlying bedrock as well as Precambrian rock fragments (Dreimanis, 1961).

The till generally consists of two to four metres of brown, weathered, dessicated and fractured till underlain by visually unweathered and unfractured blue/grey till. However, evidence exists to conclude that the upper few metres of the grey till in the St. Clair Clay Plain is fissured (Soderman and Kim, 1970, Brathwaite, 1988, and Ruland et al., 1991). The boundary between the brown and grey till is not necessarily a geologic boundary but is more likely a transition boundary from oxidizing to reducing conditions. The boundary is often not sharp and its depth varies throughout the region.

Local deposits of discontinuous sand and gravel lenses have been intersected in boreholes at various depths throughout the clay plain. They often occur in varying thicknesses of interbeds of silty sand with clay and minor amounts of gravel. The HPZ under study at the Puce Road site is such a zone. This zone has been termed "the interbedded zone" by consultants conducting subsurface investigations at nearby Essex County Landfill No. 3. M.M. Dillon Limited (1988) has attempted to correlate the interbedded zone throughout the St. Clair Clay Plain but its lack of continuity over any considerable distance leaves its origin questionable. It may be a remnant of dendritic stream channels or it may be the result of reworking of glaciodeltaic or floodplain deposits into beach bars (M.M. Dillon Limited, 1988).

A fairly continuous layer of sand and gravel exists beneath the grey till at the bedrock contact. It varies in thickness from zero to several metres.

2.3.3 Hydrogeology

Four hydrostratigraphic units can be recognized throughout the overburden in the St. Clair Clay Plain:

1) Brown weathered, fractured clay till

2) Blue/grey unweathered till

3) Sporadic interbedded zones of sand, gravel and clay

and 4) Basal sand/bedrock aquifer.

In the immediate vicinity of the study areas, water for domestic use is obtained largely from a municipal water distribution network constructed between 1982 and 1984 (M.M. Dillon Limited, 1988). However, on a more regional scale, groundwater is extensively used as evidenced by the abundance of wells listed in Ontario Ministry of the Environment (MOE) well records (1977).

Because of the very low topographic gradient and low permeability of the surficial clay soils, the main water-bearing formation throughout the St. Clair Clay Plain is the basal sand/bedrock aquifer. Since it is likely that there is no physical barrier to flow between the basal sand and bedrock zones, they probably act as a single aquifer (M.M. Dillon Limited, 1988). This aquifer has been mapped as having a probable yield of 0.15 to 0.75 L/s in the vicinity of the study areas (Ontario Water Resources Commission, 1971). In the Essex Clay Plain, 69% of the MOE well records report water found in the bedrock and 25% report water found in the basal sand unit. Of these, the groundwater use is 43% domestic, 13% agricultural, 41% combined domestic and agricultural, and 3% commercial and public.

Table 2.1 summarizes water quality data from some wells completed in the basal sand/bedrock aquifer in Maidstone and neighbouring townships as presented on the Essex County groundwater probability map (Ontario Water Resources Commission, 1971). A review of this map delineates isolated occurrences of brackish water which is likely the result of dissolution and upward movement of highly soluble chloride minerals deposited in the underlying salt strata (Desaulniers et al., 1981). Freeze and Cherry (1979) suggest that, in general, high chloride concentrations are indicative of very old groundwaters resulting from sluggish groundwater movement and limited flushing. A review of MOE well records (1977) reveals that of the wells in Maidstone and neighbouring townships, 53% produce sulphurous water and 3% produce salty water.

Serving as a secondary source of groundwater in the area are shallow dug wells and cisterns. MOE well records indicate that only one of 19 wells intersecting the shallow interbedded sand unit, which has been found at various depths throughout the St. Clair Clay Plain, derives water from that unit. This suggests that this unit is regionally not a significant aquifer.

Table 2.2 summarizes results of MOE surveys of groundwater quality in shallow dug wells in the vicinity of Essex County Landfill No. 3 (Essop 1986, 1988). A review of these data reveals that there is a wide range in concentrations in groundwater chemistry in the shallow groundwater.

M.M. Dillon Limited (1988) has compiled hydraulic conductivity values for the brown till unit, the grey till unit, and the interbedded sand unit (Table 2.3). An

Table 2.1

Summary of Water Quality in the Basal Sand/Bedrock Aquifer

Parameter	Concentration Range (mg/L)
Total hardness (as $CaCO_3$)	136 - 3260
Sodium (Na)	61 - 883
Iron (Fe)	0.10 - 1.10
Sulfate (SO_4)	90 - 1610
Chloride (Cl)	29 - 2660
Alkalinity (as $CaCO_3$)	92 - 223

NOTES: data from Groundwater Probability Map of Essex County (Ontario Water Resources Commission, 1971)

Table 2.2

Summary of Water Quality in Shallow Wells

Parameter	Concentration Range (mg/L)	
	07/86	03/88
Total hardness (as $CaCO_3$)	138 - 590	190 - 627
Sodium (Na)	7.3 - 61	5.92 - 40.8
Total Iron (Fe)	0.02 - 4.0	0.04 - 0.80
Sulfate (SO_4)	13.5 - 158	35.5 - 255
Chloride (Cl)	5.5 - 112	9.57 - 69.91
Alkalinity (as $CaCO_3$)	98.2 - 476	113 - 499.87
Organic Nitrogen (N)	0.195 - 0.945	0.10 - 1.29

NOTES: data from Essop (1986, 1988)

Table 2.3

Summary of Hydraulic Conductivity Values for Soils of the St. Clair Clay Plain

Location	Range of Values (m/s)	Mean (m/s)	No. of Tests
	BROWN, WEATHERED, FRACTURED SILTY CLAY TILL UNIT		
Chatham	1.0×10^{-7} - 1.0×10^{-7}	1.0×10^{-7}	1
Corunna	1.0×10^{-11} - 1.0×10^{-7}	2.4×10^{-9}	15
Courtright	1.3×10^{-10} - 9.0×10^{-10}	8.2×10^{-10}	46
Essex County	1.5×10^{-10} - 1.4×10^{-4}	5.8×10^{-9}	15
Maidstone	1.1×10^{-10} - 2.7×10^{-9}	4.6×10^{-10}	13
Sarnia	1.0×10^{-9} - 1.7×10^{-8}	3.7×10^{-9}	4
Windsor	1.5×10^{-10} - 2.0×10^{-7}	2.2×10^{-9}	14
TOTAL	**1.0×10^{-11} - 1.4×10^{-4}**	**1.5×10^{-9}**	**108**
	GREY SILTY CLAY TILL UNIT		
Chatham	1.0×10^{-10} - 1.0×10^{-9}	3.1×10^{-10}	5
Corunna	1.1×10^{-11} - 1.0×10^{-8}	2.3×10^{-10}	49
Courtright	1.0×10^{-11} - 5.0×10^{-10}	7.9×10^{-11}	3
Essex County	5.8×10^{-11} - 4.5×10^{-9}	2.3×10^{-10}	37
Maidstone	4.2×10^{-11} - 8.8×10^{-8}	5.5×10^{-10}	35
Sarnia	2.1×10^{-11} - 8.0×10^{-8}	2.7×10^{-10}	63
Windsor	1.3×10^{-10} - 1.2×10^{-8}	6.8×10^{-10}	28
TOTAL	**1.0×10^{-11} - 8.8×10^{-8}**	**3.2×10^{-10}**	**220**
	INTERBEDDED SAND UNIT		
Corunna	1.9×10^{-9} - 2.3×10^{-5}	7.7×10^{-8}	5
Maidstone	1.1×10^{-9} - 1.0×10^{-4}	1.8×10^{-7}	27
Sarnia	1.3×10^{-9} - 2.5×10^{-8}	8.9×10^{-9}	3
TOTAL	**1.1×10^{-9} - 1.0×10^{-4}**	**1.2×10^{-7}**	**35**

NOTES:
1. Data from M.M. Dillon Limited (1988).
2. Means are geometric.
3. Tests performed include: Hazen analysis, triaxial permeameter, field rising and falling head, in-situ constant head, tracer, 1-dimensional consolidation, and 3-dimensional consolidation.

analysis of these data reveals that the brown fractured unit is the zone of most active groundwater flow with hydraulic conductivities of at least one order of magnitude higher than the underlying grey unit at each location throughout the St. Clair Clay Plain. Where present, the interbedded sand unit, which possesses hydraulic conductivities approximately two orders of magnitude higher than the brown fractured unit, provides a local conduit for groundwater movement.

M.M. Dillon Limited (1988) has determined the regional potentiometric surface for the basal sand/bedrock aquifer from static levels reported from MOE well logs. From the contours, it was determined that the gradient is approximately 0.001 northward, closely resembling the surface topographic gradient. Similarily, Essop (1986) concluded from groundwater elevations in dug wells that shallow groundwater also flows to the north under a gradient of 0.001-0.002 with local effects from rivers and streams.

Due to the very low hydraulic conductivities of the clayey soils and the lack of topographic relief of the St. Clair Clay Plain, groundwater velocities in the region are extremely slow to negligible. Groundwater in the deeper clay tills (blue/grey unit) is more than 8000 years old (Desaulniers et al., 1981), indicating that this water is essentially immobile.

3.0 METHODS OF INVESTIGATION

3.1 Introduction

This chapter is devoted to discussing theory, strategies, and the collection of data for this study. Specifically, this chapter is divided into six sections following the introduction.

The first section deals with theoretical aspects of groundwater flow pertinent to this study. The next section discusses means of characterization of site geology and site hydrogeology. The following four sections examine each major technique for determining the degree of hydraulic connection of an HPZ to the ground surface. These are: (1) physical techniques; (2) geochemical techniques; (3) isotopic techniques; and (4) bacteriological techniques.

Each of these latter four sections consists of three subsections. The first subsection discusses theoretical considerations of the test methods; the second subsection discusses field and laboratory work; and the third subsection discusses other potential tests that were not employed in this study.

3.2 Groundwater Flow and Solute Transport in Low Permeability Media

Groundwater velocity in a saturated porous medium is based on Darcy's Law and is described by the following expression:

$$v = Ki/n \qquad (1)$$

where: v is the average linear groundwater velocity [L/T]; K is the hydraulic conductivity [L/T]; i is the hydraulic gradient [L/L]; and n is the effective porosity [dimensionless].

Transport of solutes in homogeneous saturated media under steady state flow conditions is controlled by the processes of advection and hydrodynamic dispersion. Advection is the process whereby solutes are transported by the bulk motion of flowing groundwater. Hydrodynamic dispersion refers to the tendency of a solute to spread out along its flow path due to mechanical mixing during fluid flow (which is a result of pore water velocity variation and tortuosity of the flow path) and due to molecular diffusion (which is caused by concentration gradients). These processes are described in more detail by Freeze and Cherry (1979) and Gillham and Cherry (1982).

The equation that describes solute transport in saturated porous media is the advection-dispersion equation. The one-dimensional form of this equation for non-reactive solutes in saturated isotropic materials is described as follows (Bear, 1972):

$$\partial C/\partial t = D\partial^2 C/\partial x^2 - v\partial C/\partial x \qquad (2)$$

where: x is the distance along the flow path [L]; v is the average linear groundwater velocity [L/T]; D is the coefficient of hydrodynamic dispersion along the flow path (which is equivalent to $\alpha v + D^*$, where α is the dispersivity [L] of the porous medium and D^* is the coefficient of molecular diffusion [L^2/T]); and C is the solute concentration [M/L^3]. At low groundwater velocities characteristic of clays in the St. Clair Clay Plain, diffusion is the dominant factor contributing to dispersion (Desaulniers et al., 1981). Therefore, the term αv becomes negligible and the coefficient of hydrodynamic dispersion (D) is equivalent to the coefficient of molecular diffusion (D^*). A typical range of values of D^* for nonreactive species in clayey deposits is 1×10^{-10} m^2/s to 1×10^{-11} m^2/s (Freeze and Cherry, 1979).

The solution to Equation (2) for a step-function input is described by Ogata (1970) as follows:

$$C/C_o = 1/2[\mathrm{erfc}\{(x-vt)/(2\sqrt{Dt})\} + \exp(vx/D)\, \mathrm{erfc}\{(x+vt)/(2\sqrt{Dt})\}] \qquad (3)$$

where: C/C_o is the relative concentration and erfc represents the complementary error function. For large values of x or t, the second term of Equation (3) is negligible.

Desaulniers et al. (1981) have shown that groundwater flow in clayey deposits of the St. Clair Clay Plain is extremely low and solute transport is diffusion controlled. Under these circumstances, where the groundwater velocity is so small that mechanical dispersion is negligible relative to molecular diffusion, Equation (3) simplifies to an expression relating the concentration of a diffusing substance to space and time known as Fick's second law (Freeze and Cherry, 1979). Fick's second law is defined as follows:

$$\partial C/\partial t = D^* \, \partial^2 C/\partial x^2 \qquad (4)$$

The solution to Equation (4) is (Crank, 1956):

$$C(x,t) = C_o \, erfc(x/2\sqrt{D^* t}) \tag{5}$$

Freeze and Cherry (1979), Gillham and Cherry (1982), and Johnson et al. (1989) have demonstrated that over long periods of time, the process of diffusion can cause solutes to move considerable distances, even when groundwater velocity is extremely slow. For example, Johnson et al. (1989) show that for a 1 m thick low permeability clay liner typical of waste disposal sites, simple Fickian diffusion can cause breakthrough of mobile contaminants in approximately 5 years.

3.3 Characterization of Site Geology and Hydrogeology

3.3.1 Borehole Program

The borehole program was based on a review of site stratigraphy of the Puce Road Test Site (after Brathwaite, 1988) and a review of site stratigraphy of the Whelan Farm Test Site (after Orpwood, 1984). For both test sites, it was proposed that three series of boreholes be completed. The purpose of these three series, designated as A, B, and C, was to obtain detailed definition of site stratigraphy and to allow for subsequent installation of monitoring wells for the suite of hydraulic connection tests. In addition, at the Whelan Farm Test Site, the advancement of 16 boreholes was planned as part of a pesticide and nitrate contamination study of the Great Lakes managed by Agriculture Canada. This series of borings, designated as the Ag. Can. Series, was to be used as part of this study to obtain more information regarding site stratigraphy and the occurrence of HPZ's.

At the Puce Road Test Site, each borehole series was proposed to consist of five boreholes: two at different depths in the brown weathered till; one in the upper grey clay till; one in the interbedded zone; and one in the lower grey clay till. At the Whelan Farm Test Site, each series was proposed to consist of four boreholes: one in the brown weathered till; one in the interbedded zone; and two in the underlying grey till. Lateral placement of boreholes in each series was to be as close together as possible, approximately two metres apart. The Ag. Can. series borings were to be completed at the transition zone of brown to grey clay.

3.3.2 Drilling and Soil Sampling

Drilling commenced at the Puce Road Site on May 30, 1990 and continued on May 31, 1990 and on June 11, 1990. Drilling was carried out at the Whelan Farm Site on June 12 and 13, 1990. A Central Mining Equipment (CME) 750 four wheel drive drill rig and skilled operators were contracted from Dominion Soils Investigation Inc. Boreholes were advanced with 165 mm (6.5 in) outer diameter hollow-stem augers.

Soil sampling was carried out using either standard split spoon samplers or thin-walled (Shelby Tube) samplers measuring 625 mm in length and 62.5 mm in diameter. Soil samples were taken continuously in the deepest borehole at each series to characterize the geology and to determine the depth of the next shallower borehole.

Soil samples were examined in the field with particular attention being given to soil type, degree of weathering, colour, and fractures (nature and occurrence). In subsequent boreholes at each series, soil samples were taken only near the desired depth of the well screen to ensure that the appropriate unit had been intersected.

Samples taken from the first borehole at each site were tested for moisture content. Samples from borings drilled into each unit at each nest were composited and tested for grain size distribution. Methods outlined by Lambe (1951) were used in these analyses.

At the Puce Road Site, a total of 17 boreholes were completed. Locations of the boreholes/monitoring wells are shown in Figure 3.1. Series A and B deviated slightly from the boring program; two borings were drilled in the lower grey clay in the A series and two borings were completed in the interbedded zone in the B series.

At the Wnelan Farm Site, a total of 20 boreholes were completed. Locations of the boreholes/monitoring wells are shown in Figure 3.2. Series A was completed as outlined in the borehole program. Upon drilling series B and C, the interbedded zone was not encountered. Three soil borings were drilled along the property boundary (see Figure 3.2) to a depth of approximately 4.5 m but continuity of the interbedded zone was not identified. Consequently, only the A series borings were completed. The Ag. Can. series was completed as outlined in the borehole program.

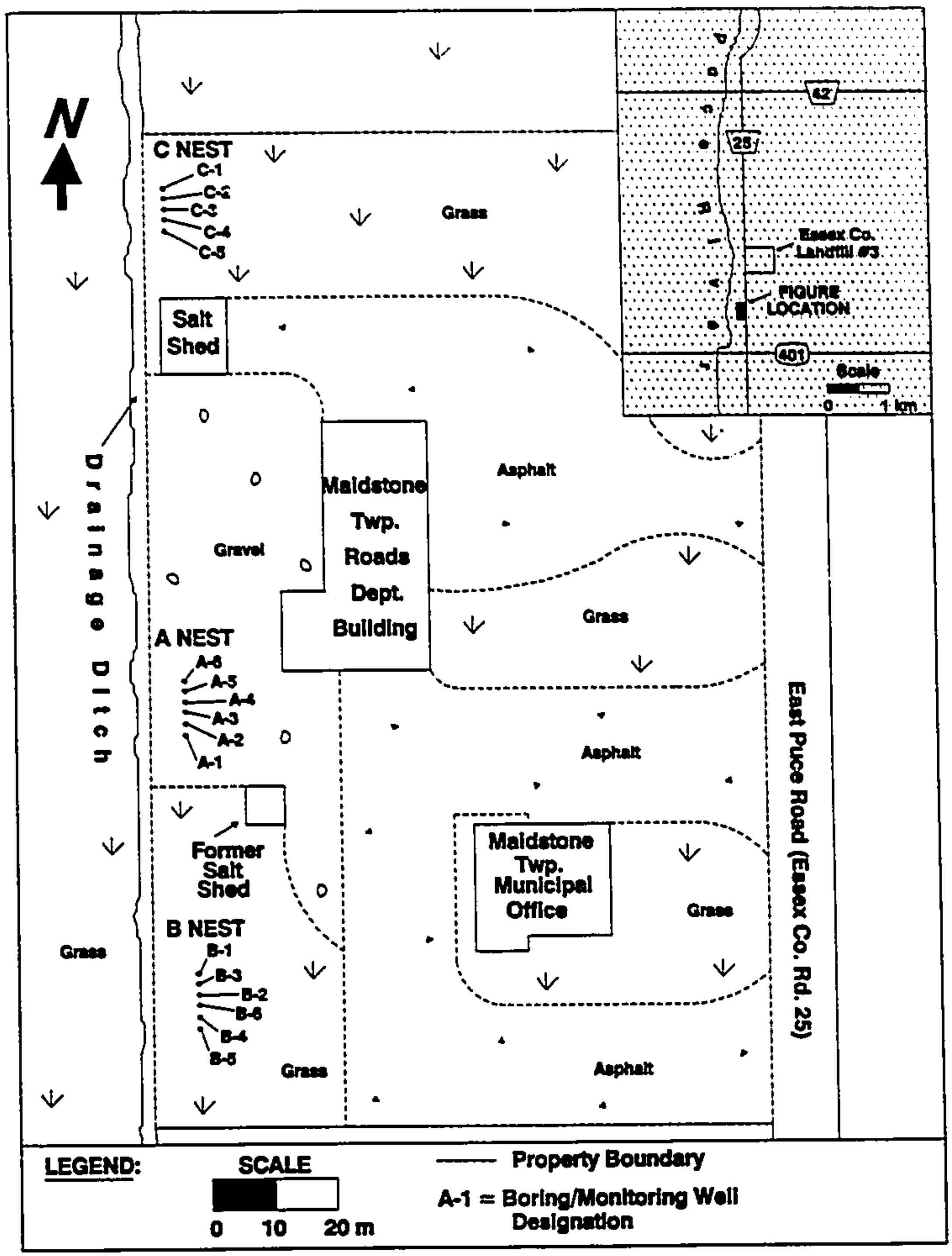


Figure 3.1. Locations of boreholes/monitoring wells at the Puce Road site.

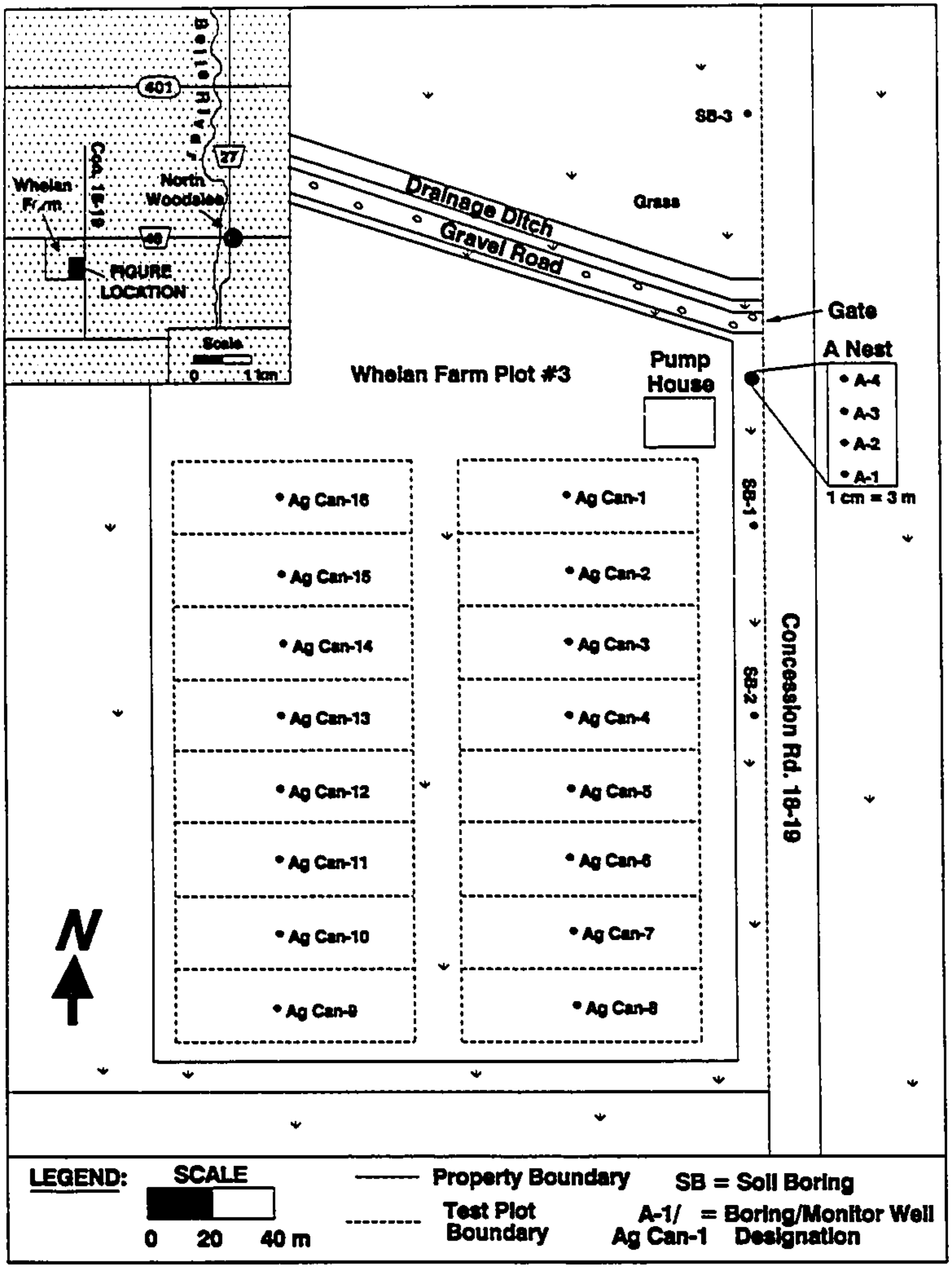


Figure 3.2. Locations of boreholes/monitoring wells at the Whelan Farm site.

3.3.3 Monitoring Well Installation

Upon completion of each borehole, groundwater monitoring wells were installed through the hollow-stem augers. The A nest was dedicated to be used for the pulse interference test, the B nest was dedicated to be used for all groundwater and soil sampling for laboratory testing, and the C nest was dedicated to be used for the induced infiltration test. At the Whelan Farm Site, the A nest was to be used for all tests.

Figure 3.3 shows general features of monitoring well construction and completion. Each monitoring well was constructed of environmentally-cleaned 50 mm (2") diameter Schedule 40 flush-threaded Triloc PVC plastic casing. At the Puce Road Site, casings were fitted with a 0.76 m (2.5 ft) long Triloc Slot 10 PVC screen. Each well was fitted with a vented PVC cap and a protective steel casing to ensure integrity of the well. At the Whelan Farm Site, the A nest casings were fitted with a 0.60 m (2 ft) long Triloc Slot 10 PVC screen. Each well was fitted with a vented PVC cap. The A nest wells were flush-mounted so as not to disrupt landscape maintenance.

Completion of all monitoring wells consisted of backfilling the annulus around and above the screen with approximately 1 m of medium-grained silica sand. Above the sand pack, the annulus was sealed with approximately 0.5 m of bentonite and then backfilled with drill cuttings to about 0.5 m below grade where another bentonite seal was placed up to the ground surface. At the ground surface, drill cuttings were packed around and graded away from the well casing to ensure proper

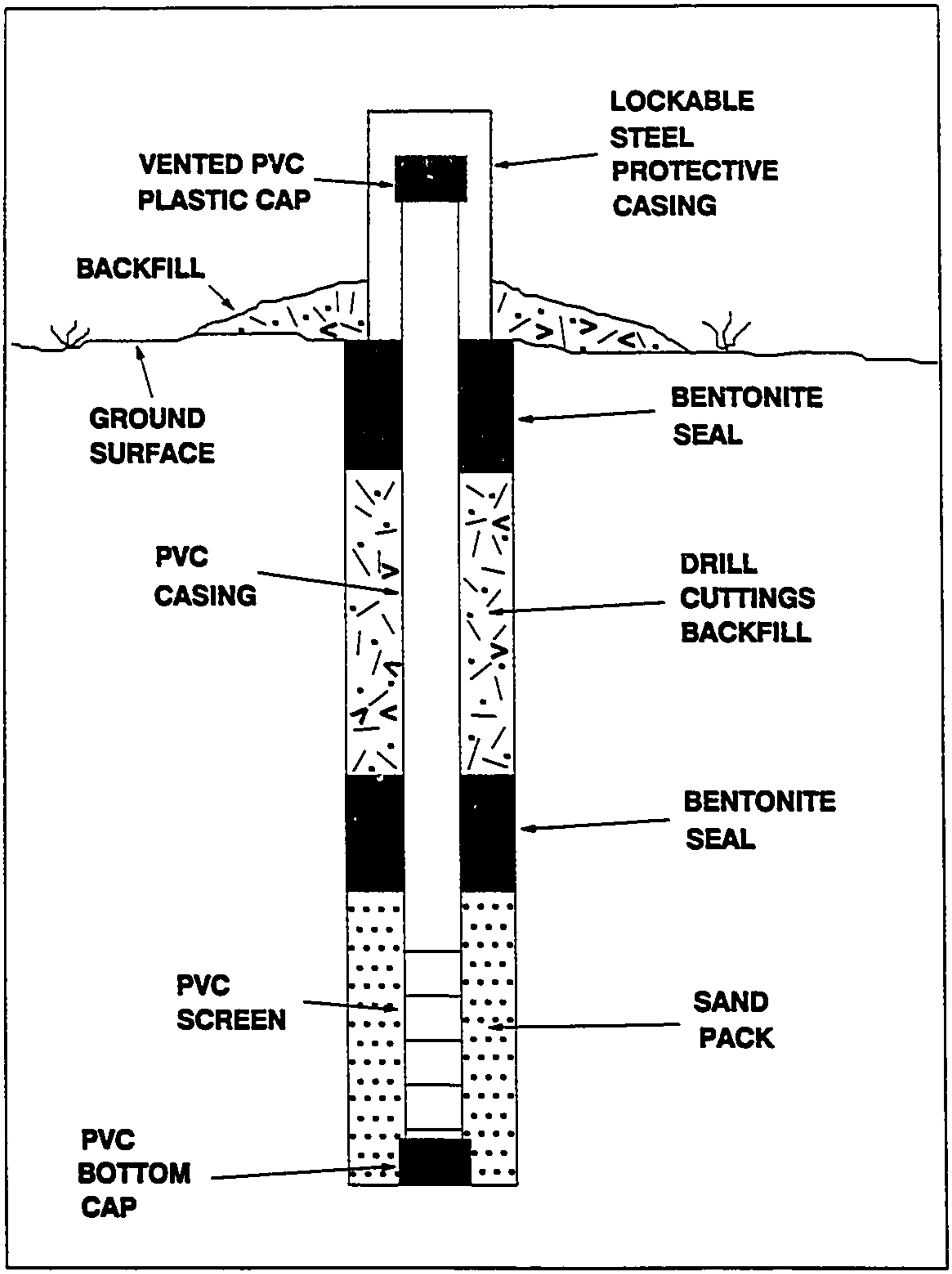


Figure 3.3. General monitoring well construction details.

drainage of surface runoff away from the well.

All monitoring wells were developed three and seven days after installation. Well development consisted of evacuating standing water with a bailer until the well was as dry as possible. The wells were developed in order to remove fines in the screen and sandpack and to draw water through the formation. This procedure helps to restore the natural hydraulic conductivity of the formation after auger disturbance.

3.3.4 Hydraulic Head and Hydraulic Conductivity

Hydraulic heads and hydraulic conductivity were determined for each well in order to determine groundwater flow directions and rates.

After well development, water levels were monitored periodically in all wells for several months. Water levels of the A and C nests at the Puce Road site were monitored from June, 1990 to May, 1991 when hydraulic connection tests began. Water levels in the B nest at the Puce Road Site and the A nest at the Whelan Farm Site were monitored from September, 1990, when sampling was completed, to April, 1991, when the physical tests for hydraulic connection began. Water level measurements were performed using a Seba-Hydrometrie water level meter and were measured to an accuracy of 0.005 m.

In order to obtain accurate hydraulic head measurements for the determination of hydraulic gradients and groundwater flow directions, ground and top of casing (T.O.C.) elevations of all wells were determined relative to mean sea level. Elevations were determined using a Lietz B2C automatic level.

At the Puce Road Site, the nearest benchmark, as determined from Ministry of Transportation and Communications (MTC) records, was on the top of the southeast corner of the north concrete weir and wingwall of a culvert over Anger Drain under Puce Road immediately south of 16 & 17 Sideroad. The elevation of this benchmark is 184.244 metres above sea level (m.a.s.l.). At the Whelan Farm Site, a site benchmark was created on a concrete culvert under Concession Road 18-19 over the Whelan Farm drain, immediately north of the east entrance gate. The elevation of this benchmark was estimated from Essex County Topographic Sheet No. 10173550 46700 as 187.000 m.a.s.l.

Hydraulic conductivities were determined in the field using single well tests after the method of Hvorslev (1951). Hvorslev single well tests were conducted at each well by monitoring water level recoveries after well development. The start of each test began once the water level in each well recovered to the top of the screen.

3.3.5 Previous Studies

At the Puce Road Site, Brathwaite (1988) installed ten monitoring wells in the vicinity of the C nest of this study. A generalized log of soils encountered at that locality consisted of:

0 - 4.2 m Brown fractured and weathered clay till

4.2 - 7.6 m Grey silty clay till

7.6 - 10.8 m Interbedded zone

10.8 - 13.7 m Grey silty clay till.

Brathwaite (1988) also examined the hydrogeology of the site. He concluded that hydraulic conductivities were of the order of 1 x 10^{-8} m/s for the the brown weathered till unit; 2 x 10^{-9} m/s for the grey till units; and 3 x 10^{-9} m/s for the interbedded zone. He also concluded from hydraulic evidence that the upper two meters of the unweathered grey till may be fractured. The lateral groundwater flow direction was to the northwest under a gradient of 0.064. Lateral groundwater velocities in the interbedded zone ranged from 55 to 66 mm/yr. The vertical groundwater flow direction was downward above the interbedded zone but was upward below the interbedded zone.

M.M. Dillon Limited (1988) conducted an extensive hydrogeologic study at the nearby Essex County Landfill #3, located approximately 1 km northeast of the Puce Road Test Site. Results of this study have been briefly discussed in sections 2.3.2 and 2.3.3. A detailed summary of site stratigraphy, soil porosities, vertical and horizontal groundwater gradients, flow directions, and flow velocities is presented in Figure 3.4.

At the Whelan Farm Test Site, Orpwood (1984) installed ten monitoring wells in three nests. A nest of two wells was located in the vicinity of the A nest of this study. A generalized log of soils encountered at that locality consisted of:

0 - 2.8 m Brown-grey weathered, fractured silty clay

2.8 - 3.7 m Interbedded sand lenses with silty clay

3.7 - 10.5 m Grey silty clay till.

Orpwood (1984) also evaluated the hydrogeology of the site. Field

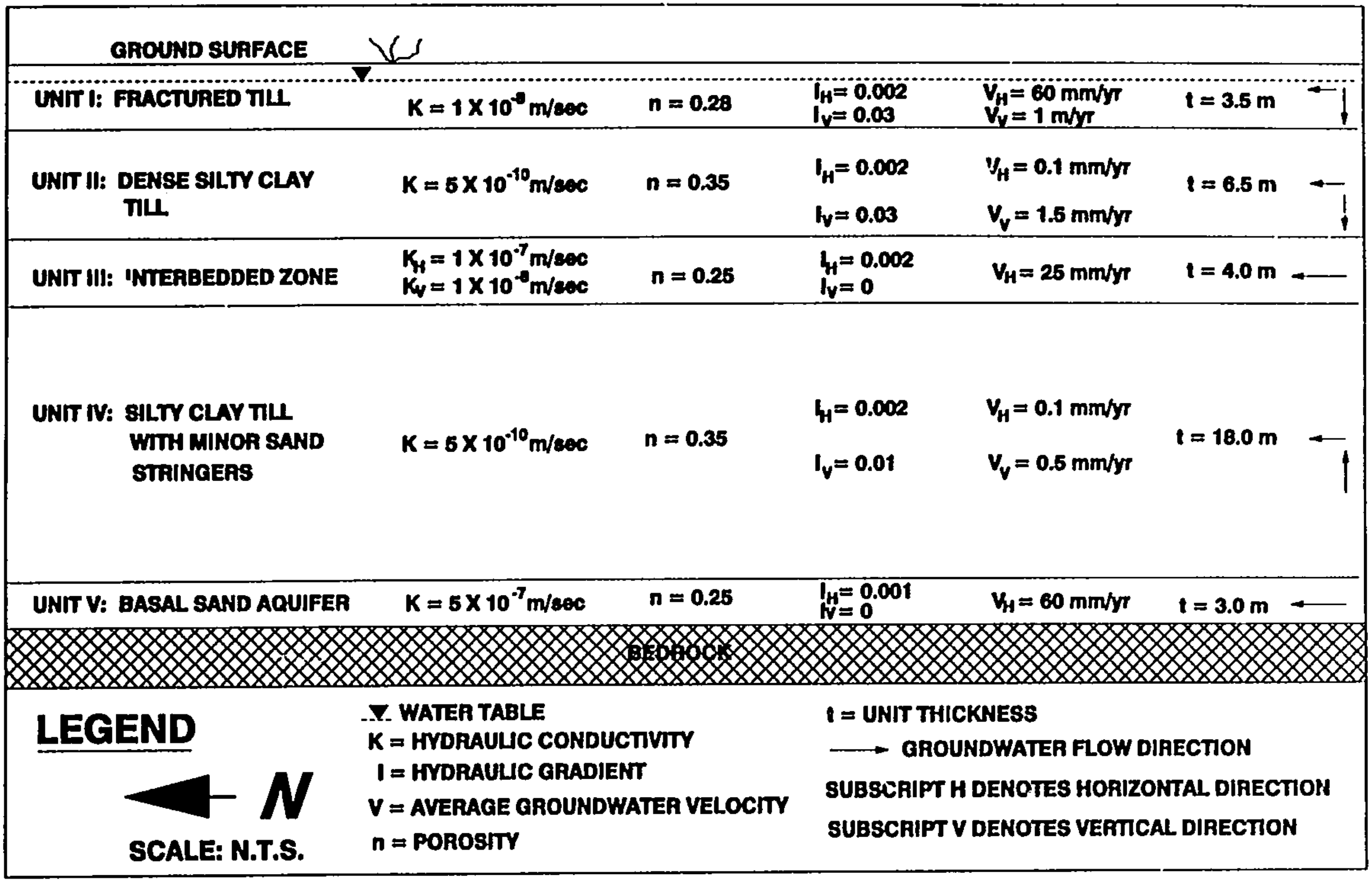


Figure 3.4. Generalized geologic and hydrogeologic cross-section of soils underlying Essex County Landfill #3 (after M.M. Dillon, Ltd., 1988).

permeability tests indicated that hydraulic conductivities were of the order of 3×10^{-9} m/s for the brown weathered clay till unit and 1×10^{-10} m/s for the grey clay till unit. Groundwater flow was to the southeast under a gradient of 0.002. Horizontal groundwater flow velocities were estimated at 3.0 to 8.0 mm/yr in the brown fractured clay till and 1.0 to 1.5 mm/yr in the unfractured grey clay till. Vertical gradients were found to range from 0.01 to 0.06 downward.

Desaulniers et al. (1981) also examined the hydrogeology of the clay tills at the Whelan Farm site. Monitoring wells were installed down to the base of the grey clay deposit near bedrock. Field permeability tests concluded that the hydraulic conductivity of the deep grey clay till unit ranged from 2.4×10^{-11} m/s to 6.0×10^{-11} m/s. Porosities ranged from 20 to 40%. Groundwater movement was primarily vertical. The upper 3 m exhibited a downward gradient whereas at depth, gradients were upward ranging from 0.01 to 0.18. Desaulniers et al. (1981) concluded that these upward gradients may be due to the presence of higher permeability zones at depth. Vertical groundwater velocity was estimated at 0.4 to 1.6 mm/s upward. Desaulniers et al. (1981) concluded that groundwater flow in the clayey soils at depth was influenced predominantly by molecular diffusion, apparently more so than by advection.

3.4 Physical Techniques for Determining Hydraulic Connection

Physical tests for determining hydraulic connection that were employed in this study were: (1) pulse interference tests, (2) induced infiltration tests, and

(3) examination of hydraulic head fluctuations versus depth profiles. These tests are discussed in detail in the following sections.

3.4.1 Theoretical Considerations

3.4.1.1 Pulse Interference Tests

Pulse interference tests can be used in two ways to determine whether or not an HPZ is hydraulically connected to the ground surface: (1) by pulsing the HPZ and monitoring a response in formations above the HPZ, and (2) by determining hydraulic properties of the HPZ.

Pulse interference tests are derived from aquifer pump tests. They were developed in order to overcome the difficulties of manitaining constant discharge from low capacity pumps often associated with the task of conducting a pump test in low permeability formations. Thus, the technique of the pulse interference test is an ideal alternative which may be used to evaluate hydraulic properties of low permeability formations when conventional pump tests are not feasible.

The theory of the pulse interference test is similar to that for an aquifer pump test; it is based on the physics of groundwater flow toward a well during pumping. Pumping a well causes an interference in the natural groundwater flow equilibrium inducing horizontal and vertical gradients around the well which cause radial flow toward the well. As a result, hydraulic heads are decreased in the aquifer around the well in the shape of a cone. Hydraulic properties (transmissivity and storativity) of the aquifer can be determined from drawdown response hydrographs of observation wells. Hydraulic connection with other units can be inferred by observing drawdown responses in these units. Details of aquifer pump tests and well hydraulics are described by Driscoll (1986), Fetter (1988), Freeze and Cherry (1979), and Kruseman and de Ridder (1991), among others.

The general approach to conducting a pulse interference test involves generating a pulse of pressure in a source well by periodic injection or removal of fluid. The term "pulse" refers to a stress imposed on the groundwater flow system for a relatively short period of time. Response to the pulse train can be monitored in observation wells with a water level meter.

In a study of hydraulic connection of an HPZ to the ground surface, pulse interference tests can be used in two ways: (1) by pulsing the HPZ and monitoring a response in formations above the HPZ, and (2) by determining hydraulic properties (i.e. storativity) of the HPZ. Each technique will be discussed in the following paragraphs.

The pulse interference test can be used to infer vertical hydraulic connection between two or more units by pulsing one unit and observing a drawdown response in another unit. Figure 3.5 depicts the effects on flow lines in response to stressing a hypothetical unit by lowering the potentiometric surface of that unit. If no drawdown is observed in observation wells in units above or below the stressed unit (i.e. Unit 2), a poor hydraulic connection can be inferred between Unit 2 and those units directly above and below (i.e. Units 1 and 3) (Figure 3.5a). If a drawdown is observed in either of the observation wells screened in Unit 1 or Unit 3, a good

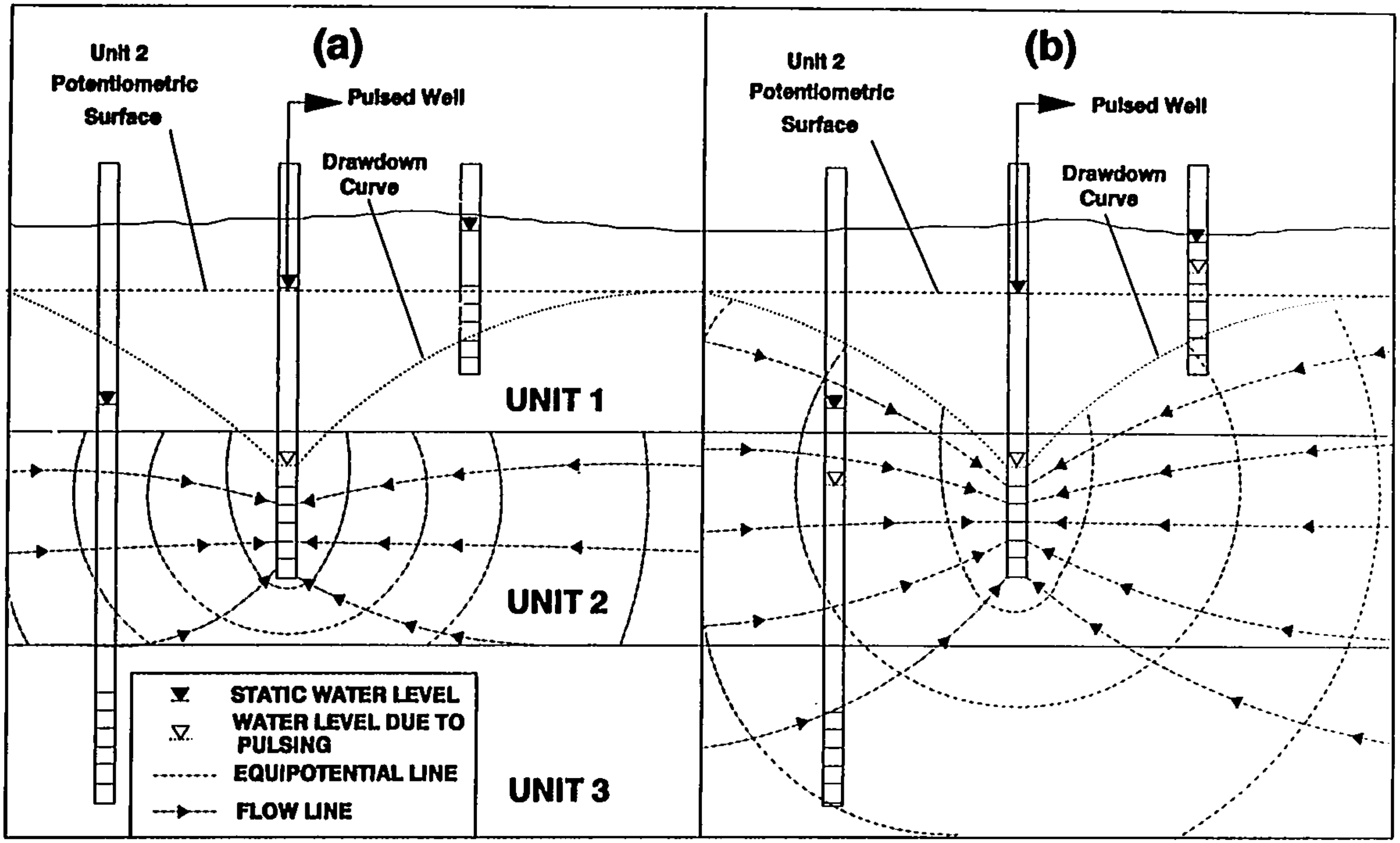


Figure 3.5. Depiction of flow lines in response to pulsing a hydrostratigraphic unit with: (a) poor hydraulic connection to units above and below, and (b) good hydraulic connection to units above and below.

hydraulic connection may be inferred between Unit 2 and the unit in which a drawdown was observed (Figure 3.5b).

The second way in which pulse interference tests can be used to determine whether or not an HPZ is hydraulically connected to the ground surface is by determining the storativity (or storage coefficient) of the HPZ. The storativity (S) of a unit represents the volume of water that an aquifer releases from storage per unit of aquifer storage area per unit change in hydraulic head (Driscoll, 1986).

The underlying principle of this technique is that the storativity of an unconfined aquifer differs by orders of magnitude from that of a confined aquifer. The storativity of an unconfined aquifer ranges from 0.01 to 0.30 (Driscoll, 1986; Freeze and Cherry, 1979) whereas the storativity of a confined aquifer ranges from 0.00005 to 0.005 (Driscoll, 1986; Freeze and Cherry, 1979). This difference is due to the fact that water is released from storage by gravity drainage in unconfined aquifers during pumping. In confined aquifers, the pores are not drained; water is released from storage as a result of compression of the aquifer and expansion of the confined water caused by reduced head pressures due to pumping (Driscoll, 1986). If an HPZ is unconfined, then it is directly connected to the surface.

Walter and Thompson (1982) present a method where storativity of low permeability formations can be determined by repeatedly pulsing a well and monitoring drawdown response in observation wells screened in the same unit. The observation well response hydrographs are analyzed by curve matching techniques.

When the pulse volume and time interval between pulses are variable, type curves for this method can be generated based on the following equation (Walter and Thompson, 1982):

$$F(t) = \Sigma V_i/(t-t_i)\exp[-B/(t-t_i)] \qquad (6)$$

where: $F(t) = 4\pi Ts$ and $B = r^2S/4T$; s is drawdown [L]; T is transmissivity [L/T]; S is the storavitity [dimensionless]; V_i is the volume of water removed during the i^{th} pulse [L^3]; t is the time [T]; and r is the distance from the pulsed well to the observation well [L]. Actual response curves can be matched to the generated type curves and T and S can be determined.

In summary, pulse interference tests can be used in two ways to determine whether or not an HPZ is hydraulically connected to the ground surface: (1) by pulsing the HPZ and monitoring a response in formations above it, and (2) by determining if the storativity of the HPZ is in the range of a confined or an unconfined aquifer.

3.4.1.2 Induced Infiltration Tests

Induced infiltration refers to the percolation of surface water from man-made storage basins into the underlying soil.

Infiltration is generally described as the process in which water penetrates a soil surface. Green and Ampt (1911) describe the process as the advancement of a square wave (wetting front) through the soil column which may be modelled by the following equation:

$$t = \frac{n - \Theta_i}{K}\left[L - (h - \Psi) \ln\left(\frac{h + L - \Psi}{h - \Psi}\right)\right] \tag{7}$$

where: t is time [T]; Θ_i is the initial soil moisture content [dimensionless]; n is soil porosity [dimensionless]; h is the head of fluid above soil surface [L]; L is the vertical length of soil column [L]; Ψ is the capillary pressure head [L]; and K is the saturated hydraulic conductivity [L/T]. Above the wetting front, soil is completely saturated but below the wetting front, soil moisture remains at its original level. If the amount of infiltrating water is large enough, the wetting front will percolate downward until it meets a lower permeability boundary or the water table at which point a mound develops which travels outward with time (Figure 3.6). The magnitude of rise of the water table in response to infiltrating water will depend, among other factors, on the duration and rate of recharge, and the size and shape of the recharging area (Hantush, 1967).

At the Puce Road and Whelan Farm test sites, infiltration rate and depth is governed by the extent to which water can readily flow through the network of fractures in the weathered clay soil. Water level increases in observation wells in response to infiltration can therefore be used to infer hydraulic connection between the ground surface and the underlying HPZ. Conversely, a poor hydraulic connection may be inferred if no water level responses are observed in the monitoring wells.

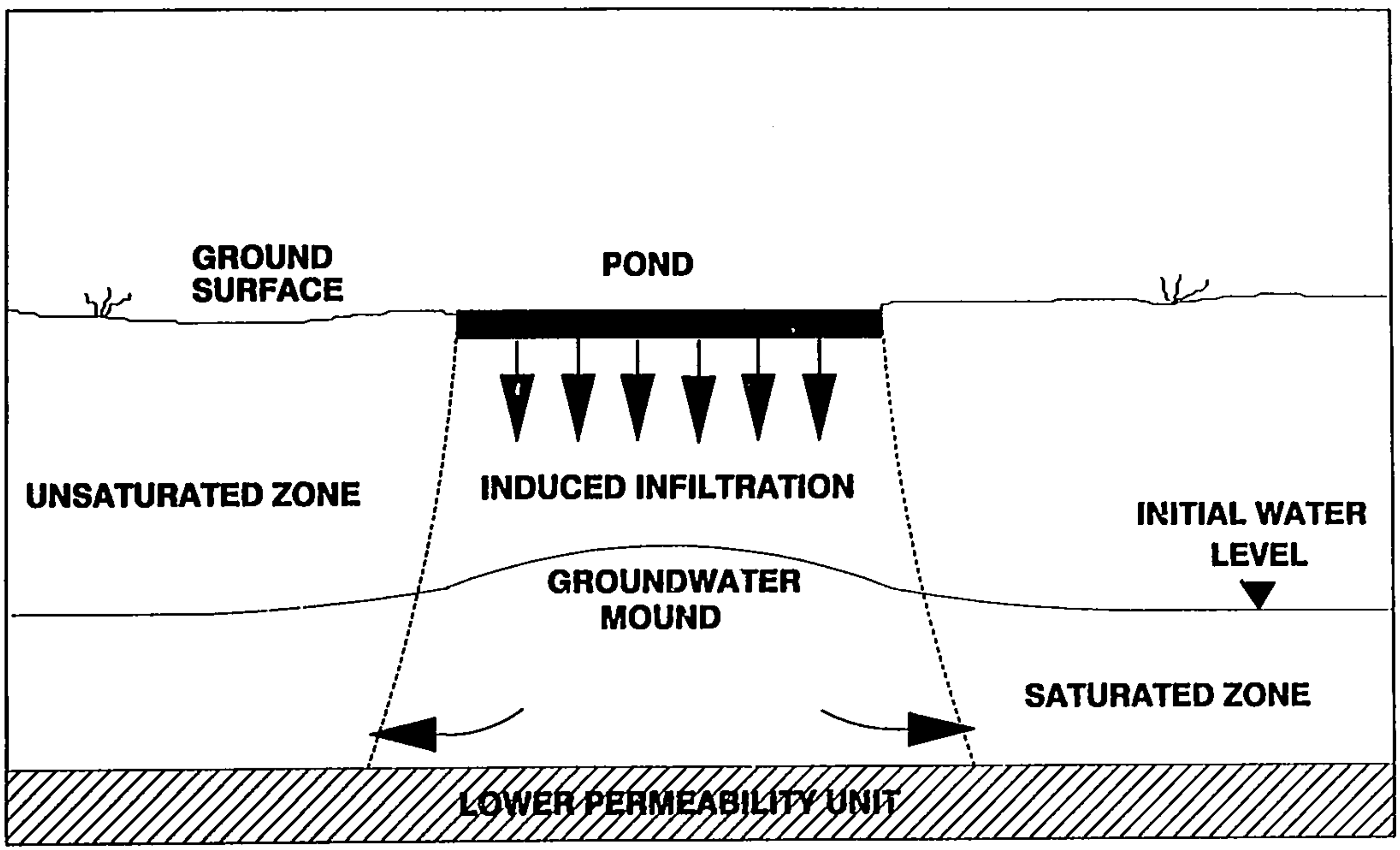


Figure 3.6. Water table response under induced infiltration.

3.4.1.3 Fluctuations in Hydraulic Head Versus Depth Profiles

Profiles of hydraulic head versus depth may be used to predict whether or not an HPZ is confined or unconfined. If an HPZ is unconfined (i.e. it is hydraulically connected to the ground surface), then the HPZ and the overlying clay essentially behave as one hydrostratigraphic unit. Therefore, the hydraulic head should uniformly increase with depth and a depth profile of hydraulic head should resemble a straight line (Figure 3.7a).

On the other hand, if the HPZ is not hydraulically connected to the ground surface, then the HPZ and the overlying clay are separate hydrostratigraphic units. Consequently, the HPZ must be recharged from below or from a lateral upgradient source. In this case the distribution of hydraulic head with depth should resemble that shown in Figure 3.7b.

A single profile of hydraulic head versus depth, however, is not representative of actual groundwater conditions. Keller et al. (1989), Ruland et al. (1991), and Rudolph et al. (1991) observed significant seasonal fluctuations in groundwater levels. In some cases these fluctuations resulted in gradient reversals. Furthermore, precipitation may quickly infiltrate the ground surface and fill up fractures resulting in increases in water levels and potential gradient reversals (Williams and Farvolden, 1967). Therefore, in low permeability media, several profiles of "static" water levels over time must be examined to determine whether or not an HPZ is connected to the surface. Large fluctuations observed in piezometers can be used to infer interconnection of fractures and an active groundwater flow zone

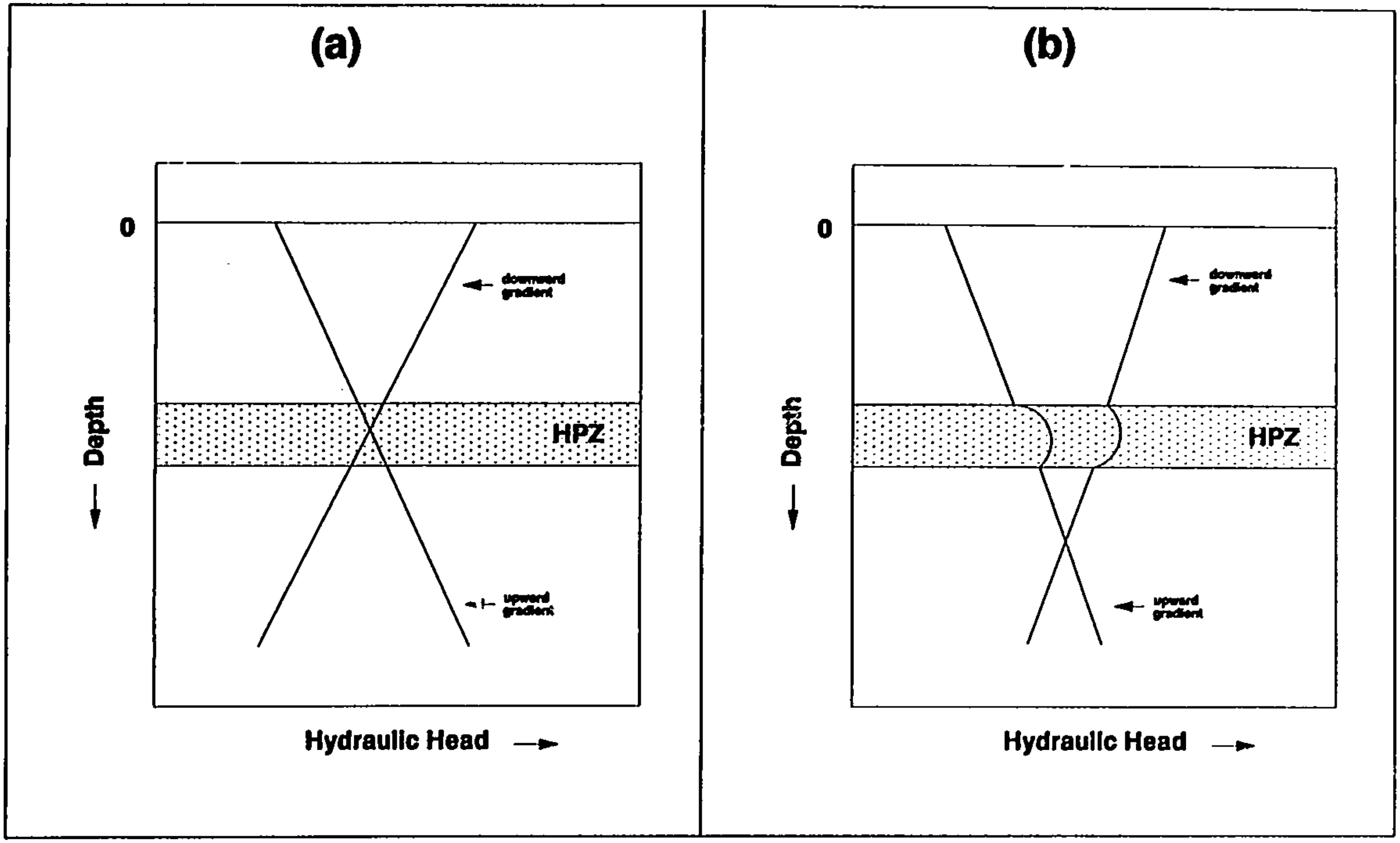


Figure 3.7. Conceptual hydraulic head variation with depth where: (a) an HPZ is hydraulically connected to the surface, and (b) an HPZ is not hydraulically connected to the surface.

(Keller et al., 1989; and Ruland et al., 1991).

In summary, profiles of hydraulic head potential with depth can be used to predict whether or not an HPZ is being recharged from above. Fluctuations of head profiles over time are representative of an active groundwater flow zone due to the presence of fractures. If an HPZ is located in this hydrogeologically active zone, then hydraulic connection of the HPZ to the surface can be inferred.

3.4.2 Field and Laboratory Work

3.4.2.1 Pulse Interference Tests

Pulse interference tests began well after it was established that all wells had reached static level. The pulse at the source well was imposed by bailing the well dry each day. The first test began at the A nest at the Puce Road Site on April 6, 1991. Well A-2, completed near the base of the brown weathered, fractured till unit, was bailed first to test for hydraulic connection above and below. During the test, the rate of bailing and water level conditions in all wells were recorded. This particular test was run for five days. When this test was concluded, well A-4, completed in the interbedded zone, was bailed in a similar fashion. This particular test was carried out from April 11 to April 18, 1991. At the same time, a test was carried out at the B nest. Well B-4, completed in the interbedded zone, was bailed to test for hydraulic connection above and below. This particular test was carried out from April 11 to April 18, 1991.

The pump-interference test at the Whelan Farm Site was conducted on

April 7, 1991. Well A-2, completed in the interbedded zone, was bailed to test for hydraulic connection above and below. Due to the quick recovery of this well, bailing was necessary every 15 minutes. Consequently, this particular test was completed in one day.

3.4.2.2 Induced Infiltration Tests

A total of three induced infiltration tests were performed in this study: one at the Whelan Farm Site (A nest) and two at the Puce Road Site (A and C nests). The test at the Puce Road A nest was conducted in order to confirm the results of the test performed at the C nest. Testing was carried out at the Whelan Farm A nest on May 4, 1991, at the Puce Road C nest on May 11, 1991, and at the Puce Road A nest on May 19, 1991.

Photographs of the plots prepared for the test are shown in Figure 3.8. Prior to testing, approximately 100 mm of sod and topsoil were dug out and removed from around the Whelan Farm A nest and the Puce Road C nest in the shape of a rectangular plot. The Whelan Farm Test Site plot measured 5.6 m by 1.3 m and the Puce Road Test Site plot measured 6.7 m by 1.3 m. Sod was left in place around each well in order to minimize leakage of water down the borehole annulus. Garden edging was placed around the inside of the plot to help contain the water. At the start of each test, the plots were covered with plastic sheeting to minimize evaporation of the water accumulating in the plot.

The supply of water at the Whelan Farm Site was from the nearby drainage

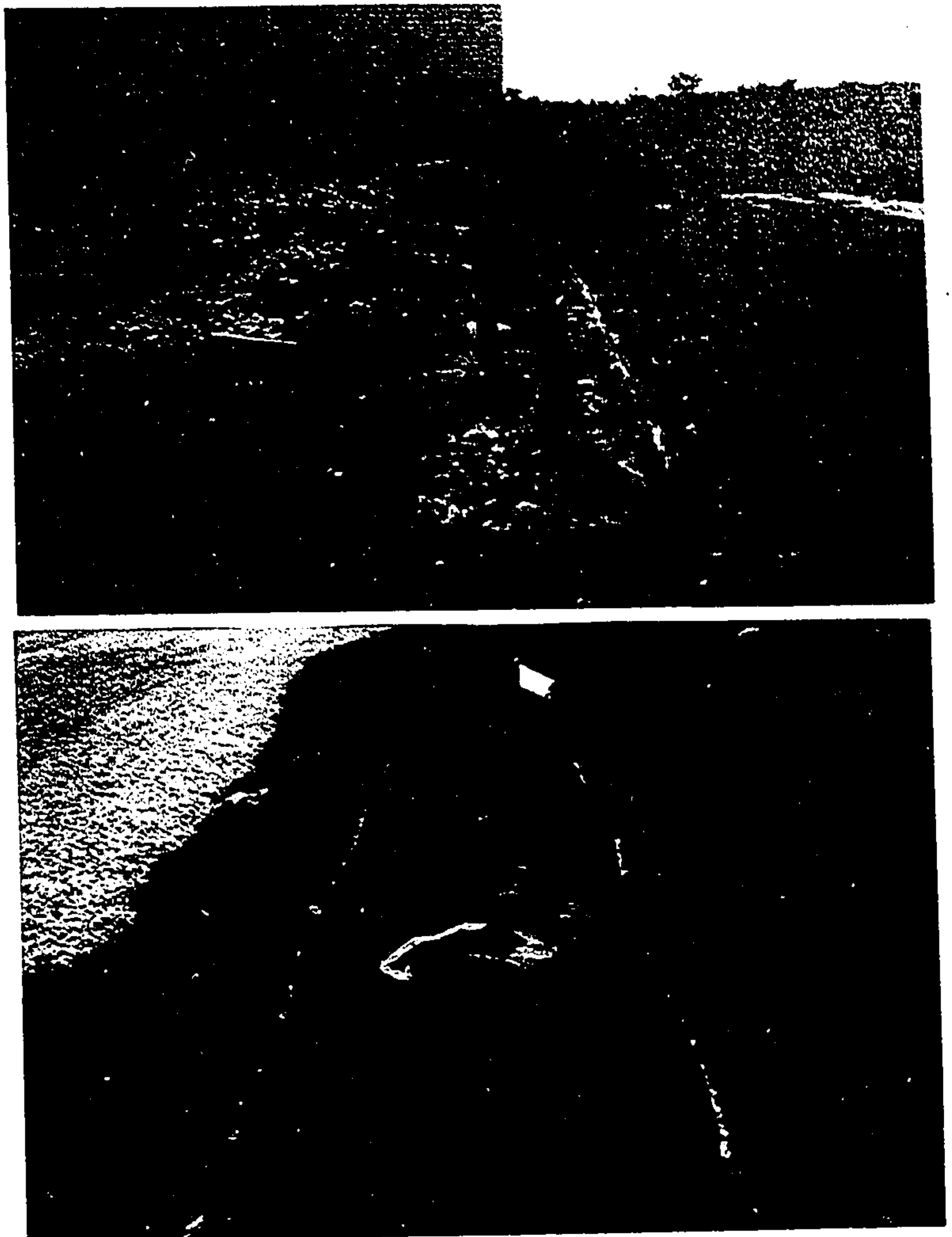


Figure 3.8. Photographs of the plots prepared for the induced infiltration test: Puce Road site C nest (upper photo) and Whelan Farm site A nest (lower photo).

ditch. At the Puce Road Site, water was supplied from an outdoor faucet. Water was evenly supplied to the plots by means of a lawn soaker which was fed by a cylindrical fiberglass tank capable of holding 0.2 m^3 of water. A constant head of 0.7 m was maintained in this tank throughout the tests by means of an overflow pipe. In total, 1.5 m^3 of water over a period of six hours was supplied to the Whelan Farm A nest plot and 2.2 m^3 of water over a period of nine hours was supplied to the Puce Road C nest plot. Water level conditions in each monitoring well were recorded periodically over the duration of the tests.

In order to confirm the observations of the induced infiltration test at the Puce Road C nest, another test was performed at the Puce Road A nest. The objective of this test was simply to check for a response in the wells installed in the fractured clay zone under induced infiltration. Consequently, this test was slightly modified from the previous tests. A 50 mm deep trough was dug around wells A-1, A-2, and A-3 (the three shallowest wells) so that garden edging could be installed to contain the water. The shape of the plot for this test was circular rather than rectangular. Water was supplied to the plot with a lawn soaker. In total, approximately 2.0 m^3 of water was supplied to the plot over a period of nine hours.

3.4.2.3 Fluctuations in Hydraulic Head Versus Depth Profiles

Field work for this particular test involved the periodic collection of accurate hydraulic head data for each monitoring well. Hydraulic head measurements have been discussed in Section 3.3.4.

3.4.3 Potential Physical Tests

3.4.3.1 Attenuation of Seasonal Hydraulic Fluctuations of the Water Table

Keller et al. (1989) present a method for determining bulk vertical hydraulic conductivity of low permeability clayey units by observation and analysis of the attenuation of seasonal hydraulic fluctuations of the water table. The field methods for this particular test require accurate piezometric data over a period of several years. Over this long period of time, well hydrographs take the shape of a sinusoidal wave. This sinusoidal shape is governed by downward propagation of the seasonal cycle of water table fluctuation which is a flow process controlled by the vertical hydraulic diffusivity (K_v/S_s where: K_v is the vertical hydraulic conductivity and S_s is the specific storage coefficient) of the clay till. By determining vertical hydraulic diffusivity and specific storage, the vertical bulk field hydraulic conductivity of the clay can be determined.

The benefit of employing this particular test in a hydraulic connection study is that vertical hydraulic conductivity is determined in situ and over a large scale. Determination of an accurate "bulk" K_v value considerably increases the confidence in estimates of vertical groundwater flow velocities.

3.5 Geochemical Techniques for Determining Hydraulic Connection

Geochemical tests for determining hydraulic connection that were employed in this study are: (1) major ion geochemistry, (2) groundwater nitrate, and (3) groundwater field chemistry. These tests are discussed in the following sections.

3.5.1 Theoretical Considerations

3.5.1.1 Major Ion Geochemistry

The major ions in groundwater are those constituents that normally occur dissolved in groundwater in concentrations greater than five milligrams per litre (mg/L) (Freeze and Cherry, 1979). These major constituents are: bicarbonate (HCO_3^-), calcium (Ca^{2+}), chloride (Cl^-), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), and sulfate (SO_4^{-2}). The total concentration of these ions normally comprises greater than 90% of the total dissolved solids in groundwater.

The usefulness of major ion geochemistry of groundwater for testing the degree of hydraulic connection of an HPZ to the surface stems from the fact that major ions serve as natural groundwater tracers; groundwaters from different hydrostratigraphic units generally differ in geochemical composition unless mixing occurs. This difference is a function of the lithology of the formation, groundwater flow patterns within the formation, and chemical reaction kinetics occurring between the groundwater and the formation minerals.

In the clay deposits of the St. Clair Clay Plain, groundwater chemistry is quite variable and complex. The weathered zone generally exhibits different groundwater chemistry from the underlying unweathered zone. The chemical weathering features of the weathered zone, such as the formation of secondary gypsum and calcite and a brown to rust colouring of the soil due to oxidation of iron-bearing minerals, probably formed during the relatively warm climatic period that existed between 9000 and 3000 years ago (Farvolden and Cherry, 1988). This warmer and drier climate is believed to have caused the water table to drop two or three metres below the present level (which is in the order of a metre or two deep) resulting in dessication of the soil and the development of fractures. The invasion of air into fractures caused the oxidation of pyrite in shale fragments producing acidic conditions which resulted in the dissolution of calcite and the precipitation of gypsum (Farvolden and Cherry, 1988).

As a result of the weathering process in the upper few metres of the clay deposit, the groundwater in this zone is relatively high in Mg^{2+}, Ca^{2+}, Na^{+}, HCO_3^-, and SO_4^{-2} (Desaulniers et al., 1981). Conversely, Cl^- concentrations are low in the weathered zone and increase with depth in the unweathered zone to bedrock.

Major ion geochemistry of groundwater in the unweathered zone is generally influenced by molecular diffusion of ions from the weathered zone and from bedrock. Mg^{2+}, Ca^{2+}, Na^{+}, HCO_3^-, and SO_4^{-2} originate in the weathered zone and diffuse downward under the influence of a concentration gradient. Cl^- originates from brine in bedrock and diffuses upward.

Major ions in groundwater can be used to assess the degree of hydraulic connection of an HPZ to the ground surface by observing the trend in geochemical composition of groundwater with depth (Figure 3.9). If an HPZ is connected to the ground surface via fractures, it will possess groundwater similar in chemical composition to the weathered zone (Figure 3.9a). Conversely, if an HPZ is isolated from the surface, it should possess groundwater that is relatively low in major ion content with respect to the weathered zone (Figure 3.9b).

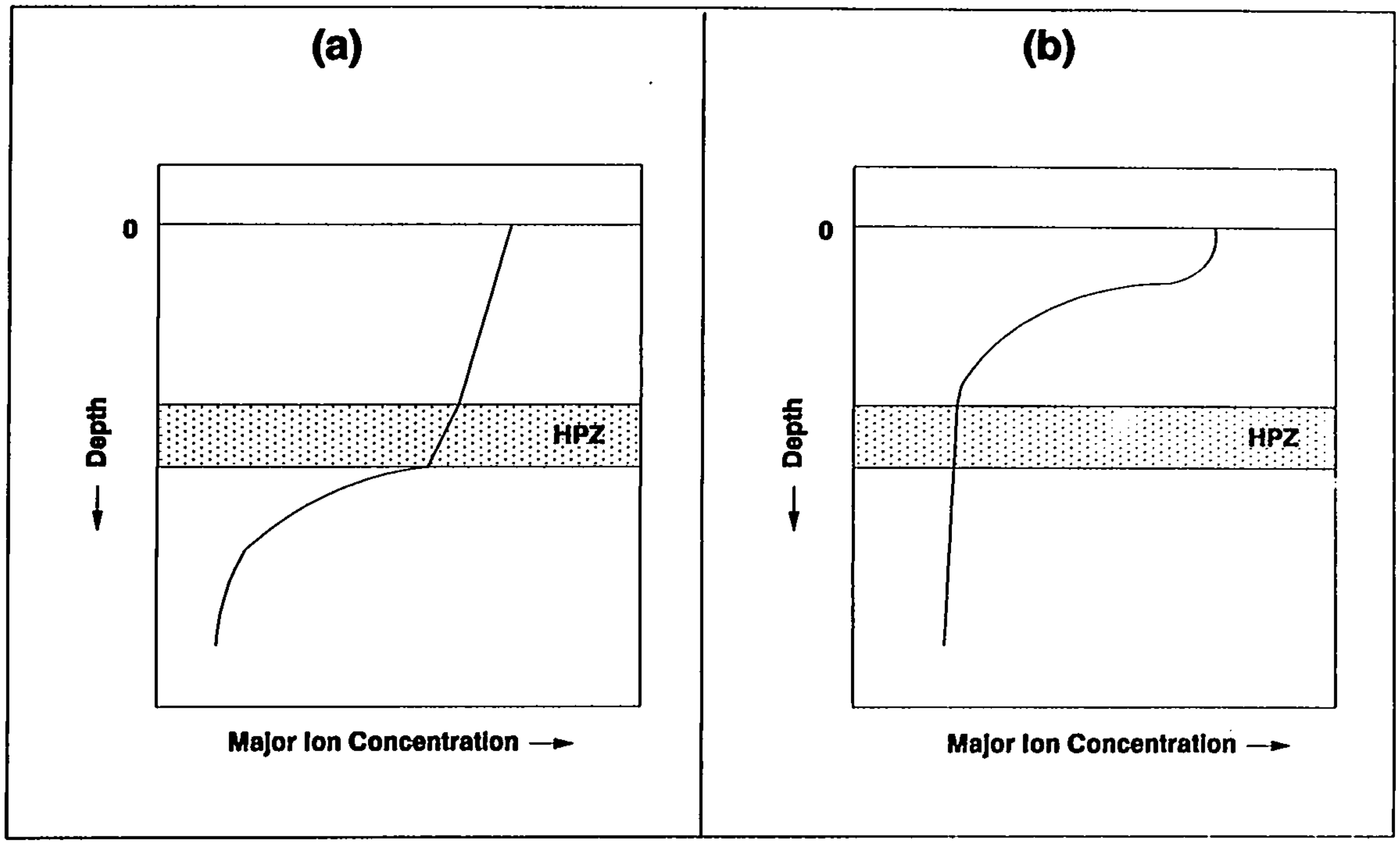


Figure 3.9. Conceptual major ion variation with depth where: (a) an HPZ is hydraulically connected to the surface, and (b) an HPZ is not hydraulically connected to the surface.

3.5.1.2 Groundwater Nitrate

Nitrate (NO_3^-) is considered to be a minor constituent in groundwater (i.e. it normally occurs in concentrations of 0.01 to 10 mg/L). Nitrate is the principal form of dissolved nitrogen in groundwater.

Unlike most other elements in groundwater, nitrate is not derived primarily from the soil or rock minerals that make up the groundwater reservoir. Nitrate is a by-product of the complex nitrogen cycle existing in the Earth's atmosphere, hydrosphere, and biosphere.

Dissolved nitrogen in the form of nitrate enters the groundwater from several natural sources (i.e. via vegetation) but the most substantial sources of groundwater nitrate originate from anthropogenic uses of nitrogen. In fact, nitrate is the most commonly identified groundwater contaminant (Freeze and Cherry, 1979). It has become increasingly widespread in groundwater because of agricultrual activities and disposal of sewage.

Because nitrate originates in groundwater near the ground surface, nitrate is a very good tracer of vertical groundwater flow. When nitrate enters the groundwater, it is very mobile because of its anionic form. It will tend not to adsorb onto negatively charged soil particle surfaces. The use of nitrate as a groundwater tracer is even more effective in areas with a history of fertilizer application or sewage disposal. The nitrogen content of these anthropogenic sources overwhelms the natural production of nitrogen. Over time, much more dissolved nitrogen in the form of nitrate will enter the groundwater system and migrate in the direction of groundwater flow. For example, Broadbent (1971) reported nitrate contamination at depths ranging from 240 to 400 m below the ground surface in an aquifer with significant downward flow components.

Nitrate, therefore, can serve as a valuable tool in determining whether or not an HPZ is hydraulically connected to the ground surface. HPZ's isolated from the atmosphere should possess very low concentrations of nitrate due to the fact that there are no major sources of nitrogen and oxygen other than near the ground surface. The actual degree of hydraulic connection of an HPZ to the surface can be inferred by comparing nitrate concentrations with near surface groundwaters. A good hydraulic connection can be suspected between an HPZ and the ground surface if their groundwater nitrate concentrations are similar (i.e. if the depth profile is similar to that of Figure 3.9a).

3.5.1.3 Groundwater Field Chemistry

Groundwater field chemistry refers to chemical properties of groundwater that can be readily determined in the field. In this study, these properties include: (1) temperature, (2) electrical conductivity (EC) and total dissolved solids (TDS), and (3) pH and Eh. The use of these parameters in determining the degree of hydraulic connection are discussed in the following paragraphs.

Groundwater temperature is a quickly and easily measured parameter that can be used to grossly estimate the degree of hydraulic connection of an HPZ to the surface. Soil and groundwater near the ground surface undergo temperature changes in response to seasonal atmospheric temperature fluctuations. Temperatures of deeper soil and groundwater are not directly affected by the atmosphere but are influenced by mixing with groundwaters from above. At a certain depth, depending on the permeability and the heat capacity of the soil, groundwater temperature is not readily influenced by the atmosphere and groundwater temperature is essentially constant. Therefore, connection of an HPZ to the ground surface can be inferred if groundwater temperature in the HPZ is similar to that above.

Another quickly and easily measured field parameter that provides a gross estimate of the degree of hydraulic connection of an HPZ to the surface is electrical conductivity of groundwater. Electrical conductivity is the ability of a substance to conduct an electrical current. It is the reciprocal of resistance and has the SI units of siemens per meter (S/m). Pure liquid possesses a very low electrical conductance, less than 0.1 μS/cm at 25°C (Hem, 1970). The presence of charged ionic species in solution are responsible for making a solution conductive. Therefore, electrical conductance of groundwater is directly proportional to total dissolved solids (TDS) which in turn, is directly proportional to total ion concentration. If an HPZ is effectively isolated from the ground surface by an overlying clay unit, the groundwater in both the clay unit and the HPZ will possess a relatively low electrical conductivity and a low concentration of total dissolved solids.

Groundwater pH and Eh are the other field parameters used to evaluate the degree of hydraulic connection of an HPZ to the surface in this study. These interdependent parameters may be used to estimate how long groundwaters have been out of contact with the atmosphere.

Baas Becking *et al.* (1964) delineated Eh and pH fields of waters occurring in the natural environment. The limits of these fields can be superimposed on an Eh-pH diagram (Figure 3.10). A review of Figure 3.10 reveals that groundwater from environments in contact with the atmosphere possess different Eh-pH signatures than do groundwaters that are isolated from the atmosphere. As water from rain and snow melt enters the groundwater flow system, it initially has a high redox potential as a result of its exposure to atmospheric oxygen. Eh values are approximately 0.6 V and pH ranges from 5 to 6 (Figure 3.10). As groundwater moves along its flow path, Eh tends to decrease as dissolved oxygen is used up in the processes of oxidation of organic material and ferric minerals. Therefore, if an HPZ is isolated from the ground surface, it should possess a negative Eh.

3.5.2 Field and Laboratory Work

3.5.2.1 Major Ions and Nitrate

Groundwater samples for major ions were collected from the Puce Road B nest and the Whelan Farm A nest (a total of nine wells) on July 22, 1990 and samples for nitrate were collected on September 2, 1990. Prior to collection, each well was bailed dry to ensure that a representative groundwater sample was being collected. Samples were collected with bailers which were washed, rinsed thoroughly, and dried before sampling the next well. Samples were stored in 250 mL acid-washed polyethylene bottles. After collection, all samples were transported in an

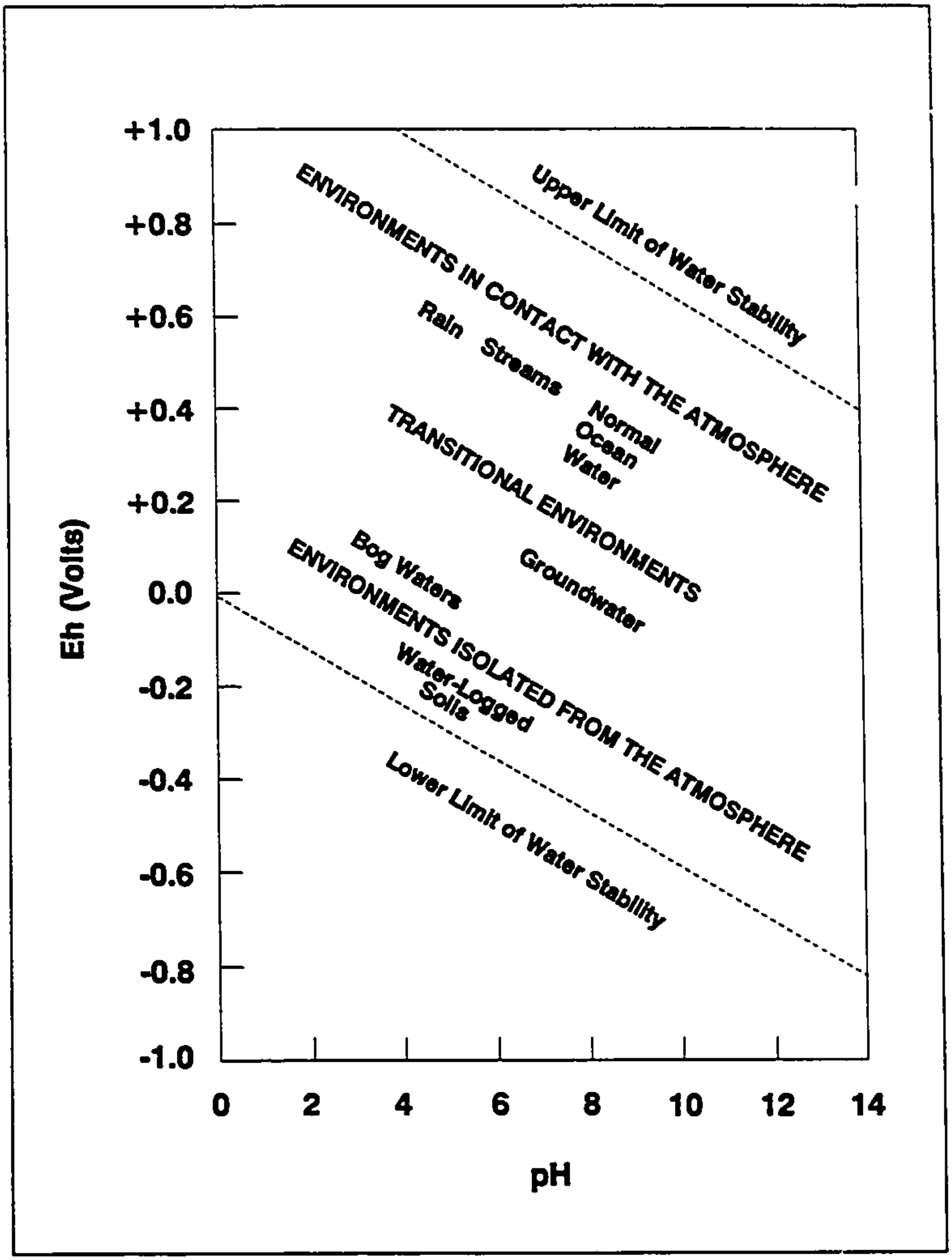


Figure 3.10. Eh-pH diagram for naturally-occurring waters (after Baas Becking et al., 1964.)

ice-packed cooler to the University of Windsor for analysis.

Prior to analysis, all samples were filtered through a 0.45 μm pore-size membrane filter. Samples for analysis of cations were preserved with nitric acid (in the ratio of 5 mL HNO_3 to 1 L of sample). Na^+, K^+, Ca^{2+}, and Mg^{2+} were analysed in the Geochemistry Laboratory, Department of Geology using an automated Model SP300 Varian Spectra Atomic Absorption Flame Photometer. Analyses were performed in accordance with methods outlined in the instrument manual. Alkalinity as HCO_3^- was derived using a titration method outlined by the American Public Health Association (1989). The SO_4^{-2} ion was analysed using the Pye Unicam Sp6 Spectrophotometer and the turbidity method described by The American Society for Testing and Materials (ASTM, 1985). Cl^- and NO_3^- were analysed in the Department of Civil and Environmental Engineering using the Orion Research Microprocessor Ionanalyzer/901 and chloride and nitrate specific electrodes based on methods described in the Orion electrode instrument manuals and in the American Public Health Association Standard Methods (1989).

3.5.2.2 Groundwater Field Chemistry

As with sampling for major ions and nitrate, all monitoring wells were bailed dry before collecting a sample to ensure that a representative sample was being measured.

Electrical conductivity, pH, and temperature of groundwater from the Puce Road B nest and the Whelan Farm A nest were measured in the field on July

21, 1990 and on May 25, 1991. Samples for total dissolved solids (TDS) were collected on July 21, 1990 and determined in the Geochemistry Laboratory by weighing the soild residue remaining after evaporating a known volume of filtered sample to dryness. Eh was measured on May 26, 1991. Field parameters were measured at the Puce Road A and C nests on June 16, 1991. Field parameters were also measured on water samples taken from the Puce River and from the Whelan Farm drainage ditch. Electrical conductivity, pH and temperature were measured using a Hydac conductivity, temperature and pH tester. Temperature was double-checked using a thermometer. Eh was measured using an ORP Eh meter. All measurements and instrument calibrations were performed in accordance with the instrument manuals.

3.5.3 Potential Geochemical Tests

3.5.3.1 Trichlorofluoromethane in Groundwater

Trichlorofluoromethane (CCl_3F), more commonly known as Freon-11 or F-11, its DuPont trade name, has favourable potential as a possible tracer of groundwater flow and an indicator of groundwater age. It is an entirely man-made chemical which has been produced around the world and has been released into the atmosphere over the past 60 years. F-11, first produced in 1931, is extensively used in the refrigeration and aerosol industries.

The usefulness of CCl_3F as a means of tracing groundwater infiltration stems from the fact that precipitation exposed to CCl_3F in the atmosphere will pick up certain concentrations of the chemical. When this precipitation infiltrates the subsurface to become groundwater, it can be differentiated from older groundwater recharged prior to the buildup of CCl_3F in the atmosphere (Thompson et al., 1974). Values reported for F-11 in the lower atmosphere range between 50 pptv and 500 pptv (where 1 pptv = 10^{-18} m^3 F-11/m^3 air) (Thompson and Hayes, 1979). Thompson and Hayes (1979) successfully utilized CCl_3F to assess groundwater ages in two aquifer systems. CCl_3F data were in good agreement with hydrogeologic controls.

3.6 Isotopic Techniques for Determining Hydraulic Connection

3.6.1 Theoretical Considerations

Naturally occurring isotopes that exist in water in the hydrologic cycle have been used in groundwater and surface water investigations since the 1950's (Freeze and Cherry, 1979). These naturally occurring isotopes are referred to as environmental isotopes.

Environmental isotopes can be utilized to obtain valuable hydrologic information that could otherwise not be obtained. They can help to determine locations of groundwater recharge and discharge areas, flow patterns in aquifers, and age of groundwater (i.e. the length of time water has been out of contact with the atmosphere). Therefore, environmental isotopes are ideal tracers in a study of hydraulic connection of an HPZ to the ground surface.

The environmental isotopes employed in this study were oxygen-18 (^{18}O or

O-18), deuterium (^{2}H or D), and tritium (^{3}H or T). These isotopes are excellent groundwater tracers for determining groundwater flow paths, age, and velocities for five main reasons. First, these isotopes are constituent parts of the water molecule and travel at the same rate as bulk groundwater. Second, these tracers have been added to the hydrologic cycle naturally and are not bound by size and cost limitations associated with injected tracer tests. Third, these isotopes are conservative tracers associated with shallow flow systems (Fritz et al., 1976a). In other words, their concentrations are not affected by chemical reactions under normal conditions once they enter the flow system. Their concentrations are altered only by physical processes such as mixing, diffusion, dispersion, and radioactive decay (Fritz et al., 1976b). Fourth, since these tracers have entered the groundwater system naturally as precipitation, the distribution of these isotopes today is a record of recharge, discharge, and flow processes for the past few decades to the past few millenia. Fifth, the distinctive input functions of these tracer isotopes can be used to determine groundwater age (i.e. when it was recharged). ^{18}O and ^{2}H can be used to delineate long term trends in flow systems and ^{3}H can be used as an indicator of recent water in flow systems.

3.6.1.1 Oxygen-18 and Deuterium

Oxygen-18 (^{18}O) and deuterium (^{2}H) are naturally occurring stable isotopes of oxygen and hydrogen, respectively. There are three stable isotopes of oxygen (^{16}O, ^{17}O, and ^{18}O) and two stable isotopes of hydrogen (^{1}H (protium) and ^{2}H (deuterium)). ^{18}O makes up approximately 0.2% of all oxygen atoms and ^{2}H comprises about 0.015% of all hydrogen atoms (Hoefs, 1987). The most abundant water molecule is $^{1}H_2{}^{16}O$, which is also the lightest.

Because absolute concentrations of ^{18}O and ^{2}H in groundwater are so low, concentrations are expressed as a ratio of the heavy to the light isotope (Craig, 1961a). The concentrations are expressed relative to a standard and are presented as "delta" or "del" (δ) values in parts per thousand ($^{o}/_{oo}$). $\delta^{18}O$ and δD values are defined by:

$$\delta^{18}O \text{ or } \delta^{2}H = [(R_x - R_{SMOW})/R_{SMOW}] \times 1000 \qquad (8)$$

where: R is the ratio of the heavy to light isotope (i.e. $^{18}O/^{16}O$ or $^{2}H/^{1}H$ (D/H)); x is the sample; and SMOW (Standard Mean Ocean Water) is the international standard for ^{18}O and ^{2}H analyses of water (Craig, 1961a). The del value of SMOW is zero. Negative del values of a sample indicate depletion of the heavier isotope relative to SMOW and positive values indicate enrichment of the heavier isotope relative to SMOW. ^{18}O and ^{2}H ratios can be easily and accurately determined with a mass spectrometer. The analytical precisions for ^{18}O and ^{2}H are approximately ± 0.2 $^{o}/_{oo}$ and ± 2 $^{o}/_{oo}$, respectively. Analytical details are presented by Fritz and Fontes (1980) and Hoefs (1987).

Different isotopic forms of water molecules have vapour pressures which are inversely proportional to their masses. Changes of state such as condensation, freezing, melting, and evaporation result in a separation or 'fractionation' of the light ($H_2{}^{16}O$) and heavy ($H^2H^{16}O$ and $H_2{}^{18}O$) water molecules. The tendency for ^{18}O to fractionate is stronger than for ^2H (Fritz et al., 1976b). Isotopic fractionation occurs mainly because molecular bonds in water molecules containing the lighter isotopes ($H_2{}^{16}O$) are more easily broken than molecular bonds in molecules containing the heavier isotopes ($HD^{16}O$ and $H_2{}^{18}O$) (Hoefs, 1987). Therefore, heavy isotopic forms of water have an affinity for the liquid phase and light isotopic forms of water tend to favour the vapour phase.

Craig (1961b) has found that the concentration of ^{18}O and ^2H in global meteoric waters which have not evaporated are linearly related. This relation is referred to as the global meteoric water line. The slope and intercept of the global meteoric water line vary slightly from region to region. Once the local meteoric water line has been established for a study area, it can be determined whether or not water samples have been evaporated. Water samples which have been evaporated or mixed with evaporated waters will plot below the meteoric water line on slopes of between 2 and 5 (Fontes, 1980). Fritz et al. (1976b) describe other processes that may alter the isotopic content of groundwaters (Figure 3.11).

Desaulniers et al. (1981) have determined the meteoric water line for southwestern Ontario based on precipitation at Simcoe, Ontario from 1975 to 1979:

$$\delta^2H = 7.5\delta^{18}O + 12.6 \quad (9)$$

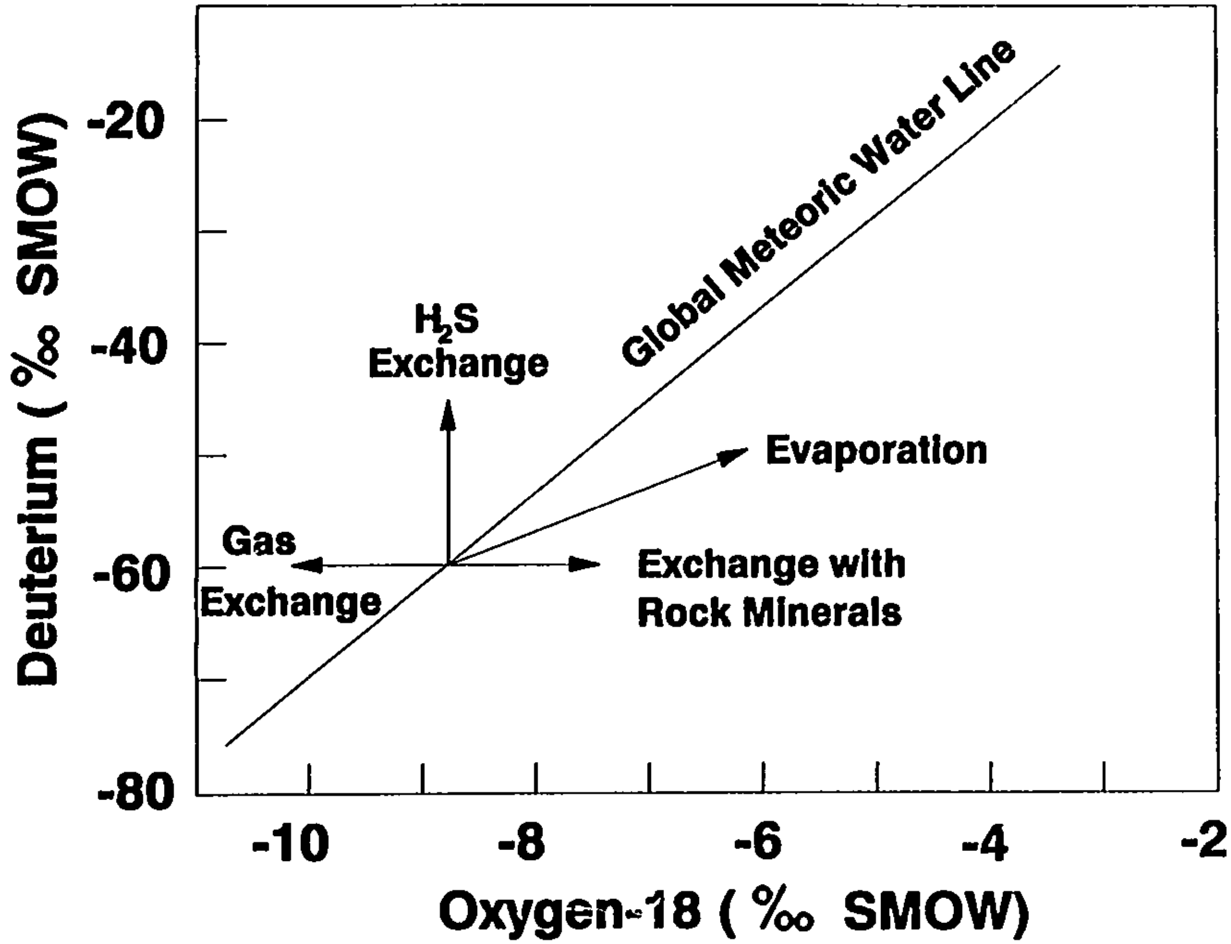


Figure 3.11. Processes altering isotopic content of meteoric waters (after Fritz et al., 1976b).

Monthly precipitation samples at Simcoe range from -18‰ to -6‰ with a mean value of -9.9‰ (Desaulniers et al., 1981). Crnokrak (1991) has established a meteoric water line for the Lake Huron to Lake Erie Corridor based on isotope data compiled from water samples from the basal sand aquifer (freshwater aquifer):

$$\delta^2H = 7.5\delta^{18}O + 2.89 \quad (10)$$

The meteoric water line established by Desaulniers et al. (1981) and Crnokrak (1991) are parallel to each other.

Since isotopic fractionation is highly dependent upon the temperature-dependent processes of evaporation and condensation, isotopic fractionation is also a temperature-dependent process. Dansgaard (1964) has found that the temperature of condensation of atmospheric waters is the most important factor governing the isotopic content of precipitation; more isotopic fractionation occurs at cooler temperatures. When precipitation recharges the groundwater system, it becomes isolated from the atmosphere and will consequently not become evaporated. Therefore, ^{18}O and ^2H concentrations in groundwater will provide a record of prevailing climatic temperatures during the time of recharge of precipitation to the groundwater system. It is this attribute that makes ^{18}O and ^2H ideal tracers in hydrogeologic studies.

The climate of southern Ontario (as well as other glaciated areas throughout the world) was much cooler during the most recent glacial period which ended approximately 10,000 years ago. Since that time, a transition to a significant warming trend has occurred which has been isotopically imprinted in groundwater of the region. Because of the extremely low permeability of the clayey deposits and the flat topography of southern Ontario, little to no flushing of the groundwater system has occurred. Carbon-14 ages of groundwater at depth in clay deposits indicate that this water is approximately 9000 years old, suggesting that the groundwaters are the original porewater that entered the sediment during or shortly after their deposition some 11,000 to 14,000 years ago (Desaulniers et al., 1981).

Using this basis that groundwaters in the clayey deposits of southern Ontario are essentially original porewaters, mixing of original and younger groundwaters can be distinguished based on their isotopic content. Groundwater recharged in southern Ontario during the past 10,000 years or so is characterized by $\delta^{18}O$ values of -9 to -11‰ and groundwater recharged prior to this time is characterized by $\delta^{18}O$ values of -15 to -20‰ (Fritz et al., 1975; Desaulniers et al., 1981, and Edwards and Fritz, 1986, 1988).

In summary, ^{18}O and ^{2}H are excellent naturally occurring conservative tracers of groundwater flow. In a study of hydraulic connection of an HPZ to the ground surface, they can be used to distinguish modern groundwater that has recently recharged from groundwater that is several thousands of years old. Their usefulness stems from the fact that concentrations of the heavy isotopes (i.e. ^{18}O and ^{2}H) in precipitation are directly related to the temperature at which atmospheric vapour condensed to form precipiation. Since groundwater originates as precipitation, the isotopic concentration of groundwater records past climatic conditions. The warming trend which terminated the last glacial episode in southern Ontario some 10,000 to 12,000 years ago has been recorded in groundwater in this area. This isotopic signature can be distinguished in the vertical dimension in clayey deposits of the St. Clair Clay Plain (Desaulniers et al., 1981; Sklash and Ibrahim, 1991). If a $\delta^{18}O$-depth profile similar to that in Figure 3.12a is observed, then a good hydraulic connection can be suspected between the HPZ and the ground surface. Conversely, recharge to the HPZ can be assumed to be extremely slow if an isotope profile similar to that of Figure 3.12b is observed. ^{2}H profiles will have a similar shape to the ^{18}O profiles.

3.6.1.2 Tritium

Tritium (^{3}H) is an environmental isotope that can be used to assess groundwater age over the past few decades (Payne, 1972). It is a radiogenic isotope of hydrogen whose half-life is 12.35 years (Fontes, 1980). It is produced naturally in the atmosphere by cosmic ray bombardment of nitrogen. Tritium in meteoric waters is typically in the form of the molecule $^{1}H^{3}H^{16}O$. Naturally produced tritium in the atmosphere, however, has been overwhelmed by anthropogenic tritium which entered the atmosphere as a result of testing of thermonuclear devices beginning in 1952. This anthropogenic tritium is commonly referred to as "bomb tritium".

There are no reliable measurements of atmospheric tritium prior to 1952. Concentrations in Ontario precipitation prior to 1952 are estimated to range

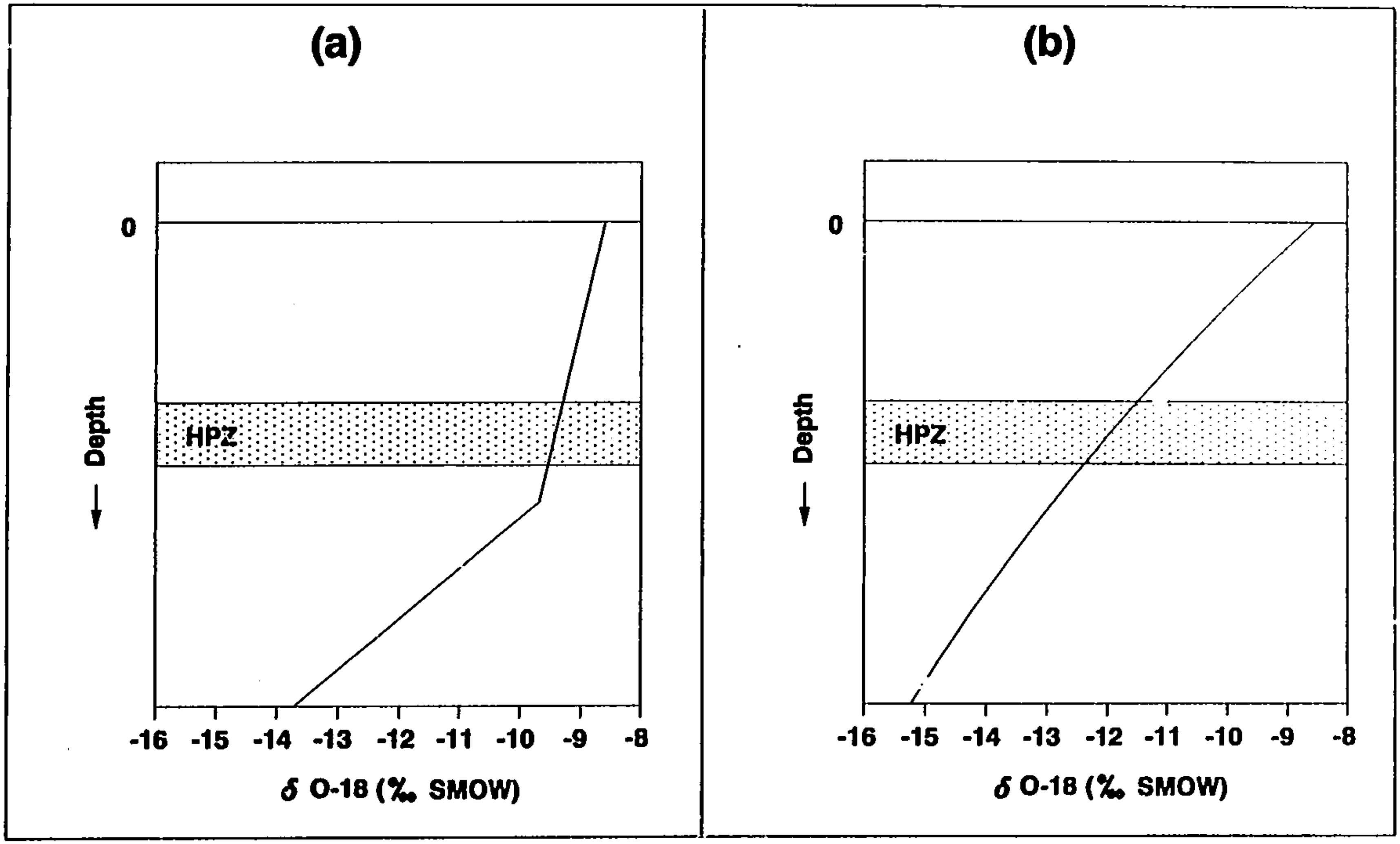


Figure 3.12. Conceptual ^{18}O variation with depth where: (a) an HPZ is hydraulically connected to the surface, and (b) an HPZ is not hydraulically connected to the surface.

from 3 to 5 tritium units (TU) (Robertson and Cherry, 1989), where 1 TU is equivalent to 1 tritium atom in 10^{18} atoms of hydrogen. The longest continuous record of tritium concentrations in precipitation is from Ottawa, Ontario which began in 1952 (Figure 3.13). This record, similar to other records observed in the northern hemisphere, shows steadily increasing concentrations of tritium in precipitation beginning in 1953 reaching a peak of several thousand TU in 1963 at the time of the U.S. and U.S.S.R. test ban treaty on the testing of thermonuclear devices. Subsequent rainfall has been characterized by progressively diminishing tritium contents but still considerably higher than normal due to release of tritium from residual storage in the upper atmosphere. At present, tritium concentrations are between 50 and 100 TU in precipitation of the northern hemisphere.

The usefulness of tritium as a tracer in assessing the degree of hydraulic connection of an HPZ to the ground surface lies in the fact that one can differentiate waters that recharged prior to 1953 from waters that recharged after that time. Since tritium forms part of the water molecule, it is not retarded with respect to groundwater flow. Its concentration, once it recharges the groundwater system is affected only by radioactive decay and hydrodynamic dispersion (Egboka et al., 1983). Because of its relatively short half life, natural tritium concentrations in groundwater related to recharge just before the start of thermonuclear testing are now in the range of 1 to 3 TU (Davis, 1988). If groundwater samples contain tritium levels above 1 TU, then mixing with at least some modern water in the past few decades has occurred.

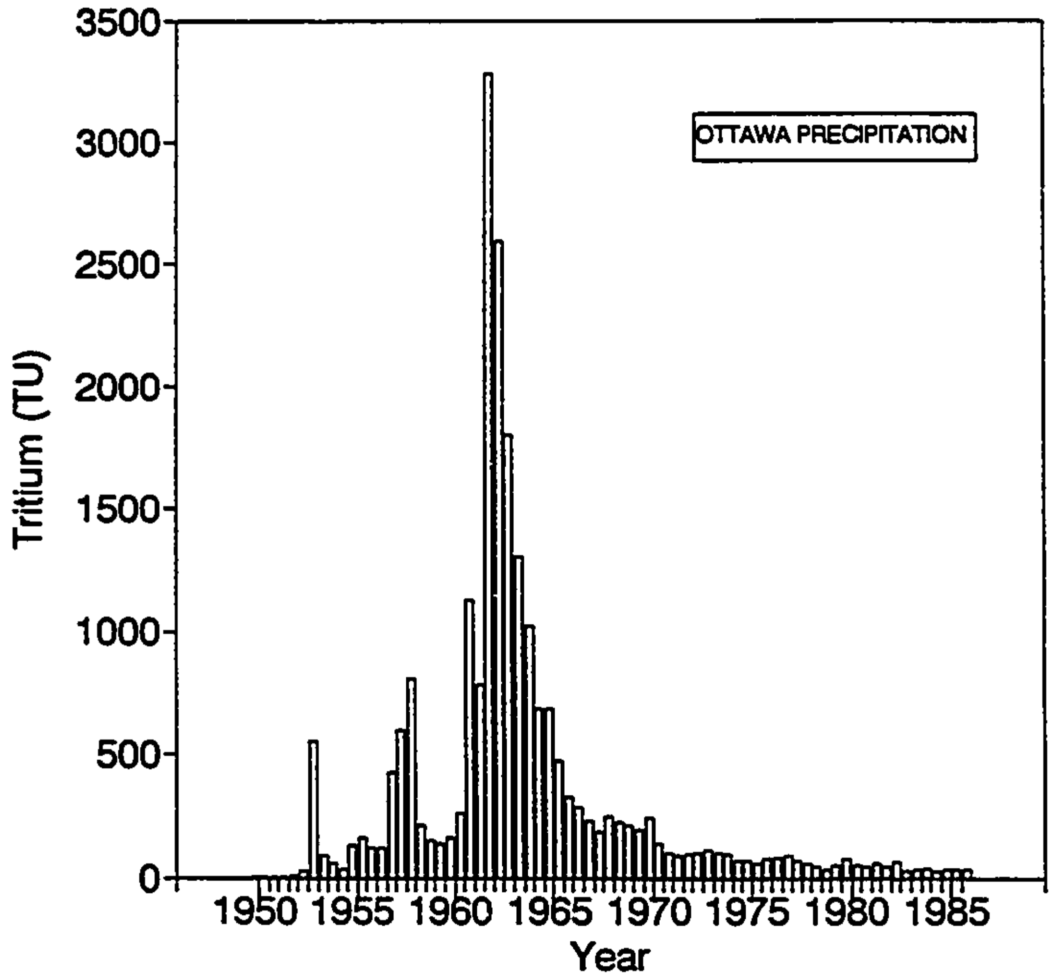


Figure 3.13. Tritium in precipitation at Ottawa, Ontario (after Robertson and Cherry, 1989).

Hendry (1988) has interpreted groundwater ages which can be deduced from tritium concentrations (Table 3.1). Based on the data in this table, predictive depth profiles can be constructed for HPZ's in low permeability media. If a tritium depth profile similar to that of Figure 3.14a is observed, a good hydraulic connection between the HPZ and the ground surface can be inferred. Conversely, if a profile similar to that of Figure 3.14b is observed, then a poor hydraulic connection can be inferred.

There are two main difficulties and limitations in using tritium as a groundwater tracer. First, tritium concentrations have not been ubiquitous in space and time and it is therefore difficult to reconstruct the tritium profile in past recharge waters for given geographic areas (Hendry, 1988). Consequently, tritium concentrations can only give a qualitative estimate of groundwater age (see Table 3.1). Second, it has been speculated that, in fractured clay media, the absence of high tritium values may be attributed to mixing by molecular diffusion of the tritium initially in the fractures with the relatively large reservoir of stagnant untritiated water in the clay "blocks" between the fractures (Day, 1977; D'Astous et al., 1989; and Ruland et al., 1991). This hypothesis has been supported by field evidence. The implications of this theory on the use of tritium as an indicator of groundwater age in fractured clay media are that the absence of bomb tritium in a groundwater sample from a certain depth does not necessarily mean that "recent" water has not reached this depth (Sklash, personal communication, 1990).

Tritium analyses are performed in few specialized laboratories

TABLE 3.1 Estimates of Groundwater Age Based on Tritium Concentrations in Groundwater*

Tritium Concentration (TU)	Interpretation
>100	Average groundwater likely recharged during thermonuclear testing between 1960 and 1965
10 - 100	Average groundwater less than 35 years old
2 - 10	Average groundwater at least 20 years old
<2.0	Average groundwater older than 30 years
<0.2	Average groundwater older than 50 years

* after Hendry (1988)

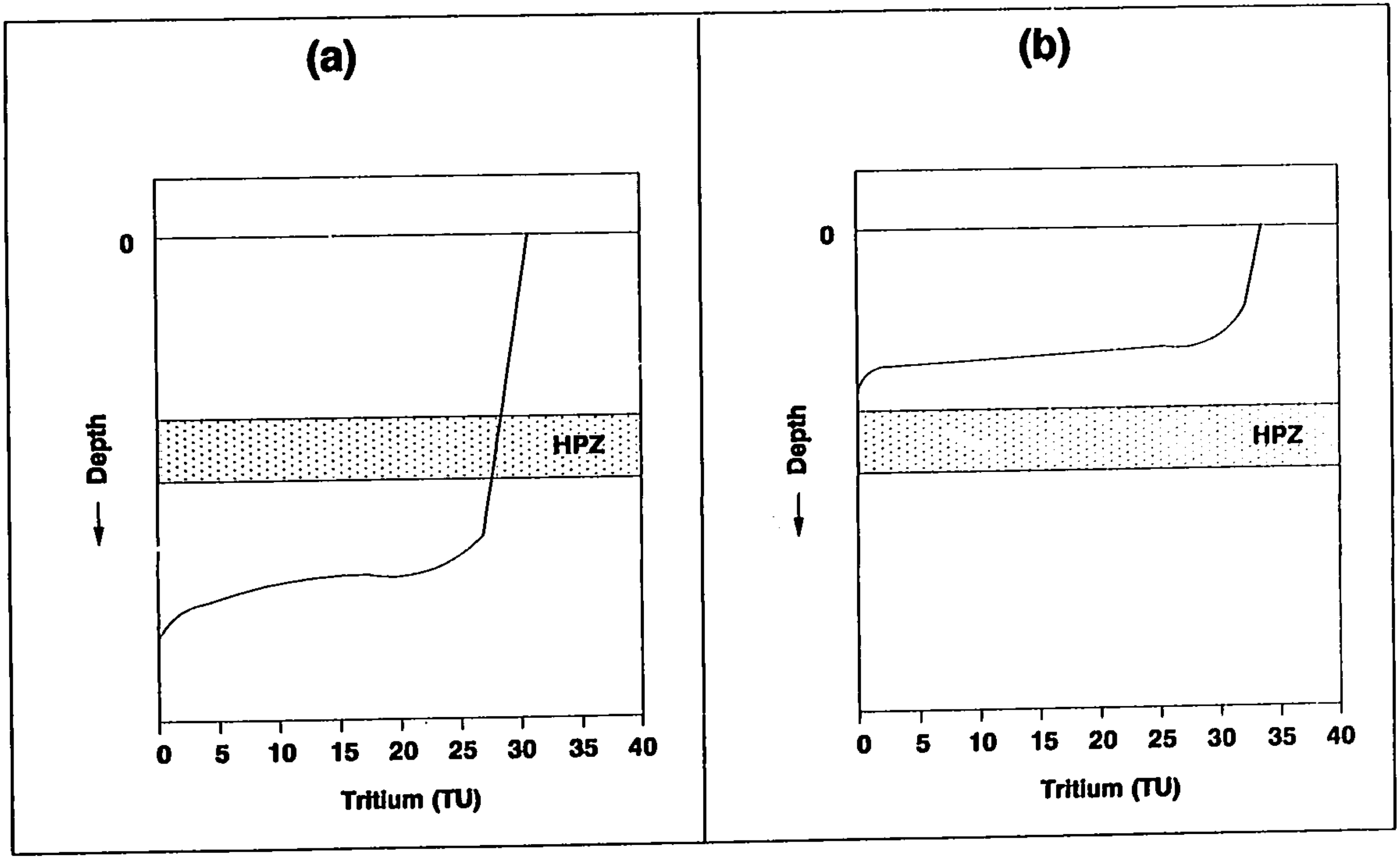


Figure 3.14. Conceptual tritium variation with depth where: (a) an HPZ is hydraulically connected to the surface, and (b) an HPZ is not hydraulically connected to the surface.

throughout the world using liquid scintillation techniques. Tritium concentrations by direct liquid scillintillation counting provide detection errors of ±6 TU. Tritium concentrations by electrolytic enrichment provide detection errors of ±0.5 TU.

3.6.2 Field and Laboratory Work

3.6.2.1 Oxygen-18 and Deuterium

Two types of techniques were utilized to obtain groundwater samples for stable isotope analysis: (1) squeezing porewater from soil cores, and (2) bailing groundwater from wells. These two methodologies were employed in order to evaluate their effectiveness in obtaining groundwater samples for isotope studies. Acquiring groundwater samples by means of porewater extraction has the main advantage over collection of groundwater from wells in that a nearly continuous isotope profile with depth can be obtained relatively economically. Also, samples can be obtained "immediately" whereas one may have to wait for weeks to months for water to enter a well in low permeability materials. Field and laboratory work regarding each methodology are discussed in the following text.

A total of 14 soil samples were collected for porewater extraction. Soil cores were collected at the Puce Road Site from boring B-5. The samples were obtained by continuously advancing sterilized shelby tube samplers 625 mm in length and 62.5 mm in diameter ahead of the augers. The shelby tubes were sterilized so that the soil and extracted groundwater could also be used for bacteriological studies (see Section 3.7).

After collection of each sample, the ends of the shelby tubes were sealed with paraffin wax in the field and wrapped in aluminum foil and plastic bags to provide an air-tight seal so that evaporation would not occur. The soil cores were extracted from the shelby tubes at Dominion Soils Investigation, Inc. soils laboratory (Windsor). Once extracted, the samples were immediately wrapped in sterilized aluminum foil and saran wrap and sealed with electrical tape. Samples were stored at the Department of Biology, University of Windsor, in a cold room which was maintained at a temperature of approximately 4°C. These measures were taken in order to minimize porewater evaporation and bacterial growth.

Porewater was extracted from each soil core using a soil squeezing device based on the design of Patterson et al. (1978) and modified and constructed by Orpwood (1984) (Figure 3.15). Samples measuring approximately 50 mm in diameter and 10 mm in length were prepared for the squeezer by shaving the outer surfaces to avoid squeezing soil which may have had some evaporated porewater. Two Whatman® #1 filter papers were placed on the top and bottom of each sample and the entire sample was wrapped with two coffee filters so as to obtain clear water samples. Water samples were obtained by depressing the plunger by means of a hydraulic jack which pushed against the reaction frame. Pressure was slowly and steadily increased to approximately 4500 kilopascals. Depending on the water content of the soil sample, 10 to 25 mL of porewater was generally collected from each sample. Porewater was collected with a glass syringe which was connected to the drainage port spout by Tygon® tubing. In this manner, evaporation of the porewater sample

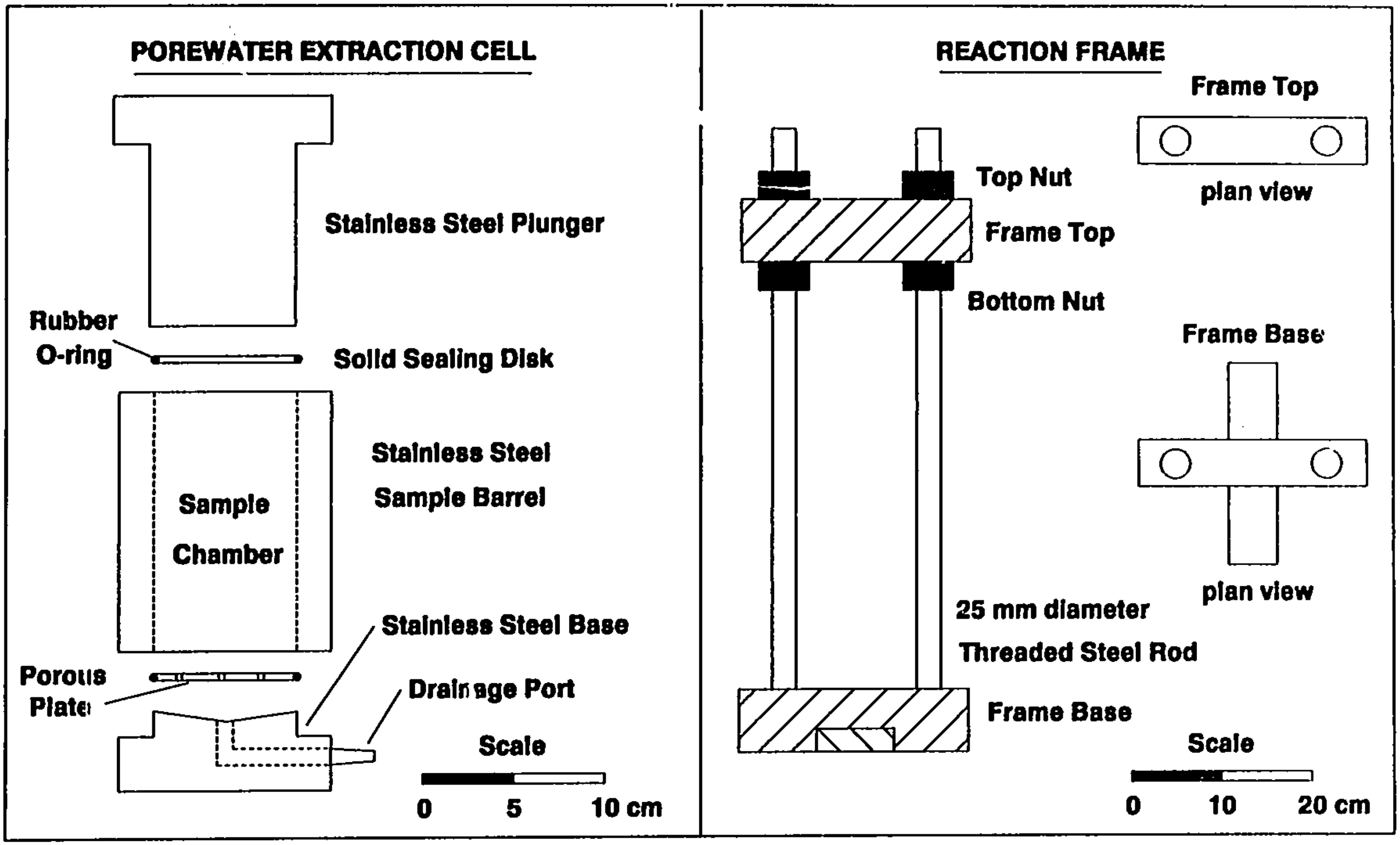


Figure 3.15. Diagram of porewater extraction apparatus.

was minimized by eliminating air contact with the sample. When at least 30 mL of porewater had been collected in the syringe, the sample was injected into two 15 mL vials - one for ^{18}O analysis and the other for ^{2}H analysis. After the collection of each sample, the entire squeezing device was sterilized with boiling water and thoroughly dried prior to squeezing the next sample.

A total of nine groundwater samples were collected for stable isotope analysis from wells at the Puce Road B nest and the Whelan Farm A nest. A sample was also collected from the Puce River to investigate it as a possible source of groundwater recharge. Sampling was conducted from July 3, 1990 to July 9, 1990.

Prior to collection of each sample, each well was bailed as close as possible to dryness to ensure that a representative groundwater sample was being collected. Samples were collected with bailers which were washed, rinsed, and dried thoroughly before sampling the next well. Samples were collected in two 20 mL glass vials from each well (one vial for ^{18}O analysis and one for ^{2}H analysis). Special care was taken to ensure that no evaporation of the samples occurred after collection. Samples were collected so that there was zero head space in each sample bottle. Sample bottle tops were lined with teflon tape and caps were secured with electrical tape to ensure an air-tight seal. Samples were kept in a cool storage place prior to analysis.

All porewater samples from squeezing and groundwater samples from wells were sent to the University of Waterloo Environmental Isotope Laboratory for ^{2}H analysis. Samples were analyzed with a Micromass Model 903 mass spectrometer.

Samples for ^{18}O analysis were first prepared in the Stable Isotope Extraction Laboratory at the University of Windsor using an extraction procedure described by Epstein and Mayeda (1953). Water samples in groups of ten were equilibrated with carbon dioxide gas (CO_2) at 25°C and sealed in glass tubes. A distilled water standard with a known $\delta^{18}O$ value was run with each group of samples as a check for laboratory quality control. The CO_2 gas samples were shipped to the University of Ottawa for ^{18}O analysis. The samples were analyzed with a SIRA-12 mass spectrometer.

3.6.2.2 Tritium

A total of nine groundwater samples for tritium analysis was collected from wells at the Puce Road B nest and the Whelan Farm A nest. Sampling was conducted from July 2 through July 9, 1990. Well B-5 at the Puce Road site was resampled on October 30, 1991 to check the validity of the first result.

Field sampling methodology for tritium was indentical to that for oxygen-18 and deuterium except that one litre of water was required for enriched tritium analysis. Therefore, one to five days were generally required before sufficient volumes were available for sampling due to the slow recovery of the wells after bailing. Well A-1 at the Whelan Farm Site could not yield sufficient quantities of water for enriched tritium analysis and consequently, 100 mL of sample was collected for direct tritium counting.

All samples for tritium analysis were shipped to the University of

Waterloo Environmental Isotope Laboratory. The samples were analyzed with a Beckman Model 7500 Scintillometer.

3.6.3 Potential Isotopic Tests

3.6.3.1 Chlorine-36

Chlorine-36 is produced naturally by cosmic ray interactions with atmospheric argon (^{40}Ar). Natural production of ^{36}Cl is overwhelmed in the atmosphere due to nuclear weapons testing at oceanic sites during the 1950's. This testing resulted transformation of ^{35}Cl in seawater to ^{36}Cl by neutron capture. Part of this ^{36}Cl was injected into the stratosphere where it was redistributed throughout the world (Bentley et al., 1986).

The use of chlorine-36 (^{36}Cl) as a "natural" tracer in hydrogeologic studies has a highly favourable outlook; its origin and use is identical to that of tritium. Tritium, with a short half life (12.35 years), has been the ideal tracer for the past two decades for dating young groundwater (see Section 3.6.1.2). However, because of its short half life, bomb tritium will be difficult to detect in 20 to 30 years.

^{36}Cl, a bomb-produced radioactive isotope with conservative properties and a long half-life (301,000 years), is the most favourable tracer capable of replacing tritium. Due to the experimental difficulty in measurement of ^{36}Cl, the technique has been rarely used. However, recent advances in accelerator mass spectrometry have led to a great increase in the sensitivity with which ^{36}Cl can be detected and to a renewed interest in the use of this isotope as a geo-tracer (Elmore et al., 1979). ^{36}Cl

has been successfully used over the past decade to date young groundwater (eg. Phillips et al., 1988). However, at the present time, analytical costs for the measurement of this isotope in water samples are extremely high relative to tritium.

3.7 Bacteriological Techniques for Determining Hydraulic Connection

This part of the study is a pilot study with the objective of examining the potential for using naturally-occurring soil and groundwater bacteria as tracers of vertical groundwater flow in fractured clay media. It was conducted jointly between the Department of Geology and the Department of Biological Sciences, University of Windsor, through grants held by Dr. M. Sklash and Dr. M. Holder-Franklin.

3.7.1 Theoretical Considerations

Naturally-occurring bacteria in soil and groundwater may be used to test for hydraulic connection of an HPZ to the surface using three approaches: (1) by determining the tolerance of soil bacteria to lead and cadmium in groundwater; (2) by taxonomically categorizing bacterial populations to determine if unique populations are maintained at discrete depths; and (3) by determining bacterial counts in soil and groundwater to see if bacterial populations vary with depth. Each of these approaches are discussed in the following paragraphs.

The first approach in examining the use of bacteria as a groundwater tracer in a hydraulic connection study is to determine bacterial tolerance to lead and cadmium. Tolerance of bacteria to lead and cadmium is directly related to their exposure to these metals. Significant inputs of lead and cadmium have been added to soil-groundwater systems by atmospheric deposition and acid rain resulting from anthropogenic uses of these metals. Since bacteria are highly adaptable to their environment, a tolerance to Pb and Cd at discrete depths can give some insight as to the vertical movement of these toxic metals from the ground surface into fractured clay media. Background concentrations of Pb and Cd in soil and groundwater must first be known.

The second approach involves taxonomically categorizing bacterial populations to determine if unique populations are maintained at discrete depths. The presence of genetically unique strains existing at discrete depths indicates that the strains are unrelated. In other words, if bacterial strains are different near the surface from those at depth, a poor hydraulic connection may be inferred.

The third approach in examining the use of bacteria as a groundwater tracer in a hydraulic connection study is to determine bacterial counts in soil and groundwater. The degree of hydraulic connection of an HPZ to the ground surface can be evaluated mainly from bacterial counts in groundwater since bacteria will migrate in the direction of groundwater flow. However, for bacteria to migrate in soil, the bacteria must be significantly smaller than the diameter of the pore spaces of the soil (Dragun, 1988). Bacteria will penetrate soil pores if the ratio, R, is greater than 25 (Dragun, 1988), where:

$$R = D_{15}/D_{85} \tag{11}$$

and: D_{15} is the diameter of particles comprising the soil where 15% of the soil mass is finer; and D_{85} is the diameter of the migrating bacteria, where 85% of the particles are finer. Ranges of diameters of soil particles and biota are presented in Figure 3.16. A review of this figure reveals that D_{85} for bacteria is approximately 1.2 μm. Therefore, for bacteria to migrate (i.e. $R \geq 25$) the D_{15} value of the soil must be at least 30 μm. This means that 85% of the soil texture must be comprised of coarse silt, sand, and/or gravel. If not, migration of bacteria through the soil will be restricted by filtration. Bacteria should only migrate through clayey soils if macropores or fractures are present. Thus, bacterial counts in groundwater in clay soils may be utilized to delineate the zone of advective groundwater flow through fractures.

3.7.2 Field and Laboratory Work

The collection of samples for bacteriological studies consisted of obtaining soil samples with shelby tubes and extracting groundwater from the soil cores. Samples were obtained along with samples for ^{18}O and ^{2}H analyses at the Puce Road site. These methods were discussed in Section 3.6.2.1.

Laboratory work was performed by microbiologists at the Department of Biology, University of Windsor. The work consisted of three main studies: (a) bacteria isolation and counting, (b) tolerance of isolates to Pb and Cd, and (c) numerical taxonomy. A brief description of the methodology, summarized from Holder-Franklin et al. (1991), is discussed in the following text.

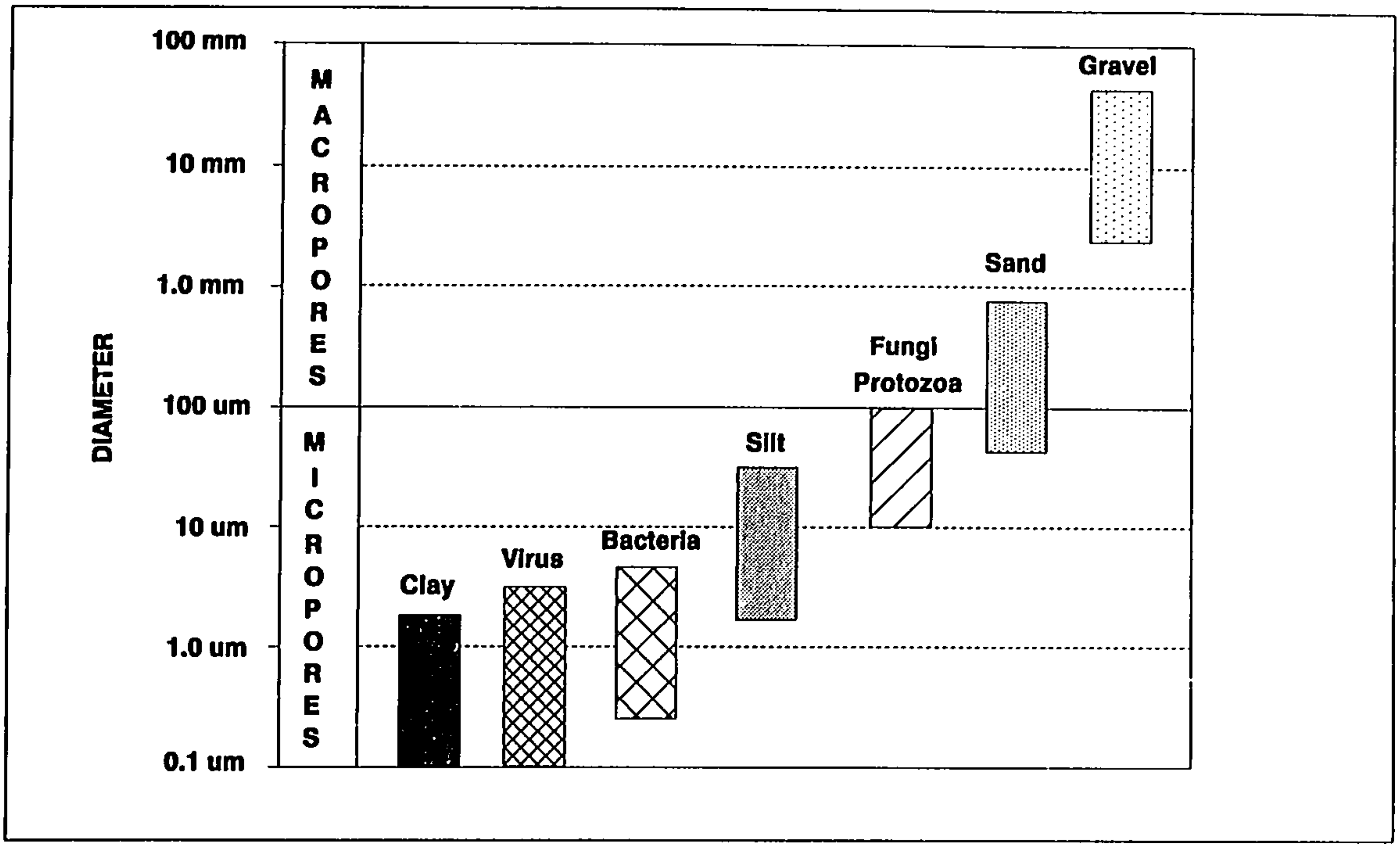


Figure 3.16. Particle size ranges of soil and microorganisms (after Dragun, 1988).

(a) Bacteria Isolation and Counting:

In order for the bacteria to be studied, they were first isolated. Bacteria were also counted during this step. Counts were recorded in colony forming units per gram (CFU/g) of soil and CFU/mL of groundwater.

The groundwater and soil samples were diluted by a factor of 10^{-2} to 10^{-4} anaerobically on Sterritts and Lester (S & L) plates. To obtain viable counts, these plates were incubated at room temperature (25 °C) and counted after 7 and 14 days. S & L is designed to permit accurate analysis of heavy metals in growing bacteria. Petri plates were used and all glassware was acid washed.

After 14 days, bacteria were isolated by picking a colony and purifying it. Plates with over 100 colonies were to be transferred to new S & L plates but most of the original plates did not produce 100 colonies. Therefore, the colonies were selected by morphology. Attempts were made to get unique bacteria for that depth among all dilutions. Three transfers on S & L plates were made to ensure isolates were pure.

(b) Tolerance of Isolates to Pb and Cd:

For the Pb and Cd tolerance study, S & L plates were made with Pb and Cd in concentrations of 0, 5, 10, 100, and 1000 mg/L. $Pb(NO_3)_2$ and $CdCl_2$ were used as sources of lead and cadmium, respectively. The plates were then inoculated and incubated at room temperature for 14 days. A multipoint inoculator apparatus (after Kaneko et al., 1977) was used to organize nine different samples per small petri plate.

Background lead and cadmium concentrations were measured for groundwater using an automated Model SP300 Varian Spectra Atomic Absorption Flame Photometer. This was done in the Department of Geology, University of Windsor.

(c) Numerical Taxonomy:

Numerical taxonomic classification of the bacteria was performed using a cluster analysis. The analysis was based on the comparison of tests conducted on isolated colonies of bacteria that were found to be tolerant to Pb and Cd. Sixty-three tests were performed. Most of these were substrate utilization tests.

Results of the tests were compared to a blank. Positive matches were assigned a value of 1 and negative matches were assigned a value of 0. Comparisons of the data were made using methods outlined by Sneath and Sokal (1973) with the aid of the NTZ500 computer program (Holder-Franklin, 1981). The NTZ500 program clustered groups of isolates that showed 75% to 100% similarity in test results for the purpose of distinguishing homogeneity or heterogeneity among the bacterial population.

4.0 OBSERVATIONS AND RESULTS

4.1 Introduction

This chapter presents the data gathered during this study. It is divided into five sections following this introduction: site geology and hydrogeology; physical techniques for determining hydraulic connection; geochemical techniques for determining hydraulic connection; isotopic techniques for determining hydraulic connection; and bacteriological techniques for determining hydraulic connection.

4.2 Site Geology and Hydrogeology

4.2.1 Puce Road Site

4.2.1.1 Site Geology

Figure 4.1 is a cross section of the Puce Road site showing the geology of the site. Borehole logs are presented in Appendix A. Soil testing results (moisture content and grain size analyses) are presented in Appendix B.

Four stratigraphic units were identified at the Puce Road site as shown in Figure 4.1. Figure 4.2 is a photograph of the soils underlying the site, showing typical split spoon core samples collected from each unit.

The uppermost unit consists of about one metre of black, organic-rich topsoil and roots and approximately three to four metres of brown weathered silty clay till. Grain size analyses of composite samples of the weathered unit indicate that it consists of 28% sand and gravel, 39% silt, and 33% clay. Fracturing of this unit was easily distinguishable by reddish-purple, yellowish-brown, and greyish-white

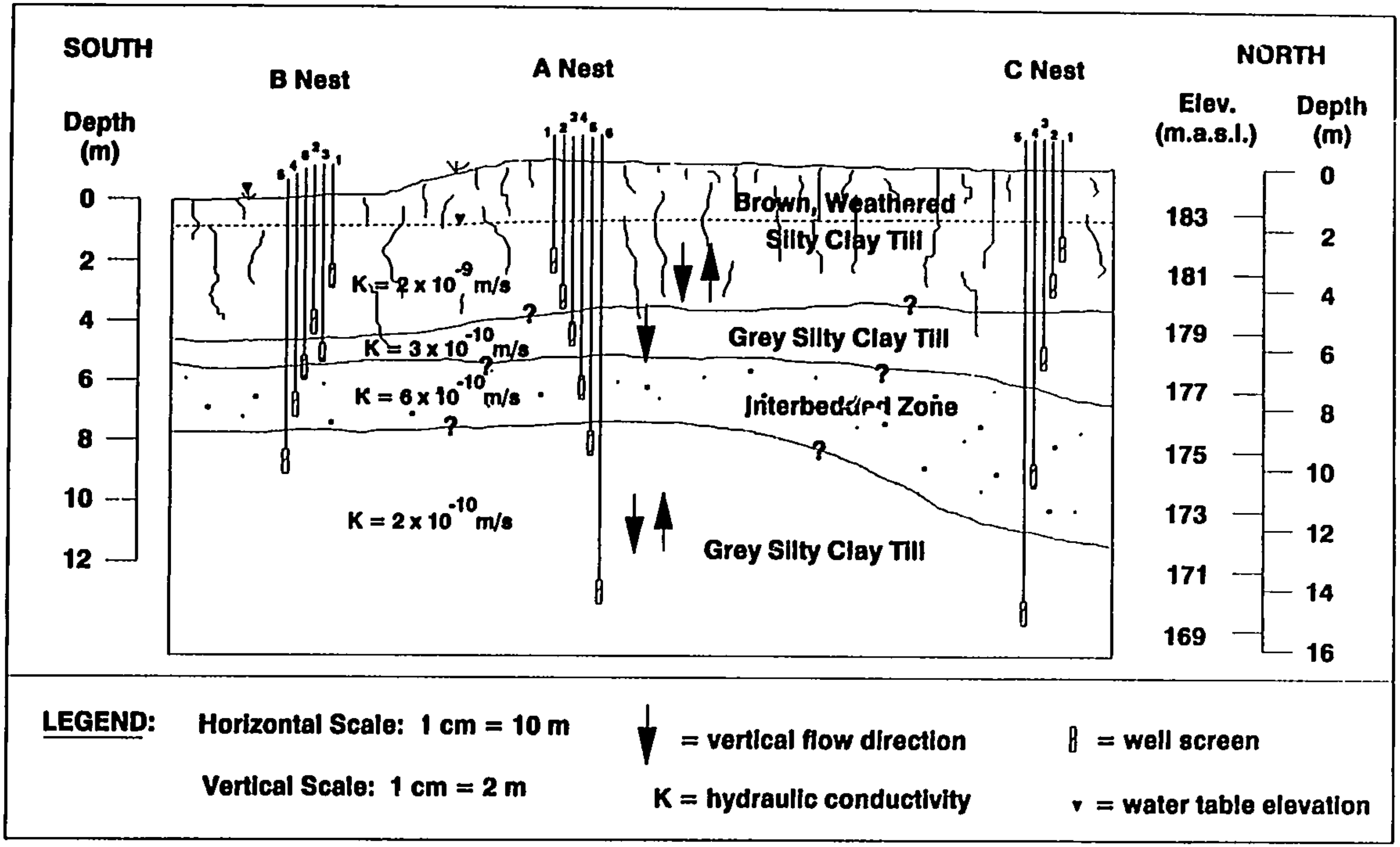


Figure 4.1. Geologic cross-section of the Puce Road site.

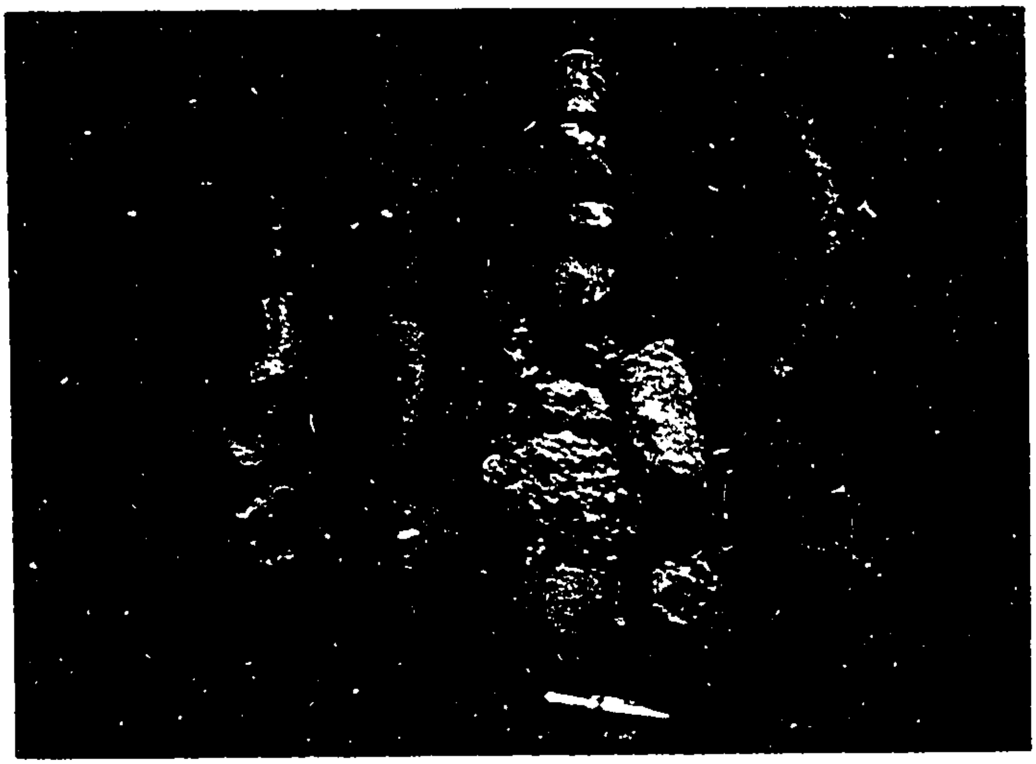


Figure 4.2. Photograph of soils underlying the Puce Road site.
From left to right: Weathered silty clay till,
Grey silty clay till (above interbedded zone);
Interbedded zone;
Grey silty clay till (below interbedded zone).

precipitate coatings associated with chemical alteration haloes. Reddish coatings are likely iron hydroxides (Quigley and Ogunbadejo, 1973) and whitish coatings are apparently calcareous (Ruland et al., 1991). Black precipitate coatings were also occassionally observed. Open fractures were visually distinguishable at shallow depths (<2 m) in split spoon samples only at the B nest. These open fractures had apertures of approximately one millimetre. Rootholes were occasionally observed to depths of 2.5 m across the entire site. Fracture frequency was found to diminish toward the base of the weathered unit, grading into a more massive greyish-brown clay till.

Underlying the brown, weathered silty clay till unit is an apparently unweathered grey silty clay till unit. This unit was found to range in thickness from one metre (at the B nest) to three metres (at the C nest). Grain size analyses of composite samples of this unit indicate that it consists of 25% sand and gravel, 33% silt, and 42% clay. This unit was visibly unweathered at this site, but others have reported fractures recognizable by parting planes at other sites (eg. Ruland et al., 1991). Fractures in this unit are generally not visible because fracture coatings are the same colour as the surrounding grey clay matrix (Ruland et al., 1991). Fracture aperture and frequency were observed to diminish with depth.

The grey silty clay till unit is underlain by the interbedded zone. This unit of interbedded sand, silt, and clay was found to be extremely variable in thickness and in composition. The thickness of this unit ranged from two metres (at the B nest) to approximately five metres (at the C nest). Grain size analyses of composite samples from this unit indicated that it consists of 61% sand and gravel, 26% silt, and 13% clay. Most of the sand in this unit is very fine; stringers of coarse sand and gravel were detected only occasionally. At the A nest, the unit was predominantly silt and clay and was difficult to distinguish from the silty clay units above and below. These observations are consistent with those of the interbedded zone below Essex County Landfill #3 as described by M.M. Dillon (1988).

Another grey silty clay unit underlies the interbedded zone. It was found to extend to the limit of the deepest boring at approximately 15 m below grade. MOE well logs and data from several other studies conducted in Essex County reveal that this unit extends to bedrock (eg. Desaulniers et al., 1981 and M.M. Dillon Limited, 1988). Grain size analyses of composite samples from this unit indicate that it consists of 18% sand and gravel, 35% silt, and 47% clay. No fracturing or weathering features were observed in this unit. Soils were noted to be softer than those of the upper grey till unit.

A plot of moisture content versus depth from borehole A-6 is shown in Figure 4.3. This plot is in very good agreement with field observations. The location of the interbedded zone can be easily distinguished by a decrease in moisture content. The grain size distribution curve (see Appendix B) of the interbedded zone confirms the presence of coarser-grained material in this unit.

A break in the plot is also observed at a depth of two to three metres. The similarity of grain size curves (Appendix B) for the weathered till unit and the upper grey till unit indicates that this decrease in moisture content is not due to an

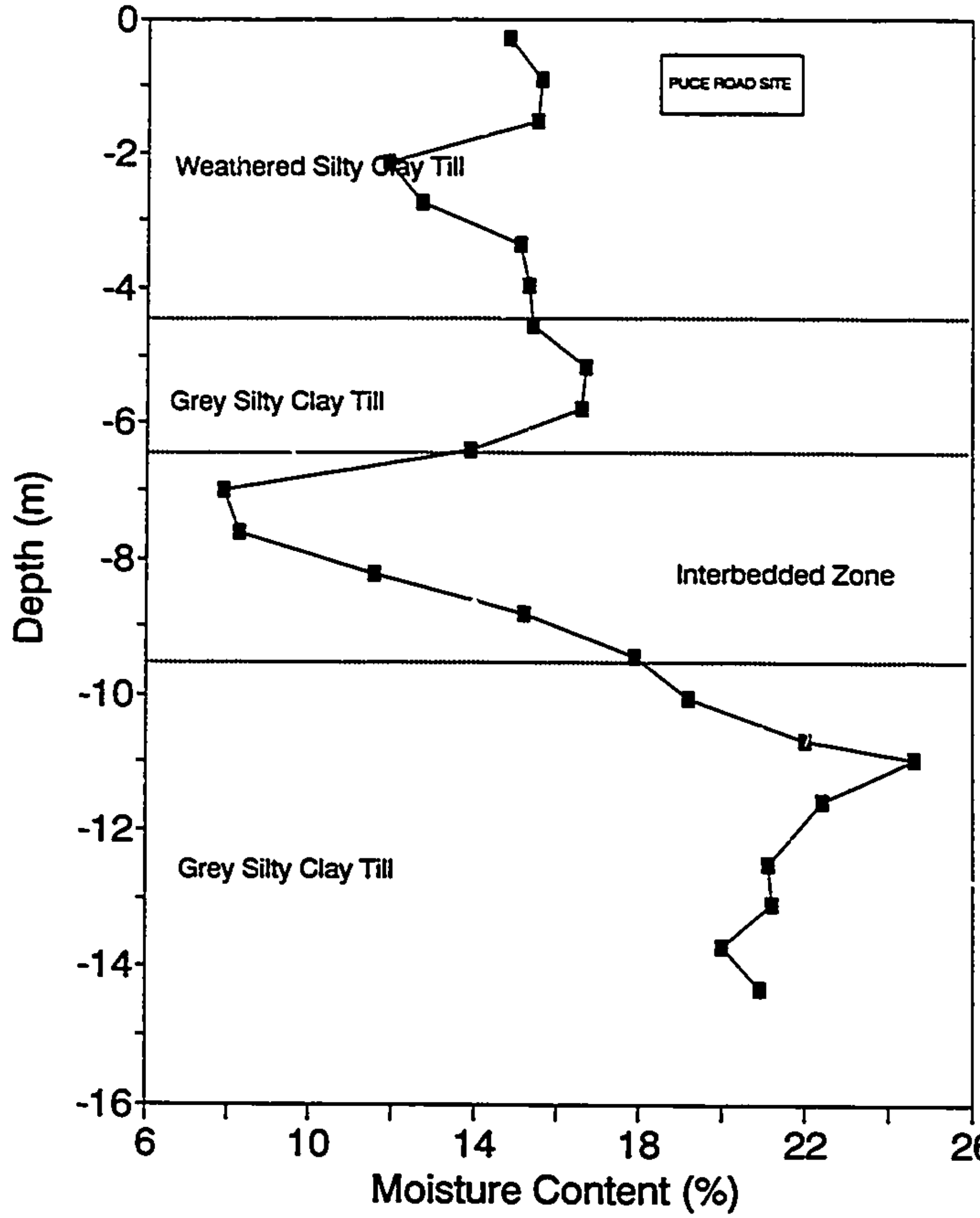


Figure 4.3. Moisture content variation with depth at the Puce Road site.

increase in sand content in the weathered zone. This decrease in moisture content may be attributed to precipitation of secondary carbonate which has been leached from above. Mineral precipitation causes expulsion of porewater from the soil and decreases porosity of the soil which results in decreased moisture content. Quigley and Ogunbadejo (1973) observed increased carbonate concentrations and a reduction in moisture content in clayey soil at the base of the weathered crust in the Sarnia area. They describe this process as a chemical weathering feature. Farvolden and Cherry (1988) describe a similar process whereby carbonate is dissolved and removed by acidic groundwaters produced by oxidation of pyrite present in shale fragments. Oxidation of pyrite was caused by invasion of air into fractures produced by desiccation of the soil during a warmer, drier climate approximately 9000 years ago.

Another property of the soil at the Puce Road site, revealed by Figure 4.3, is the general increase in moisture content with depth to approximately 11 m. This trend indicates that these soils are overconsolidated to a depth of about 11 m. Similar trends have been observed and described by others (eg. Soderman and Kim, 1970; and Quigley and Ogunbadejo, 1973). Soderman and Kim (1970) concluded that the deposits of the St. Clair Clay Plain are lightly overconsolidated at depth with a heavily overconsolidated crust in the upper 12.2 m of the deposit.

In a normally consolidated soil, moisture content should decrease with depth as a result of expulsion of water under the weight of overlying soil. Overconsolidation of the weathered zone has been attributed to desiccation caused by evapotranspiration (Adams, 1970; Soderman and Kim, 1970; Quigley and

Ogunbadejo, 1973; and Vorauer et al., 1986). The process of desiccation of clay soils is responsible for their shrinkage and for the formation of fractures and fissures. Overconsolidation in the grey, visually unweathered clay is less clear. It may be due in part to upward movement of groundwater during desiccation of the presently oxidized zone during a much warmer and drier climate some 9000 years ago.

The fact that some 13 m of clay in the St. Clair Clay Plain is overconsolidated could have implications with respect to groundwater flow in the region. If the overconsolidation in the grey till was caused by desiccation, then it is likely to be fissured. These fissures are conduits for more rapid groundwater movement.

4.2.1.2 Hydrogeologic Characteristics

Monitoring well depths, hydraulic conductivities, and vertical groundwater flow directions at the Puce Road Site are summarized in Figure 4.1. Monitoring well completion details are shown on corresponding borehole logs in Appendix A. Appendix C contains a summary of ground and top of casing (T.O.C.) elevations for each monitoring well, tabulated water level measurements, tabulated water level elevations, and well hydrographs. Appendix D contains hydraulic conductivity results of the Hvorslev single well permeability tests and Hvorslev plots.

Because monitoring wells were not installed in a triangular fashion, a groundwater contour map showing lateral flow direction could not be reliably constructed. Due to the similarity of hydraulic heads and the proximity of the Puce

River, it is likely that groundwater is flowing to the west toward the Puce River.

Shallow monitoring wells completed in the brown weathered silty clay unit reached static equilibrium in one to two weeks after being bailed dry. Deeper wells in this unit reached static equilibrium in one to three months. Water levels in these wells indicate that the water table occurs at a depth of one to two metres below grade. The water table was observed to fluctuate approximately 0.20 m over the monitoring period. Lowest levels were observed in July, 1990. The gradient was generally downward throughout the test period; gradient reversals to an upward direction were observed to occur during the late summer persisting throughout the fall and early winter months and then shifting to a downward direction again in the spring. Ruland et al. (1991) observed similar seasonal water level fluctuations. For calculation purposes, the vertical groundwater flow direction in this unit has been taken as downward under a gradient of approximately 0.05.

Hydraulic conductivities of the weathered unit based on Hvorslev single well tests range from 4.1×10^{-10} m/s to 9.5×10^{-9} m/s with a geometric mean of 2×10^{-9} m/s. Lower hydraulic conductivities were observed in the deeper portion of this unit where fracture frequency decreases. This mean value is quite similar to the mean of 1.5×10^{-9} m/s reported throughout the St. Clair Clay Plain (see Table 2.3). Brathwaite (1988) obtained a value of 1×10^{-8} m/s for the Puce Road site. Groundwater Technology Canada Limited (1991) obtained a mean value of 4×10^{-9} m/s at Essex Co. Landfill #3.

Monitoring wells completed in the upper grey silty clay till unit reached static level in three to six months. The slow rise to static level observed in these wells is indicative of the low permeability of the soil. Hydraulic conductivities range from 1.7 x 10^{-10} m/s to 3.1 x 10^{-10} m/s with a geometric mean of 3 x 10^{-10} m/s. This mean value is almost identical to the mean value of 3.2 x 10^{-10} m/s reported throughout the St. Clair Clay Plain (see Table 2.3). Brathwaite (1988) obtained a mean value for the Puce Road site of 2 x 10^{-9} m/s. The vertical direction of groundwater flow from the weathered zone to this unit is generally downward. Gradient reversals to an upward direction were observed at the A and C nests in the spring months.

Monitoring wells completed in the interbedded zone reached static level in one to three months. Field permeability testing indicated that hydraulic conductivities range from 4.2 x 10^{-10} m/s to 1.0 x 10^{-9} m/s with a geometric mean of 6.0 x 10^{-10} m/s. Using the empirical Hazen formula ($K = d_{10}^2$, where K = hydraulic conductivity in cm/s and d_{10} = grain size (in mm) at 10% passing), the hydraulic conductivity of the interbedded zone was of the order of 6.7 x 10^{-9} m/s, one order of magnitude higher than the mean K value obtained from Hvorslev tests. This range of K values exhibits the heterogeneous nature of this deposit. The mean K value obtained from field testing was 200 times lower than the mean value of 1.2 x 10^{-7} m/s reported throughout the St. Clair Clay Plain (see Table 2.3). Brathwaite (1988) obtained a mean value of 3 x 10^{-9} m/s for the interbedded zone at the Puce Road site. These discrepancies are due to the interbedded nature of the deposit. If well screens do not intersect the most conductive zones (i.e. sand stringers), then a representative

K value is not obtained. If a sand stringer is screened, hydraulic conductivity is likely to be also affected by the degree of continuity of the sand lens. These observations illustrate the difficulties in accurately determining the hydraulic conductivity of heterogeneous deposits.

The studies of M.M. Dillon Limited (1988) indicated that flow in the interbedded zone was lateral with little to no component of vertical flow. Hydraulic head elevations in the interbedded zone during the course of this study were always observed to be higher than those of the overlying grey clay unit (except on two occasions at the A nest where water levels in the interbedded zone were slightly below those of the overlying grey clay).

Monitoring wells completed in the lower grey silty clay till unit reached static level in four to seven months. The very slow rise to static level observed in these wells is indicative of the low permeability of the soil. Hydraulic conductivities range from 1.3×10^{-10} m/s to 4.9×10^{-10} m/s with a geometric mean of 2.0×10^{-10} m/s. This mean value is similar to the mean value of 3.2×10^{-10} m/s reported throughout the St. Clair Clay Plain (see Table 2.3). Brathwaite (1988) obtained a mean value of 2×10^{-9} m/s for this unit at the Puce Road site. The vertical direction of groundwater flow observed at all nests from this unit to the interbedded zone was variable. Downward gradients were observed in the late fall through the early spring months shifting to upward gradients which were observed later in the spring.

4.2.2 Whelan Farm Site

4.2.2.1 Site Geology

Figure 4.4 is a cross section of the Whelan Farm site showing the geology of the site. Borehole logs are presented in Appendix A. Soil testing results (moisture content and grain size analyses) are presented in Appendix B.

Three stratigraphic units were identified at the Whelan Farm site as shown in Figure 4.4. Figure 4.5 is a photograph of the soils underlying the site, showing typical split spoon core samples collected from each unit.

The uppermost unit is identical to the weathered unit observed at the Puce Road site except for its thickness. It consists of about one metre of black, organic-rich sandy topsoil and roots and approximately two metres of brown weathered silty clay till. Grain size analyses of composite samples of this unit indicate that it consists of 22% sand and gravel, 39% silt, and 39% clay. This grain size distribution is very similar to that of the weathered zone at the Puce Road site. Traces of fine sand and lenses of fine sand were observed in some Ag. Can. borings. Fractures in this unit possess identical features to those described at the Puce Road site. However, fracture frequency appeared to be much denser at the Whelan Farm site. A greater number of rootholes were also observed at this site, extending to depths of three metres across the entire site. At the base of this unit, where the interbedded zone was not present, a transition zone from brown to grey clay was observed. This zone was characterized by a marked decrease in fracture frequency and a darker brown colour.

At the base of the brown weathered till unit at the A nest is a

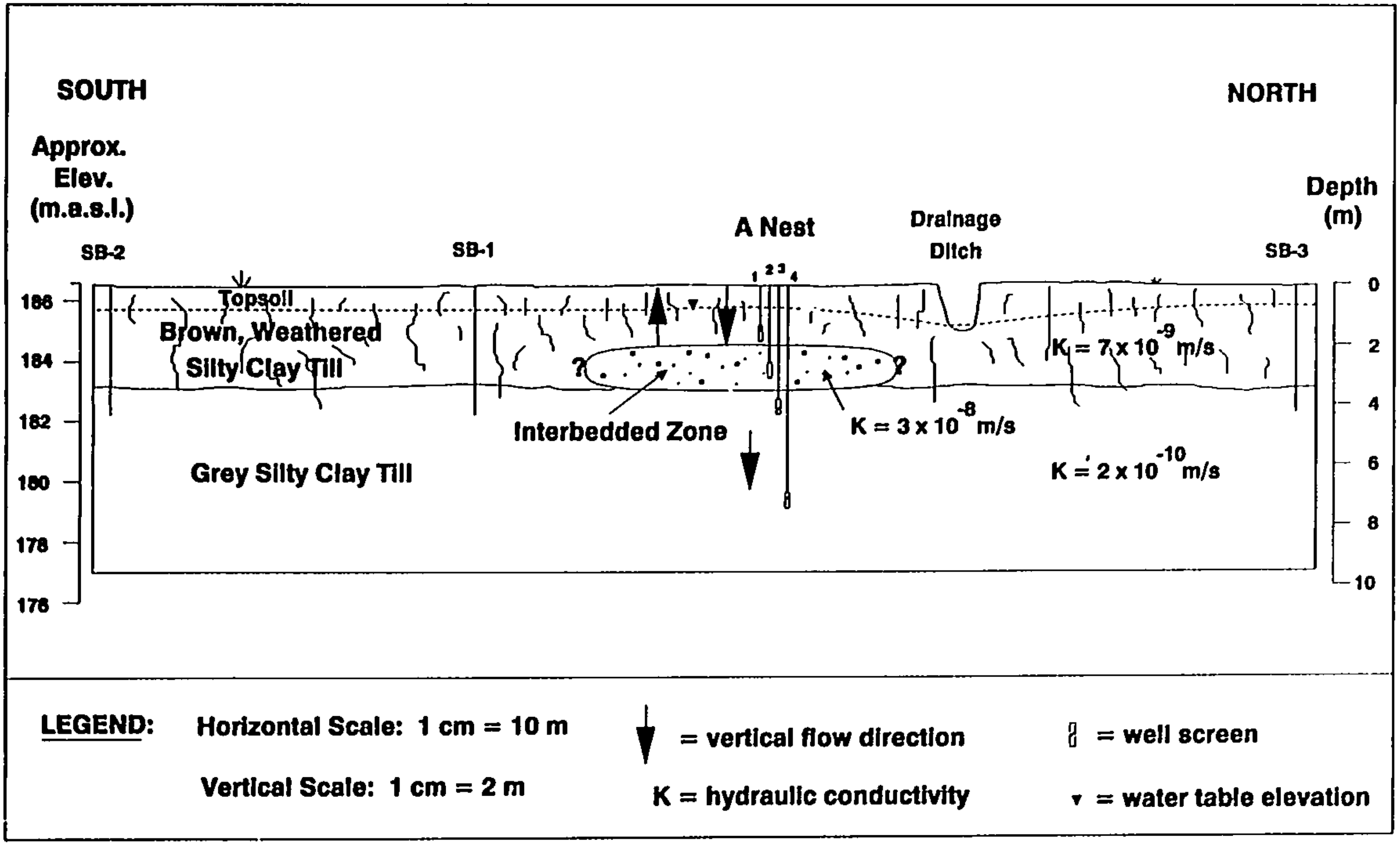


Figure 4.4. Geologic cross-section of the Whelan Farm site.

Figure 4.5. Photograph of soils underlying the Whelan Farm site.
From left to right: Weathered silty clay till,
Interbedded zone;
Grey silty clay till.

discontinuous interbedded zone of brown sandy clay and fine to medium brown sand. The thickness of this unit is approximately 1.75 m. The unit was not intersected in any other borings across the site. However, continuity of this zone was only investigated to the north and south. It is not known whether or not the unit extends further in an east-west direction. Grain size analyses of composite samples taken from this unit indicate that it consists of 76% sand and gravel, 12% silt, and 12% clay. Most of the sand in this unit occurs in the fine to medium fractions; stringers of coarse sand and gravel were detected only occasionally.

Underlying the brown, weathered silty clay till unit and the interbedded zone (where present) is an apparently unweathered grey silty clay till unit which is identical to the grey till unit found at the Puce Road site. This unit generally occurs at a depth of about 3.5 m below grade throughout the site. Occasional fractures were observed in the top metre of the unit which were identifiable by rust-coloured coatings. As previously mentioned, several studies conducted throughout the area indicate that this unit extends to bedrock. Grain size analyses of composite samples taken from the grey silty clay unit indicate that it consists of 17% sand and gravel, 38% silt, and 45% clay. This grain size distribution is very similar to that of the grey silty clay till units observed at the Puce Road site.

A plot of moisture content versus depth from borehole A-4 is shown in Figure 4.6. This plot is in very good agreement with field observations of lithologic boundaries; the location of the interbedded zone at the base of the weathered crust can be easily distinguished by a decrease in moisture content. The grain size distribution

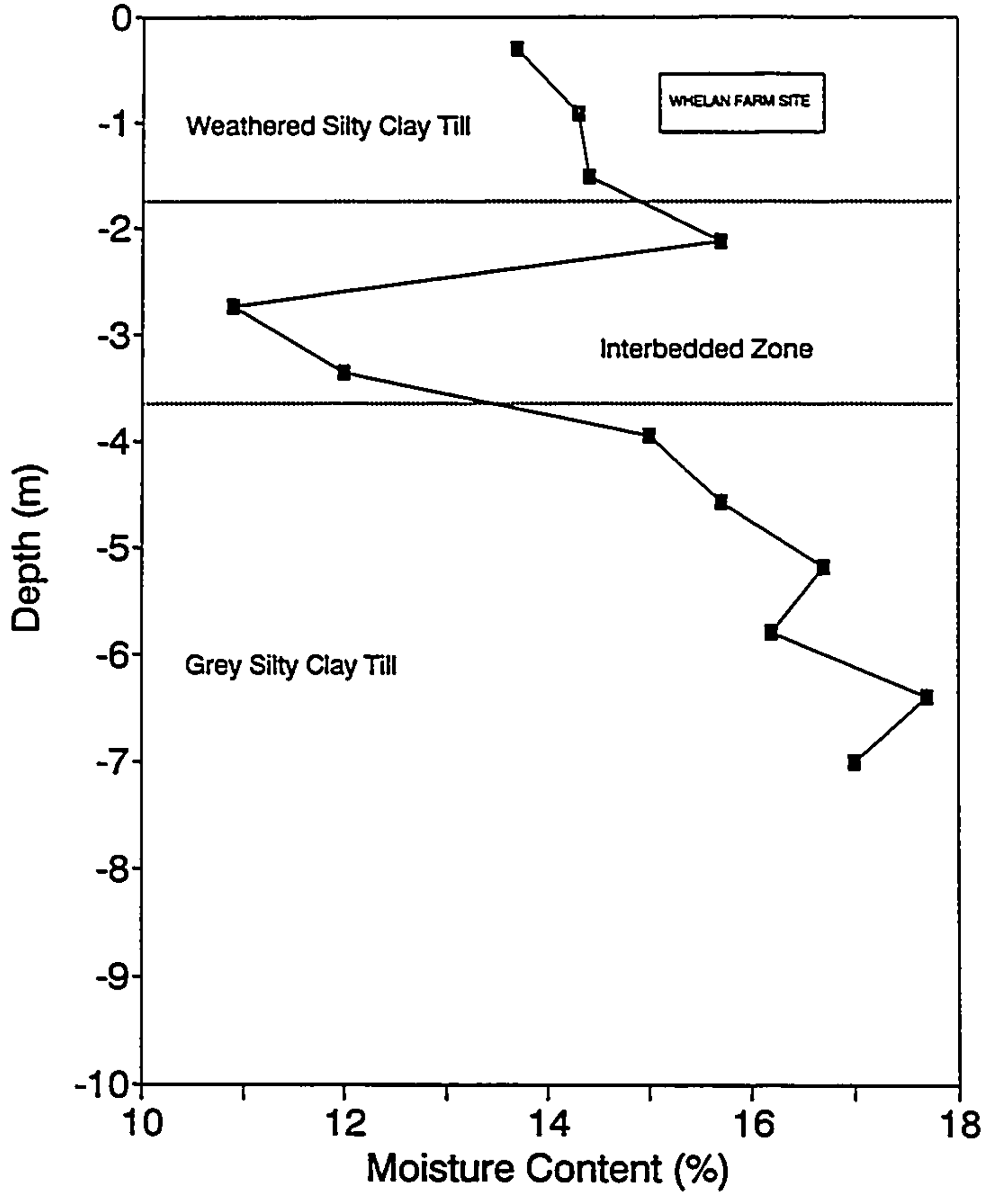


Figure 4.6. Moisture content variation with depth at the Whelan Farm site.

curve (Appendix B) of the interbedded zone confirms the presence of coarser-grained material in this unit.

Figure 4.6 shows a general increase in moisture content with depth, similar to the trend observed in the Puce Road site moisture content profile. This trend supports other observations that clayey soils in the St. Clair Clay Plain are overconsolidated. At the Whelan Farm site, soils are overconsolidated to depths of at least seven metres. Possible causes for and implications of this overconsolidation have been discussed in Section 4.2.1.1.

4.2.2.2 Hydrogeologic Characteristics

Monitoring well depths, hydraulic conductivities, and vertical groundwater flow directions at the Whelan Farm Site are summarized in Figure 4.4. Monitoring well completion details are shown on corresponding borehole logs in Appendix A. Appendix C contains a summary of ground and top of casing (T.O.C.) elevations for each monitoring well, tabulated water level measurements, tabulated water level elevations, and well hydrographs. Appendix D contains hydraulic conductivity results of the Hvorslev single well permeability tests and Hvorslev plots.

Although monitoring wells were installed across the site, a groundwater contour map showing lateral flow direction could not reliably be constructed since Ag. Can. wells were dismantled before they reached static levels. The Ag. Can wells were dismantled at the end of the 1990 growing season so that the plot could be tilled. Orpwood (1984) concluded that groundwater flows to the east toward the Belle River.

However, lateral groundwater flow at the site is likely distorted due to the presence of tile underdrains.

Monitoring well A-1 completed in the brown weathered silty clay unit reached static equilibrium in one to two weeks after being bailed dry. Water levels in this well indicate that the water table occurs at a depth of less than one metre below grade. The water table was observed to fluctuate approximately 0.20 m over the monitoring period. The gradient from the weathered zone to the interbedded zone was generally downward throughout the test period with infrequent gradient reversals to an upward direction.

Field permeability testing of well A-1 indicates that the hydraulic conductivity of the weathered unit is of the order of 6.9×10^{-9} m/s. This value is slightly higher than the mean of 1.5×10^{-9} m/s reported throughout the St. Clair Clay Plain (see Table 2.3). Orpwood (1984) obtained a value of 3×10^{-9} m/s for the same unit at the Whelan Farm site.

Monitoring well A-2, completed in the interbedded zone, reached static level in approximately two days. Field permeability testing of this well indicates that the hydraulic conductivity of this zone is of the order of 3.0×10^{-8} m/s. Using the Hazen formula, the hydraulic conductivity of the interbedded zone is calculated to be of the order of 2.3×10^{-8} m/s. This value is almost identical to that obtained from the Hvorslev test. No other K values have been reported for this unit.

Monitoring wells completed in the grey silty clay till unit (A-3 and A-4) reached static level in 20 days and seven months, respectively. The relatively quick rise of monitoring well A-3 to static level is indicative of a fracture permeability. This well was installed directly below the interbedded zone, where some fractures in the grey clay were observed. Field permeability testing of this well revealed a hydraulic conductivity of 2.7×10^{-9} m/s, closely resembling that of the weathered zone. Field permeability testing of well A-4, installed much deeper into the grey clay (approximately 7 m deep), indicates that the hydraulic conductivity of the grey clay at this depth is in the order of 2.0×10^{-10} m/s. This value is similar to the mean value of 3.2×10^{-10} m/s reported throughout the St. Clair Clay Plain (see Table 2.3). Orpwood (1984) obtained a value of 3×10^{-9} m/s for the same unit at the Whelan Farm site. Desaulniers et al. (1981) obtained values ranging from 2.4×10^{-11} m/s to 6.0×10^{-11} m/s for deeper clays at the site.

As previously mentioned, the Ag. Can. series of wells were dismantled for fall plowing before static levels were reached. An examination of well hydrographs (Appendix C) reveals that static levels were apparently achieved in a few wells in one to two months. The remainder of the wells had not quite reached static level even after four months. These observations are consistent with those of other wells installed at this site and at the Puce Road site.

Based on water level observations in wells A-3 and A-4, the vertical direction of groundwater flow in the grey silty clay unit is downward under a hydraulic gradient of 0.16.

4.3 Physical Techniques for Determining Hydraulic Connection

4.3.1 Pulse Interference Tests

4.3.1.1 Puce Road Site

Results of the Puce Road site pulse interference tests are presented in Appendix E and shown graphically in Figures 4.7 through 4.9.

Drawdown curves for wells at the Puce Road A nest in response to stressing the base of the weathered zone by bailing well A-2 are shown in Figure 4.7. An analysis of this figure shows that there is an immediate response in well A-1 installed higher up in the weathered zone, indicating that there is a rapid hydraulic connection throughout the weathered zone at this site. A slight drawdown (0.01 m) in well A-3, installed in the upper grey till unit was also observed over the four-day period of the test. This indicates that there is a some degree of hydraulic communication between the weathered zone and the upper grey till unit possibly due to fracturing of the grey till unit. No response was observed in wells installed in the interbedded zone or the lower grey till unit, indicating that there is no hydraulic connection between the weathered zone and these units.

Drawdown curves for wells at the Puce Road A nest in response to stressing the interbedded zone by bailing well A-4 are shown in Figure 4.8. An examination of this figure shows that there is no response in well A-3 installed in the upper grey till unit. In fact, the water level in well A-3 was observed to rise 0.01 m over the test period. These observations are consistent with the drawdowns observed when well A-2 was stressed, suggesting that the interbedded zone is confined by the

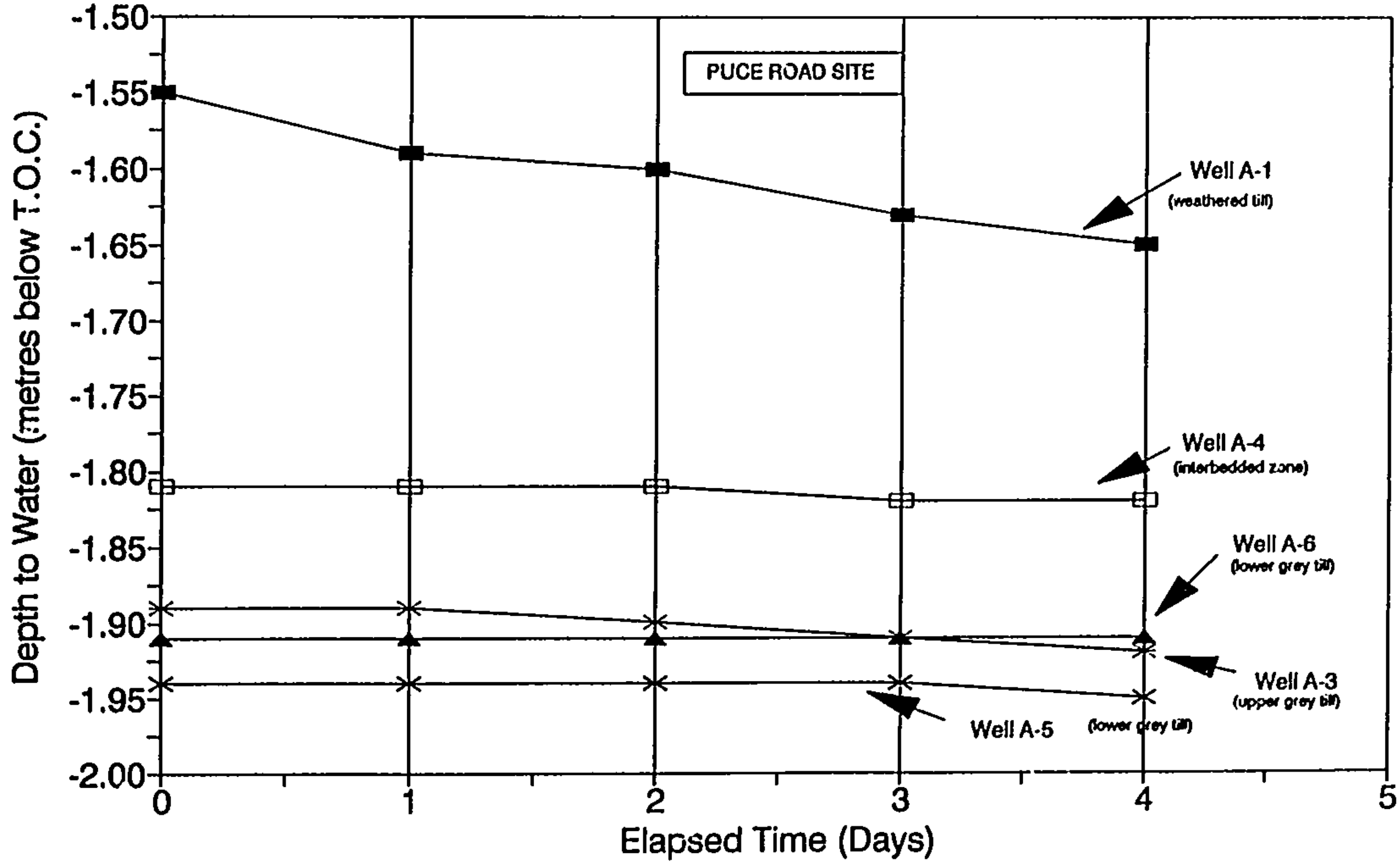


Figure 4.7. Response of the Puce Road site A nest wells as well A-2 installed near the base of the weathered zone is pulsed.

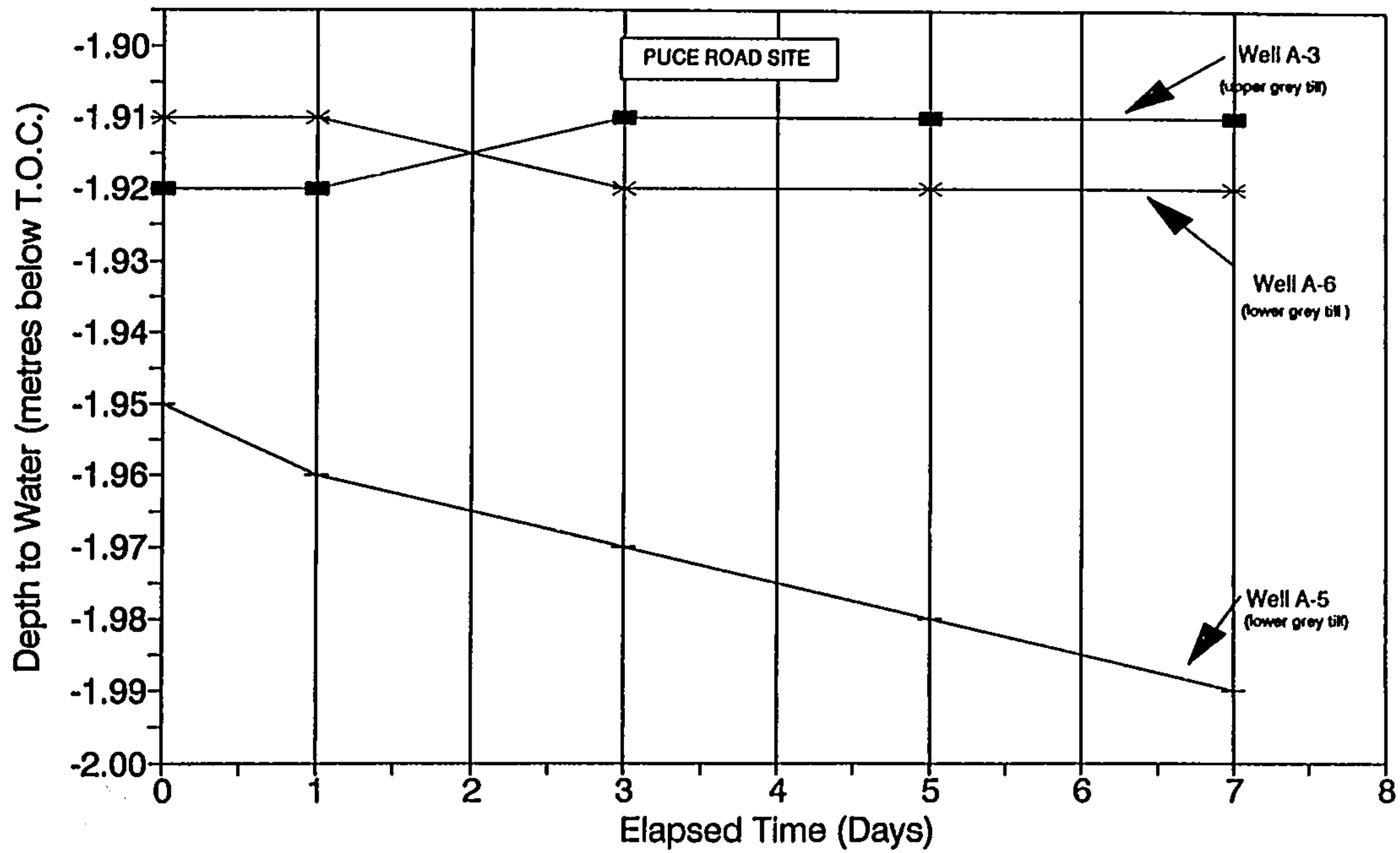


Figure 4.8. Response of the Puce Road site A nest wells as well A-4 installed in the interbedded zone is pulsed.

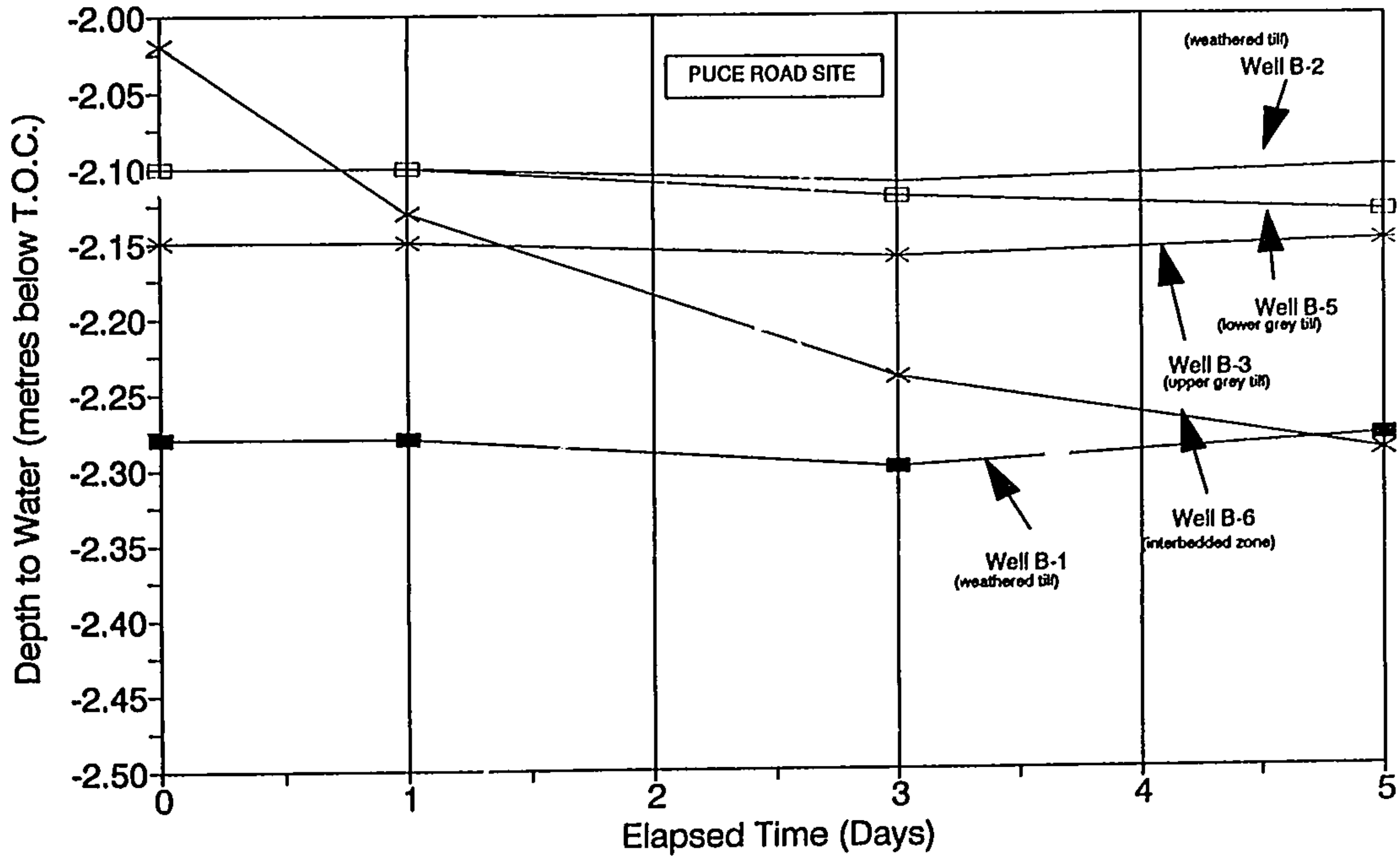


Figure 4.9. Response of the Puce Road site B nest wells as well B-4 installed in the interbedded zone is pulsed.

upper grey till unit and that there is no hydraulic connection between the interbedded zone and the ground surface. However, on the other hand, an immediate response was observed in well A-5 installed in the grey till unit just below the interbedded zone indicating that there is a hydraulic connection between the interbedded zone and the portion of the grey clay till directly below it. A drawdown of 0.04 m was observed in well A-5 after seven days. A slight drawdown was also observed in well A-6 installed much deeper into the grey clay till unit, indicating that there may be hydraulic connection between the interbedded zone and the lower grey clay unit over a vertical distance of as much as 6.7 m. These observations, along with hydraulic head observations, suggest that the interbedded zone provides a discharge conduit for deeper groundwater but not for shallower groundwater.

Drawdown curves for wells at the Puce Road B nest in response to stressing the interbedded zone by bailing well B-4 are shown in Figure 4.9. An analysis of this figure reveals that drawdowns were only observed in well B-5 installed in the lower grey clay till unit and in well B-6 also installed in the interbedded zone. These drawdown responses are consistent with those observed at the A nest and demonstrate that the interbedded zone appears to be confined by the overlying grey clay till unit but is hydraulically connected to the underlying grey clay till unit.

Using the drawdown curve for well B-6, the transmissivity (T) and storativity (S) of the interbedded zone at the Puce Road site were calculated using the method of Walter and Thompson (1982). Since this method assumes that wells are fully penetrating, a correction factor was used to adjust observed drawdowns. This correction factor was calculated using the Hydropal computer model developed by Watershed Research, Inc. (1989). Adjusted drawdowns were obtained by subtracting the correction factor from the observed drawdowns. Data output of the model calculation are shown in Appendix E. The adjusted drawdown curve for well B-6 is shown in Figure 4.10 and superimposed on calculated type curves (Figure 4.11). Type curves were generated using Equation 6 for different values of B (see the description of Equation 6 for a mathematical expression for B). An examination of Figure 4.11 shows that the drawdown curve for well B-6 closely matches the curve for B=20. A value of B=20 yields a value of transmissivity of 6.7×10^{-8} m^2/s which translates into a hydraulic conductivity of 2.7×10^{-8} m/s. This K value is one order of magnitude higher than the value of 1.0×10^{-9} m/s obtained from Hvorslev testing of well B-4. Using the above T value (6.7×10^{-8} m^2/s), a storativity estimate of 0.008 is obtained. This S value clearly indicates that the interbedded zone is confined at the Puce Road site.

4.3.1.2 Whelan Farm Site

Drawdown curves for wells at the Whelan Farm A nest in response to stressing the interbedded zone by bailing well A-2 are shown in Figure 4.12. Response data are presented in Appendix E. An examination of Figure 4.12 reveals that an immediate response was observed in well A-1 installed in the weathered zone and in well A-3 installed just below the interbedded zone in the grey clay till unit.

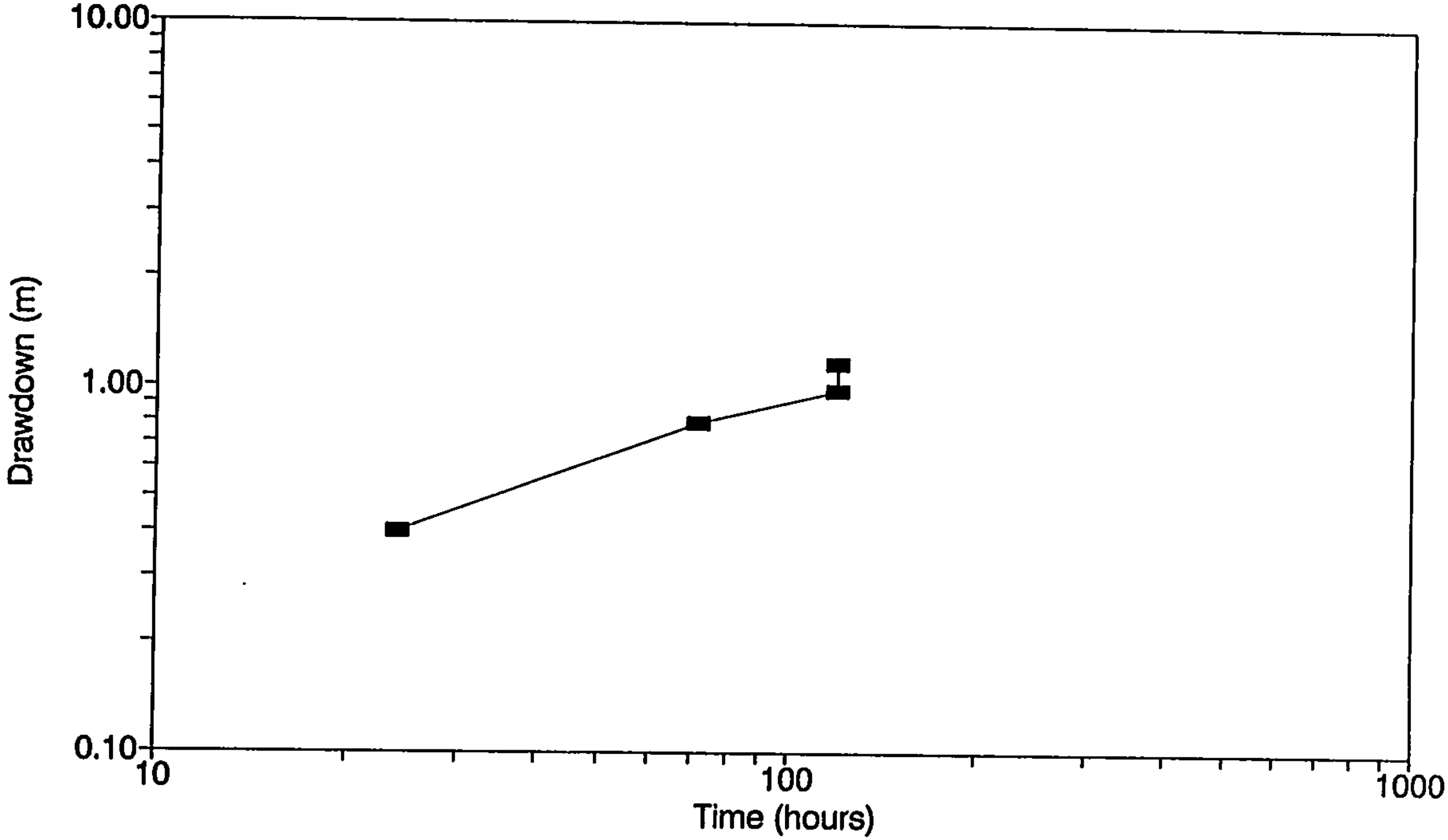


Figure 4.10. Adjusted drawdown curve for well B-6 installed in the interbedded zone at the Puce Road site in response to pulsing well B-4, also installed in the interbedded zone.

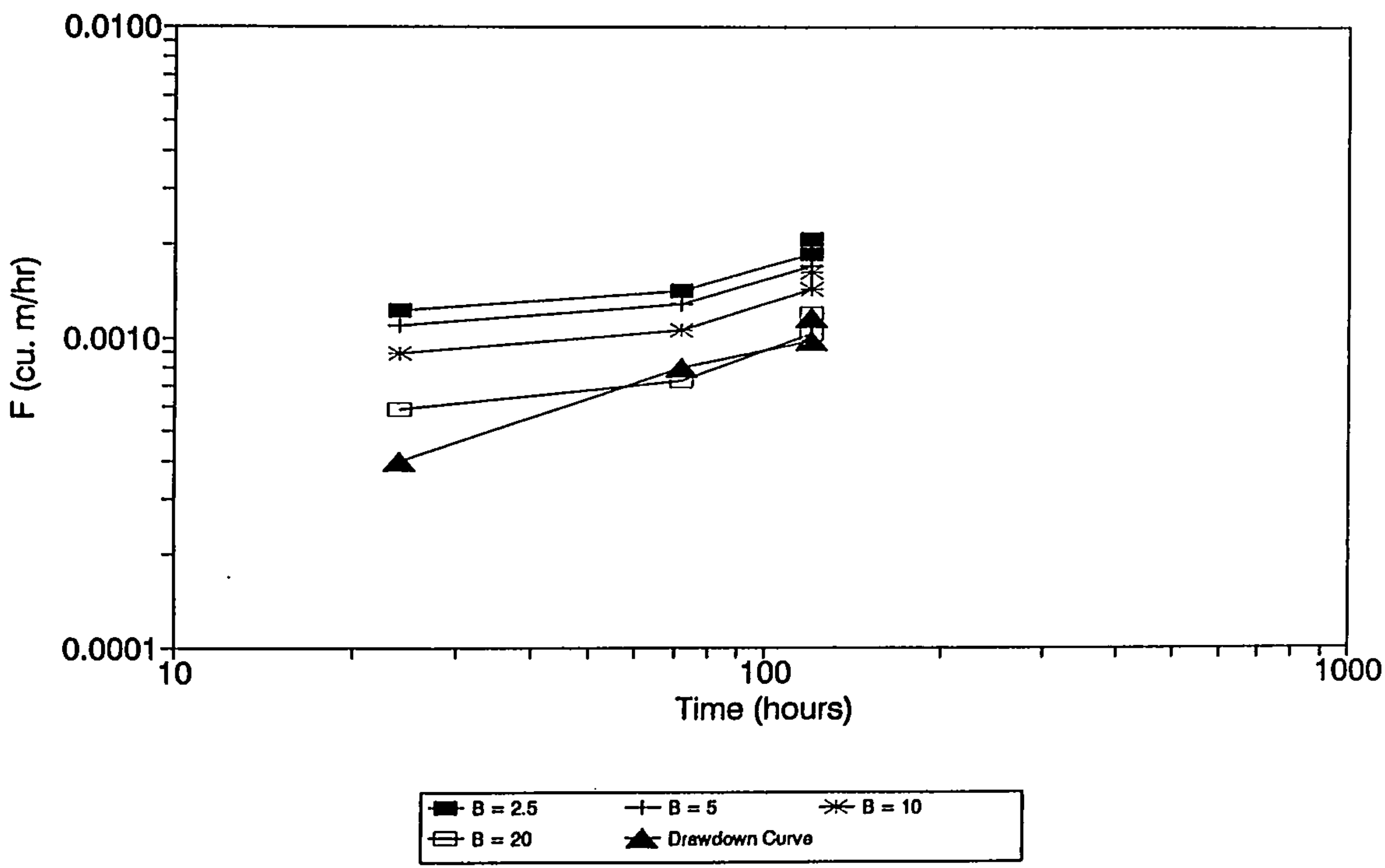


Figure 4.11. Type curves for repeated pulses in source well B-4 (after the method of Walter and Thompson, 1982) with the adjusted drawdown curve for well B-6 superimposed.

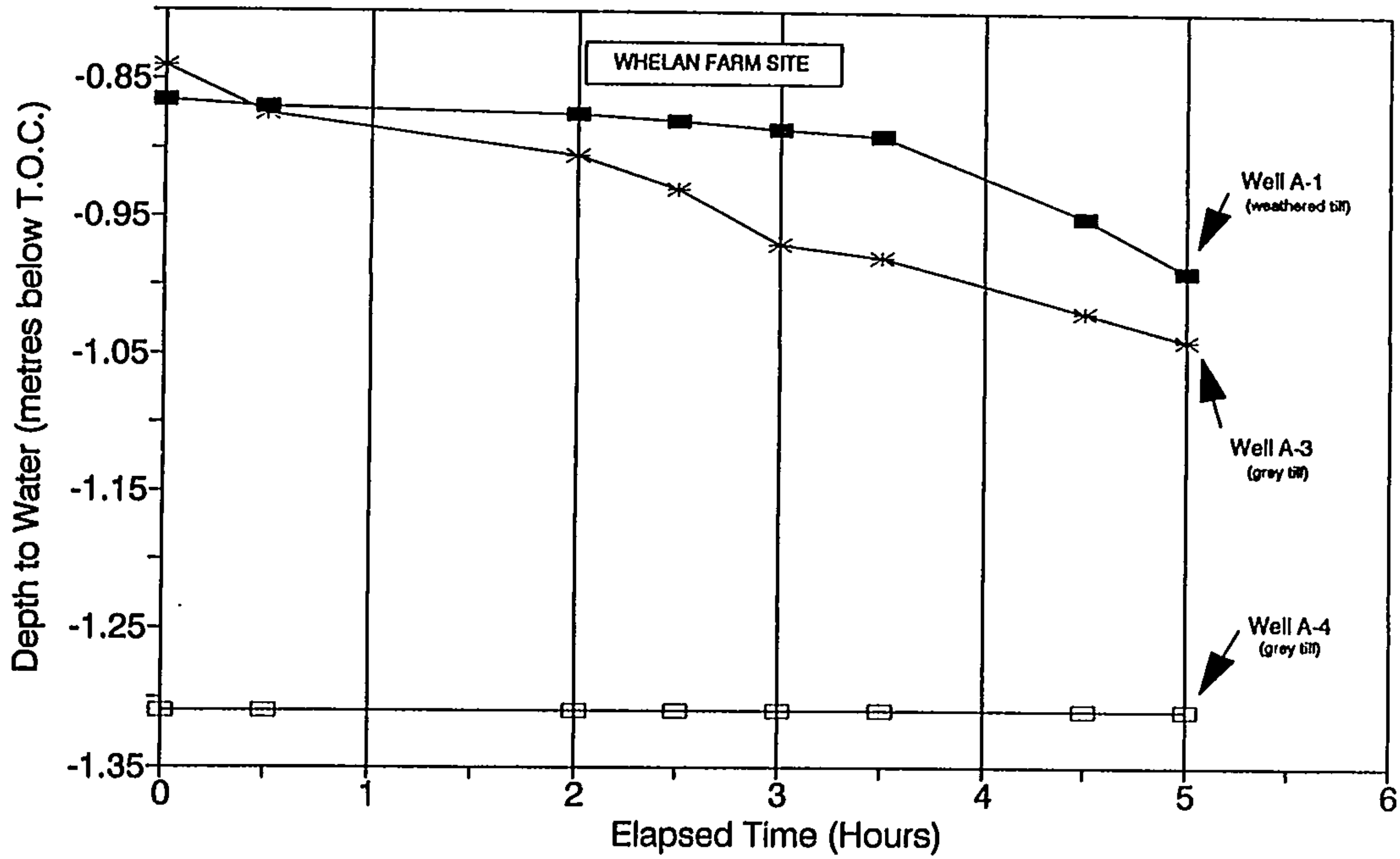


Figure 4.12. Response of the Whelan Farm site A nest wells as well A-2 installed in the interbedded zone is pulsed.

These observations indicate that there is a rapid hydraulic connection between the interbedded zone and the weathered zone (and therefore the ground surface) and between the interbedded zone and the portion of the grey clay till unit directly below it. The fact that no response was observed in well A-4 indicates that hydraulic connection between the interbedded zone and the underlying grey clay till unit is limited to some vertical distance less than 4.3 metres.

4.3.2 Induced Infiltration Tests

4.3.2.1 Puce Road Site

Results of the Puce Road site induced infiltration tests are presented in Appendix E.

A review of these data indicates that no response in any of the wells at the Puce Road C nest or the Puce Road A nest was observed. After approximately three hours after the start of each test, water was observed to be accumulating in the nearby drainage ditch. This ditch is approximately 0.5 m deep and is about five metres away from the C nest and about ten metres from the A nest (see Figure 3.1). These observations suggest that the primary pathway for migration of an isolated spill is lateral, not vertical, in the most heavily fractured root zone occurring from the ground surface to a depth of one to two metres. However, in a heavy precipitation event, this zone will quickly become saturated and water will begin to migrate vertically. This was observed to occur after a steady rainfall event lasting for three days during the pulse interference test at the B nest. Water levels in shallow wells installed in the weathered zone rose as much as 0.19 m (see Appendix E). During the same precipitation event, the water level in well A-1, also installed in the weathered zone, 0.24 m (see Appendix E).

4.3.2.2 Whelan Farm Site

Results of the Whelan Farm site induced infiltration tests are presented in Appendix E and shown graphically in Figure 4.13.

Results of the induced infiltration test at the Whelan Farm site were quite different from those observed at the Puce Road site. A rapid response was observed in well A-2 installed in the interbedded zone and a slower response was observed in well A-1 installed in the weathered zone (Figure 4.13). Fracturing, depth to the water table, and weathered zone hydraulic conductivities are almost identical from site to site. Therefore, vertical flow must be influenced by the proximity of the HPZ to the ground surface. Therefore, the results of the induced infiltration test suggest that there is a rapid hydraulic connection between the surface and the interbedded zone.

Water likely infiltrated and recharged the water table in approximately one hour (see Appendix E). At that time, water began mounding as flow began to move outward at the interface of the interbedded zone and the relatively impermeable underlying grey clay till (see Figure 3.6). Consequently, hydraulic heads were higher in the interbedded zone and a much greater response was observed in well A-2 than was observed in well A-1 installed in the weathered zone.

Assuming a porosity of the weathered zone of 0.3, an initial moisture

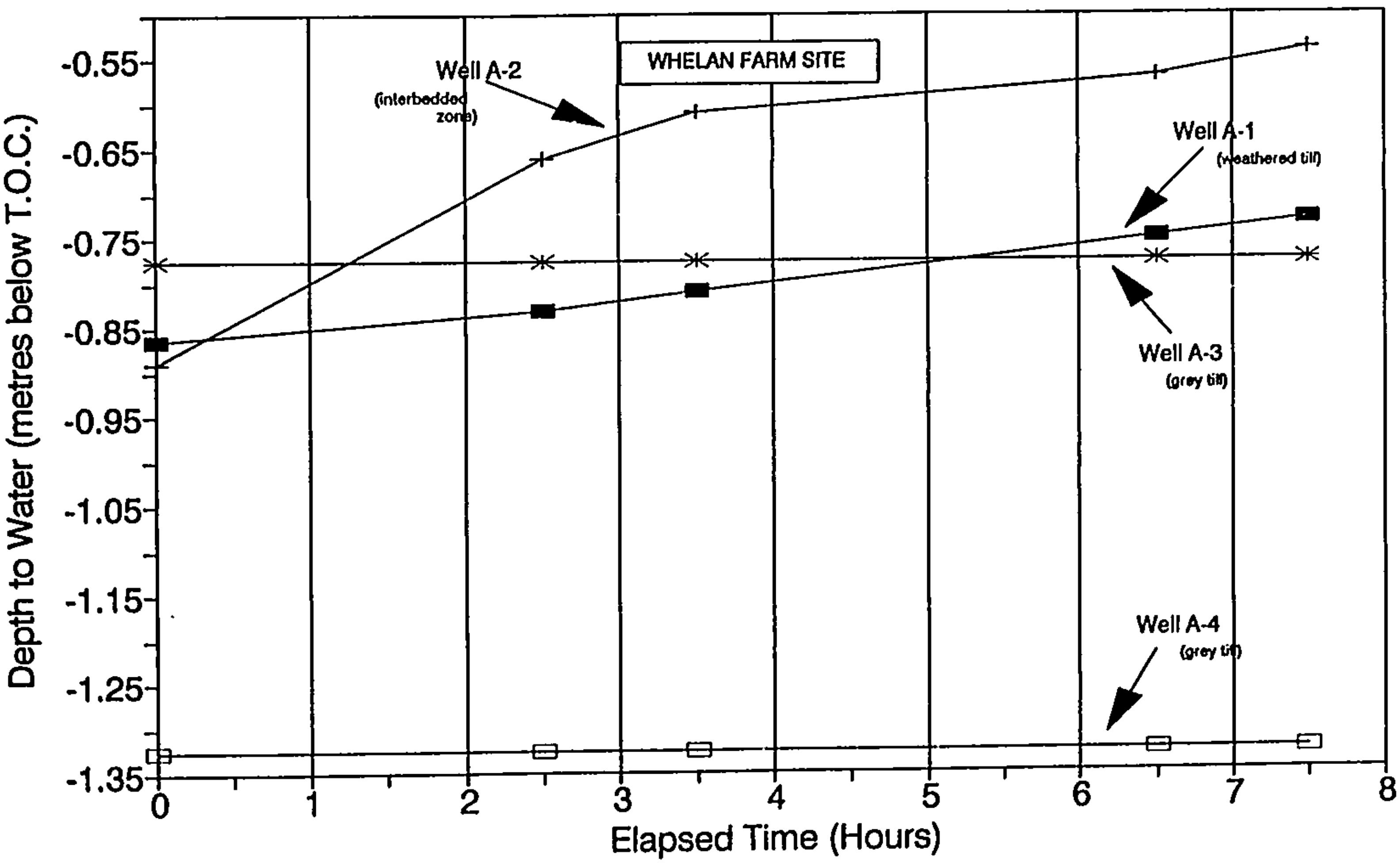


Figure 4.13. Response of the Whelan Farm site A nest to induced infiltration.

content of 0.145 (Appendix B) and a range of capillary pressures of 0.30 m to 10 m (Artz and Metzler, 1985), Equation 7 predicts the vertical hydraulic conductivity of the weathered zone to range from 4.2 x 10^{-6} m/s to 3.7 x 10^{-5} m/s. These values are approximately three to four orders of magnitude higher than the horizontal K value of 6.9 x 10^{-9} m/s obtained from field testing of well A-1 completed in the weathered zone.

4.3.3 Hydraulic Head Versus Depth Profiles

4.3.3.1 Puce Road Site

Hydraulic head versus depth profiles for each well nest at the Puce Road site are shown in Figures 4.14 through 4.16. These figures show hydraulic head versus depth profiles at various times after static levels in all wells were achieved. Water level data are presented in Appendix C.

An examination of these figures reveals that they somewhat resemble the conceptual profile shown in Figure 3.7b, indicating that the interbedded zone at the Puce Road site is confined. However, significant water level fluctuations were observed in some wells which appear to be seasonally related. These fluctuations are most obvious at the B and C nests (Figures 4.15 and 4.16). Water level fluctuations are greatest in the weathered unit and in the interbedded zone, indicating that these are the most hydraulically active units. The lack of significant water level fluctuations in the upper grey clay till unit indicate that it is hydraulically inactive and that it appears to act as a confining layer for the interbedded zone. Further,

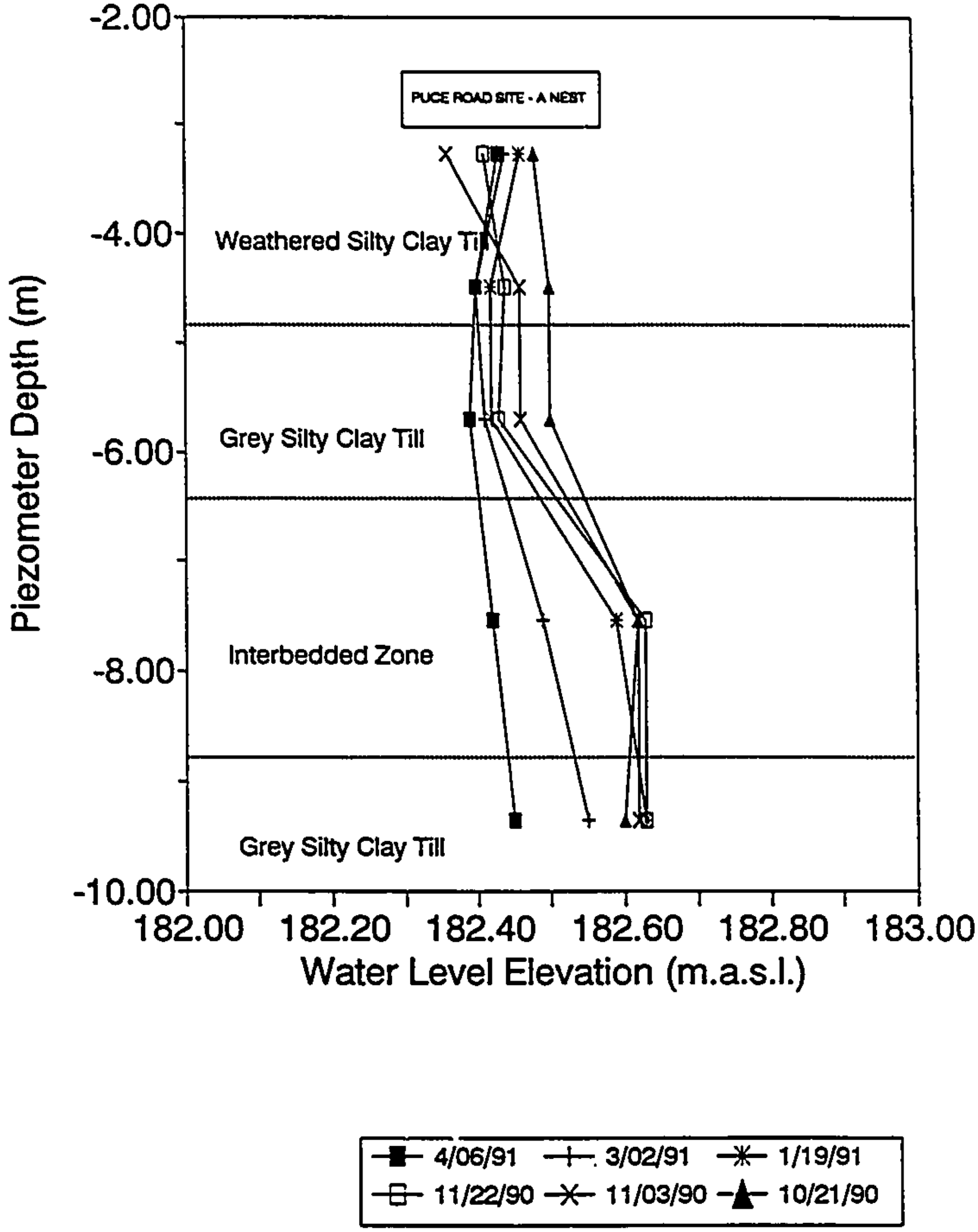


Figure 4.14. Hydraulic head profiles for the Puce Road A nest.

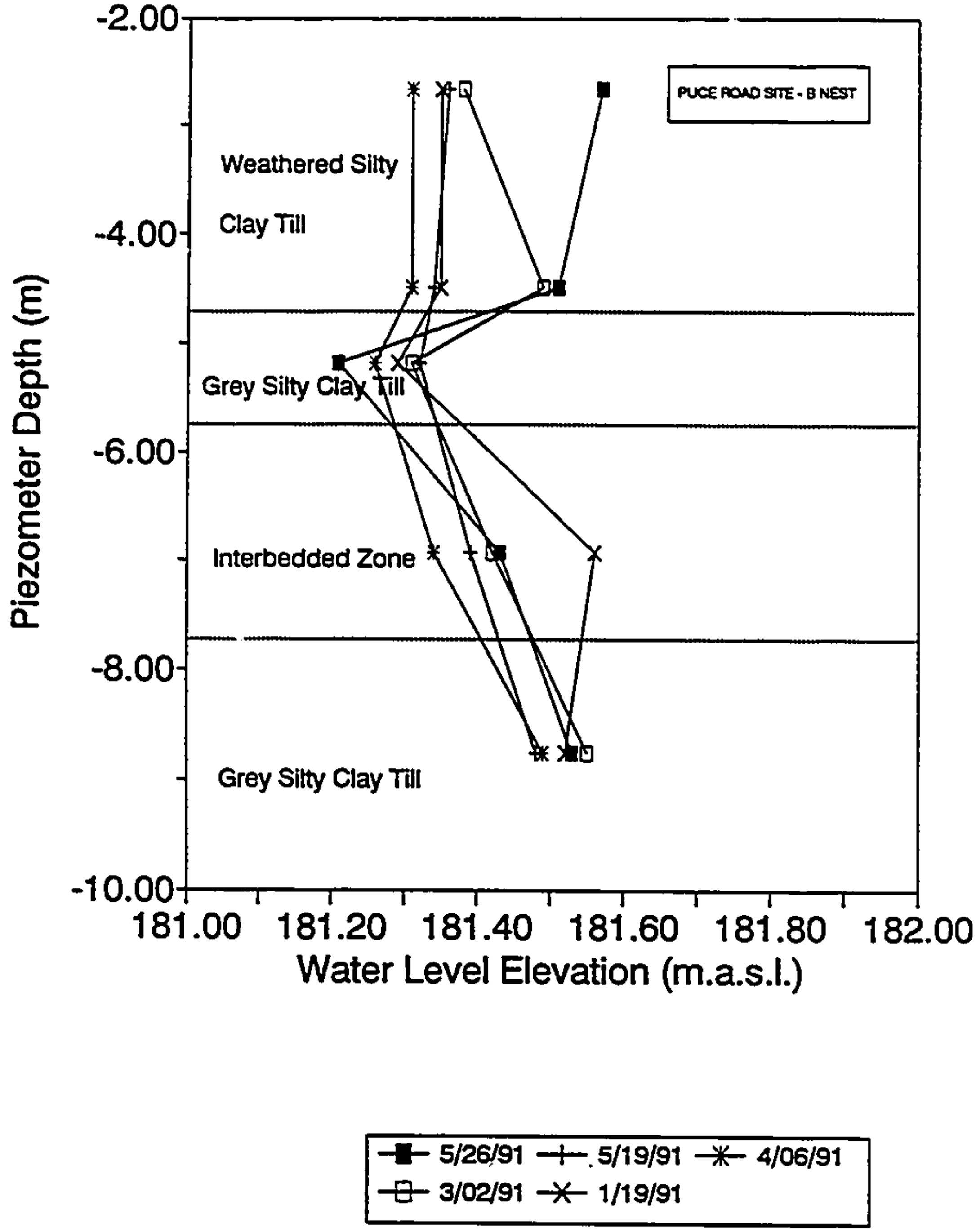


Figure 4.15. Hydraulic head profiles for the Puce Road B nest.

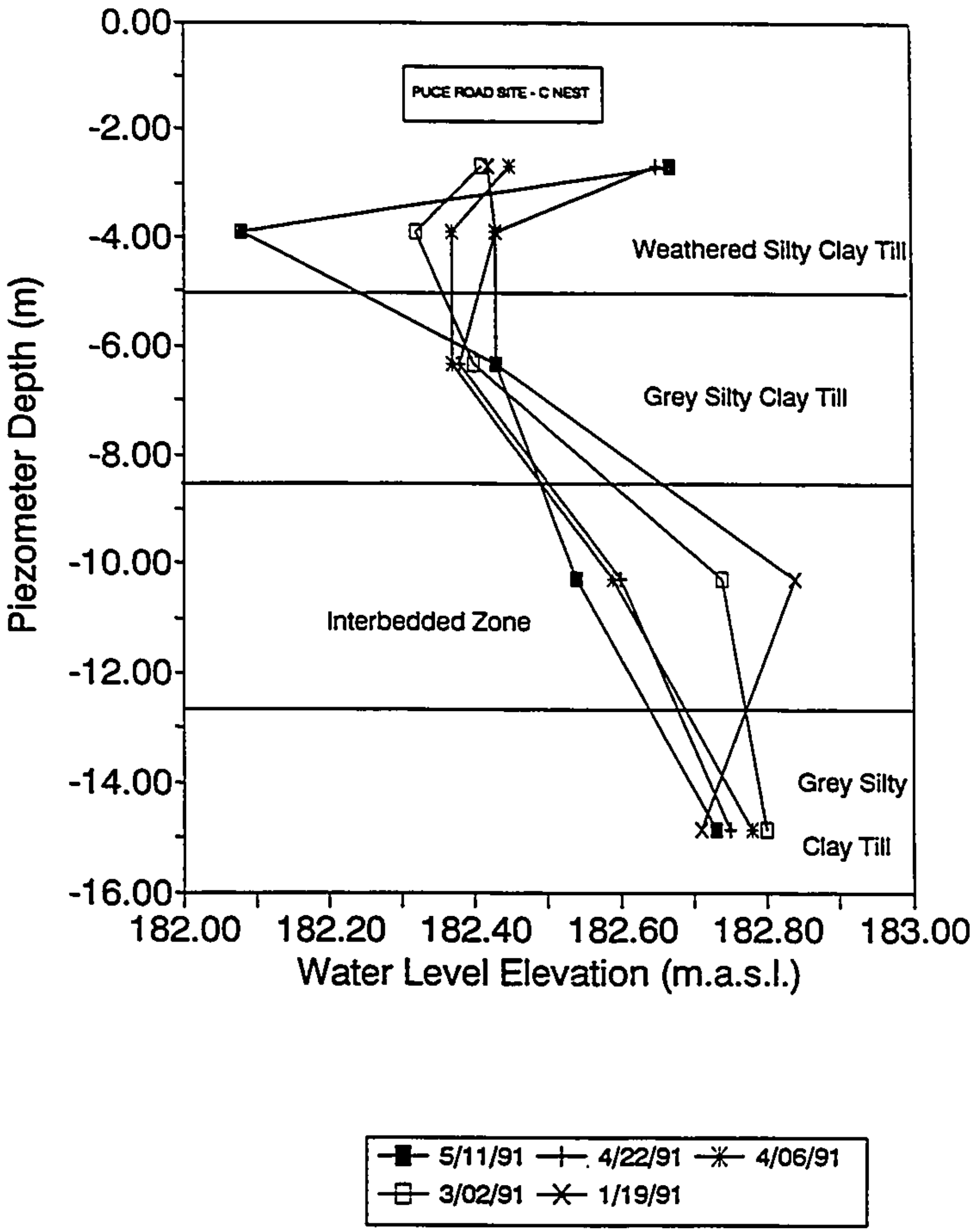


Figure 4.16. Hydraulic head profiles for the Puce Road C nest.

consistently higher hydraulic heads in the interbedded zone than in the overlying grey clay till unit suggest that the interbedded zone is confined.

The hydraulic head profile for the Puce Road A nest (Figure 4.14) is somewhat different than those for the B and C nests. An examination of this figure reveals that there is possibly a hydraulic connection between the weathered unit and the upper grey clay till unit. Similar water level fluctuations were observed in both the weathered unit and the upper grey clay till unit, indicating that they have a similar degree of hydraulic activity. This is likely due to fracturing of the grey clay till unit. Pulse interference testing also indicated that there may be a small degree of hydraulic connection between these units. However, the larger water level fluctuations in the interbedded zone suggest that this unit is more hydraulically active than above clay till units. Also, as with the B and C nests, higher hydraulic heads in the interbedded zone observed at the A nest suggest that the interbedded zone is vertically confined.

Based on the hydraulic head versus depth profiles for all nests at the Puce Road site, it may be concluded that the interbedded zone must be laterally recharged from an upgradient source and that it appears not to be locally hydraulically connected to the surface.

4.3.3.2 Whelan Farm Site

Hydraulic head versus depth profiles for the Whelan Farm A nest are shown in Figure 4.17. Water level data are presented in Appendix C.

The profiles shown in Figure 4.17 exhibit a poor resemblence to predicted

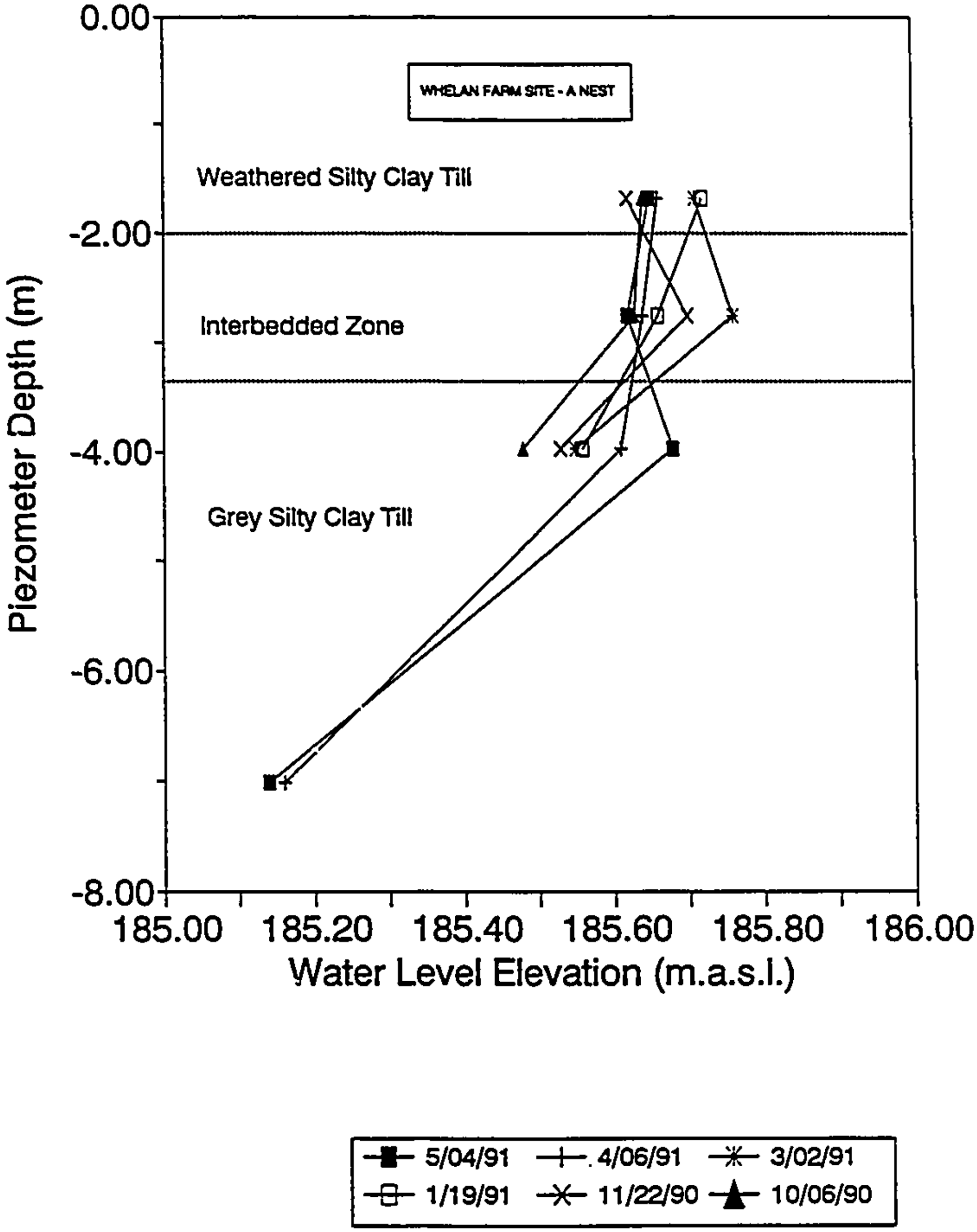


Figure 4.17. Hydraulic head profiles for the Whelan Farm A nest.

profiles shown in Figure 3.7 due to fluctuations in hydraulic heads and to the lack of detailed head measurements above the HPZ. However, an examination of Figure 4.17 does show that similar hydraulic head fluctuations were observed in the weathered unit, the interbedded zone, and the underlying grey till directly below the interbedded zone. These fluctuations indicate that these units are hydraulically active and unconfined. Therefore, based on hydraulic head profiles, it appears that the upper four metres (which includes the interbedded zone) at the Whelan Farm site is hydraulically connected to the surface.

4.4 Geochemical Techniques for Determining Hydraulic Connection

4.4.1 Major Ions and Nitrate

4.4.1.1 Puce Road Site

Major ion and nitrate data are tabulated in Appendix F. Percent charge balance error was calculated for each water sample and also tabulated in Appendix F. Concentration profiles of individual cations and anions with depth are plotted in Figures 4.18 and 4.19, respectively. Chemical concentrations are also plotted in milliequivalents per litre (meq/L) on stiff diagrams (Figure 4.20) in order to observe trends in total geochemical patterns with depth. For comparison purposes, data from the study of Brathwaite (1988) near the C nest of this study are included (Figure 4.20b).

The depth profiles show that there is a general decrease in ion concentration with depth, similar to predicted profiles shown in Figure 3.9b. The

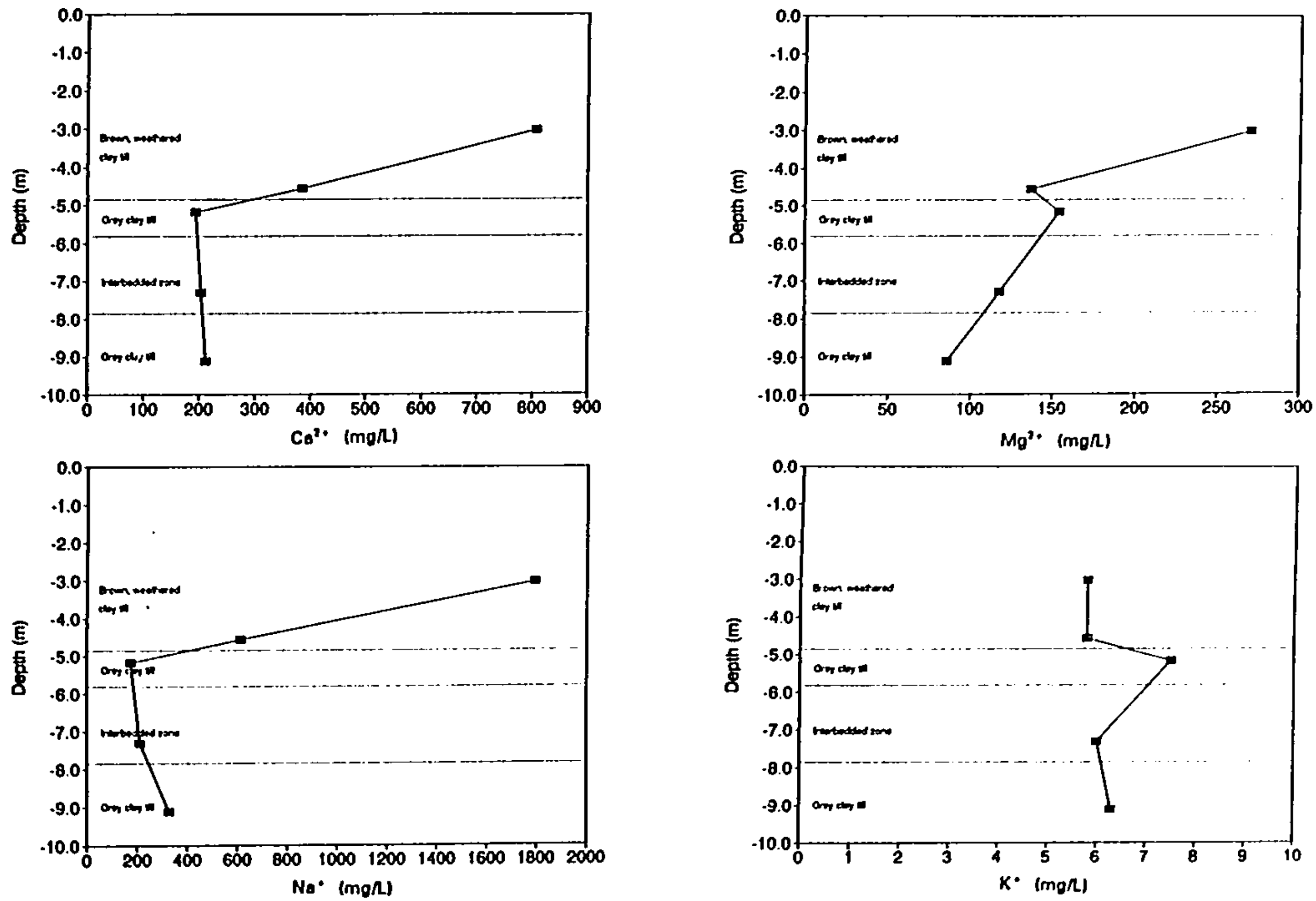


Figure 4.18. Cation depth profiles for the Puce Road site.

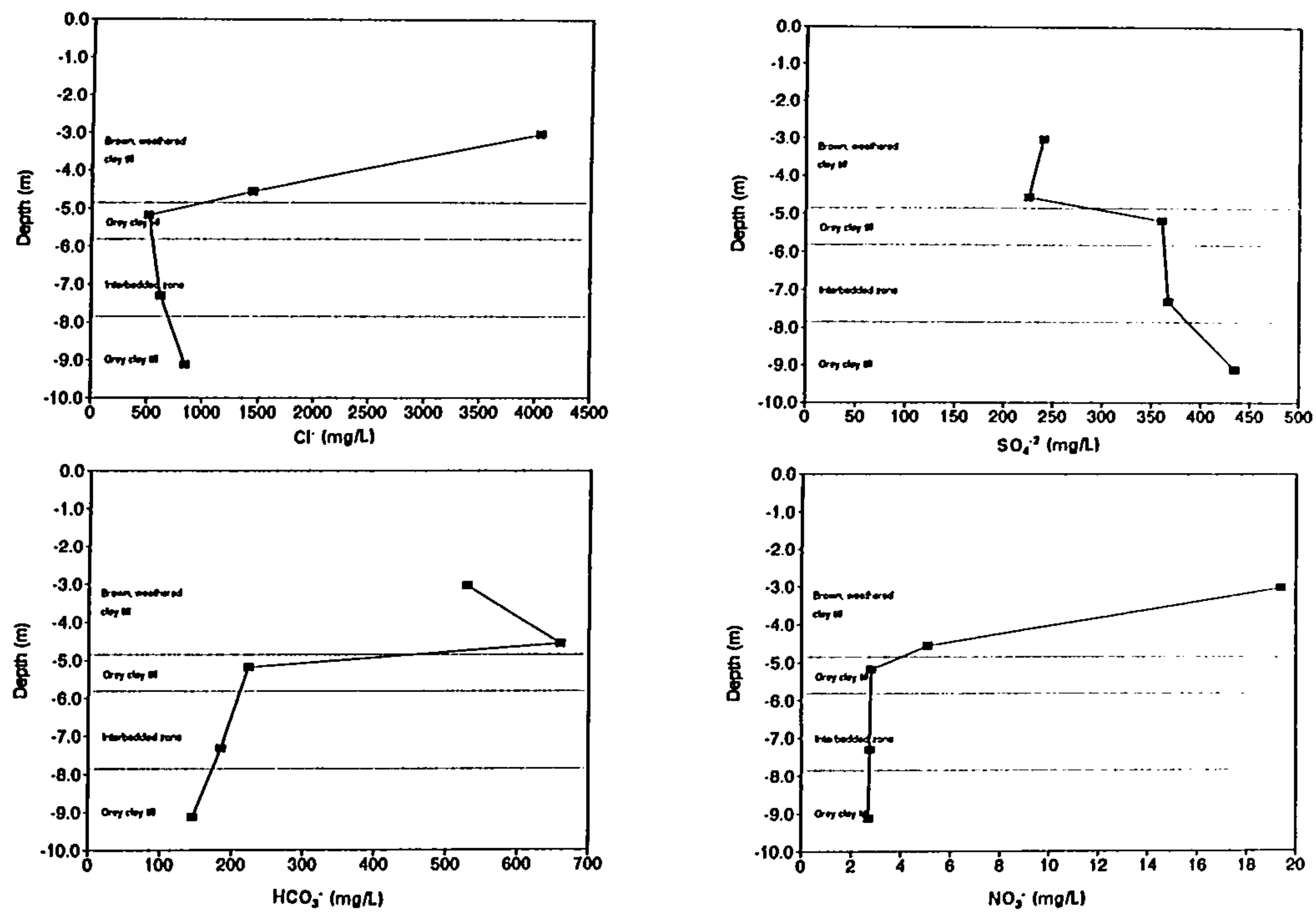


Figure 4.19. Anion depth profiles for the Puce Road site.

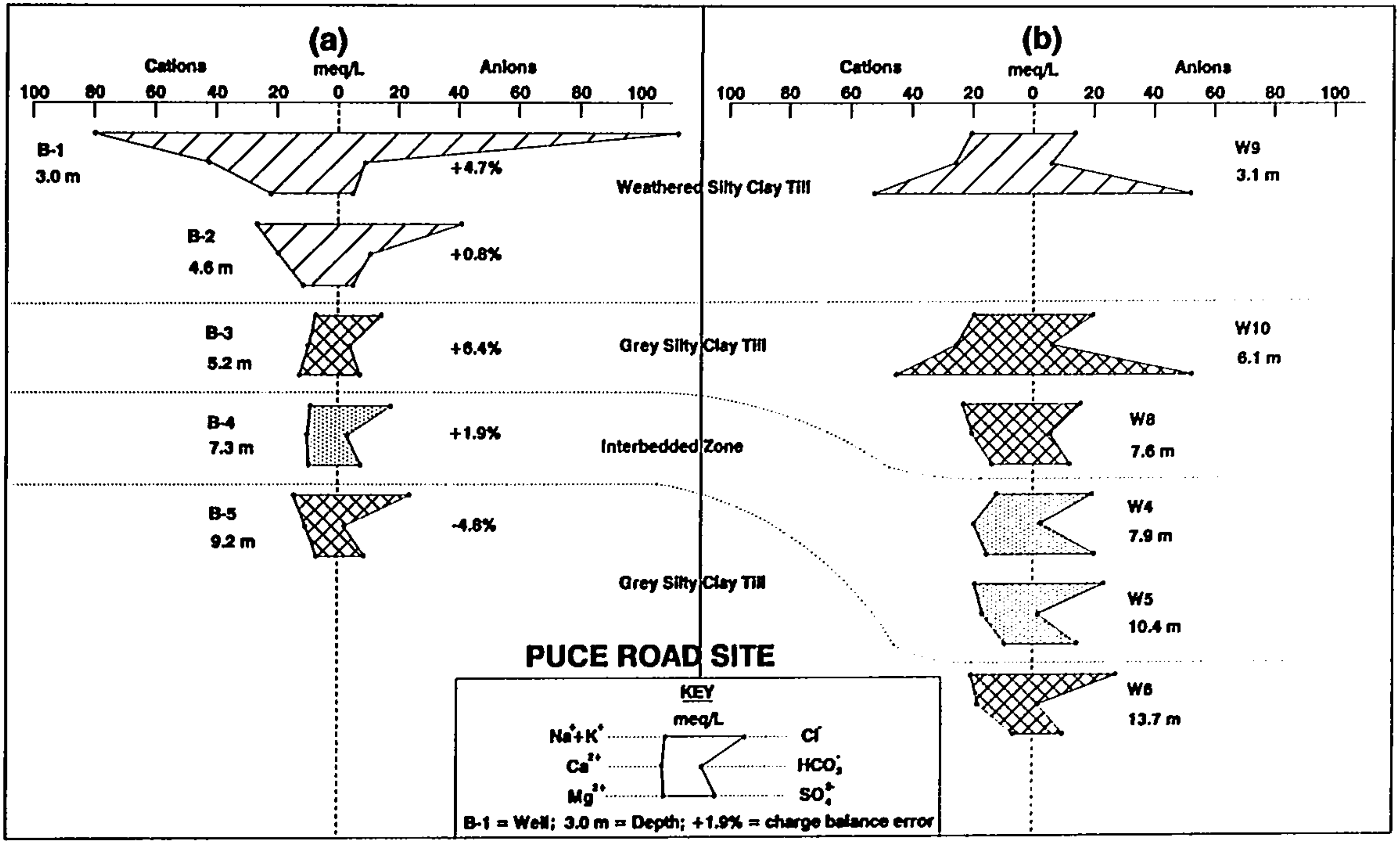


Figure 4.20. (a) Stiff diagrams for groundwater from the Puce Road site B nest.
(b) Stiff diagrams for groundwater from near the Puce Road site C nest (data from Brathwaite, 1988).

stiff diagrams clearly indicate that groundwater in the weathered zone is distinctly different in major ion content from the groundwater below. These plots suggest that the HPZ at the Puce Road site is not hydraulically connected to the weathered zone, and is therefore not connected to the ground surface. Data from Brathwaite (1988) indicate that the upper metre or so of the grey till unit is hydraulically connected to the weathered zone. Stiff diagrams from the B nest of this study do not support this conclusion.

The Ca^{2+}, Mg^{2+}, and HCO_3^- profiles are typical of groundwaters of the St. Clair Clay Plain. The concentrations of these ions are relatively high near the ground surface as a result of chemical weathering of clay minerals. HCO_3^- sharply increases near the interface of the grey clay due to the precipitation of carbonate leached from above (Quigley and Ogunbadejo, 1973). Constant concentrations of K^+ observed in this study are also common to the region.

The SO_4^{-2} profile, however, is contradictory to those normally found throughout the St. Clair Clay Plain. Sulphate in groundwater is generally higher in the weathered zone and decreases with depth. At the Puce Road B nest, the opposite occurs implying that there may be a subsurface source of SO_4^{-2}.

The most striking feature of all of the profiles is the extremely high concentrations of Na^+ and Cl^- in the weathered zone. This is not surprising considering the fact that the former salt shed is approximately 25 m away from the B nest. Furthermore, the B nest is located next to a parking lot where salt is used as a deicing agent. The fact that Cl^- concentrations drop off sharply in the grey silty clay till unit to values found by Brathwaite (1988) strongly indicates that the HPZ at the Puce Road site is not hydraulically connected to the ground surface. The Cl^- profile suggests that a chemical spill would preferentially migrate laterally in the shallow, most highly fractured zone. After decreasing sharply in the upper grey till unit, Cl^- concentrations again increase with depth. This increase is consistent with the conclusions of Desaulniers et al. (1981, 1986) that Cl^- is diffusing upward from bedrock brine.

The nitrate profile with depth is consistent with the Cl^- depth profile, implying that anthropogenic inputs of conservative constituents appear to preferentially accumulate in the weathered zone rather than migrate vertically into the unweathered zone. These observations are consistent with the conclusions of Desaulniers et al. (1981) that advective flow is the primary mechanism of solute transport in the weathered zone and below this zone, diffusion is the dominant mechanism.

4.4.1.2 Whelan Farm Site

Major ion and nitrate data are tabulated in Appendix F. Percent charge balance error was calculated for each water sample and also tabulated in Appendix F. Concentration profiles of individual cations and anions with depth are plotted in Figures 4.21 and 4.22, respectively. Stiff diagrams are shown in Figure 4.23.

The depth profiles (Figures 4.21 and 4.22) show a similar trend to the Puce Road site profiles: there is a general decrease in ion concentration with depth.

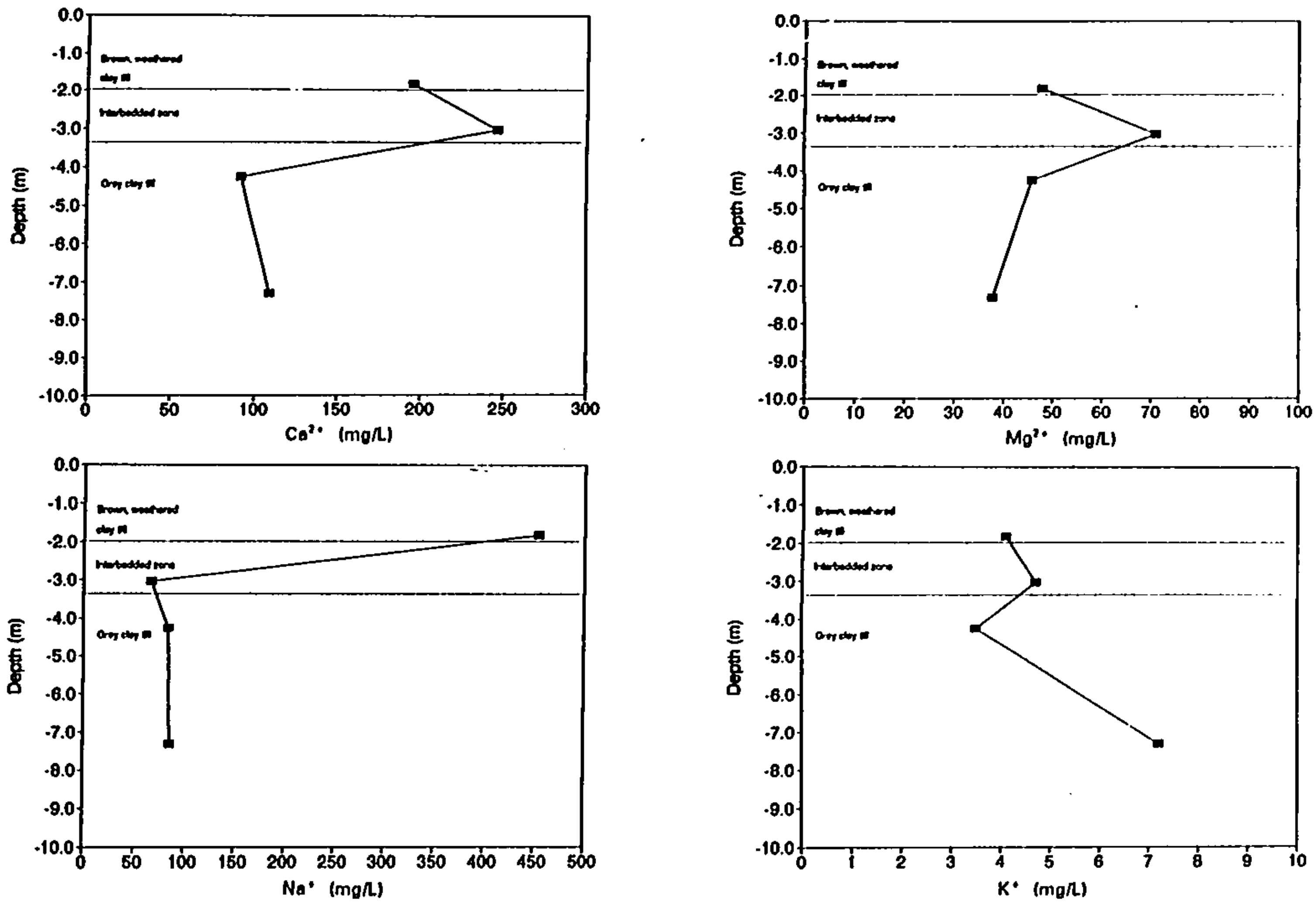


Figure 4.21. Cation depth profiles for the Whelan Farm site.

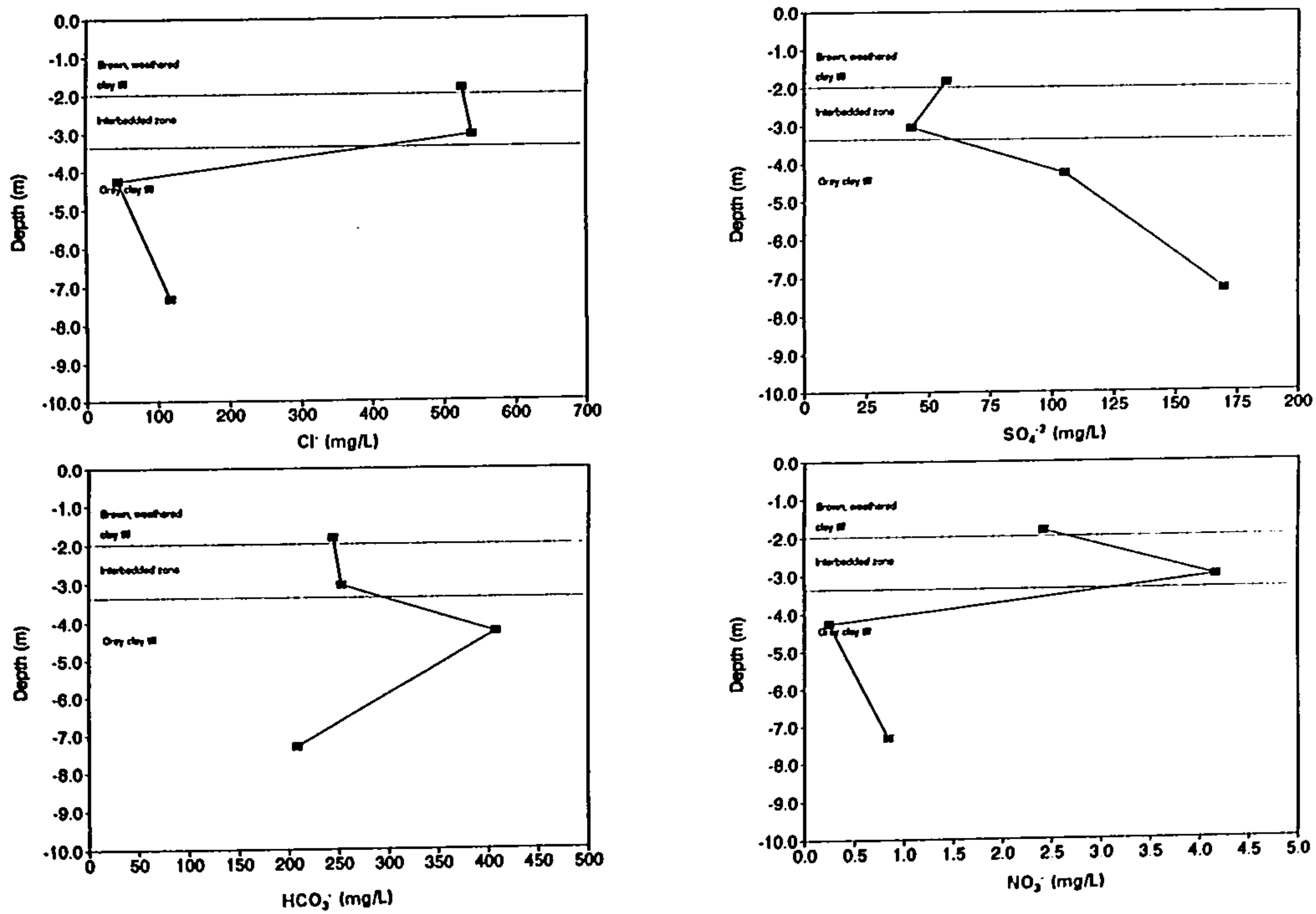


Figure 4.22. Anion depth profiles for the Whelan Farm site.

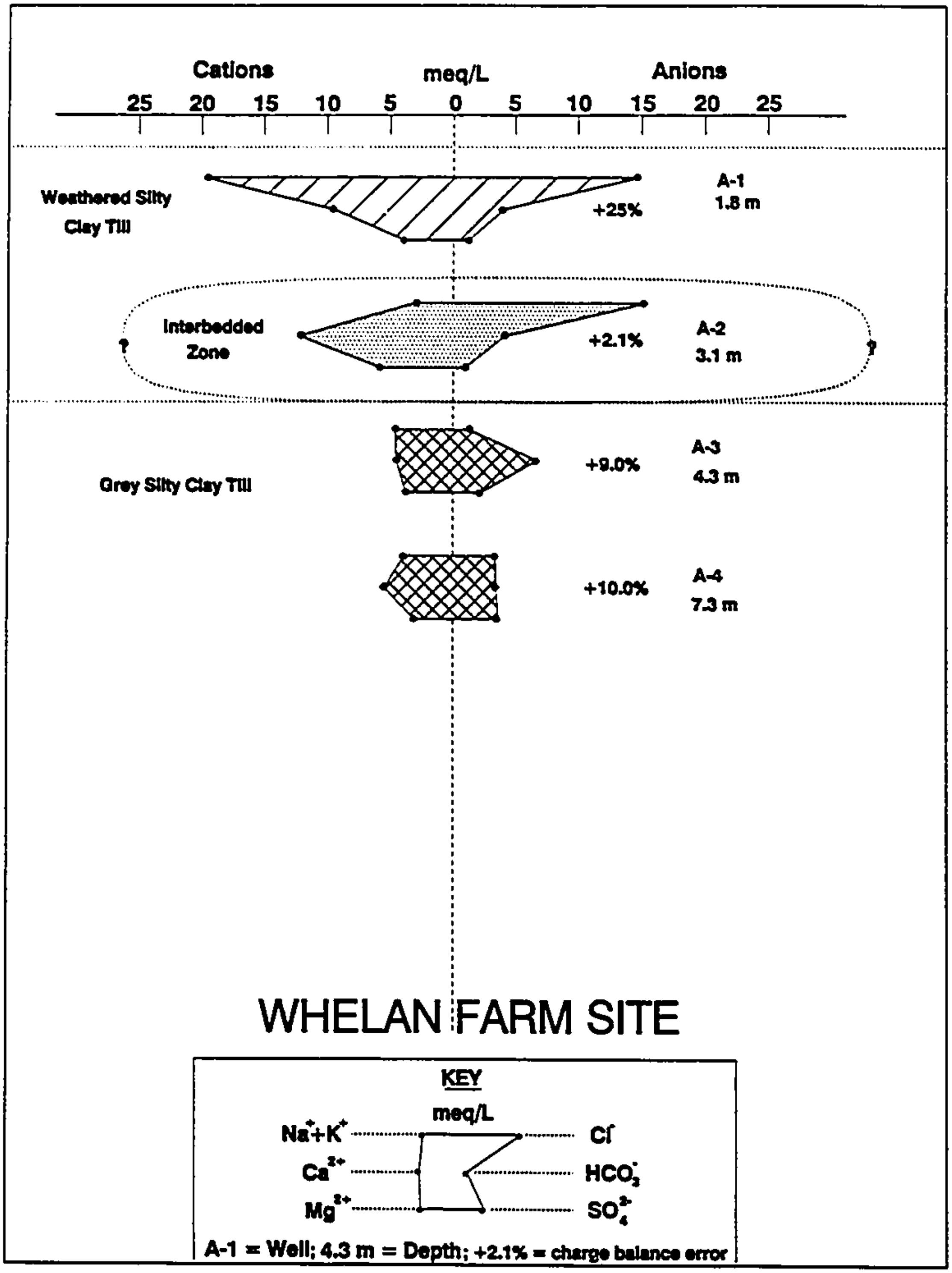


Figure 4.23. Stiff diagrams for groundwater from the Whelan Farm site A nest.

The Whelan Farm site profiles are similar to predicted profiles shown in Figure 3.9a.

Stiff diagrams (Figure 4.23) clearly indicate that groundwaters in the weathered zone and in the interbedded zone is distinctly different in major ion content from the groundwater in the unweathered zone. The relatively large percent charge balance error (25%) in the groundwater sample from the weathered zone indicates that either an error was made in the analyses or that other anions are present in the sample that were not analysed for. Nevertheless, the similarity in major ion concentration in groundwater in the interbedded zone and in the weathered zone suggests that the interbedded zone is hydraulically connected to the weathered zone, and therefore is connected to the ground surface.

4.4.2 Groundwater Field Chemistry

4.4.2.1 Puce Road Site

Figure 4.24 shows the depth profiles of pH, temperature, electrical conductivity (EC), and total dissolved solids (TDS) of groundwater collected from the B nest, where major ion and nitrate concentrations were also analysed. Electrical conductivity profiles for the A and C nests are shown in Figure 4.25. Eh is plotted against pH for groundwater from all wells in Figure 4.26. Field chemistry data are tabulated in Appendix F.

The pH depth profile reveals that groundwater is slightly acidic in the weathered silty clay till and essentially neutral in the unweathered grey silty clay till. pH measurements taken nearly one year later confirmed these results (see Appendix

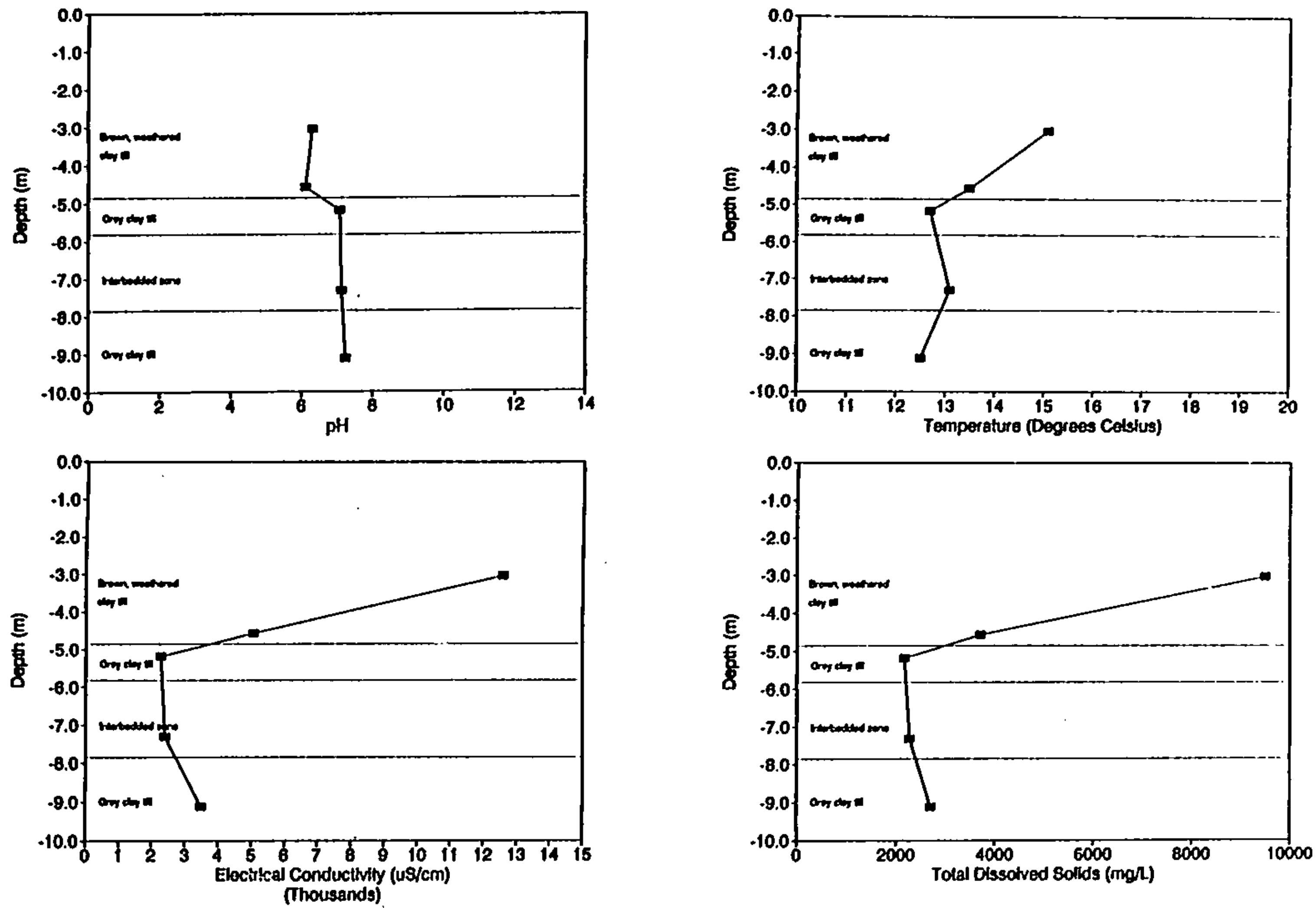


Figure 4.24. Field chemistry parameter depth profiles for the Puce Road site B nest.

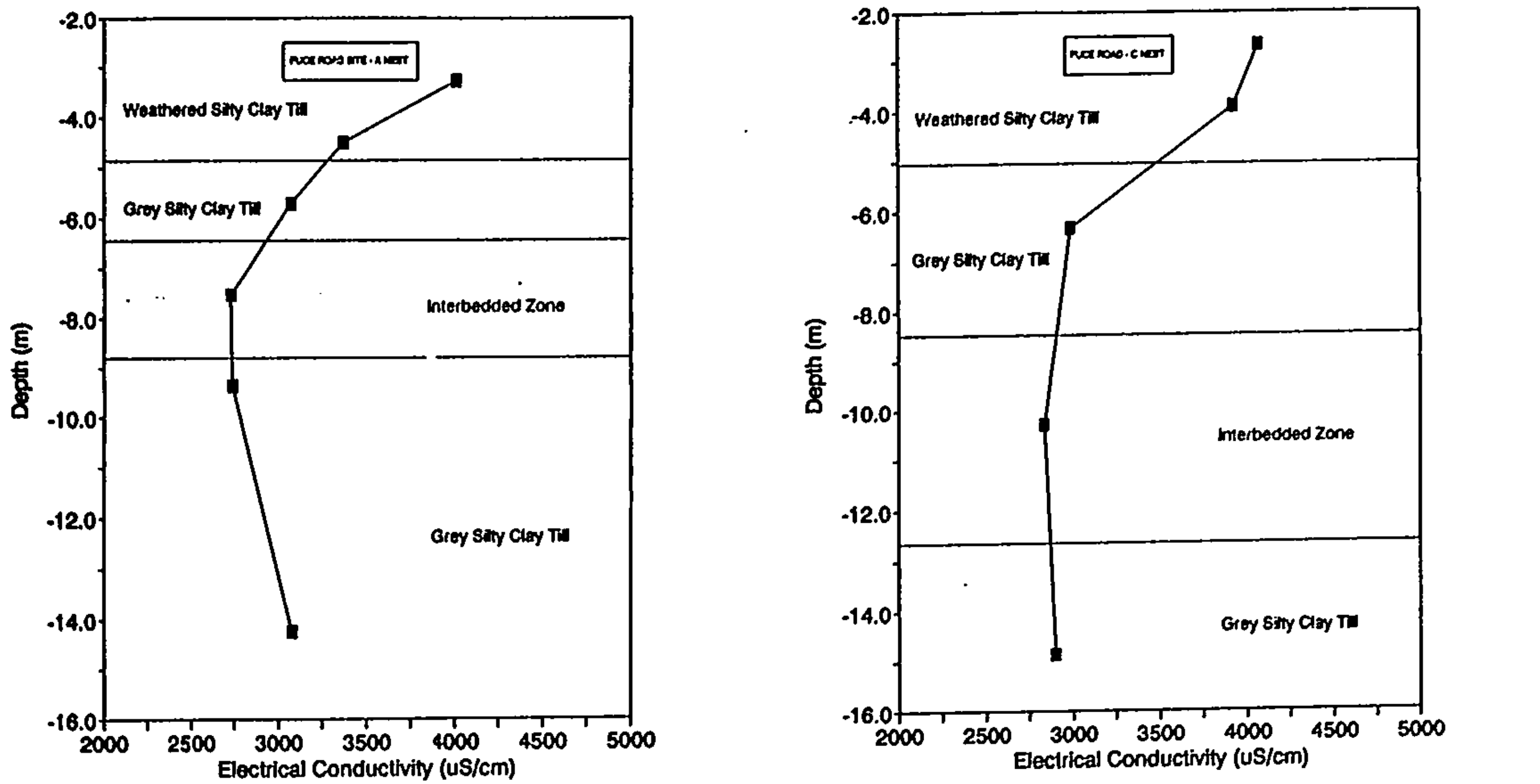


Figure 4.25. Electrical conductivity depth profiles for groundwater from the Puce Road site A and C nests.

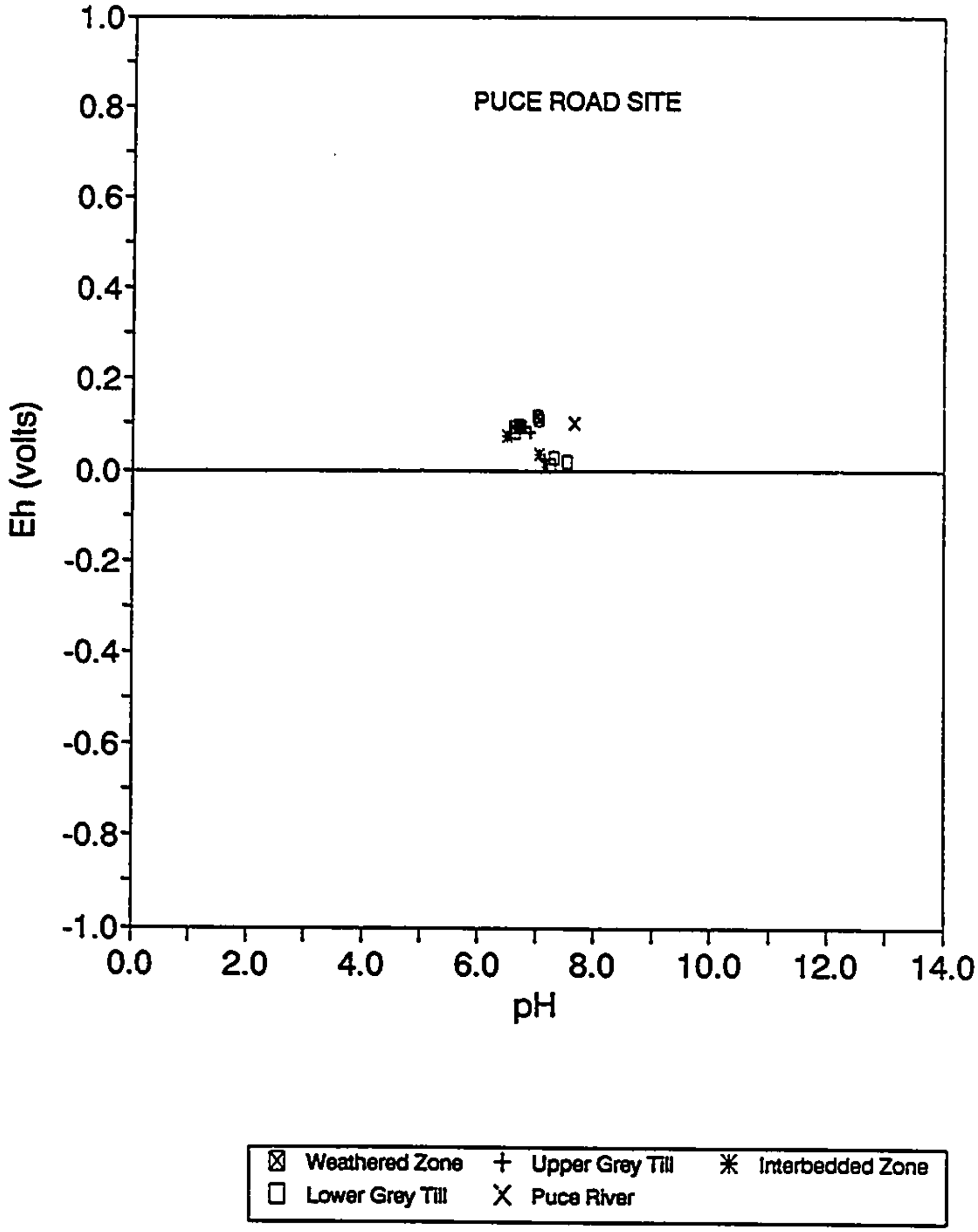


Figure 4.26. Eh-pH diagram for groundwater from the Puce Road site.

F). Such a profile is typical of groundwater of the St. Clair Clay Plain. Groundwaters are apparently buffered by the carbonate minerals and probably by the clay minerals that are ubiquitous in these deposits (Desaulniers et al., 1981).

The temperature profile shows a generally decreasing trend with depth. A sharp break in the slope of the profile at the grey clay interface suggests that there is a poor degree of mixing of groundwaters between the weathered zone and the underlying grey silty clay till. The slight increase in thermal energy in the interbedded zone is likely caused by the higher permeability of this unit which results in more active groundwater flow than in the clayey units above and below. This implies that the interbedded zone is possibly being laterally recharged.

The EC and TDS profiles from the B nest, as expected, mimic the pattern of the total major ion concentration with depth (especially the Cl^- and Na^+ profiles). EC and TDS are high in the weathered zone and sharply decrease at the grey clay interface suggesting that there is a poor degree of hydraulic connection between the weathered zone and the underlying till units. The EC depth profiles from the A and C nests (Figure 4.25) are more representative of natural groundwaters of the region. These profiles likewise show that groundwater in the weathered zone possesses a higher EC than groundwater in the unweathered till units below. Therefore, EC data from all three monitoring nests imply that there is a poor hydraulic connection between the weathered unit and the underlying unweathered till units and the interbedded zone.

An examination of the Eh-pH plot for groundwater from all nests (Figure

4.26) reveals that there is no trend with depth; Eh-pH signatures from all wells are almost identical. A comparison of this diagram with Figure 3.10 shows that all groundwaters sampled at the Puce Road site, including water from the Puce River, have an Eh-pH signature similar to waters isolated from the atmosphere. The fact that the water from the Puce River plots with groundwater implies that the Puce River is a discharge zone for the area. The reason why there is no Eh-pH trend with depth is probably because all of the dissolved oxygen in infiltrating groundwater is removed by the uppermost organic-rich topsoil causing the redox potential to decline (Freeze and Cherry, 1979). Further, any dissolved oxygen in groundwater is likely used up in weathering processes occurring in the till.

4.4.2.2 Whelan Farm Site

Figure 4.27 shows the depth profiles of pH, temperature, EC, and TDS of groundwater collected from the A nest. Figure 4.28 is an Eh-pH diagram for groundwater also from the A nest. Field chemistry data are tabulated in Appendix F.

The pH depth profile is similar to that of the Puce Road site and typical of groundwater of the St. Clair Clay Plain. Groundwaters at all depths sampled generally possess a neutral pH.

The temperature profile shows a generally decreasing trend with depth, similar to that observed at the Puce Road site. A sharp break in the slope of the profile is observed at approximately one metre below the grey silty clay till interface suggesting that there is some hydraulic connection between the weathered zone and

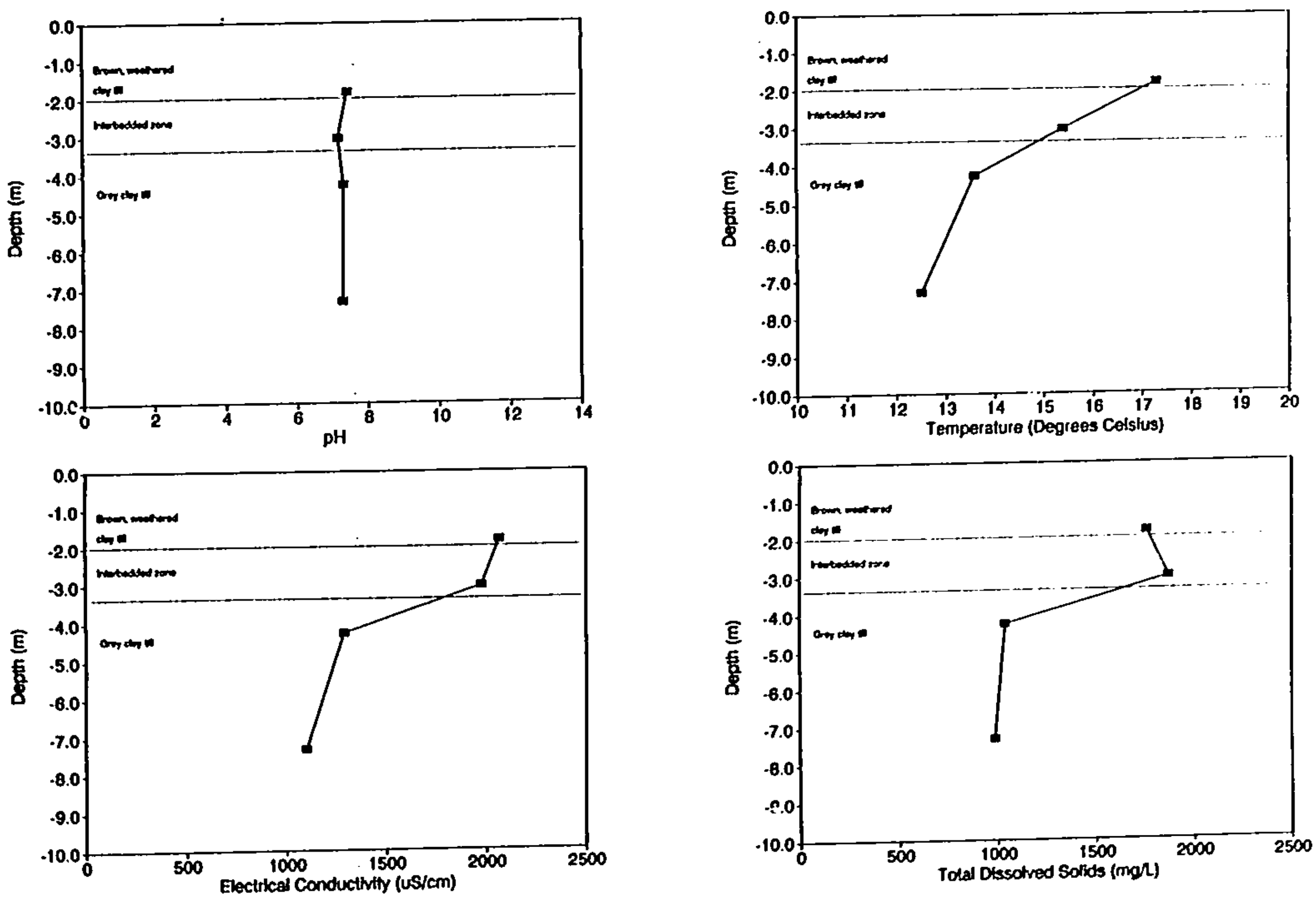


Figure 4.27. Field chemistry parameter depth profiles for the Whelan Farm site A nest.

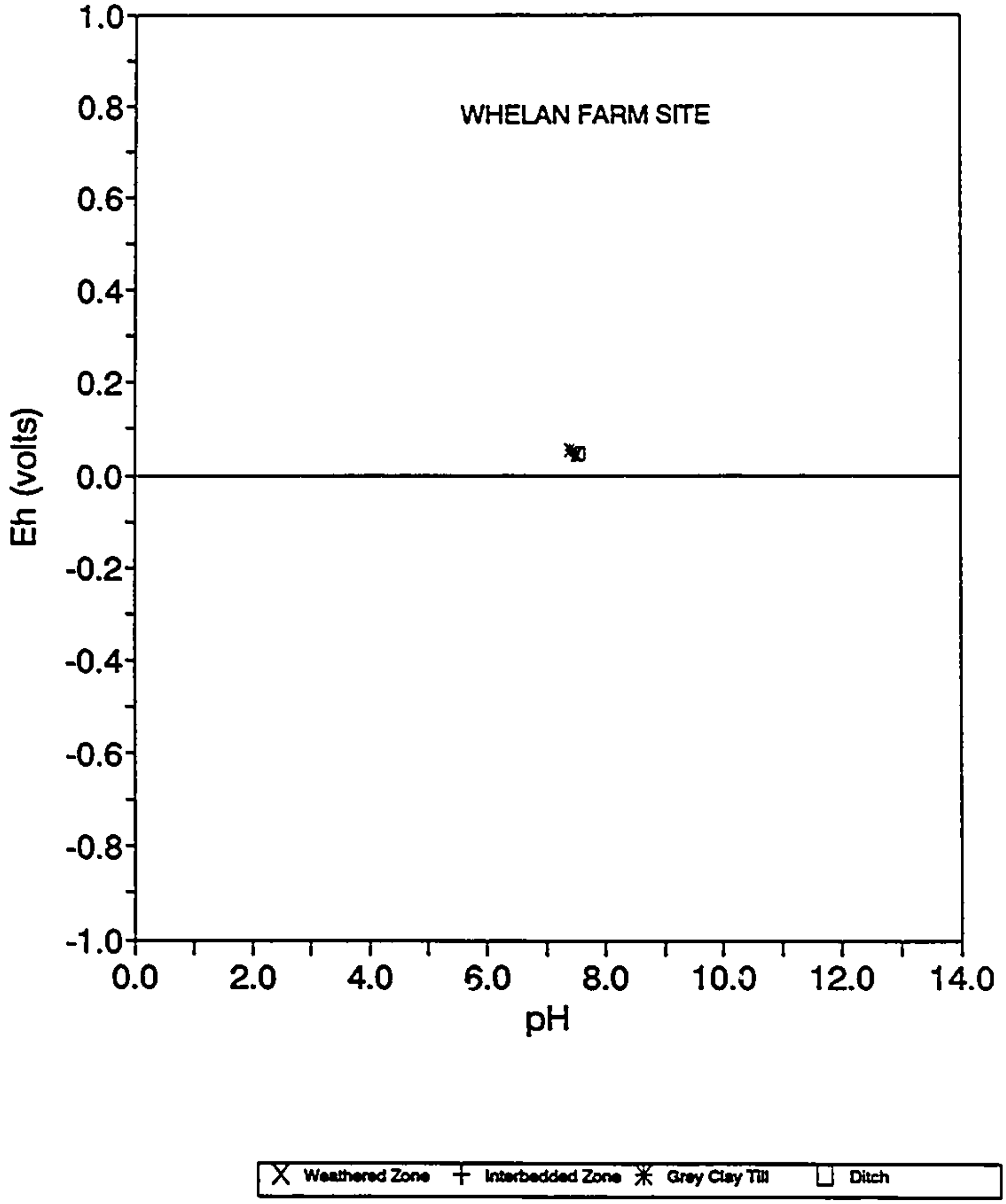


Figure 4.28. Eh-pH diagram for groundwater from the Whelan Farm site.

the top of the underlying grey silty clay till. This also suggests that the HPZ at this site is connected to the surface.

The EC and TDS profiles, as expected, mimic the pattern of the total major ion concentration with depth. The EC and TDS trends with depth are also similar to those observed at the Puce Road site. EC and TDS are high in the weathered zone and sharply decrease at the grey clay interface suggesting that there is a poor degree of hydraulic connection between the weathered zone and the underlying till units. The similarity of EC and TDS in the weathered till and in the interbedded zone implies that the two units are hydraulically connected.

An examination of the Eh-pH plot for groundwater from the A nest (Figure 4.28) reveals that, as with groundwater from the Puce Road site, Eh-pH signatures from all depths sampled are almost identical. Probable reasons for this occurrence were discussed in Section 4.4.2.1.

4.5 Isotopic Techniques for Determining Hydraulic Connection

4.5.1 Oxygen-18 and Deuterium

4.5.1.1 Puce Road Site

The isotope data are tabulated in Appendix G.

Prior to interpretation of the stable isotope data, δ^2H was plotted against $\delta^{18}O$ to ensure that the groundwater samples had not been evaporated during the sampling and analytical procedures (Figure 4.29). The data points were compared to two meteoric water lines established for southwestern Ontario: (1) the meteoric water

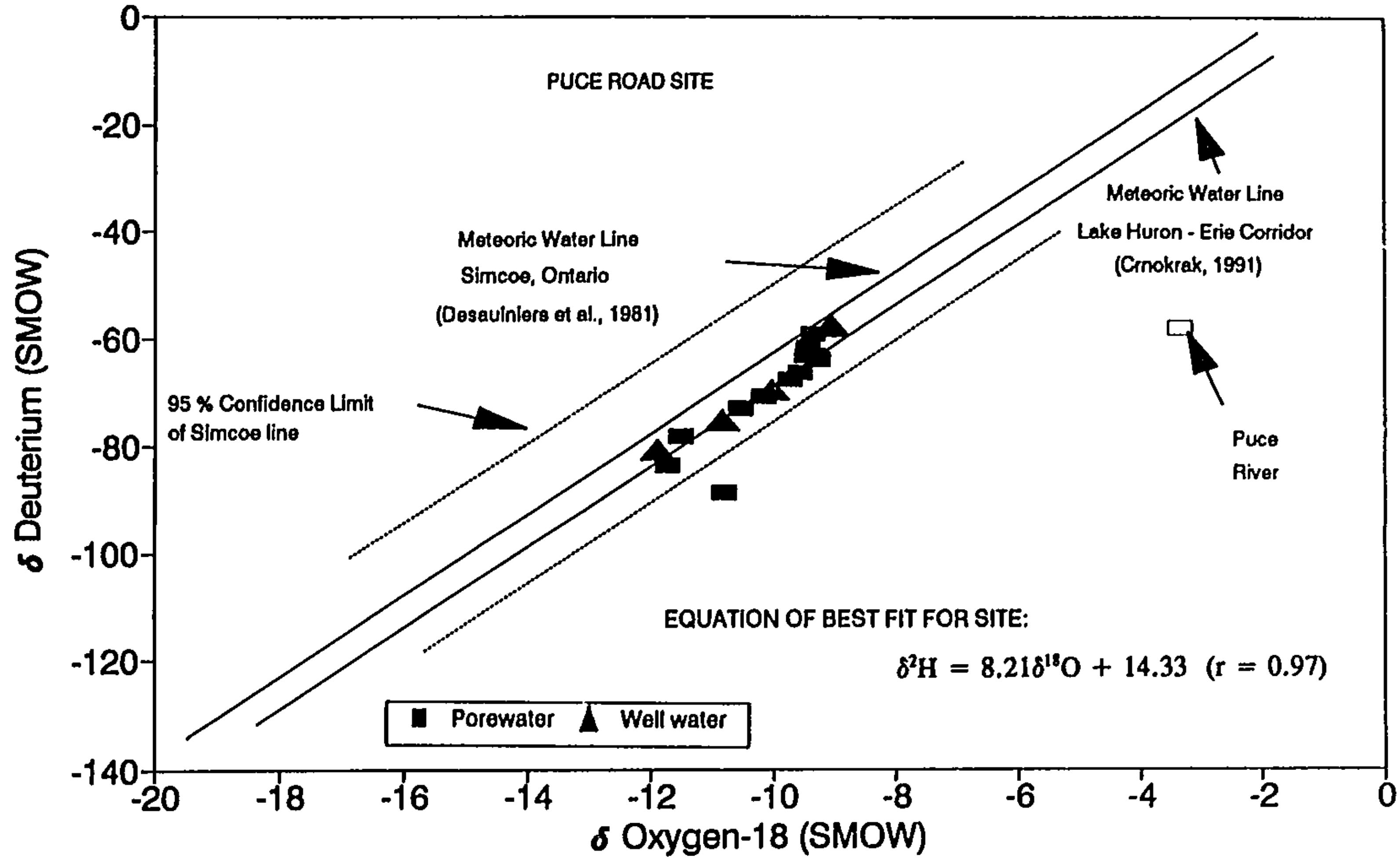


Figure 4.29. ^{2}H vs. ^{18}O for all Puce Road site water samples.

line established by Desaulniers et al. (1981) from precipitation at Simcoe, Ontario (Equation 9) and (2) the meteoric water line established by Crnokrak (1991) from well water samples from the basal sand aquifer (freshwater aquifer) in the Lake Huron to Lake Erie Corridor (Equation 10).

An analysis of Figure 4.29 reveals that all squeezed porewater and well water samples, except the squeezed sample from 6.7 to 7.3 metres, fall within the 95% confidence limit of the meteoric water line for Simcoe, Ontario established by Desaulniers et al. (1981). Most of the data points fall on the meteoric water line established by Crnokrak (1991). The squeezed sample from 6.7 to 7.3 m plots well off the meteoric water lines because its δ^2H value is relatively highly depleted. This anomalous value may be attributed to laboratory error.

As indicated by Fontes (1980), waters that have been evaporated will plot on slopes of between 2 and 5. The slope of the line of the data points from the Puce Road site samples is 8.2 which is slightly higher than 7.5, the slope of the Desaulniers et al. (1981) and Crnokrak (1991) lines. Brathwaite (1988) also obtained a slope of 7.5 for groundwater samples collected near the Puce Road site C nest. The correlation coefficient (r) of all Puce Road site samples is 0.97. Therefore, the samples have not been affected by evaporation and it may be concluded that the porewater extraction procedure used in this study is an effective means of obtaining groundwater for isotopic analyses at discrete depths. As expected, the isotopic signature of the Puce River sample plots well off the meteoric water line, indicating that it has been evaporated.

The ^{18}O versus depth profiles for well water and porewater samples are shown in Figure 4.30. The ^{2}H data show a similar trend with depth. These profiles are similar to the predicted profile shown in Figure 3.12b, suggesting that there is poor hydraulic connection between the interbedded zone and the ground surface. Throughout the weathered zone and the upper half of the grey silty clay till unit, groundwater possesses $\delta^{18}O$ values between -9 and -10°/$_{\infty}$, indicating that this water originated under modern climatic conditions. Below this depth (5.5 m), the $\delta^{18}O$ signature of the groundwater gradually becomes more depleted. A $\delta^{18}O$ value of -11.73°/$_{\infty}$ was found at a depth of 8.8 m, the deepest sampling point.

The observed ^{18}O profile was compared to a simulated profile to verify that the ^{18}O profile is diffusion controlled (Figure 4.31). In this simulation, the mean annual $\delta^{18}O$ concentration of precipitation is assumed to change quickly from a value of -18°/$_{\infty}$ to the present day average of about -9°/$_{\infty}$. Based on the review by Farvolden and Cherry (1988), this change is assumed to have occurred approximately 12,000 years before present. The relative $\delta^{18}O$ concentration (C/C_o) was calculated for discrete depths from the ground surface down to bedrock using the solution to Fick's second law (Equation 5). A diffusion coefficient of 3×10^{-10} m^2/s was used, based on the work of Desaulniers et al. (1981). The best match between the observed and simulated profiles is obtained when the simulated profile is displaced about four metres below the ground surface (Figure 4.31). This displacement corresponds closely to the thickness of the weathered and fractured zone. This implies that "modern" water rapidly infiltrates the weathered zone and then migrates downward by

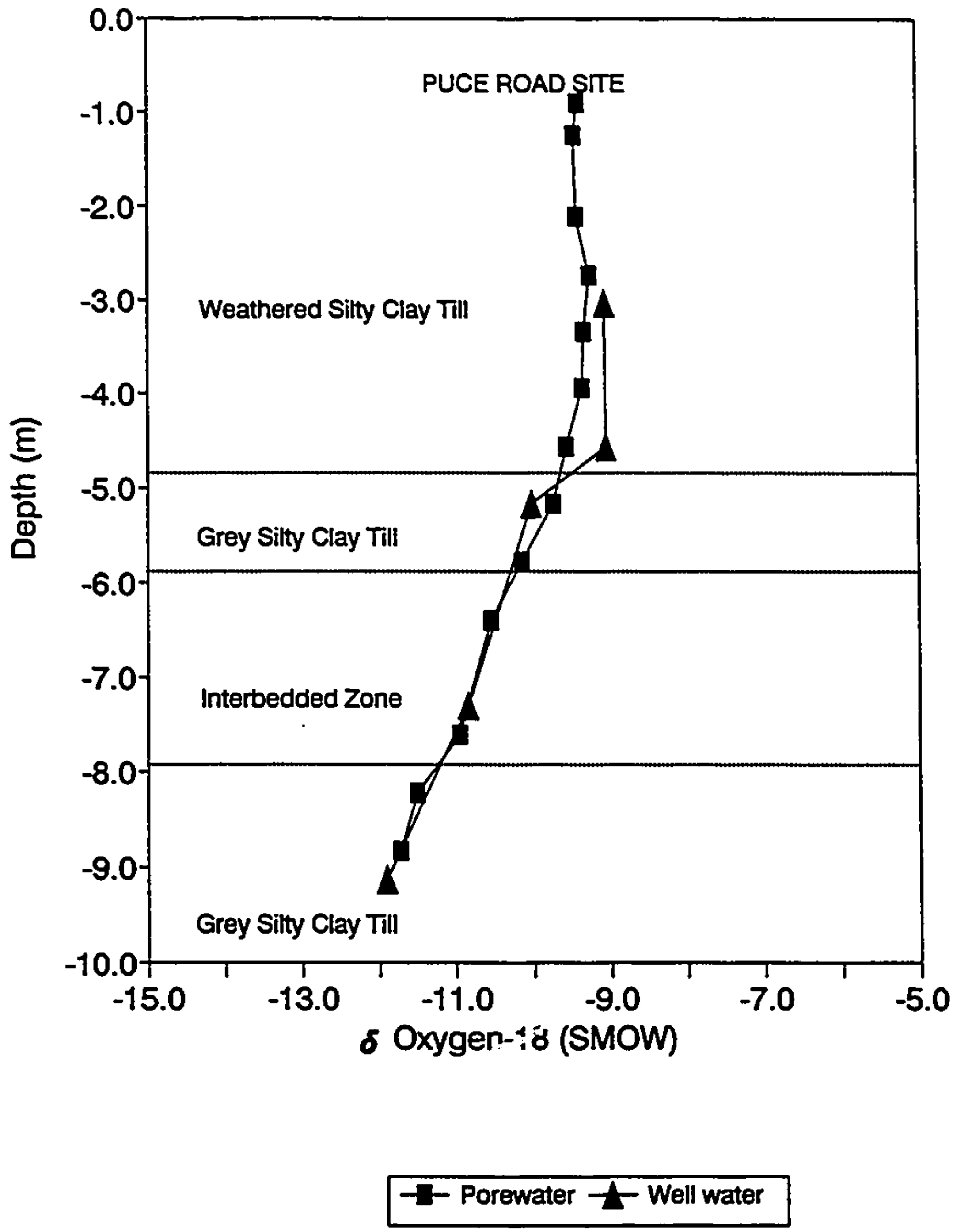


Figure 4.30. ^{18}O depth profile for well water and porewater samples from the Puce Road site B nest.

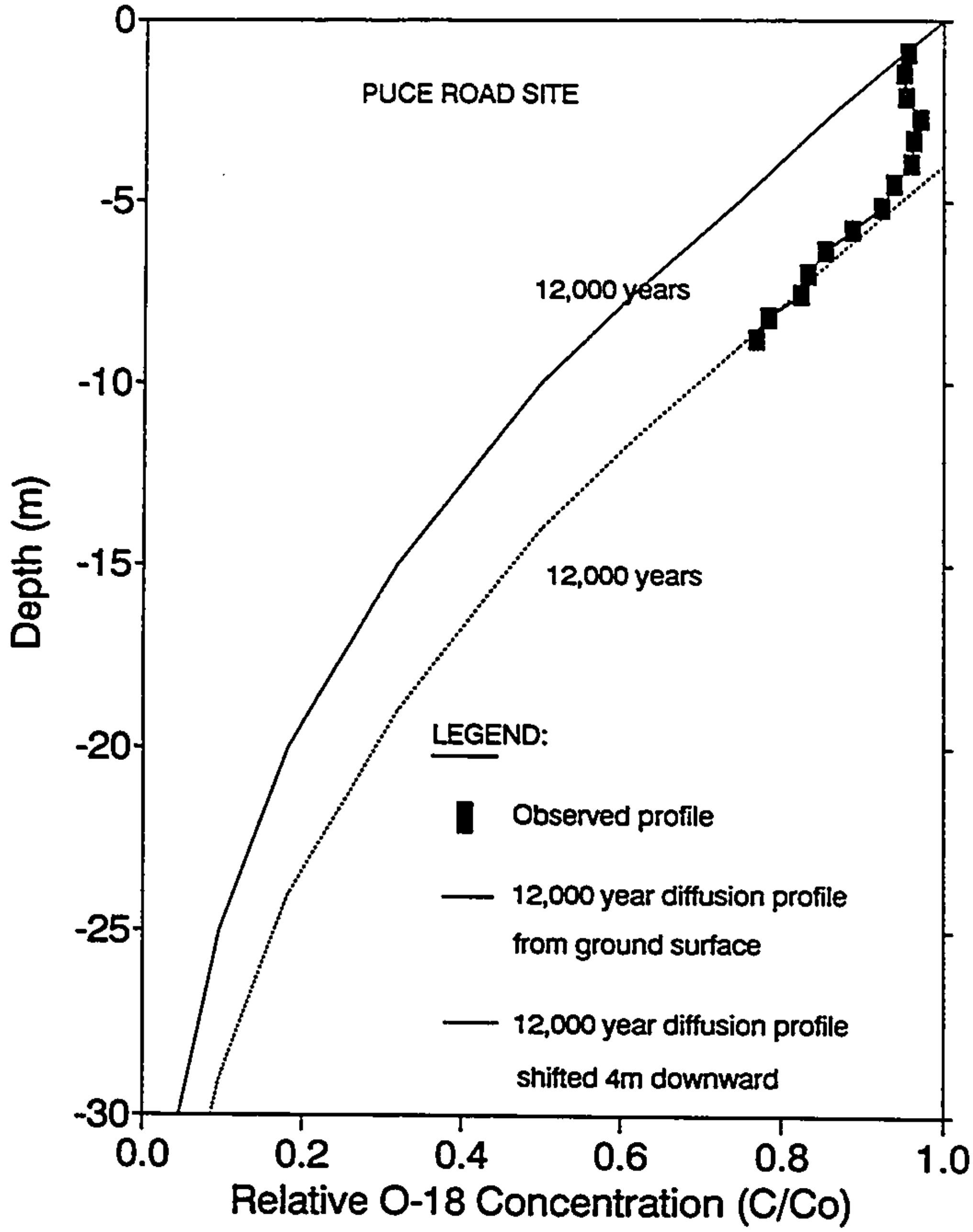


Figure 4.31. Comparison of simulated and observed ^{18}O profiles at the Puce Road site.

molecular diffusion.

4.5.1.2 Whelan Farm Site

Prior to analysis of the stable isotope data, δ^2H was plotted against $\delta^{18}O$ to ensure that the groundwater samples had not been evaporated during the sampling and analytical procedures (Figure 4.32). As with the Puce Road site, the data points were compared to the meteoric water lines established by Desaulniers et al. (1981) and Crnokrak (1991).

An analysis of Figure 4.32 reveals that all samples fall within the 95% confidence limit of the meteoric water line for Simcoe, Ontario established by Desaulniers et al. (1981). The line created by the data points closely resembles the meteoric water line established by Crnokrak (1991). As indicated by Fontes (1980), waters that have been evaporated will plot on slopes of between 2 and 5. The slope of the line of the data points from the Whelan Farm site samples is 6.5 which is slightly lower than 7.5, the slope of the Desaulniers et al. (1981) and Crnokrak (1991) lines. The correlation coefficient (r) of all Whelan Farm site samples is 0.998. Therefore, the well samples have not been affected by evaporation.

The ^{18}O versus depth profile for well water samples is shown in Figure 4.33. The ^2H data show a similar trend with depth. These profiles are similar to the predicted profile shown in Figure 3.12a, suggesting that the interbedded zone is hydraulically connected to the ground surface. Throughout the weathered zone, the interbedded zone, and about the upper two metres of the grey silty clay till unit,

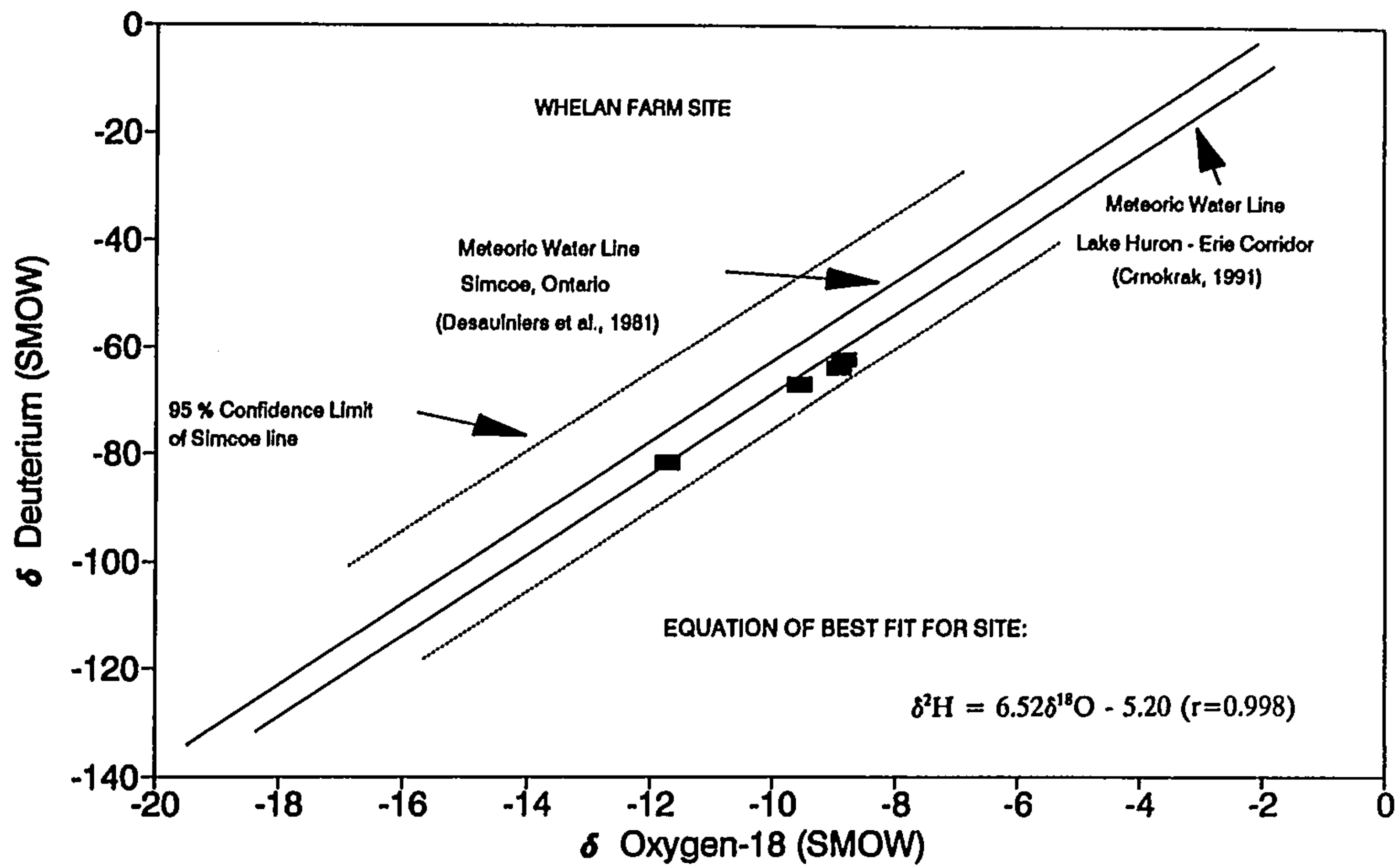


Figure 4.32. ^2H vs. ^{18}O for all Whelan Farm site water samples.

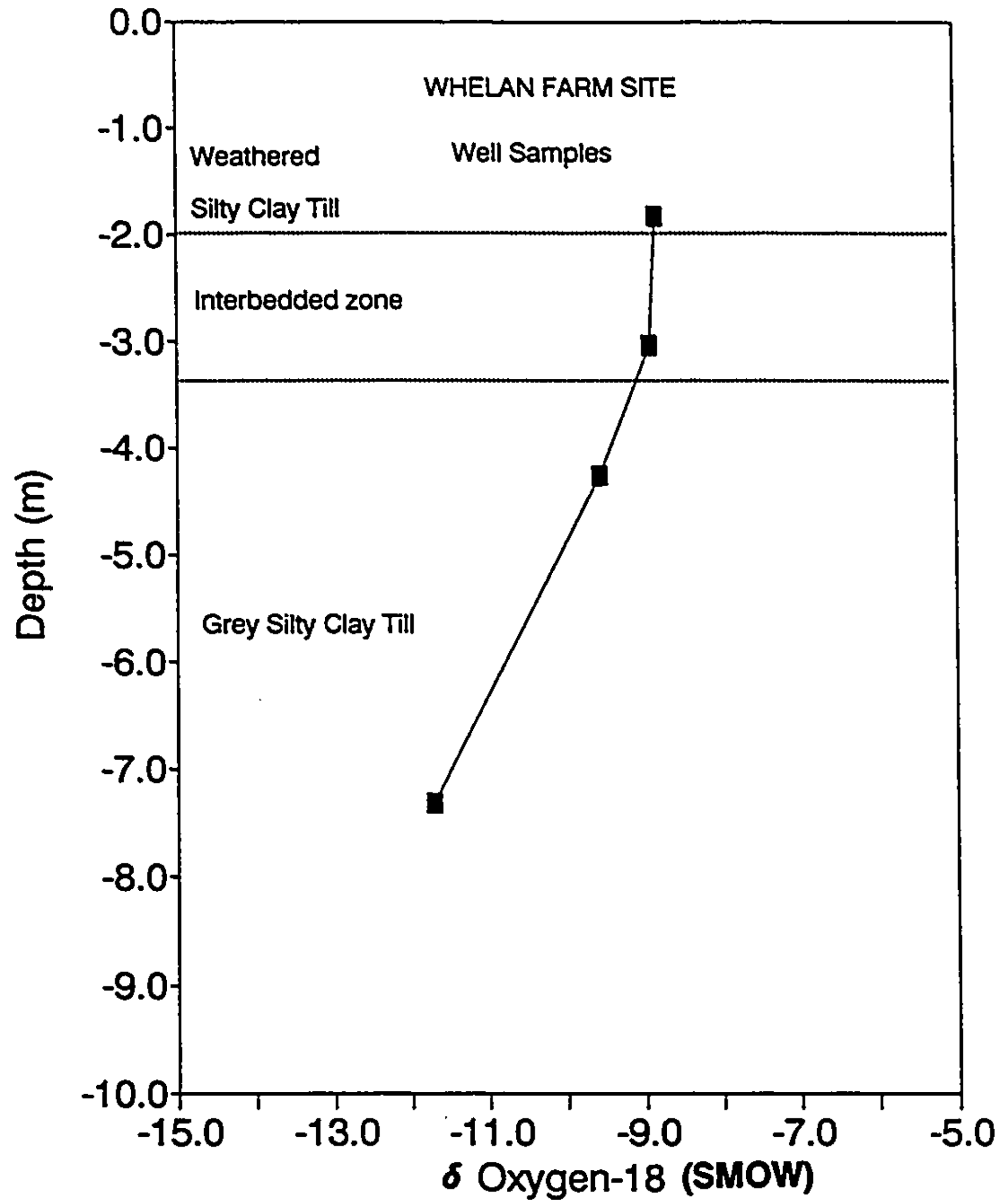


Figure 4.33. ^{18}O depth profile for well water samples from the Whelan Farm site.

groundwater possesses $\delta^{18}O$ values between -9 and -10°/$_{oo}$, indicating that this water originated under modern climatic conditions. Below this depth, the $\delta^{18}O$ signature of the groundwater gradually becomes more depleted. A $\delta^{18}O$ value of -11.5°/$_{oo}$ was found at a depth of 7.3 m, the deepest sampling point.

The observed ^{18}O profile was compared to a simulated profile to verify that the ^{18}O profile is diffusion controlled (Figure 4.34). The assumptions and input parameters for this simulation were the same as those for the Puce Road site. The best match between the observed and simulated profiles is obtained when the simulated profile is displaced about three metres below the ground surface (Figure 4.34). This displacement corresponds closely to the thickness of the weathered and fractured zone. This implies, as with the Puce Road site, that "modern" water rapidly infiltrates the weathered zone and the interbedded zone and then migrates downward by molecular diffusion.

4.5.2 Tritium

4.5.2.1 Puce Road Site

Tritium in well water samples from the Puce Road site B nest is plotted against depth in Figure 4.35. This profile is similar to the predicted profile shown in Figure 3.14b, implying that there is poor hydraulic connection between the interbedded zone and the ground surface.

The presence of high tritium values in the weathered zone characteristic of present-day (post-bomb) precipitation indicates that the weathered unit is

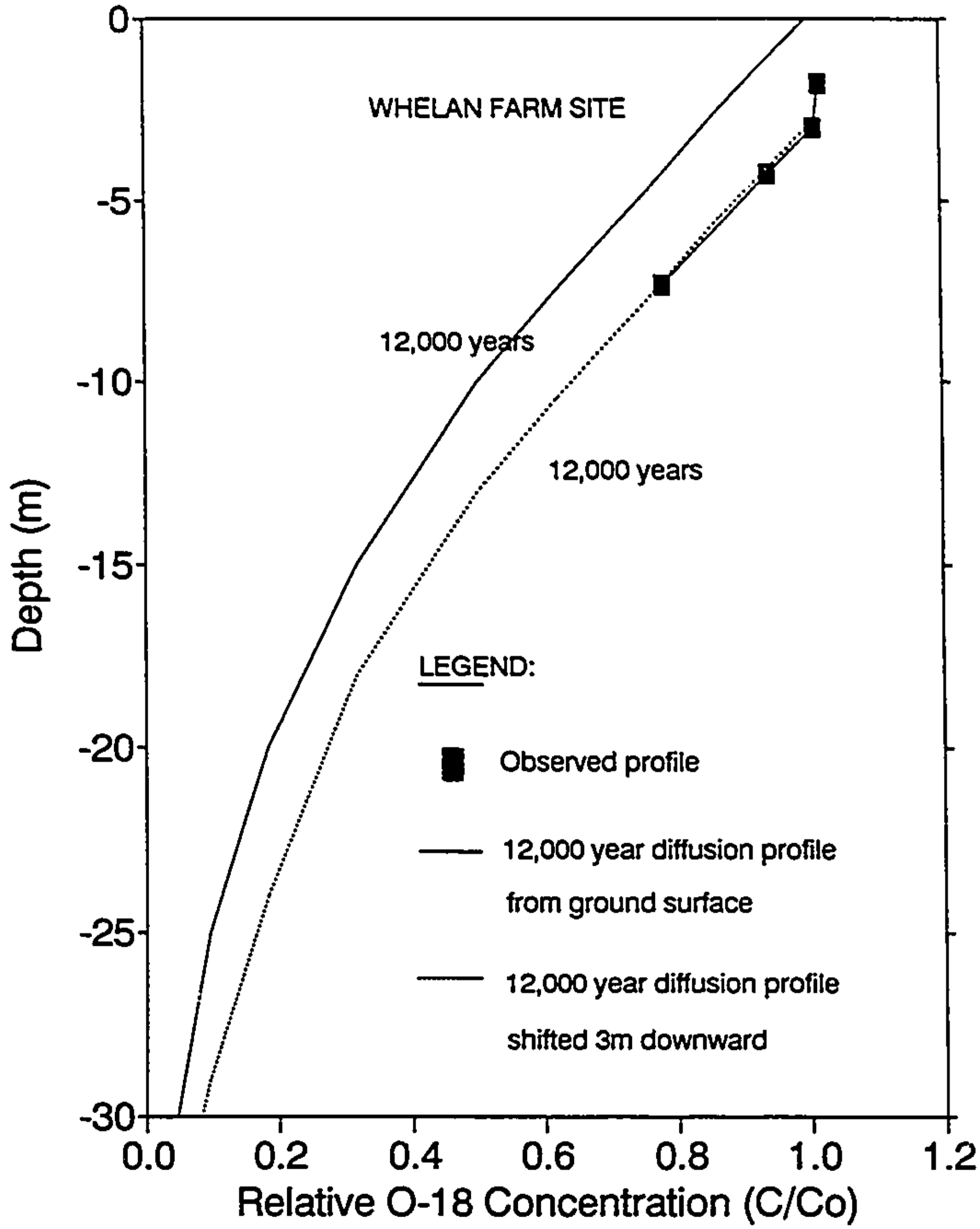


Figure 4.34. Comparison of simulated and observed ^{18}O profiles at the Whelan Farm site.

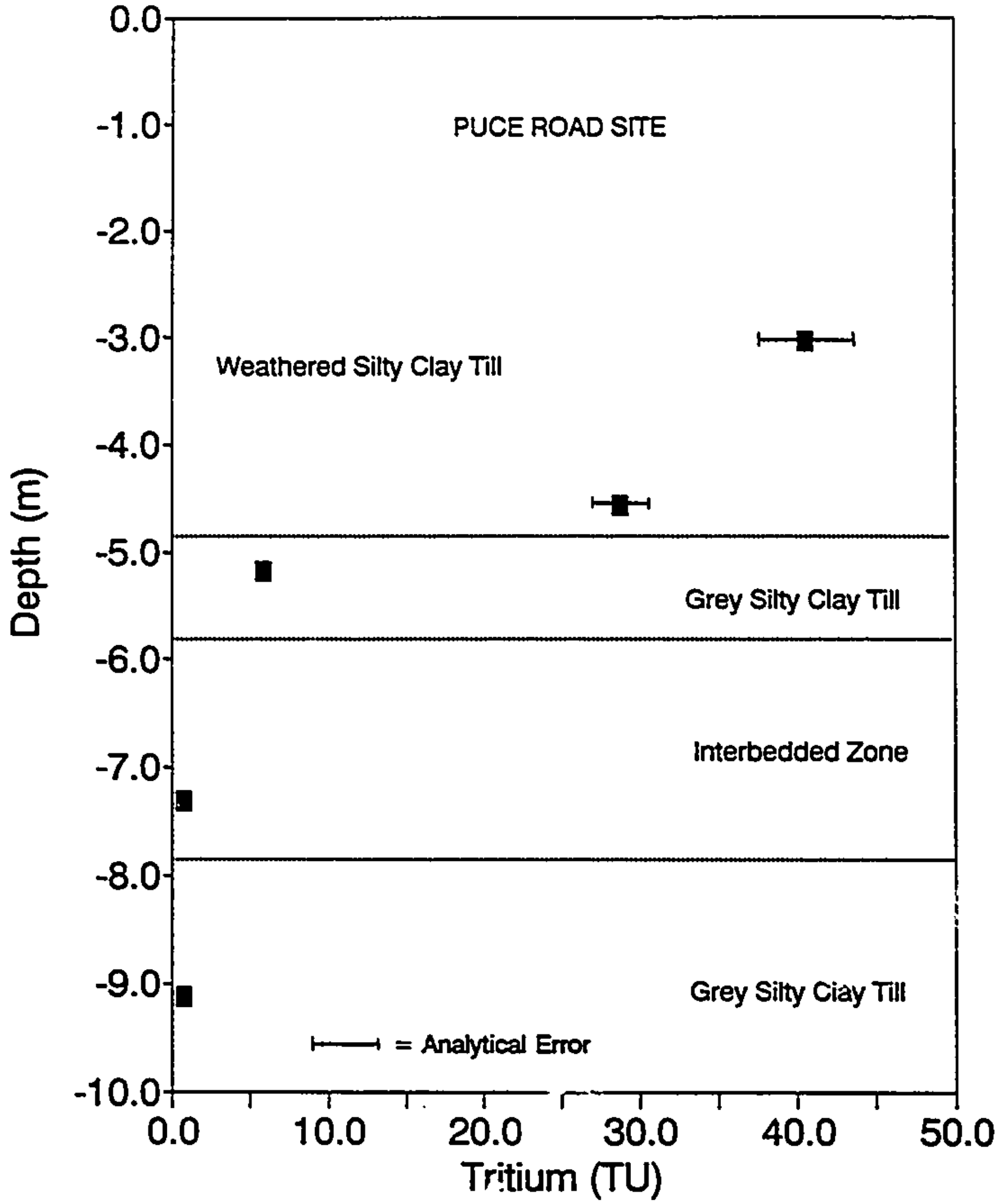


Figure 4.35. Tritium depth profile for the Puce Road site B nest.

hydraulically connected to the ground surface. Tritiated water was detected in well B-3 installed in the upper grey silty clay till unit but not in well B-4 or B-5 installed in the interbedded zone and the lower grey silty clay unit, respectively. This indicates that post 1952 precipitation has presently reached depths of somewhere between 5.5 and 7.3 m. These findings are consistent with tritium simulations performed by Desaulniers (1986) using the solution to Fick's second law (adjusted for radioactive decay of tritium) for tritium input conditions measured at Ottawa, Ontario. This simulation demonstrates that if fractures terminate at a depth of 3.5 m and if large concentrations of tritium penetrated to this depth rapidly beginning in 1953, diffusion would cause tritium at detectable levels (> 1 TU) to now occur to a depth of about 6.5 m. This simulation is also consistent with the ^{18}O profiles for the Puce Road site which show that modern water has penetrated to a depth of about six metres.

4.5.2.2 Whelan Farm Site

Tritium in well water samples from the Whelan Farm site is plotted against depth in Figure 4.36. This profile is similar to the predicted profile shown in Figure 3.14a, implying that the interbedded zone is hydraulically connected to the ground surface.

The presence of high tritium values in the weathered zone, the interbedded zone, and the upper metre of the grey silty clay till unit in concentrations typical of present-day precipitation indicates that these units are hydraulically

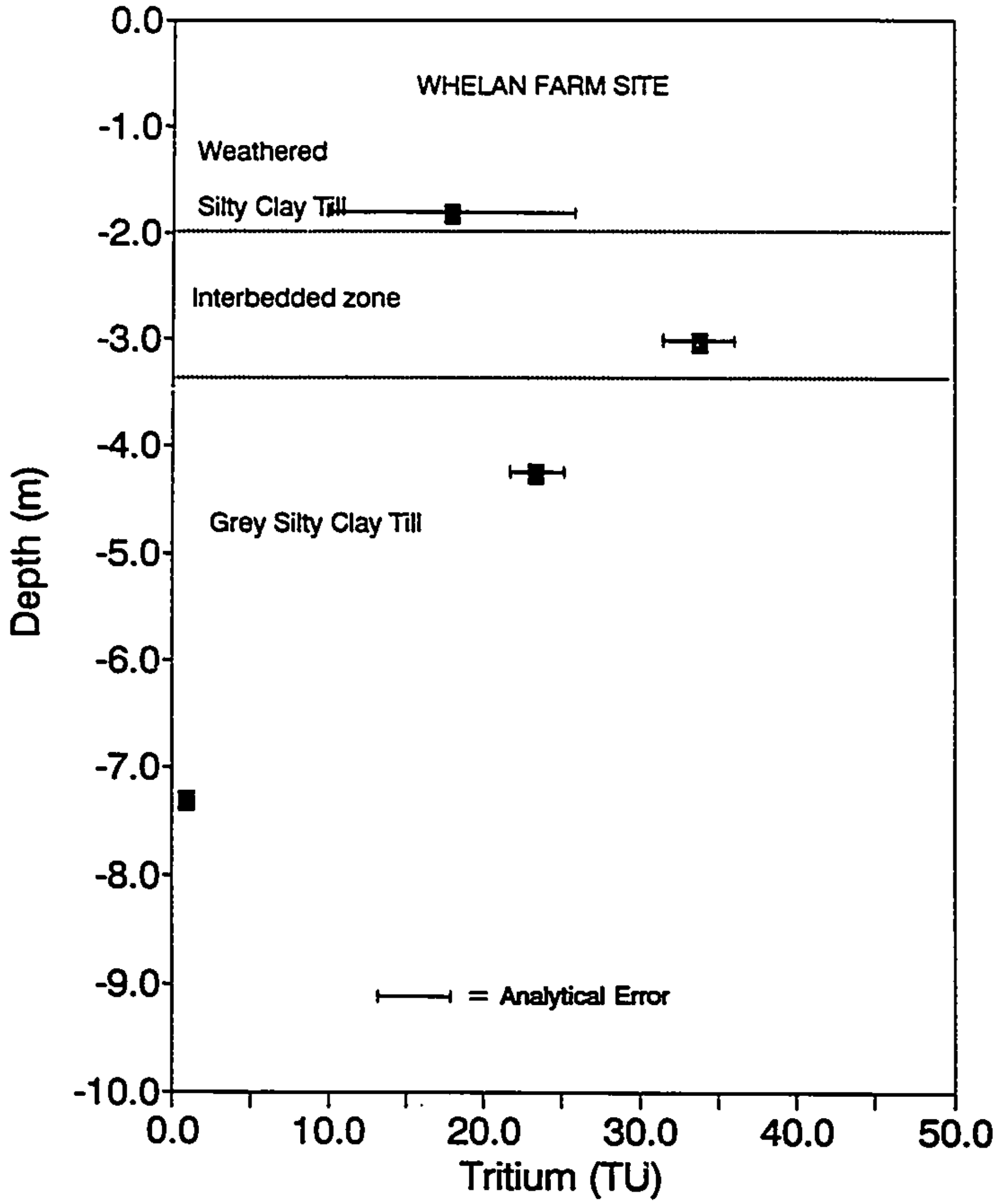


Figure 4.36. Tritium depth profile for the Whelan Farm site A nest.

connected to the ground surface. The higher concentration of tritium in the interbedded zone than in the weathered zone above may reflect the accumulation of water in this unit over decades. The fact that tritiated water was detected in well A-3 installed shallow in the grey silty clay till unit but not in well A-4 installed deeper in the grey silty clay unit indicates that post 1952 precipitation has presently reached depths of somewhere between 4.3 and 7.3 m. These findings are consistent with those of the Puce Road site and also with tritium simulations performed by Desaulniers (1986). The tritium profile is also consistent with the ^{18}O profile for the Whelan Farm site which shows that modern water has penetrated to a depth of about five metres.

4.6 Bacteriological Techniques for Determining Hydraulic Connection

The results presented in this section are summarized from Holder-Franklin et al. (1991).

Analysis of the results of the Pb and Cd tolerance study revealed that a total of 97% of the isolates are tolerant to 100 mg/L Pb and a total of 24% of the isolates are tolerant to 100 mg/L Cd. Bacterial tolerance to 100 mg/L Pb and Cd at different depths is shown in Figure 4.37.

An examination of Figure 4.37 shows that bacteria are tolerant to Pb and Cd at all depths but are more tolerant near the ground surface (i.e. in the weathered unit). However, Pb and Cd were found to be present in greater concentrations in shallow groundwater. Pb was present in concentrations ranging from 25 to 65 μg/L

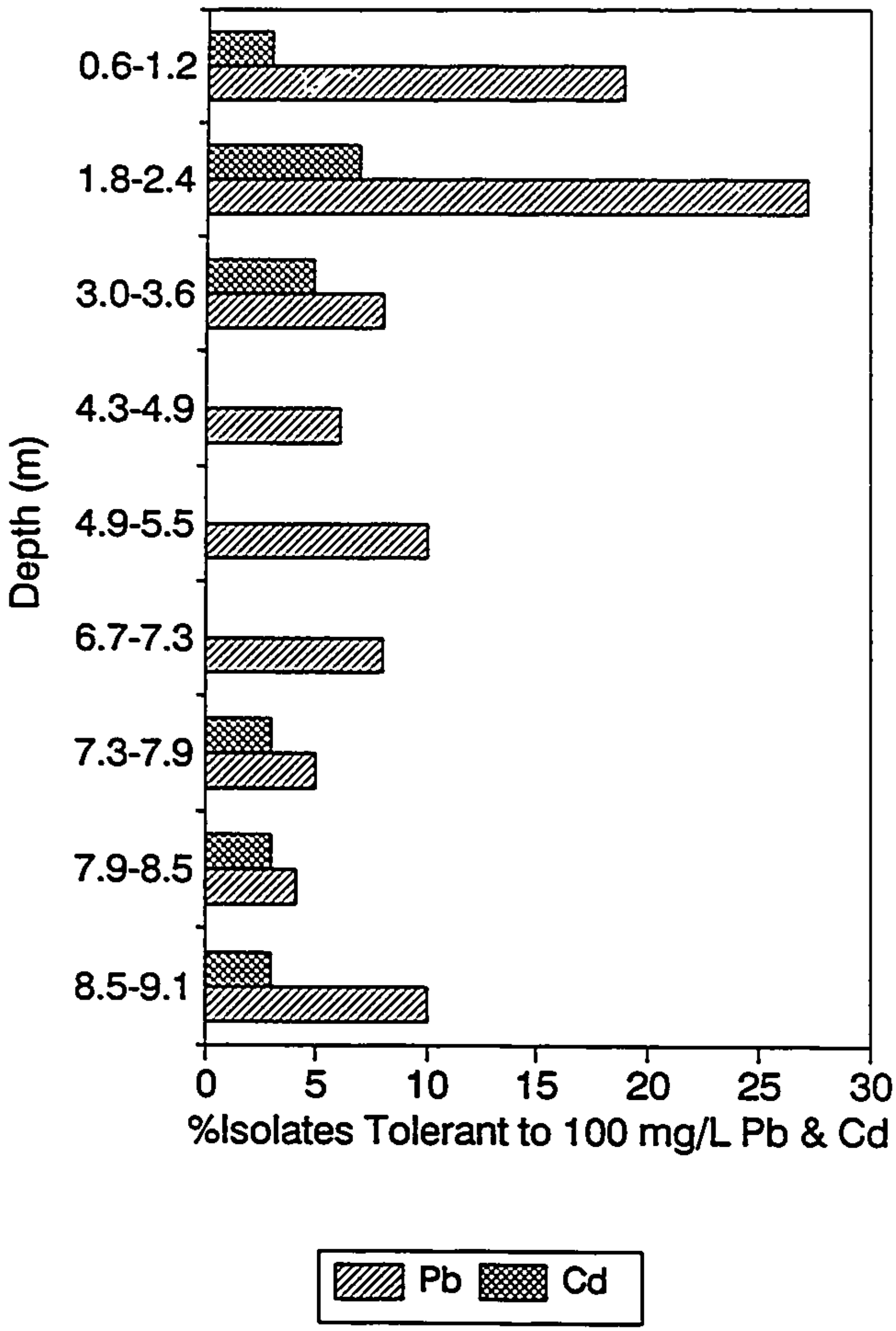


Figure 4.37. Depth profile of bacterial tolerance to 100 mg/L Pb and Cd at the Puce Road site (after Holder-Franklin et al., 1991).

and Cd was present in concentrations ranging from 2 to 10 μg/L (Holder-Franklin et al., 1991). Below the weathered zone, Pb and Cd were present in groundwater at concentrations near the method detection limit of approximately 1 μg/L. The elevated concentrations of these metals in groundwater in the weathered unit is most likely due to release of these metals from soil during weathering processes. Also, the presence of these metals in the weathered zone may be due to inputs from anthropogenic activities. The much higher tolerance of the isolates to Pb than to Cd may be attributed to the difference in background concentrations of these metals in the soil. Pb is typically present in soils of southwestern Ontario at concentrations of about 20 milligrams per kilogram (mg/kg) and Cd is typically present at concentrations of about 1 mg/kg (Dragun and Chiasson, 1991).

Bacterial tolerance to 1000 mg/L Pb is shown in Figure 4.38. None of the isolates were tolerant to 1000 mg/L Cd. The fact that isolates were tolerant to such a high concentration of Pb at all depths indicates that the bacteria have had a long exposure to Pb (Holder-Franklin et al., 1991).

Results of the numerical taxonomic classification of bacterial isolates showed that there is a mixture of bacteria existing throughout the depth profile (Holder-Franklin et al., 1991). In other words, bacterial populations were not unique to discrete depths. Rather common types of soil bacteria were found to be distributed throughout the various levels of sampling (Holder-Franklin et al., 1991).

Bacterial counts (in colony forming units (CFU)) in soil and groundwater at various depths are shown in Figure 4.39. An examination of this figure reveals that

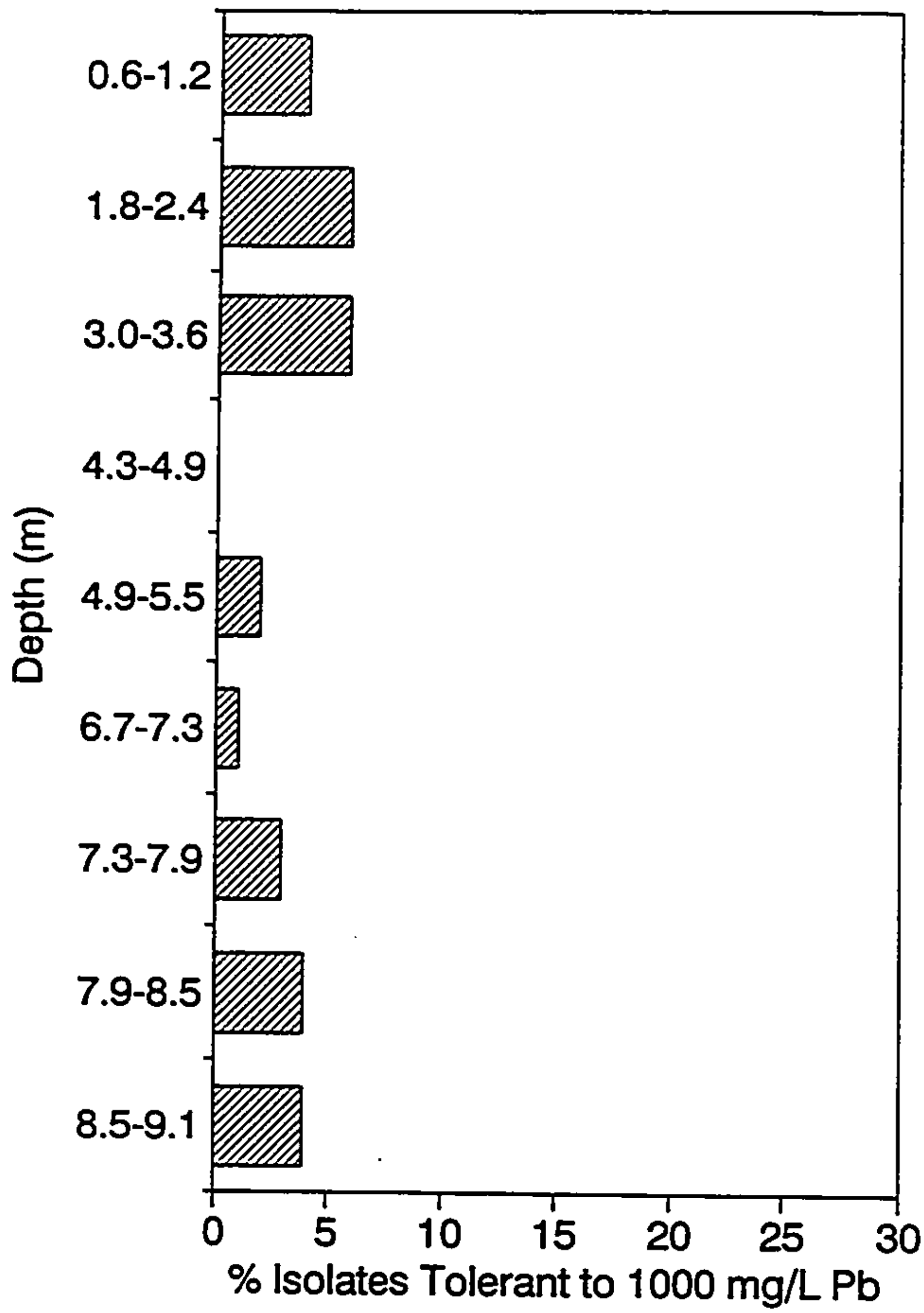


Figure 4.38. Depth profile of bacterial tolerance to 1000 mg/L Pb at the Puce Road site (after Holder-Franklin et al., 1991).

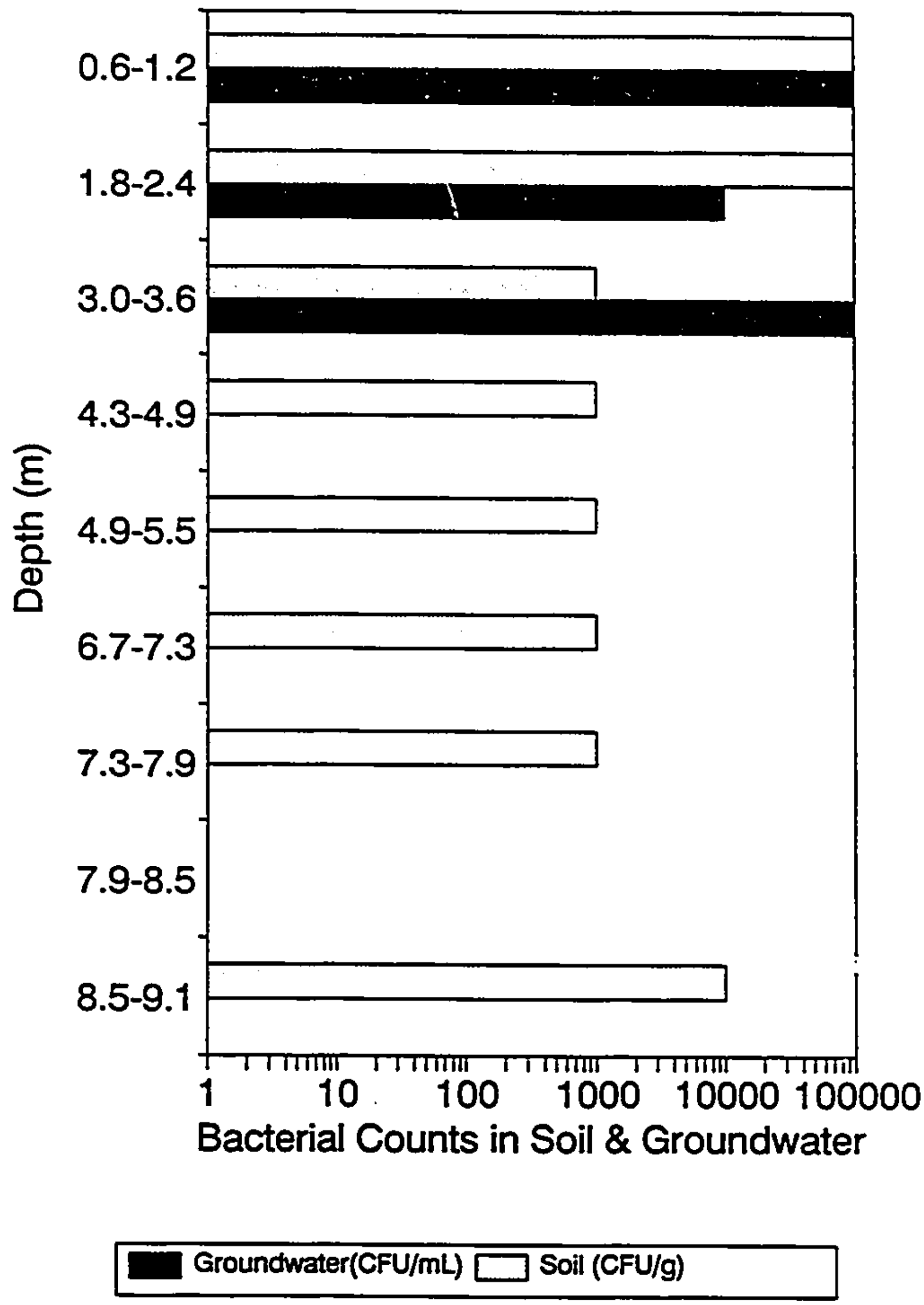


Figure 4.39. Depth profile of bacterial counts in soil and groundwater at the Puce Road site (after Holder-Franklin et al., 1991).

bacterial populations predominate near the ground surface in the weathered zone. The most important feature observed in analysis of the bacterial counts at different depths is that bacteria are essentially absent in groundwater below the weathered zone (i.e. below a depth of approximately 3.7m). As predicted by Equation (11), bacteria will only migrate through clayey soil if fractures or macropores are present. In unfractured clays, bacteria migration is restricted by filtration. Therefore, based on bacterial counts in groundwater, the most active groundwater flow occurs in the weathered zone to a depth of about 4 m. Below this zone, fracture flow does not appear to be an important mechanism of solute transport. This also suggests that bacteria present in soil below this depth may have existed there since the origin of the deposit some 15,000 years ago, assuming that groundwater transport is the only mechanism by which bacteria can migrate through the soil. These long residence times of the bacteria in the soil may explain their high tolerance to Pb.

In summary, numerical taxonomy analysis revealed that bacteria are not unique to discrete depths. Pb tolerance studies of isolates showed that the bacteria at all depths have had a long exposure to Pb. Cd tolerance studies of isolates showed that the bacteria are much less tolerant to Cd than to Pb. Bacteria are more tolerant to both Pb and Cd in the weathered zone than in the deeper clays. Bacterial counting analysis revealed that bacteria are essentially absent in groundwater below the weathered zone implying that fractures diminish below this zone. Assuming that bacteria can only migrate with groundwater, bacterial populations found at depths below the weathered zone may have originated when the soil was deposited.

5.0 DISCUSSION OF RESULTS

This chapter compares and evaluates the effectiveness of the hydraulic connection tests examined in this study. The results of the techniques are compared to results obtained from conventional field permeability testing. Where a test was not conducted at both sites (i.e. bacteriological tests), its effectiveness is compared to other tests performed at the same site. Finally, a series of tests are recommended that could be reliably employed to determine the degree of hydraulic connection of an HPZ to the ground surface.

The traditional method of estimating groundwater flow velocity is with the use of the Darcy equation for average linear groundwater velocity (Equation 1). An inspection of this equation reveals that if hydraulic conductivity (K), hydraulic gradient (i), and effective porosity (n) are known, groundwater velocity can be calculated. However, based on the results of this study, determination of accurate values of all three of these parameters in clays is uncertain.

Hydraulic conductivity values obtained from field permeability tests conducted at the Puce Road site and at the Whelan Farm site are consistent with others reported throughout the St. Clair Clay Plain (Table 2.3). Some difficulties in determining K in fractured clay media have been discussed in Chapter 1.

The determination of an accurate hydraulic gradient value is also difficult. During the course of this study, significant seasonal water level fluctuations were observed in piezometers which resulted in gradient reversals. Therefore, the direction of groundwater flow in clayey deposits is not always constant. Similar observations were noted by Ruland et al. (1991).

Estimating a value for effective porosity is also an uncertain task. For example, the intergranular porosity of clayey soils is approximately 0.40 to 0.70 (Freeze and Cherry, 1979) but Grisak (1975) obtained an effective fracture porosity of 0.0002.

For the purpose of estimating vertical groundwater flow velocity, assume that hydraulic conductivity of a fractured clay soil is approximately isotropic. Therefore, the mean vertical hydraulic conductivity of the weathered zone at the Puce Road site is approximately 2×10^{-9} m/s. Using an intergranular porosity of 0.28 (after M.M. Dillon, 1988) and a downward gradient of 0.05, Equation 1 predicts that the average linear vertical groundwater flow velocity in the weathered zone is approximately 11 mm/year. Using an effective porosity of 0.01 (after M.M. Dillon Limited, 1988), the vertical groundwater velocity is approximately 0.32 m/year. If an effective porosity of 0.0002 (after Grisak, 1975) is assumed, the vertical groundwater velocity is about 16 m/year. M.M. Dillon Limited (1988) estimated a vertical velocity of 1 m/year in the weathered zone using an estimated hydraulic conductivity of 1×10^{-8} m/s. Hydraulic conductivity was estimated because the actual mean value of 5×10^{-10} m/s was rejected as being too low. This dilemma demonstrates that the use of the Darcy equation for estimating groundwater flow velocity in fractured clays is questionable and unreliable.

The task of characterizing groundwater flow is a difficult one due to the complex nature of the subsurface environment. The literature has rigorously focussed on methods of accurately determining bulk hydraulic conductivity of low permeability soils. The other Darcy parameters (i and n) have received little to no attention. Consequently, practical methods of estimating groundwater flow rates in low permeability media have been obscured. The study of low permeability environments seems to have been influenced by experience with more permeable soils (Neuzil, 1986).

The ability to test conceptual models of flow in low permeability environments is severely limited by the constraints of time; response on a large scale takes too long to observe (Neuzil, 1986). This difficulty is nearly impossible to overcome by technological or analytical advances. In assessing the degree of hydraulic connection of an HPZ to the ground surface, a diverse suite of techniques is needed to obtain with confidence the most accurate picture of groundwater behaviour. Therefore, perhaps the only way around this problem is to seek indirect evidence for longer-term flow behaviour in low permeability media by studying processes which have been operative for long periods of time (Neuzil, 1986). This can be best accomplished by using natural groundwater tracers (i.e isotopes and bacteria).

The isotopic techniques yielded the most conservative estimate of the degree of hydraulic connection of an HPZ to the ground surface. "Conservative", from a waste disposal site selection point of view, refers to the greatest degree of hydraulic connection of an HPZ to the ground surface. Further, of the techniques tested, the isotopic techniques are the only ones that can give a quantitative estimate of groundwater age because their input functions are reasonably well-established. Therefore, based on the results of this study, isotopic techniques are the most favourable in assessing vertical groundwater flow in clay tills above HPZs.

At the Puce Road site, tritium was detected in the grey clay unit but not in the HPZ. This is consistent with oxygen-18 data which showed that groundwater in the HPZ is not of modern origin. Similarly, tritium and oxygen-18 data were consistent in showing that groundwater in the HPZ at the Whelan Farm site is modern. Since isotopes are natural tracers of groundwater flow, size and time scale problems associated with hydraulic testing of piezometers are not encountered. In fact, piezometers are not even necessary in conducting these tests. Groundwater can be obtained by soil squeezing. The isotope tests conducted in this study are rapid and inexpensive.

The results of bacteriological tests conducted at the Puce Road site, namely the bacterial counting test, agreed fairly well with the isotope tests, showing that the depth of active groundwater flow does not extend much beyond the weathered zone. As with isotopes, bacteria are natural tracers of groundwater flow. The use of bacteria as tracers can give some insight into the maximum depth penetration of larger-sized particles. The numerical taxonomy test needs to be refined, however, to identify particular species of bacteria to see if certain species are unique to discrete depths.

The results of the physical tests employed in this study were also consistent with the isotopic data. Although not performed at the Whelan Farm site, determination of the storage coefficient by pulse interference testing was consistent with isotope results in showing that the HPZ below the Puce Road site is confined. Because this test is conducted in the HPZ, it does not have the time limitations associated with other tests. Also, because the HPZ is generally composed of coarser-grained material, the possibility of borehole smearing is reduced. The use of pulse interference tests to infer vertical hydraulic connection or disconnection was also in agreement with isotope data. However, this test is a subjective one. If a drawdown response is observed in a well, one can be sure that there is a connection between the pulsed well and the observation well. However, if no response is observed in an observation well, one cannot be sure that the converse is true because responses in piezometers can be masked by poor borehole completion.

The induced infiltration test results were consistent with isotope data and pulse interference tests in concluding that the HPZ at the Whelan Farm site is hydraulically connected to the surface. An estimate of hydraulic conductivity of the weathered zone after Artz and Metzler (1985) yielded values three to four orders of magnitude higher than K values reported in the literature. However, using this value in the Darcy equation, as previously discussed, is questionable. The tests conducted at the Puce Road site yielded inconclusive results due to the proximity of a drainage ditch which collected the infiltrating water. Responses were not observed in piezometers installed in the weathered zone where isotopic data showed the groundwater to be modern. It is therefore likely that a longer recharge time is required in environments where the HPZ is relatively deep. The results can therefore be ambiguous because if no response is observed in wells, one is not sure if the HPZ is too deep or if it is unconnected to the ground surface. These shortcomings limit the practicality of the test. However, the results of the infiltration test at the Puce Road site imply that an isolated release of chemicals at the surface will preferentially migrate laterally in such environments where the HPZ is relatively deep.

Fluctuations in hydraulic head over long periods of time proved to be useful in estimating the depth of active groundwater flow. However, this test is subjective and cannot give any insight into how quickly groundwater flows vertically. The main disadvantage of this test is that it requires long periods of time (i.e. at least one year after static levels have been achieved) to conduct and it requires that the water in the piezometer not be disturbed (i.e. if the piezometer is sampled, more time will be required for the water level to re-equilibrate). However, if piezometers are required at a site for long-term monitoring, this simple test can give a good indication as to the depth of active groundwater flow.

The geochemical methods tested in this study proved to be ineffective in assessing vertical groundwater movement. Groundwater chemistry appears to be influenced more by weathering processes occurring in the tills than by vertical groundwater flow. This particularly was evident in the upper portion of the grey silty clay till unit at both the Puce Road site and the Whelan Farm site. At this depth, groundwater possesses detectable concentrations of tritium, meaning that this water is modern (post 1952). However, the similarity in major ion content of groundwater in the upper grey till to that of deeper untritiated groundwater suggests that poor or no hydraulic connection exists between the upper grey till unit and the weathered zone. Therefore, groundwater chemistry data is inconsistent with the tritium data. The use of Eh-pH diagrams also proved to be ineffective in assessing vertical groundwater flow, probably because all dissolved oxygen is used up near the ground surface. The use of anthropogenic contaminants (i.e. Cl^- and NO_3^-) in assessing vertical groundwater flow is questionable without knowing their input times and concentrations and their background concentrations in groundwater.

Based on the results of this study, the following suite of tests are recommended to determine the degree of hydraulic connection of an HPZ to the ground surface:
(1) Determine the distribution of environmental isotopes (oxygen-18, deuterium, and tritium) with depth. The distribution of these isotopes in groundwater can be used to determine the depth of penetration of recharged water over the past 40 years.
(2) Determine the vertical distribution of naturally-occurring bacteria present in groundwater. This examination can give some insight in to the maximum depth penetration of larger-sized particles. These data may be extrapolated to predict the maximum depth penetration of colloids and organic chemicals in the soil.
(3) Determine the storativity (S) of the HPZ by pulse interference tests. At the same time, responses in piezometers installed in shallower units can be used to infer vertical hydraulic connection.
(4) Demonstrate hydraulic connection/disconnection and estimate the bulk hydraulic conductivity of clayey soil overlying a shallow HPZ using an induced infiltration test.
(5) Determine the depth of active groundwater flow by long-term monitoring of water level fluctuations in piezometers (if feasible).

6.0 CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this study was to develop a series of rapid tests which can be employed at a site to determine whether or not an HPZ within otherwise low permeability soil could facilitate the spread of groundwater contamination. This study examined and evaluated four major techniques for evaluating hydraulic connection of HPZs to the ground surface. These techniques consisted of: (1) physical (hydraulic) tests, (2) geochemical tests, (3) isotopic tests, and (4) bacteriological tests. The test results were compared to results obtained from conventional field permeability testing. The techniques were employed at two sites characterized by different hydrogeologic environments (i.e. with sand lenses at different depths). The two sites selected were the Maidstone Municipal Office and Maidstone Roads Department Properties (Puce Road site) and Agriculture Canada Substation, Eugene F. Whelan Experimental Farm (Whelan Farm site) in Essex County, Ontario.

6.1 Conclusions

A series of tests which can be employed at a site to determine whether or not an HPZ could facilitate the spread of groundwater contamination, based on the results of this study, is summarized in Figure 6.1. Based on the results of this study, the following conclusions are drawn:

(1) The conventional method of estimating vertical groundwater flow velocity using the Darcy equation is questionable in low permeability media. Significant uncertainties that exist in all parameters in the Darcy equation make its applicability

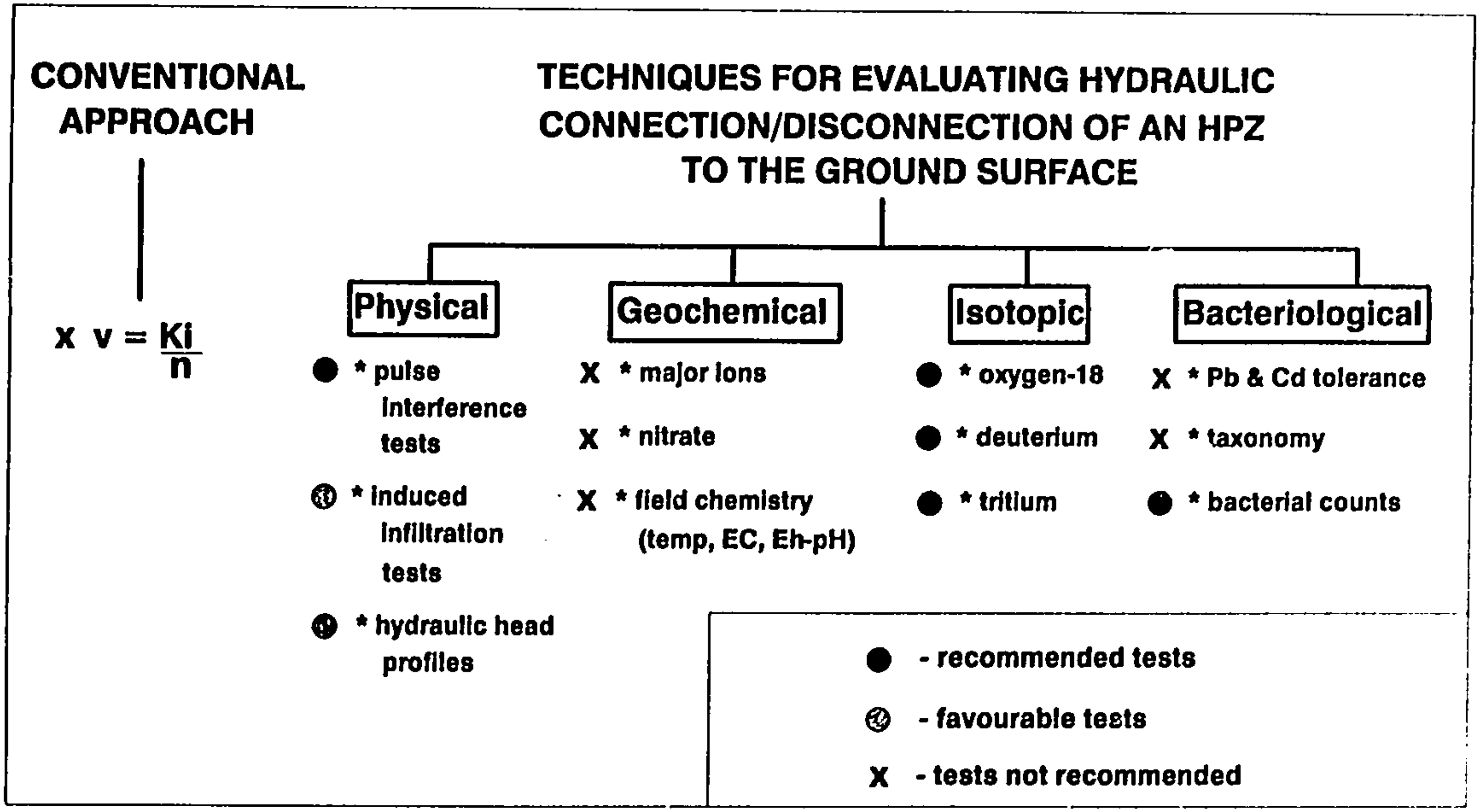


Figure 6.1. Summary chart of tests examined in this study showing recommended tests, favourable tests, and tests not recommended for determining whether or not an HPZ could facilitate the spread of groundwater contamination.

unreliable in low permeability environments.

(2) The only way to overcome the fundamental difficulties in observing groundwater flow behaviour in low permeability environments may be to seek indirect evidence of flow behaviour from processes which have been occurring over longer periods of time. This can best be accomplished by using natural groundwater tracers.

(3) Isotopic techniques are the most favourable methods for estimating the degree of hydraulic connection of an HPZ to the ground surface. Isotopes are natural groundwater tracers. They yielded the most conservative estimate of the degree of hydraulic connection of an HPZ to the ground surface. Further, they are the only method that can give a quantitative estimate of groundwater age. Environmental isotopes (oxygen-18, deuterium, and tritium) can be used to determine the depth of penetration of recently recharged waters, thus giving a indication of vertical groundwater flow rates. Their low cost and relative ease of measurement also make these techniques the most practical.

(4) Bacteriological techniques, namely the bacterial counting test, agreed with the isotopic tests in showing that active groundwater flow does not extend much beyond the weathered zone. The use of bacteria as tracers of groundwater flow can give some insight in to the maximum depth penetration of larger-sized particles (i.e. colloids and organic molecules).

(5) Determination of storativity of an HPZ by pulse interference testing of the HPZ is also effective in determining if the HPZ is hydraulically connected to the ground surface. The pulse interference test can also be used to infer hydraulic connection to

other units by checking for drawdown responses in these units. The main disadvantage of this test is that the effects on hydraulic properties of low permeability fractured soils caused by auger disturbance during piezometer installation remains unclear. However, these problems can be minimized when testing an HPZ since HPZs are generally less fractured and contain less clay than the tills. Pulse interference testing is therefore a good test to augment data obtained from isotopic studies.

(6) Induced infiltration test results were consistent with isotope and pulse interference tests in showing that the HPZ at the Whelan Farm site is hydraulically connected to the ground surface. At the Puce Road site (where the HPZ is much deeper) results implied that an isolated chemical release will tend to flow laterally rather than vertically in environments where an HPZ is relatively deep.

(7) Monitoring seasonal water level fluctuations in piezometers is effective in determining the depth of active groundwater flow. The main disadvantage of this test is that it requires a time period of over a year to conduct.

(8) Geochemical techniques are not effective in estimating vertical groundwater flow velocity in fractured clay soils. Major ion content of groundwater in clayey deposits appears to be impacted more by weathering processes occurring in the tills rather than by vertical transport of constituents from the weathered zone by groundwater flow. At both sites tested, tritium was detected in groundwater in the grey clay unit where major ion geochemistry implied that this unit was not connected to the surface. Therefore, major ions are not conservative tracers of groundwater movement. Since

electrical conductivity of groundwater is directly related to major ion content, this field chemical parameter likewise is not effective in estimating the degree of hydraulic connection of an HPZ to the ground surface.

Using anions added to the subsurface by human activities (i.e. chloride and nitrate) as groundwater tracers is questionable because their input concentrations and times are often not known. Further, groundwater in the St. Clair Clay Plain contains varying background concentrations of both these constituents.

The use of Eh-pH diagrams in estimating the degree of hydraulic connection of an HPZ to the ground surface is also ineffective. Eh-pH signatures of groundwater at both sites studied showed no variation with depth. pH does not vary due to the buffering capabilities of the clay minerals in the soil. Eh is very low and does not vary probably because all dissolved oxygen is removed from infiltrating waters by organic-rich topsoil.

6.2 Recommendations

Based on the results of this study, the following recommendations are made:

(1) More information is required regarding the geology and occurrence of HPZs in southwestern Ontario. Southwestern Ontario is only generally mapped and HPZs have received little geologic attention.

(2) The effectiveness of the chlorine-36 isotope should be evaluated for determining hydraulic connection of an HPZ to the ground surface. The usefulness of tritium is declining because of its short half life. ^{36}Cl holds some promise in replacing tritium

in future years as an indicator of recent groundwater recharge.

(3) The possibility of using radioisotopes from fallout from the Chernobyl nuclear accident as groundwater tracers should be explored.

(4) The potential for using trichlorofluoromethane as a groundwater tracer in fractured clay soils should be evaluated.

(5) Bacteriological studies need to be refined to be able to identify species of bacteria. This test may be used to determine if certain species are unique to discrete depths.

REFERENCES

Adams, J.I., 1970. Effect of groundwater levels on stress history of the St. Clair clay till deposit: discussion. Canadian Geotechnical Journal, 7, pp. 190-193.

American Public Health Association, 1989. Standard Methods for the Examination of Water and Wastewater. American Water Works Association, Water Pollution Control Federation, Washington, D.C., 1191 p.

American Society for Testing and Materials, 1985. Annual Book of ASTM Standards, Volume 11.02, Water and Environmental Technology. ASTM, Philadelphia, 1124 p.

Artz, N.S. and Metzler, S.C., 1985. Losses of stored waste oil from below-ground tanks and the potential for groundwater contamination. *In* Proceedings of the National Conference on Hazardous Wastes and Environmental Emergencies, May 14-16, 1985, Cincinnati, Ohio, pp. 60-65.

Baas Becking, L.G.M., Kaplan, I.R., and Moore, D., 1964. Limits of the natural environment in terms of pH and oxidation-reduction potentials. Journal of Geology, 68, pp. 243-284.

Bear, J., 1972. Dynamics of Fluids in Porous Media. American Elsevier, New York, New York. 764 p.

Bentley, H.W., Phillips, F.M., and Davis, S.N., 1986. Chlorine-36 in the terrestrial environment. *In* Handbook of Environmental Isotope Geochemistry, Vol.2, Fritz, P. and Fontes, J.Ch. (eds.). Elsevier, Amsterdam, pp. 427-480.

Brathwaite, S.L.A, 1988. An investigation of hydraulic connection of sand lenses in silty clay till deposits of Essex County, Ontario. Unpbl. M.A.Sc. Thesis, University of Windsor, Windsor, Ontario, 157 p.

Broadbent, F.E., 1971. Nitrogen in soil and water. *In* Symposium on Nitrogen Soil Water, University of Guelph, Guelph, Ontario, 56 p.

Chapman, L.J. and Putnam, D.F., 1984. The Physiography of Southern Ontario, Third Edition. Ontario Geological Survey Special Volume 2, Ministry of Natural Resources.

Craig, H., 1961a. Standards for reporting concentrations of deuterium and oxygen-18 in natural waters. Science, 133, p. 1833-1834.

Craig, H., 1961b. Isotopic variations in meteoric water. Science, 133, pp. 1702-1703.

Crank, J., 1956. The Mathematics of Diffusion. Oxford University Press, Oxford. 347 p.

Cravens, S.J. and Ruedisili, L.C., 1987. Water movement in till of east-central South Dakota. Ground Water, 25, 5, pp. 555-561.

Crnokrak, B., 1991. An environmental isotope and computer flow model investigation of the freshwater aquifer in the Lake Huron to Lake Erie Corridor. Unpbl. M.A.Sc. Thesis, University of Windsor, Windsor, Ontario, 122 p.

Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus, 16, pp. 436-468.

D,Astous, A.Y., Ruland, W.W., Bruce, J.R.G., Cherry, J.A., and Gillham, R.W., 1989. Fracture effects in the shallow groundwater zone in weathered Sarnia-area clay. Canadian Geotechnical Journal, 26, pp. 43-56.

Davis, S.N., 1988. Natural radionuclides in ground water. Journal of Geological Education, 36. pp. 24-29.

Day, M.J., 1977. Analysis of the hydrogeology and hydrogeochemistry of the Lake Agassiz clays in the Winnipeg area. Unpbl. M.Sc. Thesis, University of Waterloo, Waterloo, Ontario.

Desaulniers, D.E., Cherry, J.A., and Fritz, P., 1981. Origin, age and movement of pore water in argillaceous Quaternary deposits at four sites in southwestern Ontario. Journal of Hydrology, 50, pp. 231-257.

Desaulniers, D.E., 1986. Groundwater origin, geochemistry and solute transport in three major glacial clay plains of east central North America. Ph.D. thesis, University of Waterloo, Waterloo, Ontario, 450 p.

Desaulniers, D.E., Kaufman, R.S., Cherry, J.A., and Bentley, H.W., 1986. ^{37}Cl-^{35}Cl variations in a diffusion-controlled groundwater system. Geochimica et Cosmochimica Acta, 50, pp. 1757-1764.

Dragun, J., 1988. The Soil Chemistry of Hazardous Materials. Hazardous Materials Control Research Institute, Silver Spring, Maryland, 458 p.

Dragun, J. and Chiasson, A., 1991. Elements in North American Soils. Hazardous Materials Control Resources Institute, Greenbelt, Maryland, 230 p.

Dreimanis, A., 1961. Tills of southern Ontario. *In* Soils in Canada (R.F. Leggett, Ed.). Royal Society of Canada Special Publication 3, University of Toronto Press, pp. 80-96.

Driscoll, F.G., 1986. Groundwater and Wells. Johnson Filtration Systems Inc., St. Paul, Minnesota, 1089 p.

Dusseault, M.B. and Vorauer, A.G., 1986. Geomechanical investigation of near-surface fractures in clay tills, part 2: laboratory investigation of strength and mineralogy. *In* Proceedings of the Technology Transfer Conference, December 8-9, 1986, Sheraton Centre, Toronto, Part C.

Edwards, T.W.D. and Fritz, P., 1986. Assessing meteoric water composition and relative humidity from ^{18}O and ^{2}H in wood cellulose: paleoclimatic implications for southern Ontario. Applied Geochemistry, 1, pp. 715-723.

Edwards, T.W.D. and Fritz, P., 1988. Stable-isotope paleoclimate records for southern Ontario, Canada: comparison of results from marl and wood. Canadian Journal of Earth Sciences, 25, pp. 1397-1406.

Egboka, B.C.E., Cherry, J.A., Farvolden, R.N., and Frind, E.O., 1983. Migration of contaminants in groundwaters at a landfill: a case study, 3, tritium as an indicator of dispersion and recharge. Journal of Hydrology, 63, pp. 51-80.

Elmore, D., Fulton, B.R., Clover, M.R., Marsden, J.R., Gove, H.E., Naylor, H., Purser, K.H., Kilius, L.R., Beukens, R.P., and Litherland, A.E., 1979. Analysis of ^{36}Cl in environmental water samples using an electrostatic accelerator. Nature, 277, 4, pp. 22-25.

Epstein, S. and Mayeda, T.K., 1953. Variations of ^{18}O content of waters from natural sources. Geochimica et Cosmochimica Acta, 4, pp. 213-224.

Essop, S., 1986. Ground Water Quality Survey of Shallow Wells Situated within a 2 km Radius of Essex No. 3 Landfill Site, Township of Maidstone, County of Essex. Ontario Ministry of the Environment, July 1986.

Essop, S., 1988. Ground Water Quality Assessment of Shallow Wells Situated within a 3 km Radius of Essex No. 3 Landfill Site, Township of Maidstone, County of Essex. Ontario Ministry of the Environment, March 1988.

Farvolden, R.N. and Cherry, J.A., 1988. Region 15, St. Lawrence Lowland. *In* The Geology of North America, Volume O-2, Hydrogeology, The Geological Society of North America. Back, W., Rosenshein, J.S., and Seaber, P.R. (eds.), Chapter 18, pp. 133-140.

Fetter, C.W., 1988. Applied Hydrogeology, Second Edition. Merrill Publishing Co., Columbus, Ohio, 592 p.

Fontes, J.Ch., 1980. Environmental isotopes in groundwater hydrology. *In* Handbook of Environmental Isotope Geochemistry, Volume 1, The Terresterial Environment, Fritz, P. and Fontes, J. Ch. (eds.), Elsevier, Amsterdam, pp. 75-140.

Freeze, R.A. and Cherry, J.A., 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 604 p.

Fritz, P., Anderson, T.W., and Lewis, C.F.M., 1975. Late Quaternary climatic trends and history of Lake Erie from stable isotope studies. Science, 190. pp. 267-269.

Fritz, P., Cherry, J.A., Weyer, K.U., and Sklash, M.G., 1976a. Runoff analysis using environmental isotopes and major ions. *In* Interpretation of Environmental Isotope and Hydrochemical Data in Groundwater Hydrology, International Atomic Energy Agency, Vienna, pp. 111-130.

Fritz, P., Matthess, G., and Brown, R.M., 1976b. Deuterium and oxygen-18 as indicators of leachwater movement from a sanitary landfill. *In* Interpretation of Environmental Isotope and Hydrochemical Data in Groundwater Hydrology, International Atomic Energy Agency, Vienna, pp. 131-142.

Fritz, P. and Fontes, J. Ch., 1980. Handbook of Environmental Isotope Geochemistry, Volume 1 The Terresterial Environment. Elsevier, Amsterdam, 564 p.

Gillham, R.W. and Cherry, J.A., 1982. Contaminant migration in saturated unconsolidated geologic deposits. *In* Recent Trends in Hydrogeology, Geological Society of America Special Publication 189. T.N. Narisimhan (ed.), pp. 31-62.

Green, W.H. and Ampt, G.A., 1911. Studies on soil physics. Journal of Agricultural Science, IV, pp. 1-24.

Grisak, G.E., 1975. The fracture porosity of glacial till. Canadian Journal of Earth Sciences, 12, pp. 513-515.

Grisak, G.E. and Cherry, J.A., 1975. Hydrologic characteristics and response of fractured till and clay confining a shallow aquifer. Canadian Geotechnical Journal, 12, 23, pp. 23-43.

Groundwater Technology Canada Limited, 1991. County of Essex Landfill #3 Fracture Investigation, Draft Report, July, 1991, 98 p.

Hantush, M.S., 1967. Growth and decay of groundwater-mounds in response to uniform percolation. Water Resources Research, 3, 1, pp. 227-234.

Hem, J.D., 1970. Study and interpretation of the chemical characteristics of natural water. United States Geological Survey, Water-Supply Paper 1473, 363 p.

Hendry, M.J., 1982. Hydraulic conductivity of a glacial till in Alberta. Ground Water, 20, 2, pp. 162-169.

Hendry, M.J., 1988. Hydrogeology of clay till in a prarie region of Canada. Ground Water, 26, 5, pp. 607-614.

Hendry, M.J., 1988. Do isotopes have a place in ground-water studies? Groundwater, 26, 4, pp. 410-415.

Hoefs, J., 1987. Stable Isotope Geochemistry. Springer-Verlag, New York, 241 p.

Holder-Franklin, M.A., 1981. Methods of studying population shifts in aquatic bacteria in response to environmental change. Inland Waters Directorate, Ottawa, Canada, pp. 12-15.

Holder-Franklin, M.A., Favrin, K., Sklash, M., Chiasson, A., and Georges, S., 1991. Resistance to lead and cadmium in groundwater bacteria. Canadian Society of Microbiologists. 1991 Annual Meeting, Abstract.

Hunt, C.B., 1974. Natural Regions of the United States and Canada. W.H. Freeman and Company, San Francisco.

Hvorslev, M.J., 1951. Time lag and soil permeability in groundwater observations. United States Army Corps of Engineers Waterways Experimental Station Bulletin 36, Vicksburg, Mississippi, 50 p.

Johnson, R.L., Cherry, J.A., and Pankow, J.F., 1989. Diffusive contaminant transport in natural clay: a field example and implications for clay-lined waste disposal sites. Environmental Science & Technology, 23, 3, pp. 340-349.

Kaneko, T., Holder-Franklin, M.A., and Franklin, M., 1977. A multiple syringe inoculator for agar plates. Applied and Environmental Microbiology, 33, pp. 982-985.

Keller, C.K., van der Kamp, G., and Cherry, J.A., 1986. Fracture permeability and groundwater flow in clayey till near Saskatoon, Saskatchewan. Canadian Geotechnical Journal, 23, pp. 229-240.

Keller, C.K., van der Kamp, G., and Cherry, J.A., 1988. Hydrogeology of two Saskatchewan tills. Journal of Hydrology, 101, pp. 97-121.

Keller, C.K., van der Kamp, G., and Cherry, J.A., 1989. A multiscale study of the permeability of a thick clayey till. Water Resources Research, 25, 11, pp. 2299-2317.

Kruseman, G.P. and de Ridder, N.A., 1991. Analysis and evaluation of pumping test data, Second Edition. International Institute for Land Reclamation and Improvement Bulletin 11, Wageningen, The Netherlands, 377 p.

Lafleur, J., Giroux, F., and Huot, M., 1987. Field permeability of the weathered Champlain clay crust. Canadian Geotechnical Journal, 24, pp. 581-589.

Lambe, T.W., 1951. Soil Testing for Engineers. John Wiley & Sons, New York, New York, 165 p.

M.M. Dillon Limited, 1988. Essex County Landfill No. 3 Application for Continued Use, Hydrogeological Analysis, 171p.

Neuzil, C.E., 1986. Groundwater flow in low-permeability environments. Water Resources Research, 22, 8, pp. 1163-1195.

Ogata, A., 1970. Theory of dispersion in a granular medium. United States Geological Professional Paper 411-I.

Ontario Ministry of Natural Resources, 1975. Essex Region Conservation Report.

Ontario Ministry of the Environment (MOE), 1977. Water Well Records for Ontario, Essex 1946-1974. Water Resources Bulletin 2-19, Ground Water Series, 1977.

Ontario Water Resources Commission, 1971. Ground Water Probability, County of Essex, 1971. Water Resources Map No. 3107-1.

Orpwood, T.G., 1984. An evaluation of methods used to measure groundwater flow and transport characteristics in clayey deposits at two sites in Essex County, Ontario. Unpubl. M.A.Sc. Thesis, University of Windsor, Windsor, Ontario, 156 p.

Patterson, R.J., Frape, S.K., Dykes, L.S., and McLeod, R.A., 1978. A coring and squeezing technique for the detailed study of subsurface water chemistry. Canadian Journal of Earth Sciences, 15, pp. 162-169.

Payne, B.R., 1972. Isotope hydrology. Advances in Hydroscience, 8, pp. 95-138.

Phillips, F.M., Mattick, J.L., Duval, T.A., Elmore, D., and Kubik, P.W., 1988. Chlorine 36 and tritium from nuclear weapons fallout as tracers for long-term liquid and vapor movement in desert soils. Water Resources Research, 24, 11, pp. 1877-1891.

Prudic, D.E., 1982. Hydraulic conductivity of a fine-grained till, Cattaraugus County, New York. Ground Water, 20, 2, pp. 194-204.

Quigley, R.M. and Ogunbadejo, T.A., 1973. Soil weathering, soil structure and engineering properties, Sarnia clay crust. *In* Soil Microscopy, G.K. Rutherford (ed.), Limestone Press, Kingston, Ontario, pp. 165-178.

Robertson, W.D. and Cherry, J.A., 1989. Tritium as an indicator of recharge and dispersion in a groundwater system in central Ontario. Water Resources Research, 25, 6, pp. 1097-1109.

Rudolph, D.L., Cherry, J.A., and Farvolden, R.N., 1991. Groundwater flow and solute transport in fractured lacustrine clay near Mexico City. Water Resources Research, 27, 9, pp. 2187-2201.

Ruland, W.W., Cherry, J.A., Feenstra, S., 1991. The depth of fractures and active ground-water flow in a clayey till plain in southwestern Ontario. Ground Water, 29, 3, pp. 405-417.

Sharp, J.M., 1984. Hydrogeologic characteristics of shallow glacial drift aquifers in dissected till plains (North-Central Missouri). Groundwater, 22, 6, pp. 683-689.

Sklash, M.G. and Ibrahim, O.A., 1991. Grant 389. Hydrogeological implications of buried eskers in Essex County, Ontario: results from year 1. *In* Geoscience Research Grant Program, Summary of Research, 1990-91. V.G. Milne (ed.), Ontario Geological Survey Miscellaneous Paper, p. 24.

Sneath, P.H.A. and Sokal, R.R., 1973. Numerical Taxonomy: The Principles and Practice of Numerical Classification. W.H. Freeman and Company, San Francisco.

Soderman, L.G. and Kim, Y.D., 1970. Effect of groundwater levels on the stress history of the St. Clair till deposit. Canadian Geotechnical Journal, 7, pp. 173-187.

Telford, P.G. and Russell, D.J., 1981. Paleozoic Geology of the Windsor-Essex and Pelee Island Area, Southern Ontario. Ontario Geological Survey Preliminary Map P.2396.

Thompson, G.M. and Hayes, J.M., 1979. Trichlorofluoromethane in groundwater - a possible tracer and indicator of groundwater age. Water Resources Research, 15, 3, pp. 546-554.

Thompson, G.M., Hayes, J.M., and Davis, S.M., 1974. Fluorocarbon tracers in hydrology. Geophysics Research Letters, 1, pp. 177-180.

Tóth, J., 1962. A theory of groundwater motion in small drainage basins in central Alberta, Canada. Journal of Geophysical Research, 67, 11, pp. 4375-4387.

Vagners, V.J., 1972. Quaternary Geology of the Windsor-Essex Area (Eastern Part), Southern Ontario. Ontario Department of Mines and Northern Affairs, Preliminary Map P.750.

Vorauer, A.G., Harding, D.W., Dusseault, M.B., and Cherry, J.A., 1986. The nature of near-surface fractures in clay tills of southwestern Ontario. *In* 3rd Canadian Hydrogeological Conference Proceedings, Saskatoon, April 21-23, 1986.

Walter, G.R. and Thompson, G.M., 1982. A repeated pulse technique for determining the hydraulic properties of tight formations. Groundwater, 20, 2, pp. 186-193.

Watershed Research, Inc., 1989. Hydropal 1 + 2, Interactive Hydrogeologic Applications, Version 4.0. Watershed Research, Inc., White Bear Lake, Minnesota.

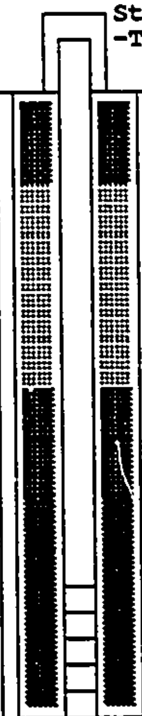
Williams, R.E. and Farvolden, R.N., 1967. The influence of joints on the movement of ground water through glacial till. Journal of Hydrology, 5, pp. 163-170.

APPENDIX A

BOREHOLE LOGS AND WELL COMPLETION DIAGRAMS

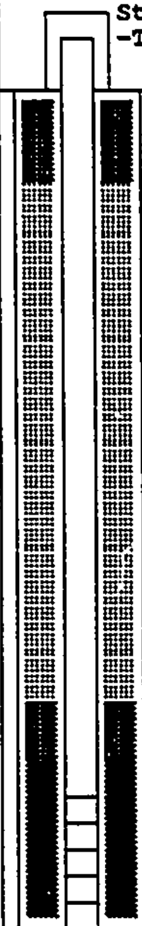
LOCATION: Puce Road Site
BORING NO.: A-1
DATE DRILLED: June 11, 1990
WEATHER CONDS.: Sunny, 85 deg.
BOREHOLE DIAMETER: 165mm
CASING DIAMETER: 50.8mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 183.983m
0	0	FILL with gravel, tar, diesel odour		Ground Elev. = 183.628m
		Dark brown CLAY TILL		Bentonite Seal: 0-0.5m
				Drill Cuttings Backfill
5	1.5			Bentonite Seal: 1.71-2.23m
				Sand Pack Interval: 2.23-3.66m
10	3.0	Stiff, brown CLAY TILL, fractured and weathered	1/SS	Screened Interval: 2.90-3.66m
		END OF BOREHOLE		
15	4.6			
20	6.1			



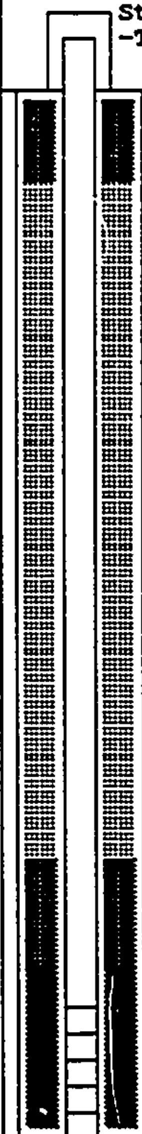
LOCATION: Puce Road Site BORING NO.: A-2
DATE DRILLED: May 31, 1990 WEATHER CONDS.: Sunny, 70 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 184.265m
0	0	FILL with gravel, tar, diesel and gasoline odour		Ground Elev. = 183.621m
		Brown, weathered CLAY TILL, mottled texture		Bentonite Seal: 0-0.5m
				Drill Cuttings Backfill
5	1.5			
10	3.0			Bentonite Seal: 3.50-3.81m
		Dark brown, stiff, CLAY TILL, fractured	1/SS	Sand Pack Interval: 3.81-4.88m
15	4.6			Screened Interval: 4.11-4.88m
		END OF BOREHOLE		
20	6.1			



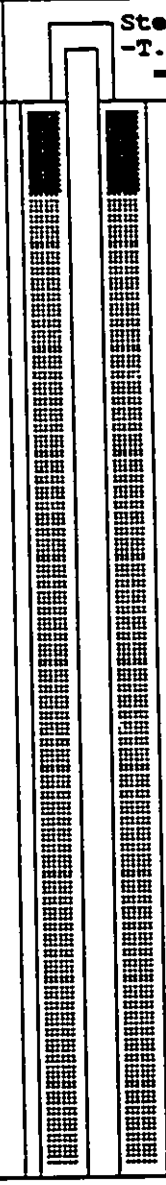
LOCATION: Puce Road Site BORING NO.: A-3
DATE DRILLED: May 31, 1990 WEATHER CONDS.: Sunny, 72 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 184.270m
0	0	FILL with gravel and clay, diesel odour		Ground Elev. = 183.655m Bentonite Seal: 0-0.5m Drill Cuttings Backfill
5	1.5	Brown, fractured CLAY TILL		
10	3.0			
		Dark brown, stiff CLAY TILL, fractured and weathered	1/SS	
15	4.6			Bentonite Seal: 4.57-5.03m
		Grey CLAY TILL at 4.7m, plastic, wet, no visible fractures	2/SS	
		Same as above	3/SS	Sand Pack Interval 5.03-6.10m
20	6.1	--END OF BOREHOLE----		Screened Interval: 5.33-6.10m

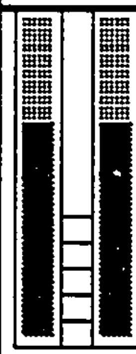


LOCATION: Puce Road Site BORING NO.: A-4
DATE DRILLED: May 30, 1990 WEATHER CONDS.: Sunny, 60's
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 184.226m
0	0	FILL with gravel and clay		Ground Elev. = 183.721m
		Brown, fractured, mottled CLAY TILL		Bentonite Seal: 0-0.5m
				Drill Cuttings Backfill
5	1.5			
10	3.0			
15	4.6			
		Grey CLAY TILL, more plastic, soft		
		Same as above, no visible fractures	1/SS	
20	6.1	CONTINUED		CONTINUED

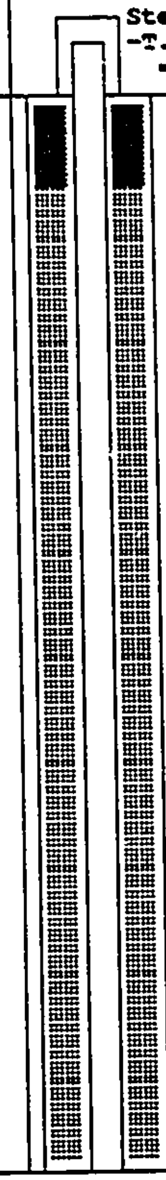


LOCATION: Puce Road Site   BORING NO.: A-4 (Cont.)
DATE DRILLED: May 30, 1990   WEATHER CONDS.: Sunny, 60's
BOREHOLE DIAMETER: 165 mm   CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
20	6.1	Same as above	2/SS	
		Interbedded silty CLAY with FINE SAND Silty, sandy CLAY, grey, dense (at 22')	3/SS	Bentonite Seal: 6.56-6.86m
		Silty CLAY, less sand than above, grey	4/SS	Sand Pack Interval: 6.86-7.92m
25	7.6			Screened Interval: 7.16-7.92m
		END OF BOREHOLE		
30	9.1			
35	10.7			
40	12.2			

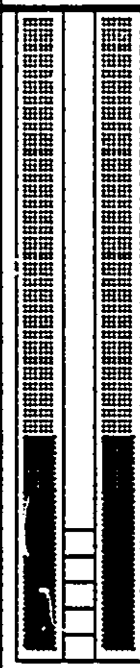
LOCATION: Puce Road Site
BORING NO.: A-5
DATE DRILLED: May 30, 1990
WEATHER CONDS.: Sunny, cool
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 184.388m
0	0	FILL with gravel and clay		Ground Elev. = 183.732m
		Brown, fractured, weathered CLAY TILL		Bentonite Seal: 0-0.5m
				Drill Cuttings Backfill
5	1.5			
10	3.0			
15	4.6	Grey CLAY TILL, plastic		
20	6.1	CONTINUED	1/SS	CONTINUED



LOCATION: Puce Road Site BORING NO.: A-5 (Cont.)
DATE DRILLED: May 30, 1990 WEATHER CONDS.: Sunny, cool
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
20	6.1	Same as above, becoming more silty at 21 ft. (6.4m)	1/SS	Drill Cuttings Backfill
		Water-bearing, dense grey, FINE to MEDIUM SAND, some pebbles	2/SS	
		Same as above, with SILT and interbedded CLAY	3/SS	
25	7.6			
		Same as above	4/SS	
				Bentonite Seal: 8.38-8.68m
		Grey, plastic CLAY TILL, some SILT and large pebbles, soft	5/SS	Sand Pack Interval: 8.68-9.75m
30	9.1	Grey silty CLAY TILL no visible fractures	6/SS	Screened Interval: 8.99-9.75m
		END OF BOREHOLE		
35	10.7			
40	12.2			



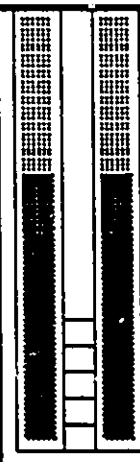
LOCATION: Puce Road Site　　BORING NO.: A-6
DATE DRILLED: May 30, 1990　　WEATHER CONDS.: Sunny, cool
BOREHOLE DIAMETER: 165 mm　　CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 184.518m
0	0	TOPSOIL, with gravel roots, pebbles	1/SS	Ground Elev. = 183.756m
		Brown-grey, weatherad CLAY TILL, pebbles, mottled texture, hard	2/SS	Bentonite Seal: 0-0.5m
		Same as above, moist	3/SS	Drill Cuttings Backfill
5	1.5			
		Same as above, more plastic	4/SS	
		Same as above, large fracture noted sealed with finer greyish-purple clay	5/SS	
10	3.0	Same as above	6/SS	
		Same as above except color is darker brown, less mottling	7/SS	
		Dark brown CLAY TILL very stiff	8/SS	
15	4.6	Grey SILTY CLAY TILL no visible fractures pebbles, plastic	9/SS	
		Same as above		
		Same as above	10/SS	
20	6.1	CONTINUED	11/SS	CONTINUED

LOCATION: Puce Road Site
BORING NO.: A-6 (Cont.)
DATE DRILLED: May 30, 1990
WEATHER CONDS.: Sunny, cool
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

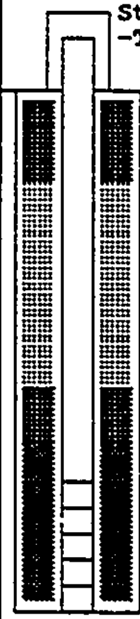
DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
20	6.1	Grey SILTY CLAY TILL increasing silt content	11/SS	Drill Cuttings Backfill
		Grey SILTY CLAY with pockets of SILT and FINE SAND, dense	12/SS	
		Same as above with an increase in FINE SAND content, dense	13/SS	
25	7.6			
		Same as above	14/SS	
		Same as above with less fine sand, pockets or "pods" of SILT in CLAY	15/SS	
30	9.1	Same as above	16/SS	
		Grey CLAY TILL, plastic and very soft		
		Same as above, no visible fractures	17/SS	
		Same as above	18/SS	
35	10.7			
		Same as above	19/SS	
		Same as above	20/SS	
40	12.2	Same as above CONTINUED	21/SS	CONTINUED

LOCATION: Puce Road Site BORING NO.: A-6 (Cont.)
DATE DRILLED: May 30, 1990 WEATHER CONDS.: Sunny, cool
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
40	12.2	Grey CLAY TILL, soft plastic	21/SS	 Bentonite Seal: 12.96-13.26m Sand Pack Interval: 13.26-14.63m Screened Interval: 13.87-14.63m
		Same as above	22/SS	
		Same as above	24/SS	
45	13.7			
		Same as above	26/SS	
		END OF BOREHOLE		
50	15.2			
55	16.8			
60	18.3			

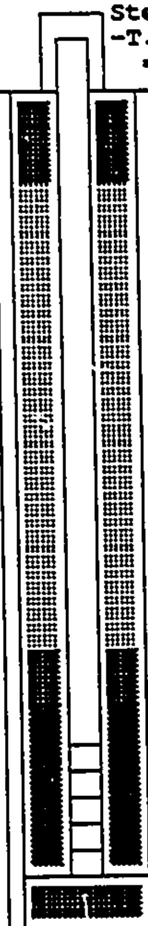
LOCATION: Puce Road Site BORING NO.: B-1
DATE DRILLED: June 11, 1990 WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 183.674m
0	0	Black TOPSOIL, grass, roots		Ground Elev. = 182.844m
		Brown, CLAY TILL, mottled texture		Bentonite Seal: 0-0.5m
5	1.5			Drill Cuttings Backfill
				Bentonite Seal: 1.69-1.99m
		Brown FINE SAND, wet	1/SS	Sand Pack Interval: 1.99-3.05m
		Brown CLAY TILL, highly fractured, wet		
10	3.0	END OF BOREHOLE		Screened Interval: 2.29-3.05m
15	4.6			
20	6.1			



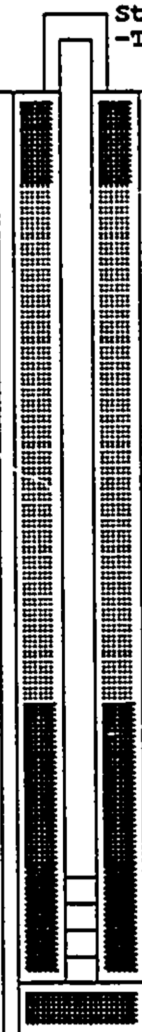
LOCATION: Puce Road Site
BORING NO.: B-2
DATE DRILLED: May 31, 1990
WEATHER CONDS.: Sunny, 75 deg.
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 183.508m
0	0	Black TOPSOIL, grass, roots		Ground Elev. = 182.806m Bentonite Seal: 0-0.5m
		Brown CLAY TILL, mottled texture		Drill Cuttings Backfill
5	1.5			
10	3.0	Yellow-brown FINE SAND, water-bearing		Bentonite Seal: 3.20-3.50m
		Brown CLAY TILL, weathered and fractured, pebbles, stiff	1/SS	Sand Pack Interval: 3.50-4.57m
		Same as above	2/SS	Screened Interval: 3.81-4.57m
15	4.6	Grey CLAY TILL, soft and very plastic		
		END OF BOREHOLE at 16 ft. (4.9m)		
20	6.1			



LOCATION: Puce Road Site BORING NO.: B-3
DATE DRILLED: June 11, 1990 WEATHER CONDS.: Sunny, 85 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 183.461m
0	0	Black TOPSOIL, grass, roots		Ground Elev. = 182.834m Bentonite Seal: 0-0.5m
		Brown, weathered CLAY TILL, mottled texture		Drill Cuttings Backfill
5	1.5			
		Yellowish-brown FINE SAND, some silt		
10	3.0	Brown CLAY TILL, fractured, very stiff	1/SS	
		Same as above, less fracturing	2/SS	Bentonite Seal: 3.50-4.42m
			3/SS	
15	4.6	Grey CLAY TILL, very plastic, no visible fractures		Sand Pack Interval: 4.42-5.49m
		Same as above	4/SS	Screened Interval: 4.88-5.49m
		Grey FINE to MEDIUM SAND, very dense		
20	6.1	END OF BOREHOLE at 18 ft. (5.18m)		



LOCATION: Puce Road Site BORING NO.: B-4
DATE DRILLED: May 31, 1990 WEATHER CONDS.: Sunny, 70's
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 183.473m
0	0	Black TOPSOIL, grass, roots		Ground Elev. = 182.786m
		Brown CLAY TILL, mottled texture, pebbles		Bentonite Seal: 0-0.5m
5	1.5			Drill Cuttings Backfill
		Yellowish-brown FINE SAND		
10	3.0	Dark brown CLAY TILL very stiff		
15	4.6	Grey SILTY CLAY TILL		
		Same as above, no visible fractures	1/SS	
			2/SS	Bentonite Seal: 5.48-6.24m
		Interbedded SILT and CLAY, some SAND, grey		
20	6.1	CONTINUED	3/SS	CONTINUED

LOCATION: Puce Road Site
DATE DRILLED: May 30, 1990
BOREHOLE DIAMETER: 165 mm
DRILLING METHOD: Hollow Stem Auger

BORING NO.: B-4 (Cont.)
WEATHER CONDS.: Sunny, 70's
CASING DIAMETER: 51mm (2")

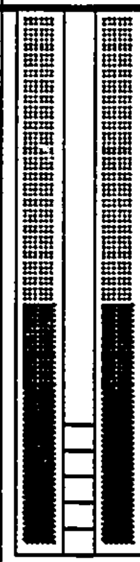
DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
20	6.1	Interbedded grey SAND, SILT, and CLAY dense	3/SS	 Sand Pack Interval: 6.24-7.32m
		Same as above	4/SS	Screened Interval: 6.55-7.32m
		Grey CLAY TILL, plastic, soft		
25	7.6	END OF BOREHOLE		
30	9.1			
35	10.7			
40	12.2			

LOCATION: Puce Road Site　　BORING NO.: B-5
DATE DRILLED: May 31, 1990　　WEATHER CONDS.: Sunny, 65 deg.
BOREHOLE DIAMETER: 165 mm　　CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			ST= Shelby Tube	Steel Casing -T.O.C. Elev. = 183.566m
0	0	Black TOPSOIL, grass, roots	1/ST auto-claved	Ground Elev. = 182.806m
		Brown CLAY TILL, highly fractured and mottled	2/ST auto-claved	Bentonite Seal: 0-0.5m
			3/ST auto-claved	Drill Cuttings Backfill
5	1.5			
		FINE to MEDIUM SAND, light brown, water-bearing	4/ST auto-claved	
		Brown CLAY TILL, highly fractured, water dripping from Shelby tube	5/ST auto-claved	
10	3.0	Same as above, less fracturing	6/ST auto-claved	
		Dark brown CLAY TILL becoming more stiff	7/ST auto-claved	
		Same as above	8/ST auto-claved	
15	4.6	Grey CLAY TILL, pl_stic		
		Same as above	9/ST auto-claved	
		Same as above	10/ST	
20	6.1	Grey SILTY CLAY TILL with pockets of SILT	11/ST	CONTINUED

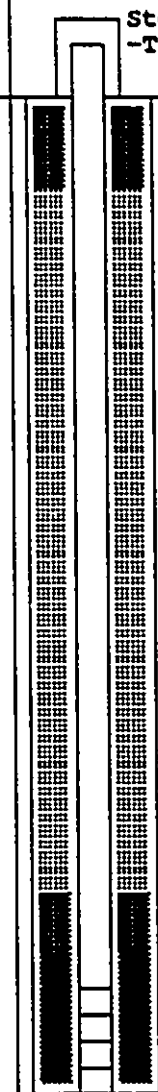
LOCATION: Puce Road Site BORING NO.: B-5 (Cont.)
DATE DRILLED: May 31, 1990 WEATHER CONDS.: Sunny, 65 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
20	6.1	Interbedded SILT and CLAY, minor amounts of FINE SAND	11/ST	
		Same as above, less sand	12/ST	
		Grey MEDIUM SAND, dense, with Grey CLAY	13/ST	
25	7.6			Bentonite Seal: 7.62-8.08m
		Grey CLAY TILL, plastic, soft	14/ST	
		Same as above		Sand Pack Interval: 8.08-9.14m
		Same as above	15/ST	Screened Interval: 8.38-9.14m
30	9.1	END OF BOREHOLE		
		Note: Water in hole		
35	10.7			
40	12.2			



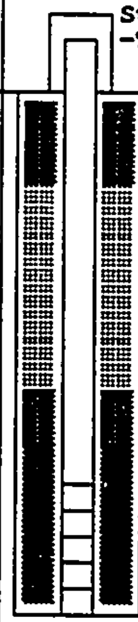
LOCATION: Puce Road Site BORING NO.: B-6
DATE DRILLED: May 31, 1990 WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 183.368m
0	0	Black TOPSOIL, grass, roots		Ground Elev. = 182.796m
		Brown, weathered CLAY TILL, mottled texture		Bentonite Seal: 0-0.5m
5	1.5			Drill Cuttings Backfill
		Yellowish-brown FINE SAND, some silt		
10	3.0	Brown CLAY TILL, fractured, stiff	1/SS	
		Same as above, less fracturing	2/SS	
			3/SS	
15	4.6	Grey CLAY TILL, very plastic, no visible fractures		Bentonite Seal: 4.57-4.88m
		Same as above	4/SS	
		Grey FINE to MEDIUM SAND, very dense		Sand Pack Interval: 4.88-5.79m
20	6.1	END OF BOREHOLE at 19 ft. (5.79m)		Screened Interval: 5.18-5.79m



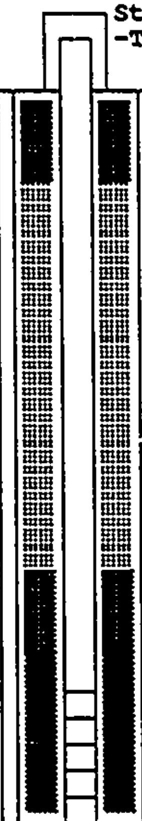
LOCATION: Puce Road Site BORING NO.: C-1
DATE DRILLED: June 11, 1990 WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 184.598m
0	0	TOPSOIL, dark brown-black, roots		Ground Elev. = 183.651m
		Brown CLAY TILL		Bentonite Seal: 0-0.5m
				Drill Cuttings Bachfill
5	1.5			Bentonite Seal: 1.68-1.99m
		Brown CLAY TILL, fractured and weathered, mottled, stiff	1/SS	Sand Pack Interval: 1.99-3.05m
10	3.0	END OF BOREHOLE		Screened Interval: 2.29-3.05m
15	4.6			
20	6.1			



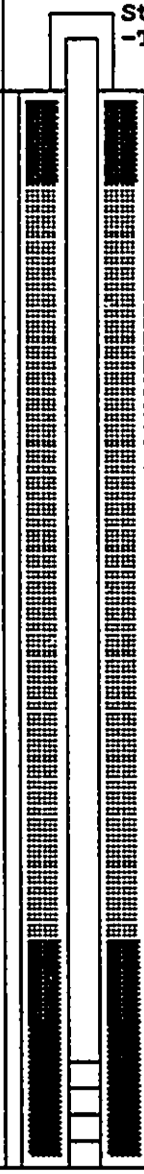
LOCATION: Puce Road Site
BORING NO.: C-2
DATE DRILLED: June 11, 1990
WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 184.243m
0	0	TOPSOIL, dark brown-black, roots		Ground Elev. = 183.641m
		Brown CLAY TILL		Bentonite Seal: 0-0.5m
5	1.5			Drill Cuttings Backfill
				Bentonite Seal: 2.74-3.20m
10	3.0	Brown CLAY TILL, some pebbles, sealed fractures	1/SS	Sand Pack Interval: 3.20-4.27m
		Brownish-grey CLAY TILL, no apparent fractures, heavy and very stiff	2/SS	Screened Interval: 3.50-4.27m
		END OF BOREHOLE		
15	4.6			
20	6.1			

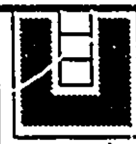


LOCATION: Puce Road Site BORING NO.: C-3
DATE DRILLED: June 11, 1990 WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 184.340m
0	0	TOPSOIL, dark brown-black, roots		Ground Elev. = 183.640m
		Brown CLAY TILL		Bentonite Seal: 0-0.5m
				Drill Cuttings Backfill
5	1.5			
10	3.0			
15	4.6	Dark brown-grey CLAY TILL, minor fractures	1/SS	
		Same as above, very stiff	2/SS	Bentonite Seal: 4.88-5.33m
		Blue-grey CLAY TILL, plastic, no visible fractures	3/SS	Sand Pack Interval: 5.33-6.40m
20	6.1	CONTINUED	4/SS	CONTINUED

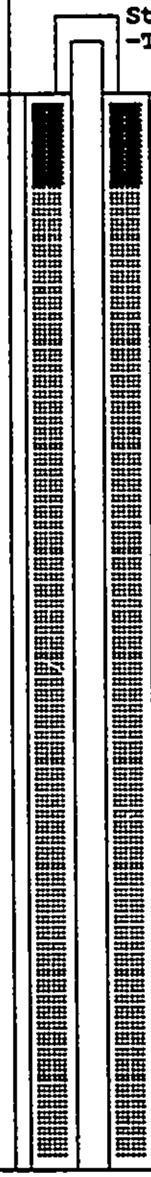


LOCATION: Puce Road Site
BORING NO.: C-3 (Cont.)
DATE DRILLED: June 11, 1990
WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
20	6.1	Same as above	4/SS	 Screened Interval: 5.64-6.40m
		END OF BOREHOLE		
				Note: Sand bridged annulus during installation of sand pack and the well bottom was pulled up to 21 feet to free the sand.
25	7.6			
30	9.1			
35	10.7			
40	12.2			

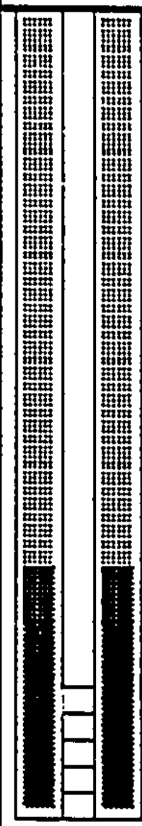
LOCATION: Puce Road Site
BORING NO.: C-4
DATE DRILLED: June 11, 1990
WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 184.509m
0	0	TOPSOIL, black, roots		Ground Elev. = 183.648m
		Brown CLAY TILL, pebbles, mottled		Bentonite Seal: 0-0.5m
				Drill Cuttings Backfill
5	1.5			
10	3.0			
15	4.6			
		Grey silty CLAY TILL plastic, soft		
20	6.1	CONTINUED		CONTINUED



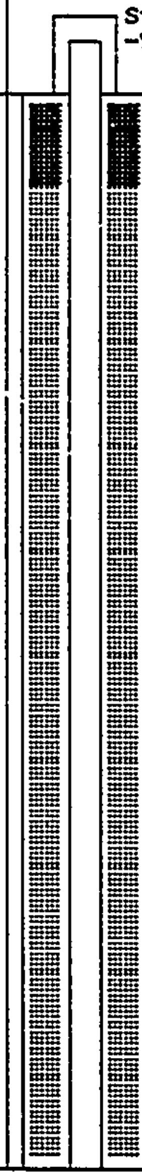
LOCATION: Puce Road Site   BORING NO.: C-4 (Cont.)
DATE DRILLED: June 11, 1990   WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm   CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
20	6.1	Grey silty CLAY TILL plastic, soft		
		Same as above, no visible fractures occasional pebbles	1/SS	
		Same as above	2/SS	
25	7.6			
		Same as above	3/SS	
		Same as above	4/SS	
30	9.1	Grey silty CLAY with interbedded FINE SAND, grey	5/SS	Bentonite Seal: 9.15-9.45m
		Grey FINE to MEDIUM SAND with lenses of silty CLAY	6/SS	Sand Pack Interval: 9.45-10.67m
				Screened Interval: 9.91-10.67m
35	10.7	END OF BOREHOLE		
40	12.2			



LOCATION: Puce Road Site
BORING NO.: C-5
DATE DRILLED: June 11, 1990
WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Steel Casing -T.O.C. Elev. = 184.403m
0	0	TOPSOIL, black, roots		Ground Elev. = 183.647m
		Brown CLAY TILL, weathered, mottled		Bentonite Seal: 0-0.5m
				Drill Cuttings Backfill
5	1.5			
10	3.0			
15	4.6	Brown-grey CLAY TILL weathered, stiff	1/SS	
		Grey silty CLAY TILL soft, plastic, pebbles	2/SS	
		Same as above	3/SS	
20	6.1	CONTINUED		CONTINUED



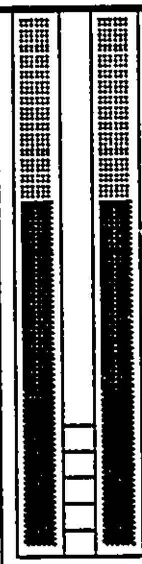
LOCATION: Puce Road Site
DATE DRILLED: June 11, 1990
BOREHOLE DIAMETER: 165 mm
DRILLING METHOD: Hollow Stem Auger

BORING NO.: C-5 (Cont.)
WEATHER CONDS.: Sunny, 80 deg.
CASING DIAMETER: 51mm (2")

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
20	6.1	Grey silty CLAY TILL		
		Same as above	4/SS	
		Same as above	5/SS	
25	7.6	Same as above, becoming more silty	6/SS	
		Water-bearing grey SAND, very dense, no sample recovery	7/SS	
		Interbedded COARSE SAND seams and CLAY, grey	8/SS	
30	9.1			
		Interbedded FINE to MEDIUM SAND with CLAY, grey	9/SS	
		Same as above	10/SS	
35	10.7	Increase in CLAY content, MEDIUM SAND seam at 11.1m	11/SS	
		Grey silty CLAY with interbedded fine seams of FINE SAND	12/SS	
		Same as above	13/SS	
40	12.2	CONTINUED		CONTINUED

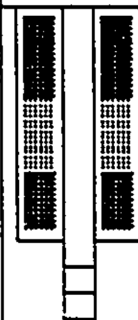
LOCATION: Puce Road Site
BORING NO.: C-5 (Cont.)
DATE DRILLED: June 11, 1990
WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
40	12.2	Grey silty CLAY with very slight occurrences of FINE SAND seams	14/SS	
		Grey silty CLAY TILL plastic	15/SS	Bentonite Seal: 13.11-14.17m
45	13.7	Same as above	16/SS	
		Same as above	17/SS	Sand Pack Interval: 14.17-15.24m
		Same as above	18/SS	Screened Interval: 14.48-15.24m
50	15.2	END OF BOREHOLE		
55	16.8			
60	18.3			



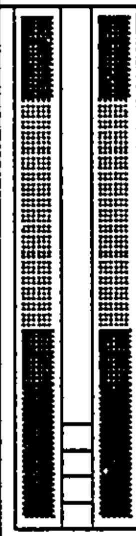
LOCATION: Whelan Farm Site BORING NO.: A-1
DATE DRILLED: June 12, 1990 WEATHER CONDS.: Drizzle, cool
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Ground Elevation = 186.522m Well is flush mounted
0	0	TOPSOIL, grass, roots, black, sandy	1/SS	Bentonite Seal: 0-0.5m
		Brown-grey CLAY TILL highly weathered and fractured, pebbles, stiff	2/SS	Drill Cuttings Backfill
			3/SS	Bentonite Seal: 1.22-1.83m
5	1.5			
		END OF BOREHOLE		Screened Interval 1.52-1.83m
				Note: Well was installed by placing screen in a Shelby Tube hole; no sand pack was used.
10	3.0			
15	4.6			
20	6.1			

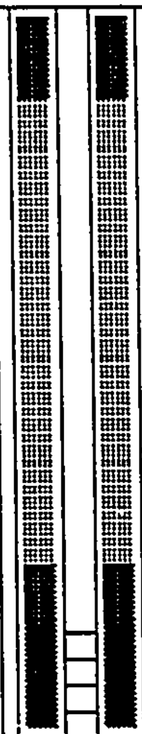


LOCATION: Whelan Farm Site BORING NO.: A-2
DATE DRILLED: June 12, 1990 WEATHER CONDS.: Drizzle, cool
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Ground Elevation = 186.510m Well is flush mounted
0	0	TOPSOIL, black, grass, roots, sandy		Bentonite Seal: 0-0.5m
		Brown, highly fractured CLAY TILL, pebbles, stiff	1/SS	
		Same as above	2/SS	Drill Cuttings Backfill
5	1.5			
		Brown SANDY CLAY with lenses of FINE to MEDIUM SAND, roots in clay fractures	3/SS	Bentonite Seal: 1.82-2.13m
			4/SS	Sand Pack Interval: 2.13-3.05m
10	3.0	END OF BOREHOLE		Screened Interval: 2.44-3.05m
15	4.6			
20	6.1			



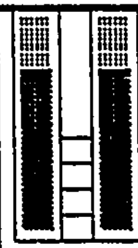
LOCATION: Whelan Farm Site　　BORING NO.: A-3
DATE DRILLED: June 12, 1990　　WEATHER CONDS.: Drizzle, cool
BOREHOLE DIAMETER: 165 mm　　CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Ground Elevation = 186.454m Well is flush mounted
0	0	TOPSOIL, black, grass, roots, sandy		 Bentonite Seal: 0-0.5m
		Brown, highly fractured SANDY CLAY TILL, many pebbles, stiff	1/SS	
			2/SS	Drill Cuttings Backfill
5	1.5			
			3/SS	
		Seams of FINE SAND in brown CLAY Water-bearing, brown FINE to MEDIUM SAND, very dense	4/SS	
10	3.0		5/SS	
		Grey silty CLAY TILL plastic, pebbles, fracture with brown coating	6/SS	Bentonite Seal: 3.20-3.50m
				Sand Pack Interval: 3.50-4.27m
15	4.6	END OF BOREHOLE		Screened Interval: 3.66-4.27m
20	6.1			

LOCATION: Whelan Farm Site BORING NO.: A-4
DATE DRILLED: June 12, 1990 WEATHER CONDS.: Rainy, cool
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Ground Elevation = 186.465m Well is flush mounted
0	0	TOPSOIL, black, grass, roots, sandy	1/SS	Bentonite Seal: 0-0.5m
		Brown, highly fractured and weathered SANDY CLAY, pebbles Fractures infilled with grey clay minerals, stiff	2/SS	Drill Cuttings Backfill
5	1.5		3/SS	
		Interbedded seams of FINE to MEDIUM SAND in SANDY CLAY, brown, large pebbles	4/SS	
10	3.0	Same as above, less sandy	5/SS	
			6/SS	
		Grey CLAY TILL, many pebbles, no visible fractures	7/SS	
15	4.6	Same as above, very plastic	8/SS	
		Same as above	9/SS	
20	6.1	CONTINUED	10/SS	CONTINUED

LOCATION: Whelan Farm Site
BORING NO.: A-4 (Cont.)
DATE DRILLED: June 12, 1990
WEATHER CONDS.: Rainy, cool
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
20	6.1	Grey CLAY TILL, very plastic	10/SS	 Bentonite Seal: 6.25-6.55m
		Same as above	11/SS	Sand Pack Interval: 6.55-7.32m
		END OF BOREHOLE		Screened Interval: 6.71-7.32m
25	7.6			
30	9.1			
35	10.7			
40	12.2			

LOCATION: Whelan Farm Site   BORING NO.: SB-1
DATE DRILLED: June 12, 1990   WEATHER CONDS.: Drizzle, cool
BOREHOLE DIAMETER: 165 mm   CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Ground Elevation = --
0	0	TOPSOIL, black, grass, roots		Drill Cuttings Backfill
		Brown CLAY TILL, highly fractured and weathered, pebbles	1/SS	
			2/SS	
5	1.5			
		Dark brown CLAY TILL more stiff, less fracturing than above	3/SS	
			4/SS	
10	3.0		5/SS	
		Grey CLAY TILL, soft and plastic, pebbles	6/SS	
		END OF BOREHOLE		
15	4.6			
20	6.1			

LOCATION: Whelan Farm Site BORING NO.: SB-2
DATE DRILLED: June 12, 1990 WEATHER CONDS.: Drizzle, cool
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

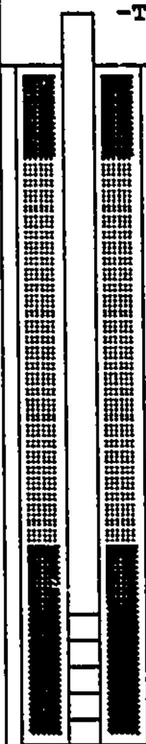
DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Ground Elevation = --
0	0	TOPSOIL, black, grass, roots		Drill Cuttings Backfill
		Brown CLAY TILL, highly fractured and weathered, pebbles	1/SS	
			2/SS	
5	1.5			
		Dark brown CLAY TILL more stiff, less fracturing than above	3/SS	
			4/SS	
10	3.0		5/SS	
		Grey CLAY TILL, soft and plastic, pebbles	6/SS	
		END OF BOREHOLE		
15	4.6			
20	6.1			

LOCATION: Whelan Farm Site
BORING NO.: SB-3
DATE DRILLED: June 12, 1990
WEATHER CONDS.: Drizzle, cool
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51mm (2")
DRILLING METHOD: Hollow Stem Auger

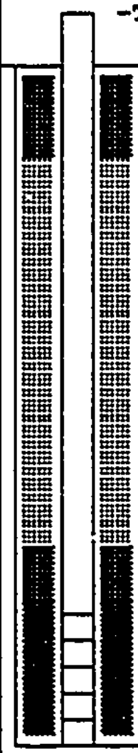
DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	Ground Elevation = --
0	0	TOPSOIL, black, grass, roots		
		Brown CLAY TILL, highly fractured and weathered, pebbles	1/SS	
			2/SS	Drill Cuttings Backfill
5	1.5			
		Dark brown CLAY TILL more stiff, less fracturing than above	3/SS	
			4/SS	
10	3.0		5/SS	
		Grey CLAY TILL, soft and plastic, pebbles Fracture coated with oxide precipitate	6/SS	
		END OF BOREHOLE		
15	4.6			
20	6.1			

LOCATION: Whelan Farm Site BORING NO.: Ag Can-1
DATE DRILLED: June 13, 1990 WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 186.943m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.448m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m Drill Cuttings Backfill
5	1.5			
10	3.0			Bentonite Seal: 2.74-3.05m
		Grey CLAY TILL		Sand Pack Interval: 3.05-3.96m
		END OF BOREHOLE		Screened Interval: 3.20-3.96m
15	4.6			
20	6.1			

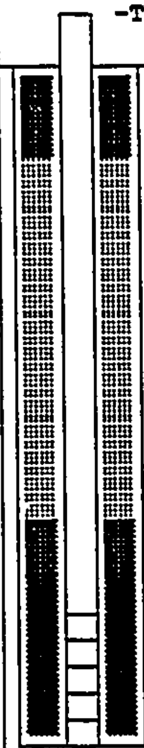


LOCATION: Whelan Farm Site BORING NO.: Ag Can-2
DATE DRILLED: June 13, 1990 WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger



DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 186.936m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.477m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m Drill Cuttings Backfill
5	1.5			
10	3.0			Bentonite Seal: 2.74-3.05m Sand Pack Interval: 3.05-3.96m
		Grey CLAY TILL		
		END OF BOREHOLE		Screened Interval: 3.20-3.96m
15	4.6			
20	6.1			

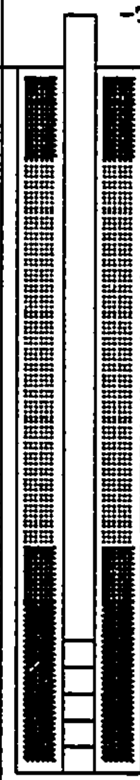
LOCATION: Whelan Farm Site
BORING NO.: Ag Can-3
DATE DRILLED: June 13, 1990
WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger



DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 187.050m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.518m Bentonite Seal: 0-0.5m
		Brown CLAY TILL, pebbles		Drill Cuttings Backfill
5	1.5			
10	3.0			Bentonite Seal: 2.59-2.89m
		Grey CLAY TILL		Sand Pack Interval: 2.89-3.96m
		END OF BOREHOLE		Screened Interval: 3.20-3.96m
15	4.6			
20	6.1			

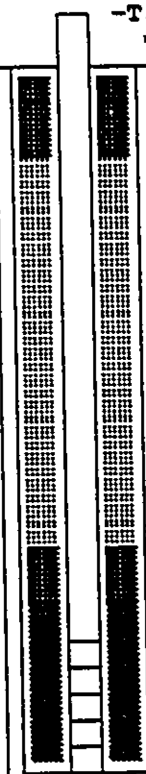
LOCATION: Whelan Farm Site BORING NO.: Ag Can-4
DATE DRILLED: June 13, 1990 WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 186.891m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.478m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m Drill Cuttings Backfill
5	1.5			
10	3.0			Bentonite Seal: 2.74-3.04m
		Grey CLAY TILL		Sand Pack Interval: 3.04-4.11m
		END OF BOREHOLE		Screened Interval: 3.35-4.11m
15	4.6			
20	6.1			



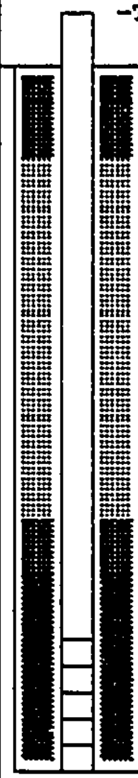
LOCATION: Whelan Farm Site
BORING NO.: Ag Can-5
DATE DRILLED: June 13, 1990
WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 186.976m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.531m; Bentonite Seal: 0-0.5m
		Brown CLAY TILL, pebbles		Drill Cuttings Backfill
5	1.5			
10	3.0			Bentonite Seal: 2.74-3.04m; Sand Pack Interval: 3.04-4.11m
		Grey CLAY TILL		Screened Interval: 3.35-4.11m
		END OF BOREHOLE		
15	4.6			
20	6.1			



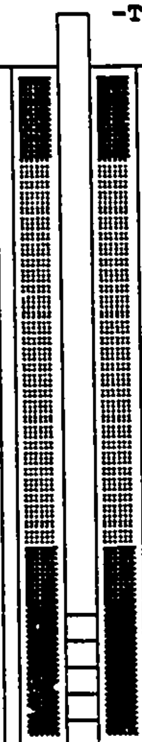
LOCATION: Whelan Farm Site　　BORING NO.: Aq Can-6
DATE DRILLED: June 13, 1990　　WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm　　CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 186.887m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.594m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m Drill Cuttings Backfill
5	1.5			
10	3.0			Bentonite Seal: 2.59-2.89m Sand Pack Interval: 2.89-4.11m
		Grey CLAY TILL		Screened Interval: 3.35-4.11m
		END OF BOREHOLE		
15	4.6			
20	6.1			



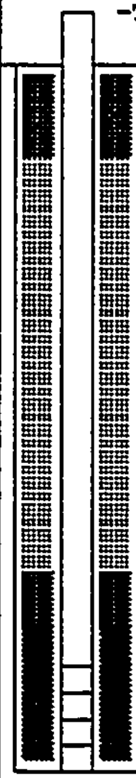
LOCATION: Whelan Farm Site
BORING NO.: Ag Can-7
DATE DRILLED: June 13, 1990
WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 187.184m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.664m
		Brown CLAY TILL, pebbles, sandy		Bentonite Seal: 0-0.5m Drill Cuttings Backfill
5	1.5			
10	3.0			Bentonite Seal: 2.74-3.05m Sand Pack Interval: 3.05-3.96m
		Grey CLAY TILL		Screened Interval: 3.20-3.96m
		END OF BOREHOLE		
15	4.6			
20	6.1			



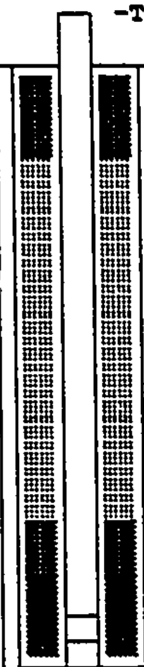
LOCATION: Whelan Farm Site BORING NO.: Ag Can-8
DATE DRILLED: June 13, 1990 WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 187.122m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.647m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m Drill Cuttings Backfill
5	1.5			
10	3.0			Bentonite Seal: 2.81-3.12m Sand Pack Interval: 3.12-4.11m
		Grey CLAY TILL		Screened Interval: 3.50-4.11m
		END OF BOREHOLE		
15	4.6			
20	6.1			



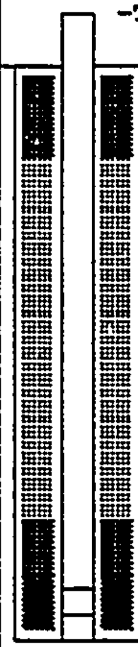
LOCATION: Whelan Farm Site BORING NO.: Ag Can-9
DATE DRILLED: June 13, 1990 WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 187.168m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.668m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m
				Drill Cuttings Backfill
5	1.5			
				Bentonite Seal: 2.58-2.89m
10	3.0	Grey CLAY TILL		Sand Pack Interval: 2.89-3.50m
		END OF BOREHOLE		Screened Interval: 3.20-3.50m
15	4.6			
20	6.1			



LOCATION: Whelan Farm Site   BORING NO.: Ag Can-10
DATE DRILLED: June 13, 1990   WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm   CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

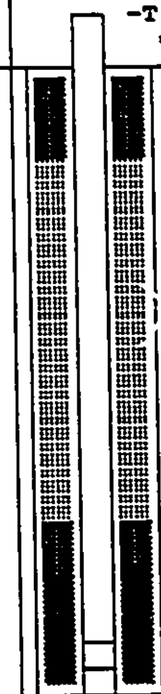
DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 187.148m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.630m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m Drill Cuttings Backfill
5	1.5			
				Bentonite Seal: 2.60-2.90m
10	3.0	Grey CLAY TILL		Sand Pack Interval: 2.90-3.35m
		END OF BOREHOLE		Screened Interval: 3.05-3.35m
15	4.6			
20	6.1			



LOCATION: Whelan Farm Site
DATE DRILLED: June 13, 1990
BOREHOLE DIAMETER: 165 mm
DRILLING METHOD: Hollow Stem Auger

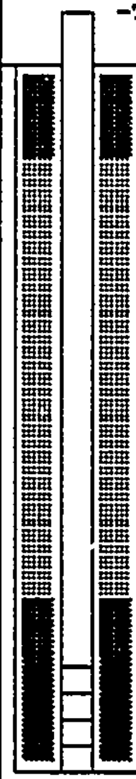
BORING NO.: Ag Can-11
WEATHER CONDS.: Sunny, 80 deg.
CASING DIAMETER: 51 mm (2")

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 187.062m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.598m; Bentonite Seal: 0-0.5m
		Brown CLAY TILL, pebbles		Drill Cuttings Backfill
5	1.5	Brown clayey FINE SAND		
		Brown CLAY TILL		Bentonite Seal: 2.59-2.90m
10	3.0			Sand Pack Interval: 2.90-3.66m
		Grey CLAY TILL		Screened Interval: 3.35-3.66m
		END OF BOREHOLE		
15	4.6			
20	6.1			



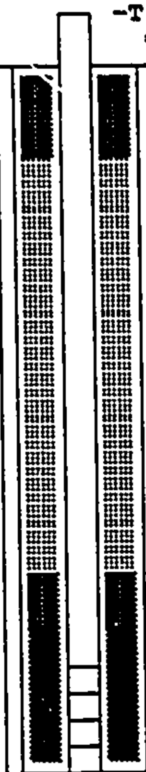
LOCATION: Whelan Farm Site BORING NO.: Ag Can-12
DATE DRILLED: June 13, 1990 WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 186.985m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.562m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m
5	1.5	Brown clayey FINE SAND		Drill Cuttings Backfill
		Brown CLAY TILL		
10	3.0			Bentonite Seal: 3.05-3.35m
				Sand Pack Interval: 3.35-4.11m
		Grey CLAY TILL		
		END OF BOREHOLE		Screened Interval: 3.50-4.11m
15	4.6			
20	6.1			



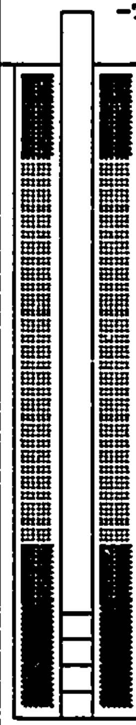
LOCATION: Whelan Farm Site
BORING NO.: Ag Can-13
DATE DRILLED: June 13, 1990
WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 187.122m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.603m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m; Drill Cuttings Backfill
5	1.5			
10	3.0			Bentonite Seal: 2.90-3.20m
		Grey CLAY TILL		Sand Pack Interval: 3.20-4.11m
		END OF BOREHOLE		Screened Interval: 3.50-4.11m
15	4.6			
20	6.1			

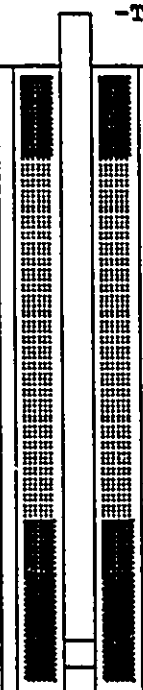


LOCATION: Whelan Farm Site BORING NO.: Ag Can-14
DATE DRILLED: June 13, 1990 WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 187.130m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.638m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m
				Drill Cuttings Backfill
5	1.5			
				Bentonite Seal: 2.74-3.05m
10	3.0			Sand Pack Interval: 3.05-3.81m
		Grey CLAY TILL		
		END OF BOREHOLE		Screened Interval: 3.20-3.81m
15	4.6			
20	6.1			



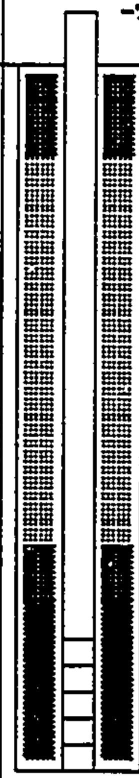
LOCATION: Whelan Farm Site
BORING NO.: Ag Can-15
DATE DRILLED: June 13, 1990
WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm
CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger



DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 187.075m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.656m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m Drill Cuttings Backfill
5	1.5			
				Bentonite Seal: 2.59-2.90m
10	3.0			Sand Pack Interval: 2.90-3.66m
		Grey CLAY TILL		
		END OF BOREHOLE		Screened Interval: 3.35-3.66m
15	4.6			
20	6.1			

LOCATION: Whelan Farm Site | BORING NO.: Ag Can-16
DATE DRILLED: June 13, 1990 | WEATHER CONDS.: Sunny, 80 deg.
BOREHOLE DIAMETER: 165 mm | CASING DIAMETER: 51 mm (2")
DRILLING METHOD: Hollow Stem Auger

DEPTH ft.	DEPTH m	DESCRIPTION	SAMPLES No./Type	MONITORING WELL CONSTRUCTION
			SS= Split Spoon	-T.O.C. Elev. = 187.084m
0	0	TOPSOIL, black, tilled		Ground Elev. = 186.628m
		Brown CLAY TILL, pebbles		Bentonite Seal: 0-0.5m Drill Cuttings Backfill
5	1.5			
10	3.0			Bentonite Seal: 2.74-3.04m Sand Pack Interval: 3.04-4.11m
		Grey CLAY TILL		Screened Interval: 3.35-4.11m
		END OF BOREHOLE		
15	4.6			
20	6.1			



APPENDIX B

SOIL TESTING RESULTS

* Moisture Contents

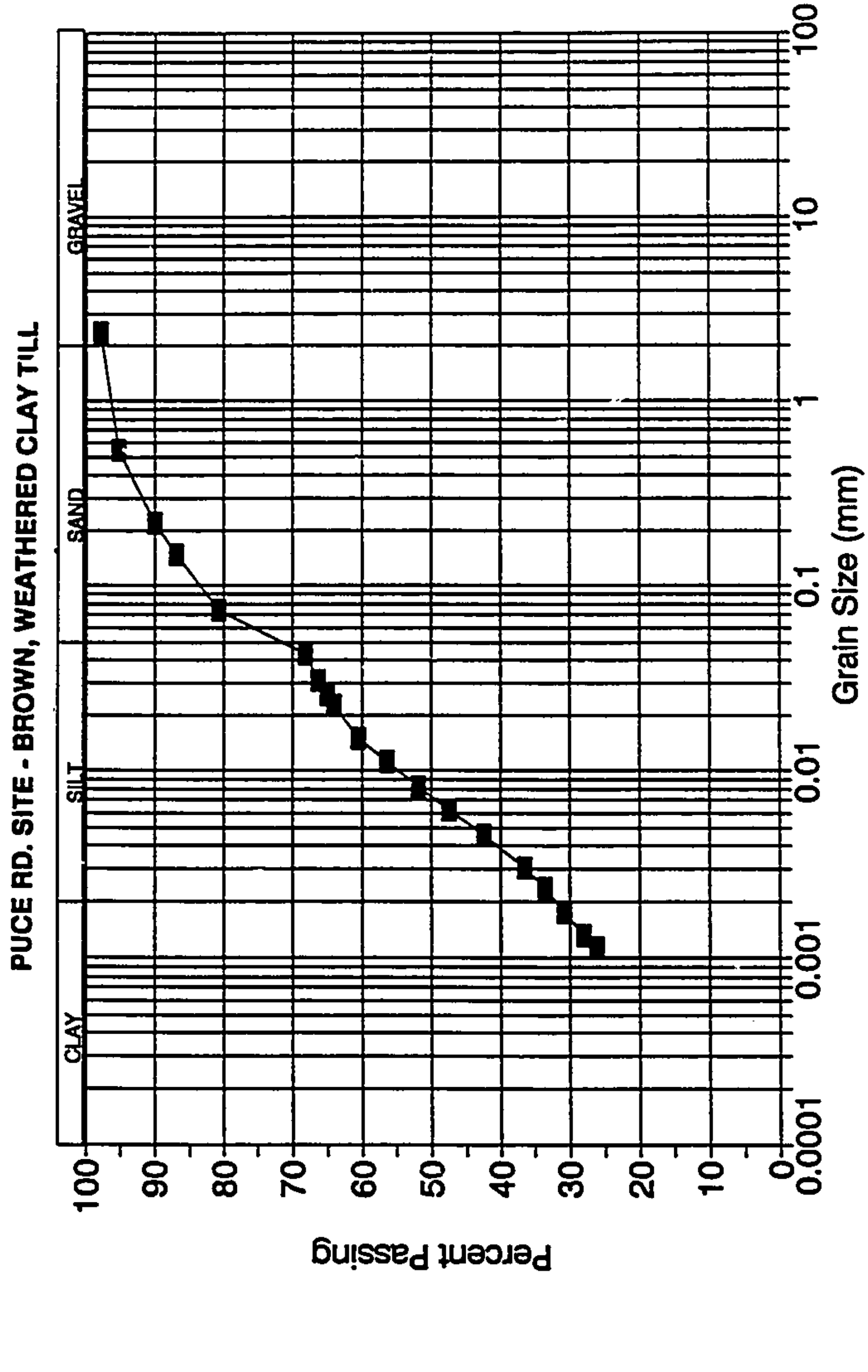
* Grain Size Analyses

Puce Road Site

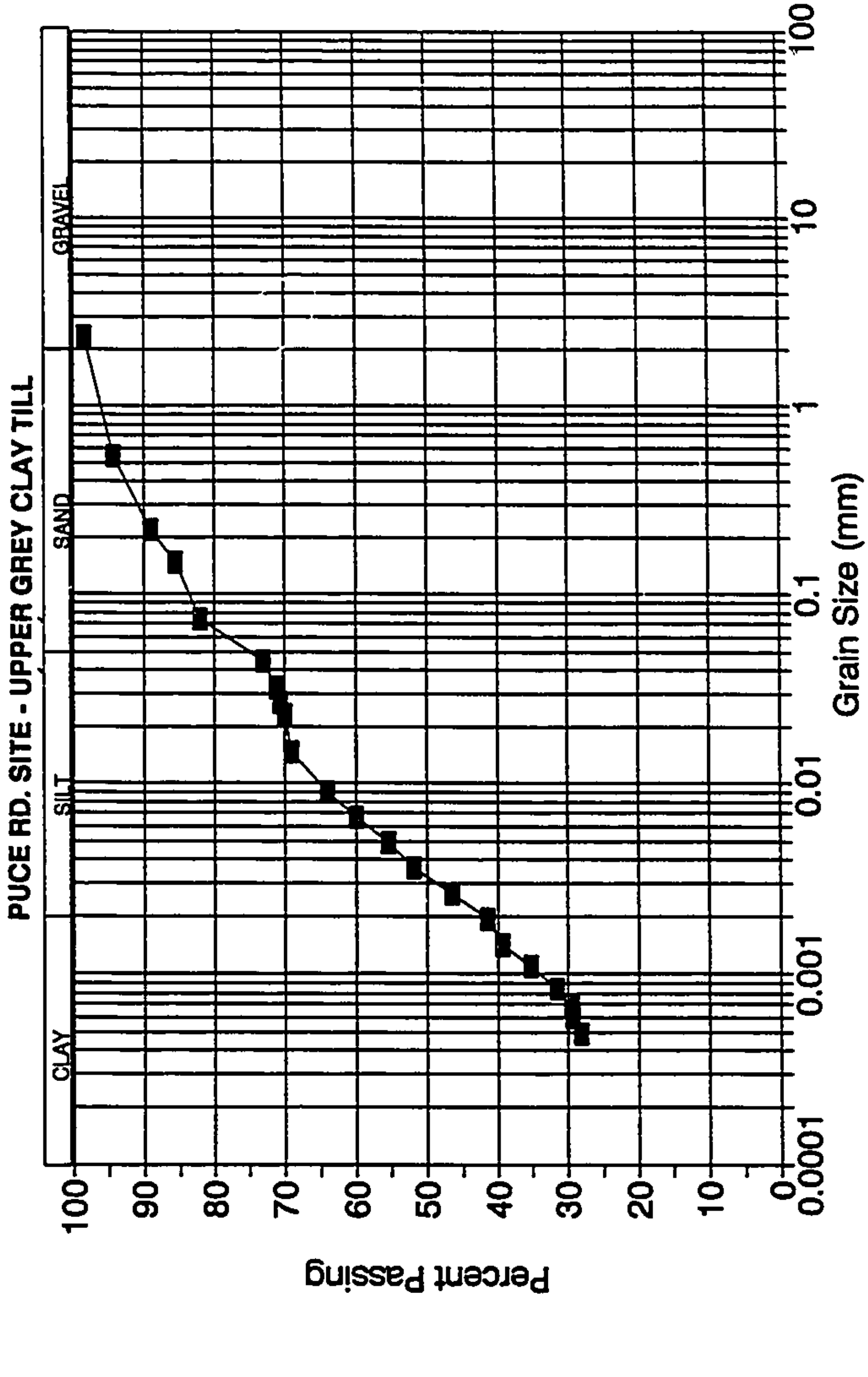
Sample Interval (feet)	Moisture Content (%)
0-2	14.8
2-4	15.6
4-6	15.5
6-8	11.9
8-10	12.7
10-12	15.1
12-14	15.3
14-16	15.4
16-18	16.7
18-20	16.6
20-22	13.9
22-24	7.9
24-26	8.3
26-28	11.6
28-30	15.2
30-32	17.9
32-34	19.2
34-36	22.0
36-38	24.6
38-40	22.4
40-42	21.1
42-44	21.2
44-46	20.0
46-48	20.9

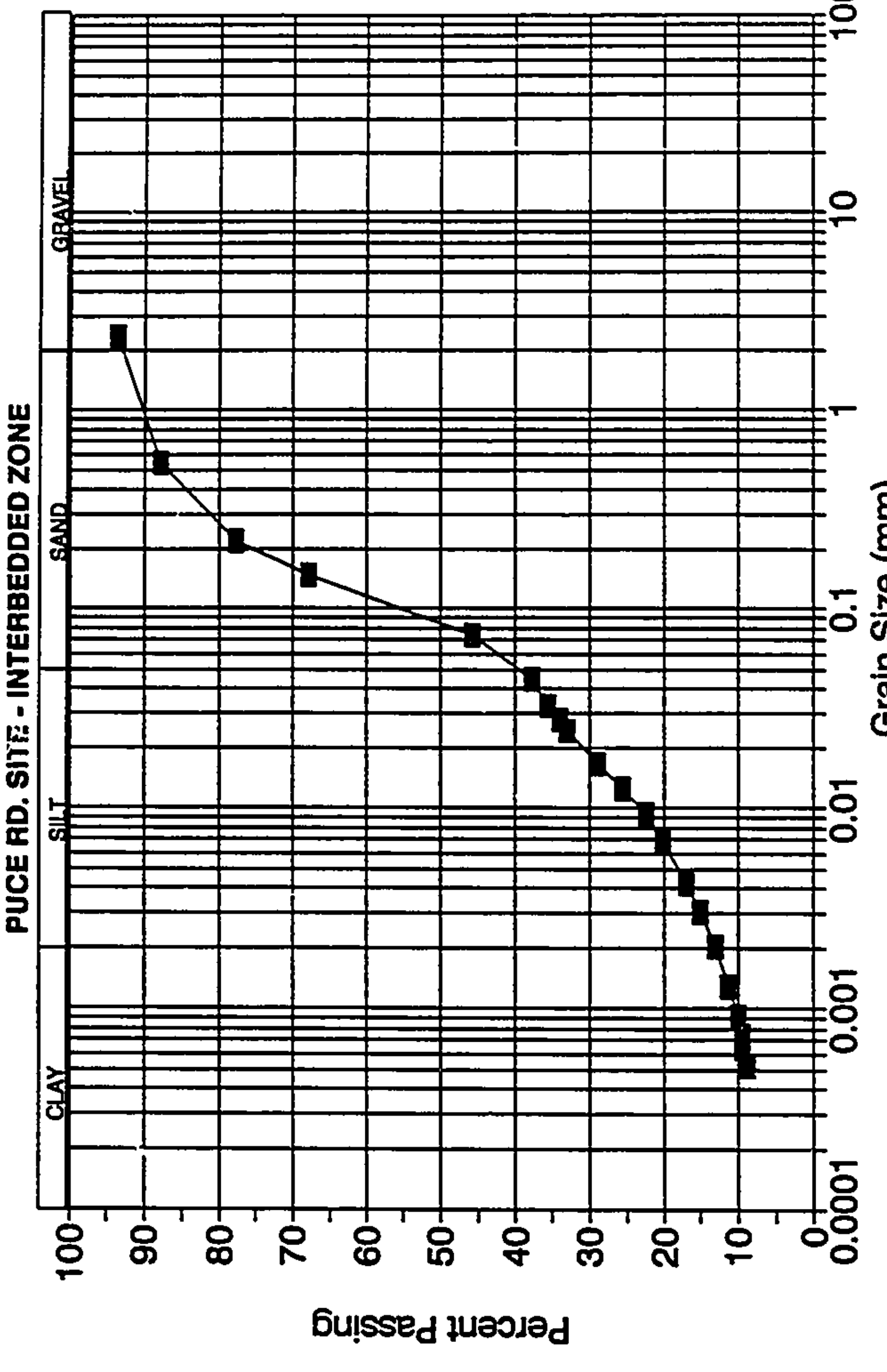
Whelan Farm Site

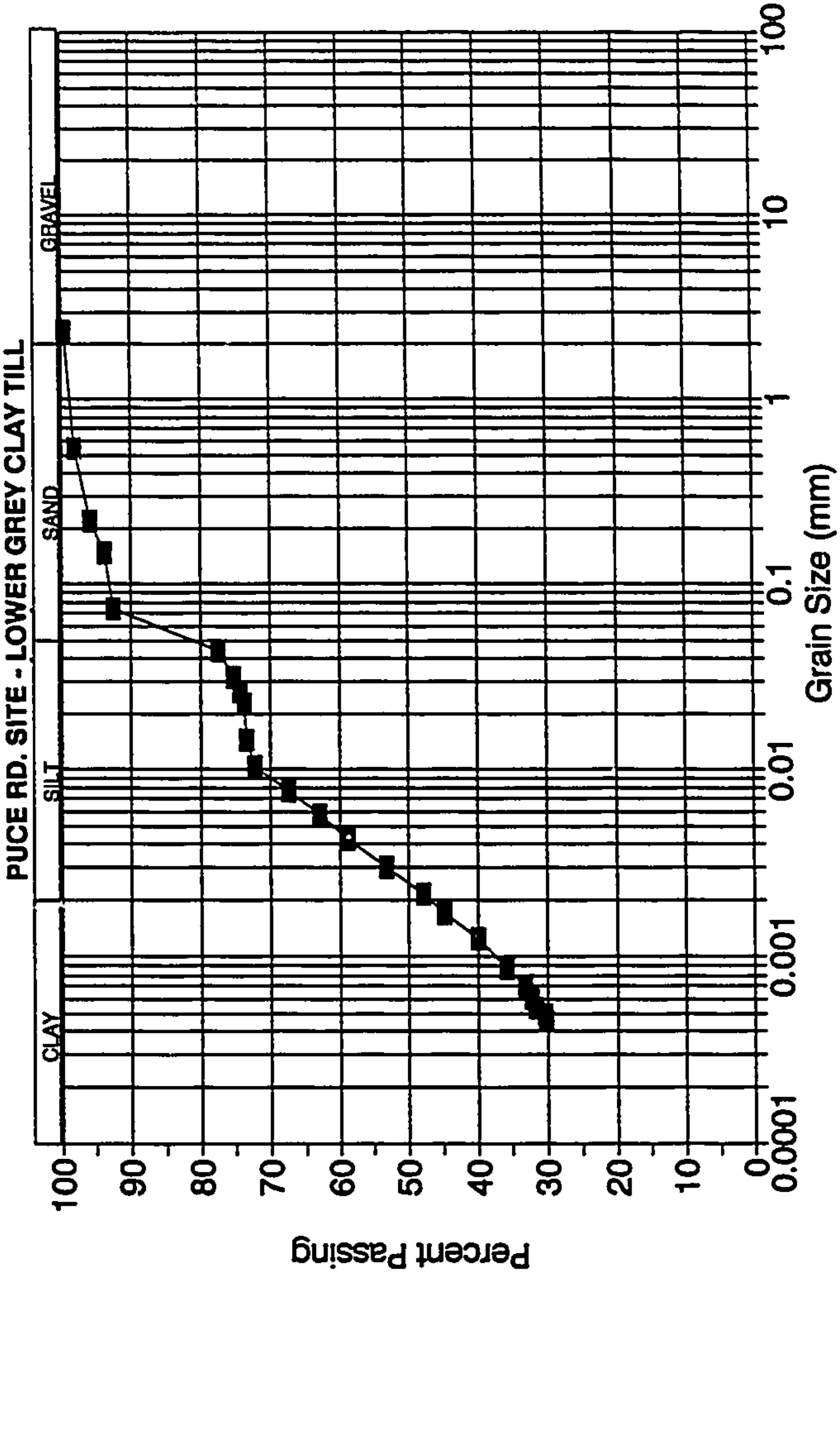
Sample Interval (feet)	Moisture Content (%)
0-2	13.7
2-4	14.3
4-6	14.4
6-8	15.7
8-10	10.9
10-12	12.0
12-14	15.0
14-16	15.7
16-18	16.7
18-20	16.2
20-22	17.7
22-24	17.0

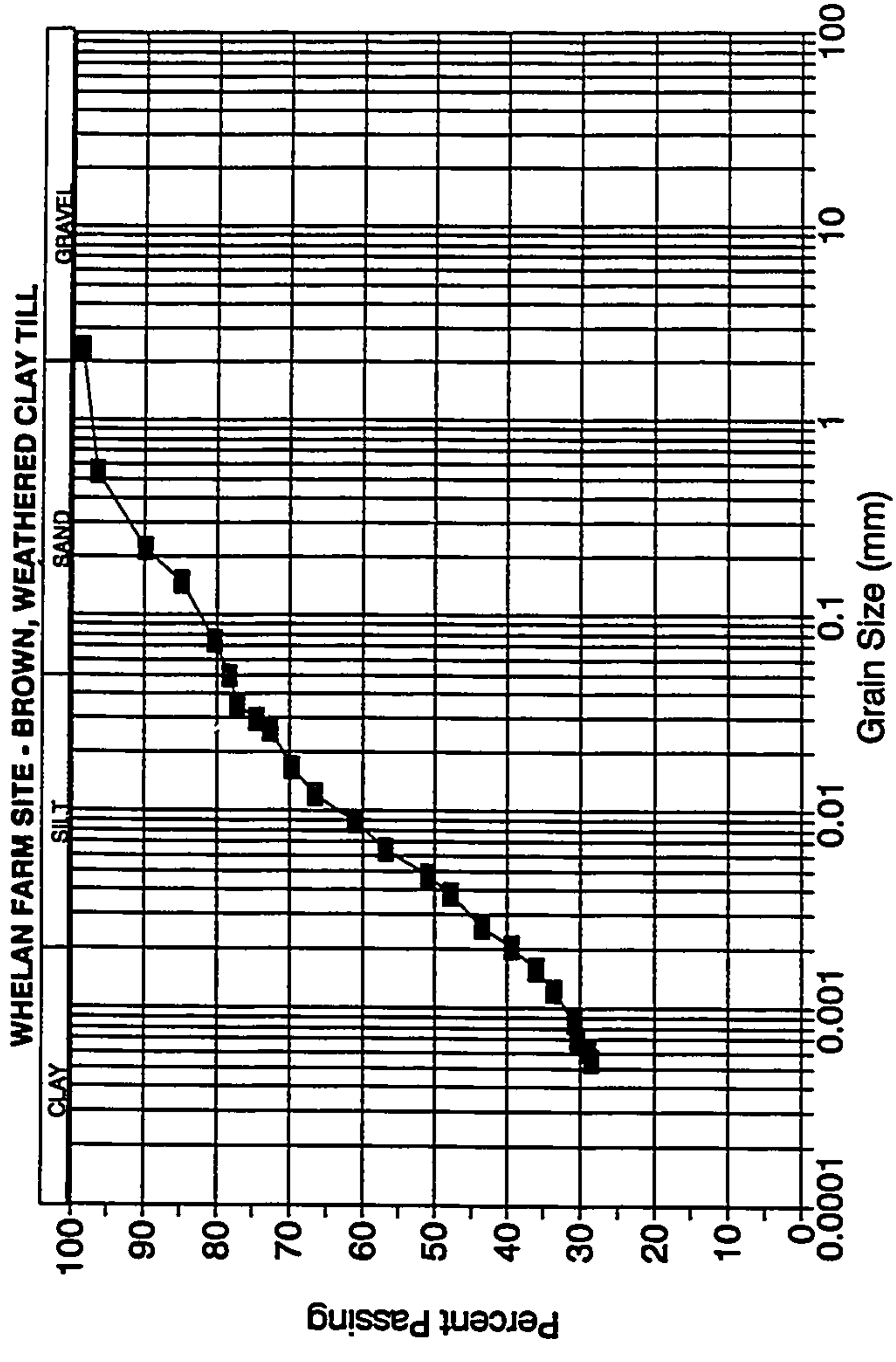


PUCE RD. SITE - BROWN, WEATHERED CLAY TILL
CLAY
SILT
SAND
GRAVEL
Percent Passing
Grain Size (mm)
0
10
20
30
40
50
60
70
80
90
100
0.0001
0.001
0.01
0.1
1
10
100

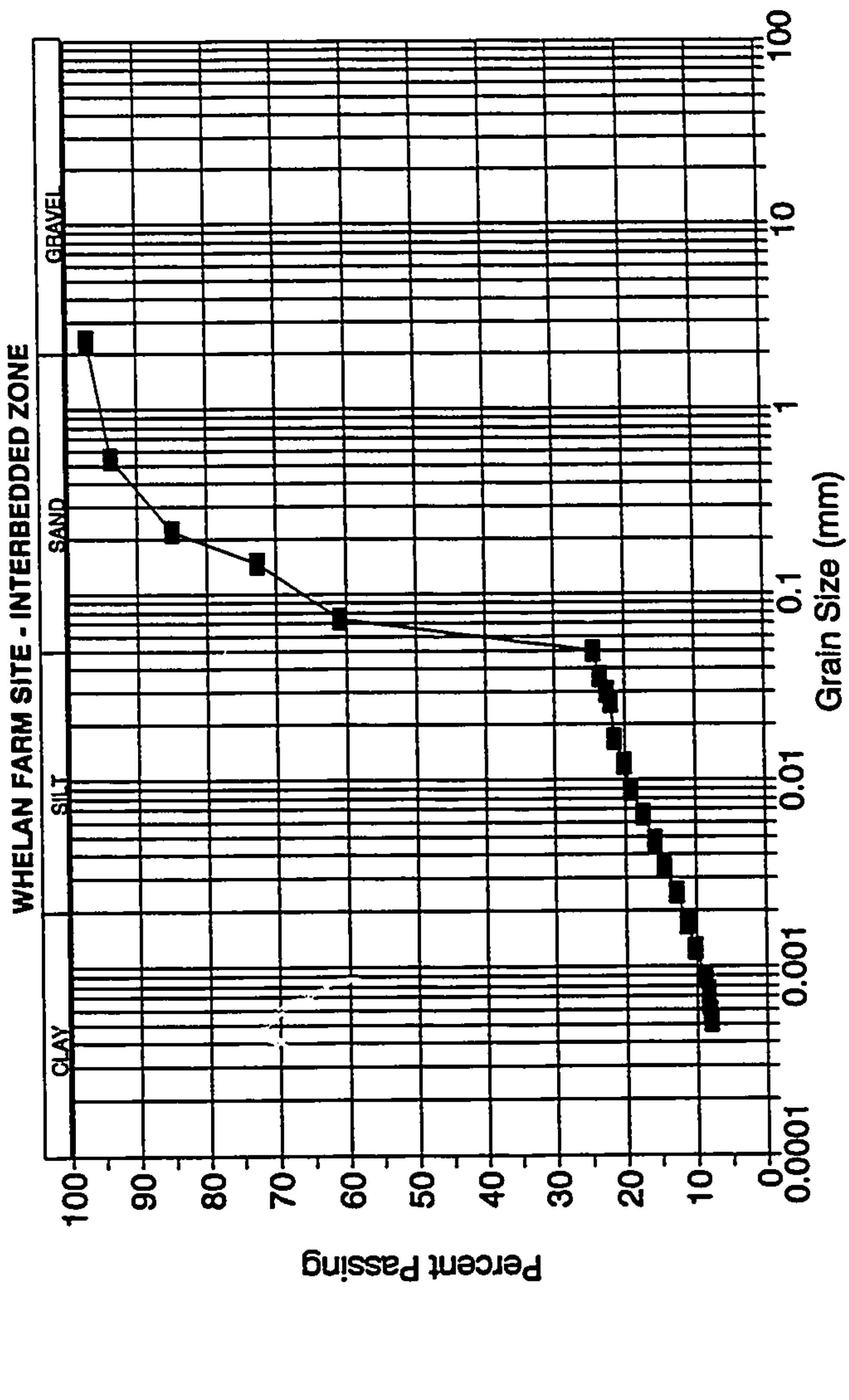

PUCE RD. SITE - UPPER GREY CLAY TILL
CLAY
SILT
SAND
GRAVEL
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.0001
0.001
0.01
0.1
1
10
100
Grain Size (mm)

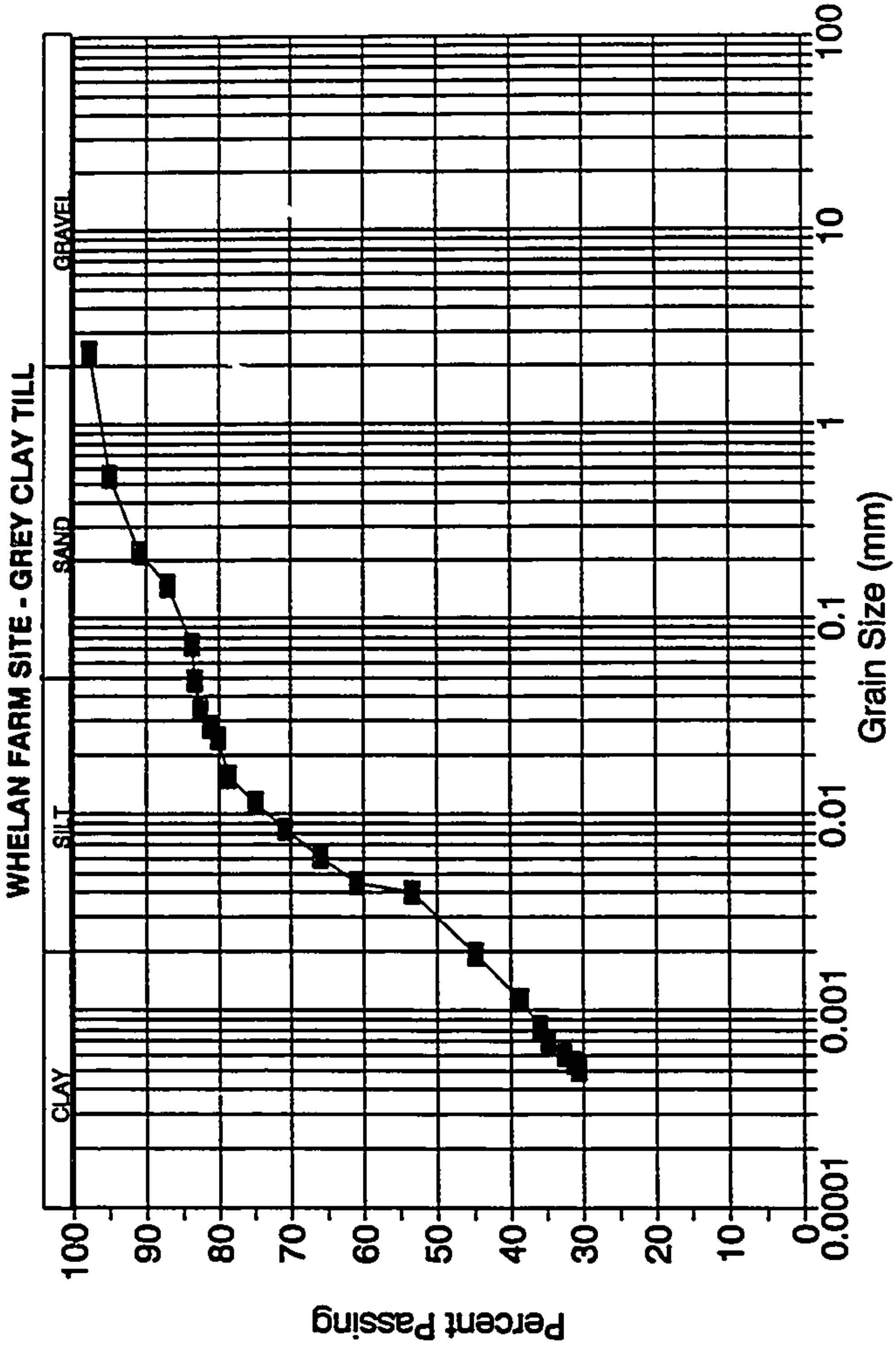

PUCE RD. SITE - INTERBEDDED ZONE
CLAY
SILT
SAND
GRAVEL
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.0001
0.001
0.01
0.1
1
10
100
Grain Size (mm)


PUCE RD. SITE - LOWER GREY CLAY TILL
CLAY
SILT
SAND
GRAVEL
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.0001
0.001
0.01
0.1
1
10
100
Grain Size (mm)



WHELAN FARM SITE - BROWN, WEATHERED CLAY TILL
CLAY
SILT
SAND
GRAVEL
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.0001
0.001
0.01
0.1
1
10
100
Grain Size (mm)


WHELAN FARM SITE - INTERBEDDED ZONE
CLAY
SILT
SAND
GRAVEL
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.0001
0.001
0.01
0.1
1
10
100
Grain Size (mm)


WHELAN FARM SITE - GREY CLAY TILL
CLAY
SILT
SAND
GRAVEL
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.0001
0.001
0.01
0.1
1
10
100
Grain Size (mm)

APPENDIX C

WATER LEVEL DATA

* Monitoring Well Elevation Data
* Water Level Measurements
* Water Level Elevations
* Well Hydrographs

MONITORING WELL ELEVATION DATA
Puce Road Site

Monitoring Well	Ground Elevation (m.a.s.l.)	T.O.C. Elevation (m.a.s.l.)
A-1	183.628	183.983
A-2	183.621	184.265
A-3	183.655	184.270
A-4	183.721	184.266
A-5	183.732	184.388
A-6	183.756	184.756
B-1	182.844	183.674
B-2	182.806	183.508
B-3	182.834	183.461
B-4	182.786	183.473
B-5	182.806	183.566
B-6	182.796	183.368
C-1	183.651	184.598
C-2	183.641	184.243
C-3	183.640	184.340
C-4	183.648	184.509
C-5	183.647	184.403

Notes: m.a.s.l. = metres above sea level
T.O.C. = top of casing

MONITORING WELL ELEVATION DATA
Whelan Farm Site

Monitoring Well	Ground Elevation (m.a.s.l.)	T.O.C. Elevation (m.a.s.l.)
A-1	186.522	186.522
A-2	186.510	186.510
A-3	186.454	186.454
A-4	186.465	186.465
Ag. Can-1	186.448	186.943
Ag. Can-2	186.477	186.936
Ag. Can-3	186.518	187.050
Ag. Can-4	186.478	186.891
Ag. Can-5	186.531	186.976
Ag. Can-6	186.594	186.887
Ag. Can-7	186.664	187.184
Ag. Can-8	186.647	187.122
Ag. Can-9	186.668	187.168
Ag. Can-10	186.630	187.148
Ag. Can-11	186.598	187.062
Ag. Can-12	186.562	186.985
Ag. Can-13	186.603	187.122
Ag. Can-14	186.638	187.130
Ag. Can-15	186.656	187.075
Ag. Can-16	186.628	187.084

Notes: m.a.s.l. = metres above sea level
T.O.C. = top of casing

DEPTH TO WATER (metres below T.O.C.) - PUCE ROAD SITE

Well	6/17/90	6/19/90	6/21/90	6/26/90	7/02/90	7/05/90	7/09/90	7/18/90	7/29/90	8/06/90	8/23/90	9/03/90	9/05/90	9/14/90
A1	3.72	1.75	1.65	1.63	1.63	1.63	1.62	1.61	1.57	1.56	1.51	--	--	1.46
A2	5.48	5.29	5.15	4.29	3.38	3.10	2.79	2.39	2.14	2.05	1.90	--	--	1.81
A3	6.69	6.45	6.22	5.57	5.07	4.75	4.47	3.74	3.27	2.75	2.30	--	--	1.74
A4	8.20	7.90	7.67	6.62	5.58	5.13	4.60	3.70	2.98	2.63	2.10	--	--	1.81
A5	10.50	10.10	9.46	7.83	6.32	5.71	5.02	3.92	3.14	2.77	2.29	--	--	1.99
A6	14.50	14.10	13.71	12.92	12.71	11.96	11.05	10.12	9.21	8.42	7.05	--	--	6.05
B1	--	--	--	--	--	--	--	--	--	--	--	3.59	3.35	2.20
B2	--	--	--	--	--	--	--	--	--	--	--	2.25	2.15	2.03
B3	--	--	--	--	--	--	--	--	--	--	--	5.70	5.62	5.34
B4	--	--	--	--	--	--	--	--	--	--	--	7.57	7.28	4.05
B5	--	--	--	--	--	--	--	--	--	--	--	9.72	9.61	8.62
C1	3.69	3.39	3.22	2.91	2.53	2.30	2.05	1.90	1.86	1.84	1.85	--	--	1.81
C2	4.91	4.80	4.77	4.73	4.62	4.49	3.95	3.00	2.86	2.60	2.42	--	--	2.17
C3	6.77	6.38	6.32	6.16	5.90	5.74	5.50	5.16	4.73	4.46	3.82	--	--	3.04
C4	11.18	7.29	6.90	5.88	4.94	4.64	4.16	3.35	2.94	2.76	2.42	--	--	2.13
C5	15.75	15.23	14.57	12.93	11.25	10.52	9.59	7.93	6.42	5.56	4.25	--	--	3.22

DEPTH TO WATER (metres below T.O.C.) (CONTINUED) - PUCE ROAD SITE

Well	9/20/90	9/29/90	10/06/90	10/21/90	11/03/90	11/22/90	1/19/91	3/2/91	4/6/91	4/14/91	4/22/91	4/28/91	5/11/91	5/19/91	5/26/91
A1	1.46	1.50	1.52	1.50	1.62	1.57	1.52	1.54	1.55	--	--	--	--	--	--
A2	1.81	1.80	1.79	1.77	1.81	1.83	1.85	1.87	1.87	--	--	--	--	--	--
A3	1.73	1.74	1.77	1.77	1.81	1.84	1.85	1.86	1.88	--	--	--	--	--	--
A4	1.75	1.69	1.67	1.61	1.61	1.60	1.64	1.74	1.81	--	--	--	--	--	--
A5	1.96	1.93	1.85	1.79	1.77	1.76	1.76	1.84	1.94	--	--	--	--	--	--
A6	5.54	5.03	4.74	4.09	3.52	2.40	1.94	1.89	1.91	--	--	--	--	--	--
B1	2.20	2.30	2.31	2.30	2.36	2.36	2.32	2.29	2.36	--	--	--	--	2.31	2.10
B2	2.02	2.10	2.12	2.13	2.20	2.20	2.16	2.02	2.20	--	--	--	--	2.17	2.00
B3	4.5[illegible]	4.31	3.91	3.26	2.91	2.58	2.17	2.15	2.20	--	--	--	--	2.14	2.25
B4	3.04	2.40	2.18	1.93	1.90	1.88	1.91	2.05	2.13	--	--	--	--	2.08	2.04
B5	7.57	6.31	5.51	4.21	3.47	2.80	2.05	2.02	2.08	--	--	--	--	2.09	2.04
C1	1.85	1.84	1.90	1.92	2.05	2.08	2.18	2.19	2.15	2.08	1.95	1.86	1.93	--	--
C2	2.05	1.98	1.92	1.92	1.87	1.85	1.81	1.92	1.87	1.85	1.81	1.79	2.16	--	--
C3	3.23	2.96	2.79	2.46	2.27	2.08	1.91	1.94	1.97	1.97	1.96	1.93	1.91	--	--
C4	2.04	1.96	1.90	1.75	1.72	1.65	1.67	1.77	1.92	1.92	1.92	1.95	1.97	--	--
C5	3.01	2.76	2.61	2.33	2.15	1.97	1.69	1.60	1.62	1.63	1.65	1.65	1.67	--	--

WATER LEVEL ELEVATIONS (m.a.s.l.) - PUCE ROAD SITE

Well	6/17/90	6/19/90	6/21/90	6/26/90	7/02/90	7/05/90	7/09/90	7/18/90	7/29/90	8/06/90	8/23/90	9/03/90	9/05/90	9/14/90
A1	180.26	182.23	182.33	182.35	182.35	182.35	182.36	182.37	182.41	182.42	182.47	--	--	182.52
A2	178.79	178.98	179.12	179.98	180.89	181.17	181.48	181.88	182.13	182.22	182.37	--	--	182.46
A3	177.58	177.82	178.05	178.70	179.20	179.52	179.80	180.53	181.00	181.52	181.97	--	--	182.53
A4	176.03	176.33	176.56	177.61	178.65	179.10	179.63	180.53	181.25	181.60	182.13	--	--	182.42
A5	173.89	174.29	174.93	176.56	178.07	178.68	179.37	180.47	181.25	181.62	182.10	--	--	182.40
A6	170.02	170.42	170.81	171.30	171.81	172.56	173.47	174.40	175.31	176.10	177.47	--	--	178.47
B1	--	--	--	--	--	--	--	--	--	--	--	180.08	180.32	181.47
B2	--	--	--	--	--	--	--	--	--	--	--	181.26	181.36	181.48
B3	--	-	--	--	--	--	--	--	--	--	--	177.76	177.84	178.12
B4	--	--	--	--	--	--	--	--	--	--	--	175.90	176.19	179.42
B5	--	--	--	--	--	--	--	--	--	--	--	173.85	173.96	174.95
C1	180.91	181.21	181.38	181.69	182.07	182.30	182.55	182.70	182.74	182.76	182.75	--	--	182.79
C2	179.33	179.44	179.47	179.51	179.62	179.75	180.29	181.24	181.38	181.64	181.82	--	--	182.07
C3	177.57	177.96	178.02	178.18	178.44	178.60	178.84	179.18	179.61	179.88	180.52	--	--	181.30
C4	173.33	177.22	177.61	178.63	179.57	179.87	180.35	181.16	181.57	181.75	182.09	--	--	182.38
C5	168.65	169.17	169.83	171.47	173.15	173.88	174.81	176.47	177.98	178.84	180.15	--	--	181.18

WATER LEVEL ELEVATIONS (m.a.s.l.) (CONTINUED) - PUCE ROAD SITE

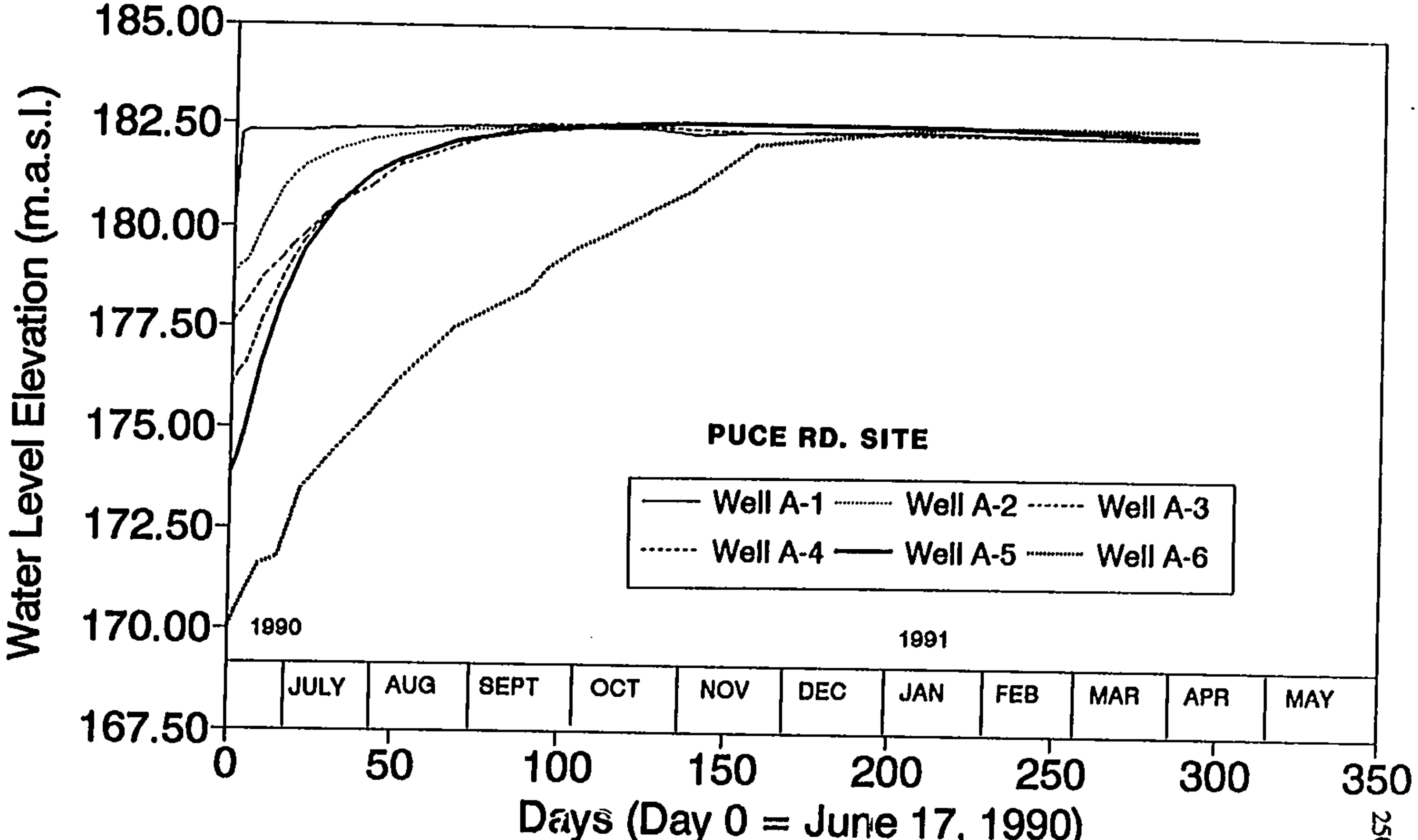
Well	9/20/90	9/29/90	10/06/90	10/21/90	11/03/90	11/22/90	1/19/91	3/2/91	4/6/91	4/14/91	4/22/91	4/28/91	5/11/91	5/19/91	5/26/91
A1	182.52	182.48	182.46	182.48	182.36	182.41	182.46	182.44	182.43	--	--	--	--	--	--
A2	182.46	182.47	182.48	182.50	182.46	182.44	182.42	182.40	182.40	--	--	--	--	--	--
A3	182.54	182.53	182.50	182.50	182.46	182.43	182.42	182.41	182.39	--	--	--	--	--	--
A4	182.48	182.54	182.56	182.62	182.62	182.63	182.59	182.49	182.42	--	--	--	--	--	--
A5	182.43	182.46	182.54	182.60	182.62	182.63	182.63	182.55	182.45	--	--	--	--	--	--
A6	178.98	179.49	179.78	180.43	181.00	182.12	182.58	182.63	182.61	--	--	--	--	--	--
B1	181.47	181.37	181.36	181.37	181.31	181.31	181.35	181.38	181.31	--	--	--	--	181.36	181.57
B2	181.49	181.41	181.39	181.38	181.31	181.31	181.35	181.49	181.31	--	--	--	--	181.34	181.51
B3	178.53	179.15	179.55	180.20	180.53	180.88	181.29	181.31	181.26	--	--	--	--	181.32	181.21
B4	180.43	181.07	181.29	181.54	181.57	181.59	181.56	181.42	181.34	--	--	--	--	181.39	181.43
B5	176.00	177.26	178.06	179.36	180.10	180.77	181.52	181.55	181.49	--	--	--	--	181.48	181.53
C1	182.75	182.76	182.70	182.68	182.55	182.52	182.42	182.41	182.45	182.52	182.65	182.74	182.67	--	--
C2	182.19	182.26	182.32	182.32	182.37	182.39	182.43	182.32	182.37	182.39	182.43	182.45	182.08	--	--
C3	181.11	181.38	181.55	181.88	182.07	182.26	182.43	182.40	182.37	182.37	182.38	182.41	182.43	--	--
C4	182.47	182.55	182.61	182.76	182.75	182.86	182.84	182.74	182.59	182.59	182.59	182.56	182.54	--	--
C5	181.39	181.64	181.79	182.07	182.25	182.43	182.71	182.80	182.78	182.77	182.75	182.75	182.73	--	--

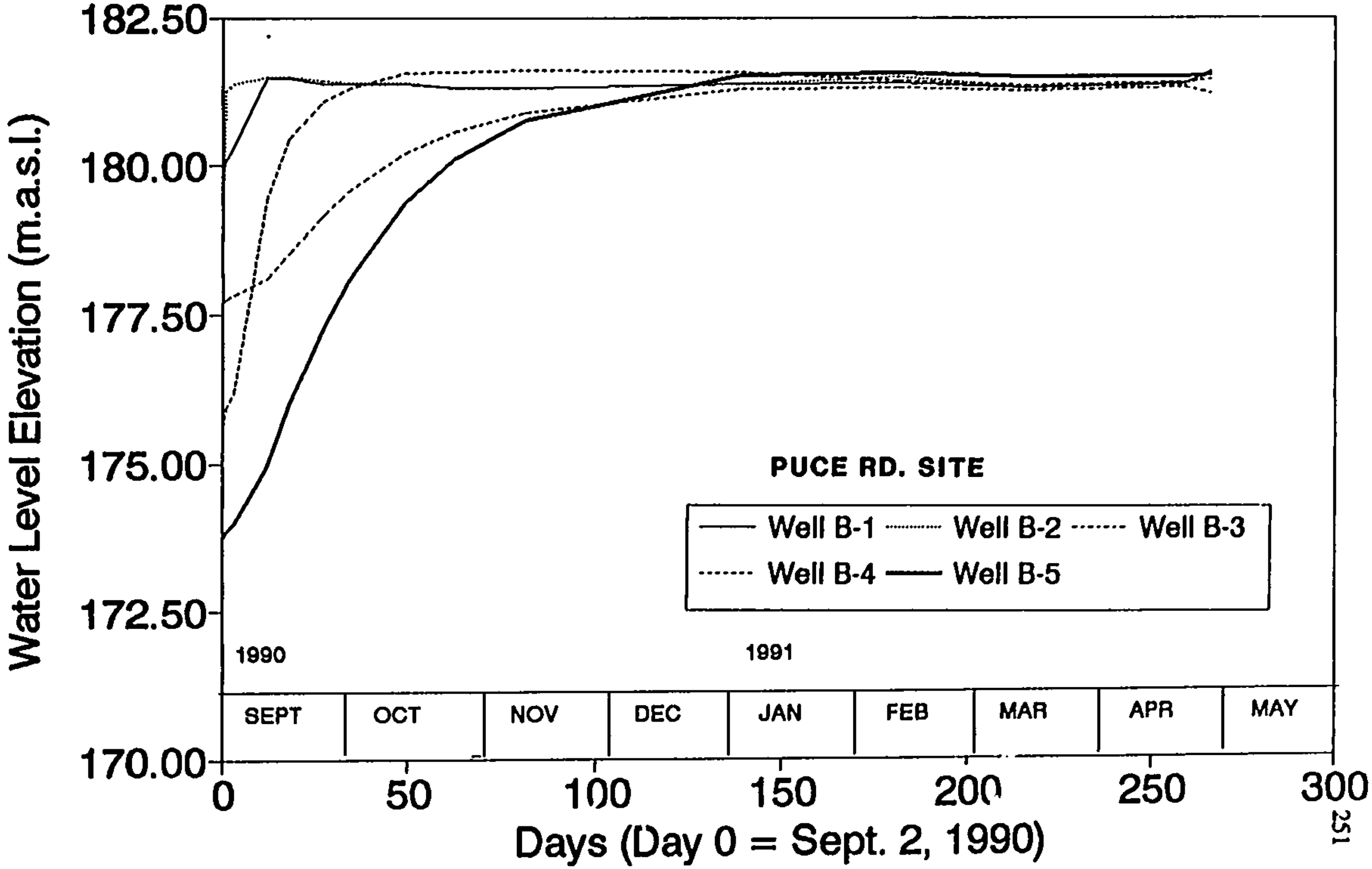
DEPTH TO WATER (metres below T.O.C.) - WHELAN FARM SITE

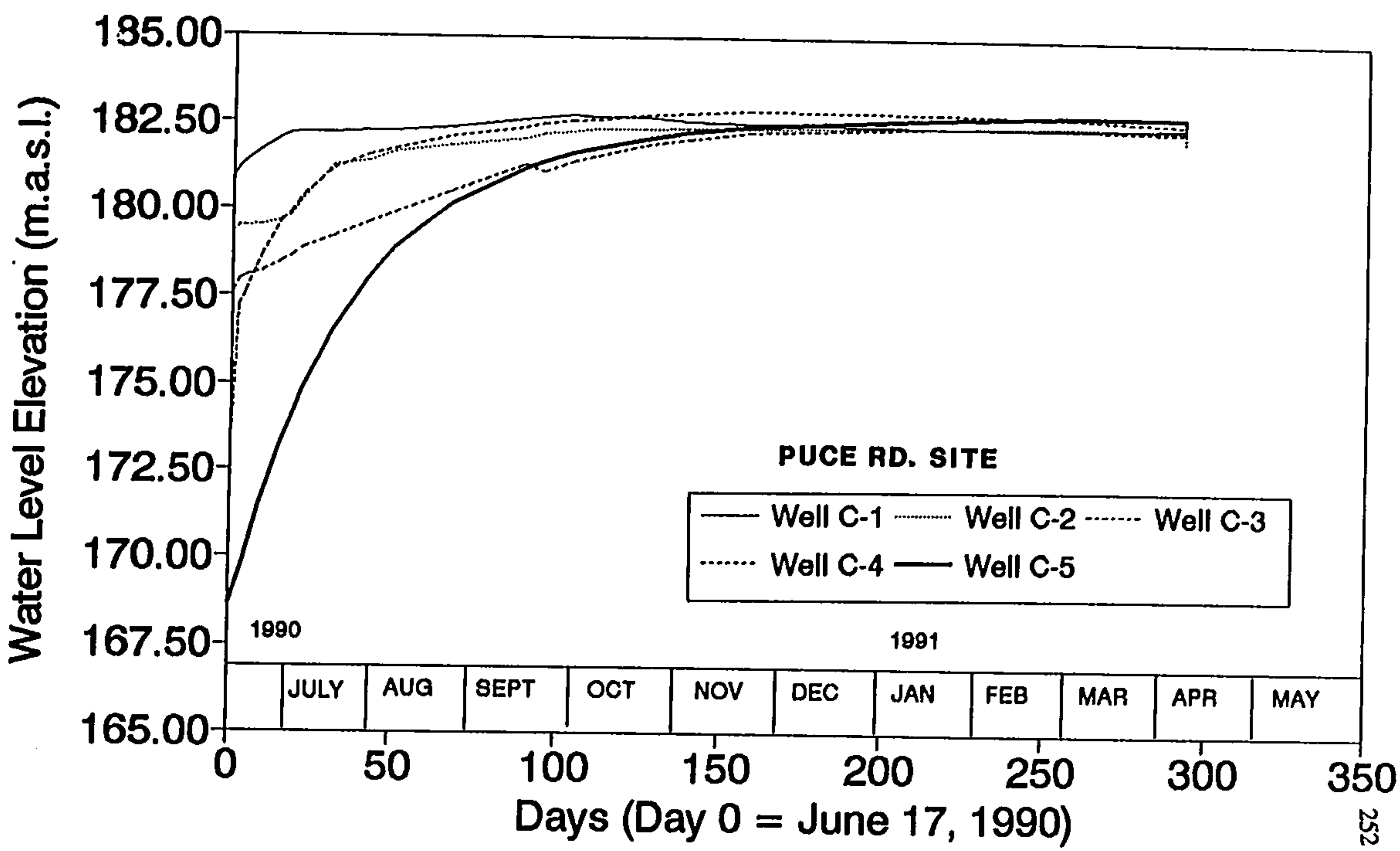
Well	6/12/90	7/08/90	8/06/90	9/01/90	9/02/90	9/03/90	9/05/90	9/14/90	9/20/90	9/29/90	10/06/90	11/03/90	11/22/90	1/19/91	3/02/91	4/06/91	5/04/91
A1	--	--	--	1.68	1.32	1.23	1.18	0.87	0.70	0.84	0.88	0.93	0.90	0.80	0.81	0.86	0.87
A2	--	--	--	2.71	0.96	0.87	0.88	0.87	0.77	0.89	0.88	0.95	0.81	0.85	0.75	0.87	0.89
A3	--	--	--	4.02	2.51	2.00	2.02	1.15	1.01	0.98	0.97	0.93	0.92	0.89	0.90	0.84	0.77
A4	--	--	--	7.18	7.13	7.10	7.05	6.64	6.10	5.53	5.10	3.65	2.88	1.79	1.42	1.30	1.32
Ag Can 1	3.45	1.29	1.29	--	1.25	--	--	--	--	--	0.91	--	--	--	--	--	--
Ag Can 2	4.44	4.42	1.34	--	1.17	--	--	--	--	--	0.89	--	--	--	--	--	--
Ag Can 3	4.49	1.40	1.59	--	1.14	--	--	--	--	--	1.01	--	--	--	--	--	--
Ag Can 4	4.52	1.16	1.42	--	0.98	--	--	--	--	--	0.85	--	--	--	--	--	--
Ag Can 5	4.56	4.35	3.52	--	2.51	--	--	--	--	--	1.64	--	--	--	--	--	--
Ag Can 6	4.41	2.22	1.24	--	0.98	--	--	--	--	--	0.68	--	--	--	--	--	--
Ag Can 7	4.64	4.32	3.81	--	2.79	--	--	--	--	--	1.90	--	--	--	--	--	--
Ag Can 8	4.58	4.23	3.46	--	2.38	--	--	--	--	--	1.55	--	--	--	--	--	--
Ag Can 9	4.01	3.35	1.85	--	1.07	--	--	--	--	--	0.79	--	--	--	--	--	--
Ag Can 10	3.87	3.60	1.71	--	1.10	--	--	--	--	--	0.87	--	--	--	--	--	--
Ag Can 11	4.21	4.21	4.12	--	2.84	--	--	--	--	--	1.89	--	--	--	--	--	--
Ag Can 12	4.54	3.24	1.36	--	0.90	--	--	--	--	--	0.70	--	--	--	--	--	--
Ag Can 13	4.63	4.19	3.35	--	2.32	--	--	--	--	--	0.84	--	--	--	--	--	--
Ag Can 14	4.30	4.30	4.25	--	3.02	--	--	--	--	--	2.12	--	--	--	--	--	--
Ag Can 15	4.08	4.01	3.44	--	2.53	--	--	--	--	--	1.71	--	--	--	--	--	--
Ag Can 16	4.56	4.00	2.40	--	1.73	--	--	--	--	--	1.22	--	--	--	--	--	--

WATER LEVEL ELEVATIONS (m.a.s.l.) - WHELAN FARM SITE

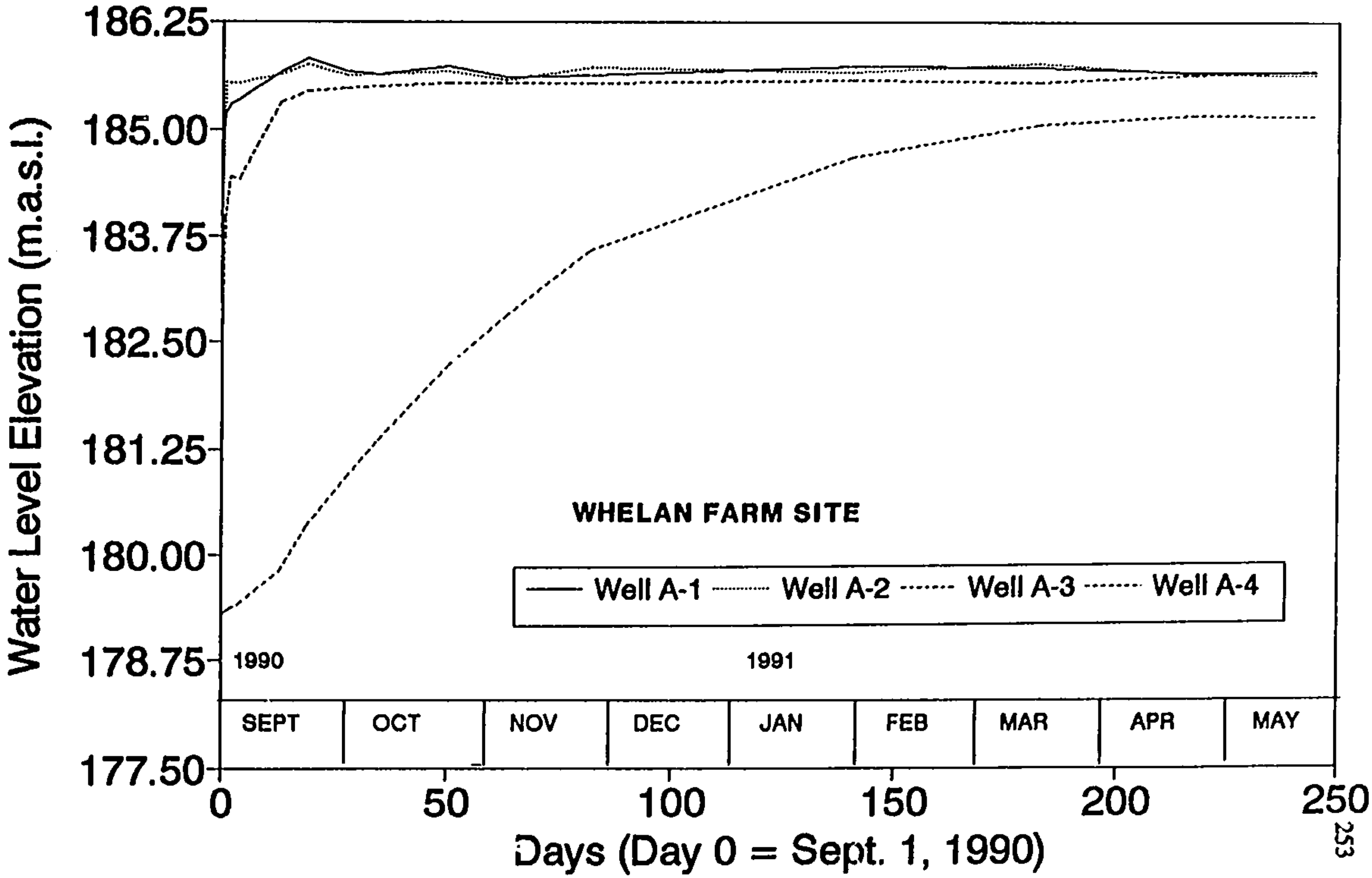
Well	6/12/90	7/08/90	8/06/90	9/01/90	9/02/90	9/03/90	9/05/90	9/14/90	9/20/90	9/29/90	10/06/90	11/03/90	11/22/90	1/19/91	3/02/91	4/06/91	5/04/91
A1	--	--	--	184.84	185.20	185.29	185.34	185.65	185.82	185.68	185.64	185.59	185.62	185.72	185.71	185.66	185.65
A2	--	--	--	183.80	185.55	185.64	185.63	185.64	185.74	185.62	185.63	185.56	185.70	185.66	185.76	185.64	185.62
A3	--	--	--	182.43	183.94	184.45	184.43	185.30	185.44	185.47	185.48	185.52	185.53	185.56	185.55	185.61	185.68
A4	--	--	--	179.28	179.33	179.36	179.41	179.82	180.36	180.93	181.36	182.81	183.58	184.67	185.04	185.16	185.14
Ag Can 1	183.49	185.65	185.61	--	185.69	--	--	--	--	--	186.03	--	--	--	--	--	--
Ag Can 2	182.50	182.52	185.60	--	185.77	--	--	--	--	--	186.05	--	--	--	--	--	--
Ag Can 3	182.56	185.65	185.46	--	185.60	--	--	--	--	--	186.03	--	--	--	--	--	--
Ag Can 4	182.37	185.73	185.47	--	185.91	--	--	--	--	--	186.04	--	--	--	--	--	--
Ag Can 5	182.42	182.63	183.46	--	184.47	--	--	--	--	--	185.34	--	--	--	--	--	--
Ag Can 6	182.48	184.67	185.65	--	185.91	--	--	--	--	--	186.21	--	--	--	--	--	--
Ag Can 7	182.54	182.86	183.37	--	184.39	--	--	--	--	--	185.28	--	--	--	--	--	--
Ag Can 8	182.54	182.89	183.66	--	184.74	--	--	--	--	--	185.57	--	--	--	--	--	--
Ag Can 9	183.16	183.82	185.32	--	186.10	--	--	--	--	--	186.38	--	--	--	--	--	--
Ag Can 10	183.28	183.55	185.44	--	186.05	--	--	--	--	--	186.28	--	--	--	--	--	--
Ag Can 11	182.85	182.94	183.22	--	184.22	--	--	--	--	--	185.17	--	--	--	--	--	--
Ag Can 12	182.45	183.76	185.64	--	186.09	--	--	--	--	--	186.30	--	--	--	--	--	--
Ag Can 13	182.49	182.93	183.77	--	184.80	--	--	--	--	--	186.28	--	--	--	--	--	--
Ag Can 14	182.83	182.88	183.35	--	184.11	--	--	--	--	--	185.01	--	--	--	--	--	--
Ag Can 15	183.00	183.08	183.65	--	184.56	--	--	--	--	--	185.38	--	--	--	--	--	--
Ag Can 16	182.52	183.08	184.68	--	185.35	--	--	--	--	--	185.86	--	--	--	--	--	--


PUCE RD. SITE
Well A-1
Well A-2
Well A-3
Well A-4
Well A-5
Well A-6
Water Level Elevation (m.a.s.l.)
185.00
182.50
180.00
177.50
175.00
172.50
170.00
167.50
1990
1991
JULY
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
0
50
100
150
200
250
300
350
Days (Day 0 = June 17, 1990)

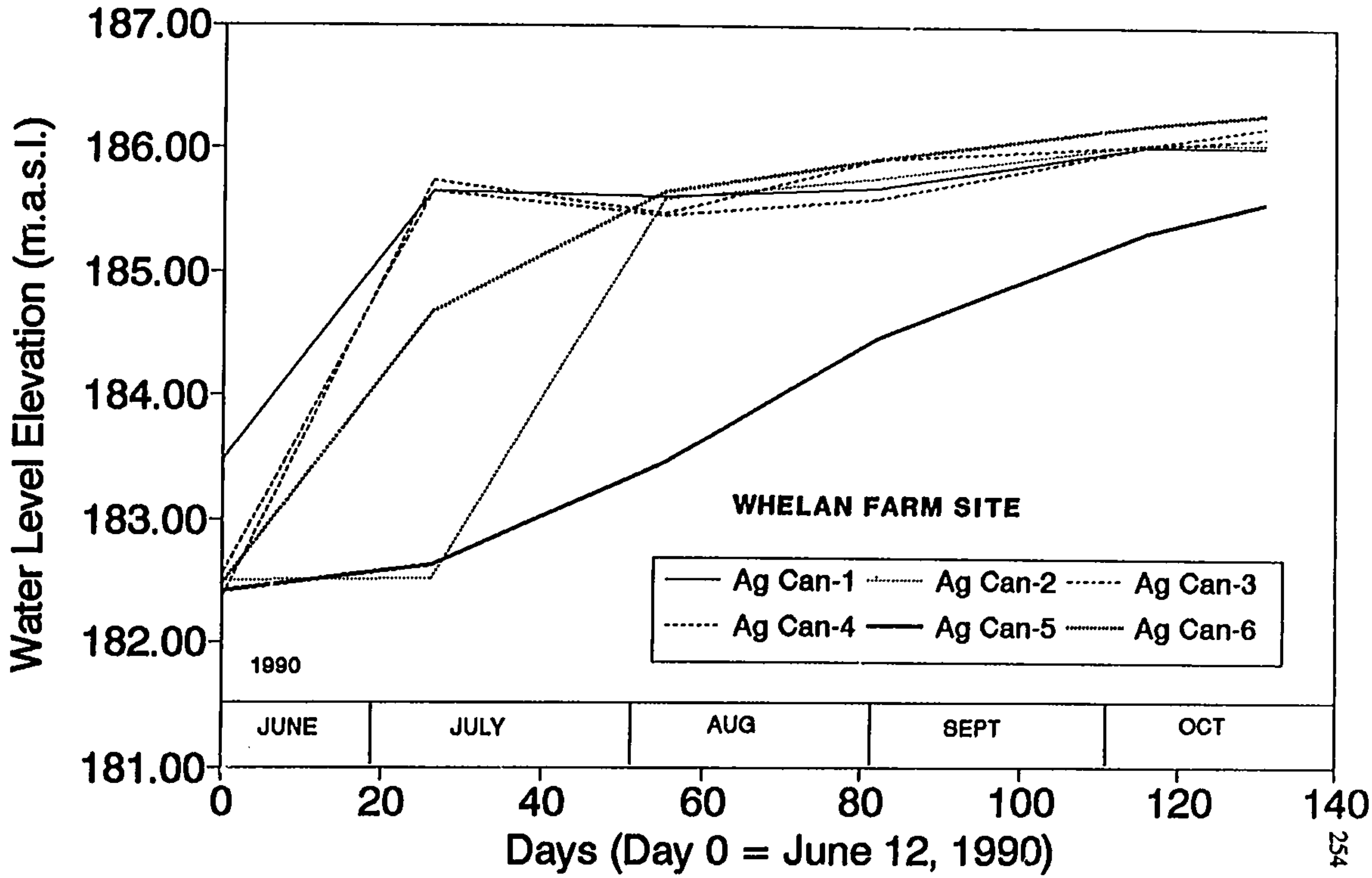

PUCE RD. SITE
Well B-1
Well B-2
Well B-3
Well B-4
Well B-5
Water Level Elevation (m.a.s.l.)
182.50
180.00
177.50
175.00
172.50
170.00
1990
1991
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
0
50
100
150
200
250
300
Days (Day 0 = Sept. 2, 1990)



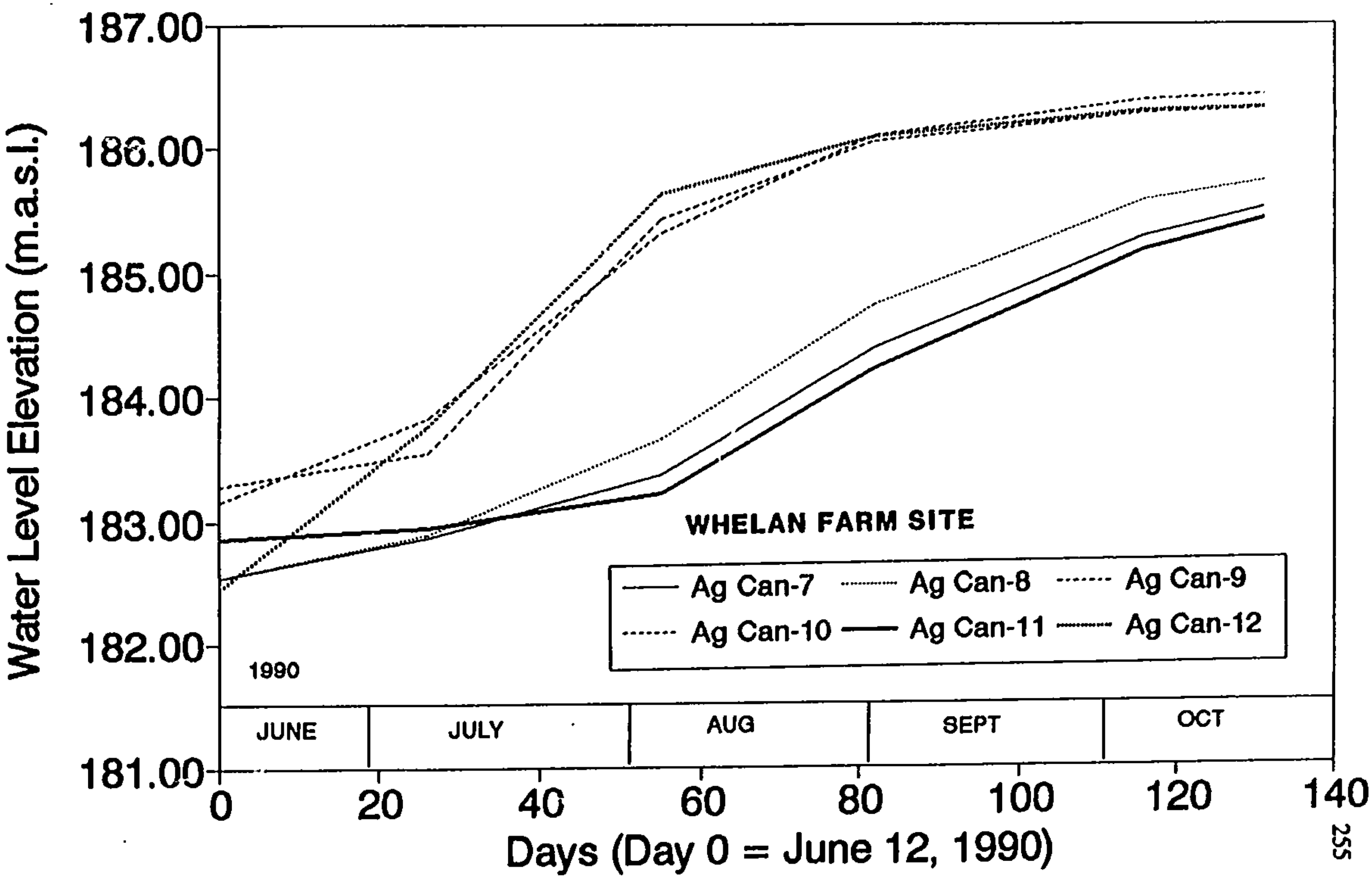
Water Level Elevation (m.a.s.l.)
185.00
182.50
180.00
177.50
175.00
172.50
170.00
167.50
165.00
PUCE RD. SITE
Well C-1
Well C-2
Well C-3
Well C-4
Well C-5
1990
1991
JULY
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
0
50
100
150
200
250
300
350
Days (Day 0 = June 17, 1990)

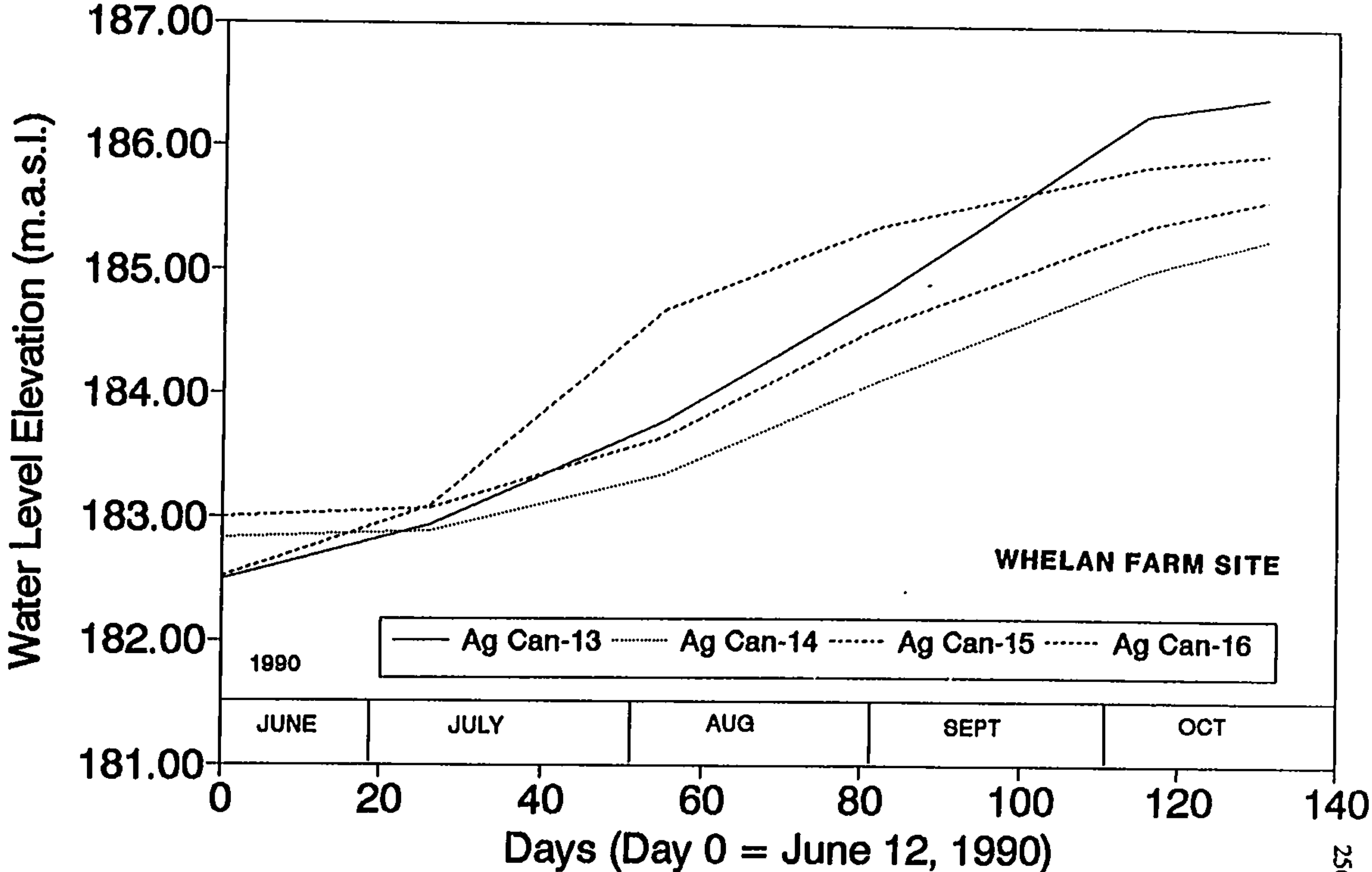


186.25
185.00
183.75
182.50
181.25
180.00
178.75
177.50
Water Level Elevation (m.a.s.l.)
WHELAN FARM SITE
Well A-1
Well A-2
Well A-3
Well A-4
1990
1991
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
0
50
100
150
200
250
Days (Day 0 = Sept. 1, 1990)



187.00
186.00
185.00
184.00
183.00
182.00
181.00
Water Level Elevation (m.a.s.l.)
WHELAN FARM SITE
Ag Can-1
Ag Can-2
Ag Can-3
Ag Can-4
Ag Can-5
Ag Can-6
1990
JUNE
JULY
AUG
SEPT
OCT
0
20
40
60
80
100
120
140
Days (Day 0 = June 12, 1990)


WHELAN FARM SITE
Ag Can-7
Ag Can-8
Ag Can-9
Ag Can-10
Ag Can-11
Ag Can-12
1990
JUNE
JULY
AUG
SEPT
OCT
Water Level Elevation (m.a.s.l.)
187.00
186.00
185.00
184.00
183.00
182.00
181.00
0
20
40
60
80
100
120
140
Days (Day 0 = June 12, 1990)


WHELAN FARM SITE
Ag Can-13
Ag Can-14
Ag Can-15
Ag Can-16
1990
JUNE
JULY
AUG
SEPT
OCT
Water Level Elevation (m.a.s.l.)
187.00
186.00
185.00
184.00
183.00
182.00
181.00
0
20
40
60
80
100
120
140
Days (Day 0 = June 12, 1990)

APPENDIX D

HYDRAULIC CONDUCTIVITY DATA

* Hydraulic Conductivity Details
* Hvorslev Single Well Test Data and Plots

Hydraulic Conductivity Details
Pace Road Site

Well No.	Unit Monitored	Casing Radius (r) (mm)	Screen Length L (m)	Intake Radius R (mm)	Time Lag To (days)	Hydraulic Conductivity* K (m/sec)
A-1	Weathered Till	25.4	0.76	82.5	1.15	9.5 E-9
A-2	Weathered Till	25.4	0.76	82.5	14.31	7.6 E-10
A-3	Grey Till	25.4	0.76	82.5	34.65	3.1 E-10
A-4	I.Z.	25.4	0.76	82.5	26.25	4.2 E-10
A-5	Grey Till	25.4	0.76	82.5	22.00	4.9 E-10
A-6	Grey Till	25.4	0.76	82.5	81.12	1.3 E-10
B-1	Weathered Till	25.4	0.76	82.5	2.00	5.5 E-9
B-2	Weathered Till	25.4	0.76	82.5	3.63	3.0 E-9
B-3	Grey Till	25.4	0.61	82.5	36.80	3.0 E-10
B-4	I.Z.	25.4	0.76	82.5	10.60	1.0 E-9
B-5	Grey Till	25.4	0.76	82.5	34.14	3.2 E-10
C-1	Weathered Till	25.4	0.76	82.5	6.10	1.8 E-9
C-2	Weathered Till	25.4	0.76	82.5	26.50	4.1 E-10
C-3	Grey Till	25.4	0.76	82.5	62.96	1.7 E-10
C-4	I.Z.	25.4	0.76	82.5	25.00	4.4 E-10
C-5	Grey Till	25.4	0.76	82.5	36.30	3.0 E-10

NOTES: I.Z. = Interbedded Zone
$K = r^2 \ln(L/R)/[2LTo]$ (after Hvorslev, 1951)

Hydraulic Conductivity Details
Whelan Farm Site

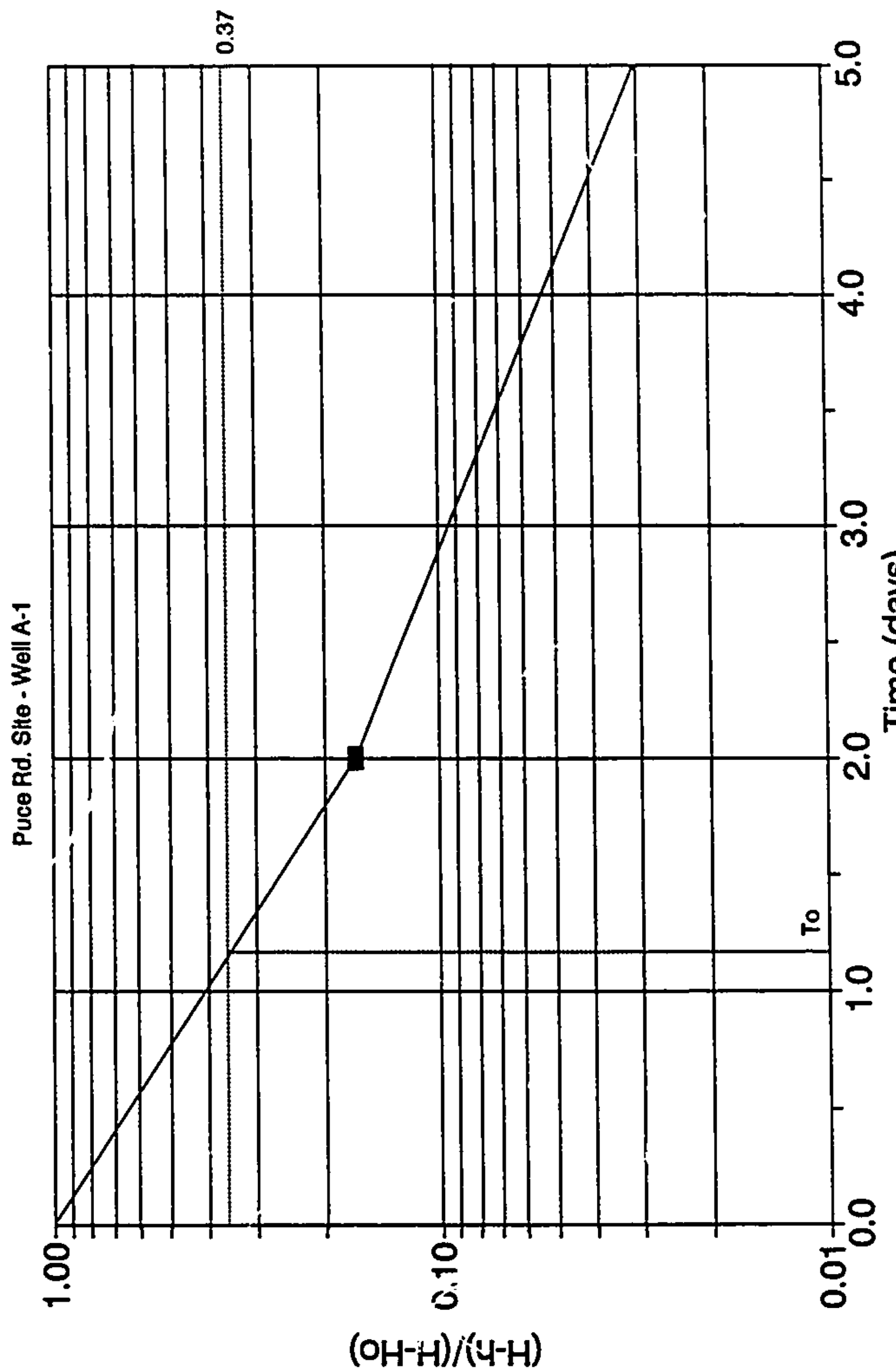
Well No.	Unit Monitored	Casing Radius (r) (mm)	Screen Length L (m)	Intake Radius R (mm)	Time Lag To (days)	Hydraulic Conductivity* K (m/sec)
A-1	Weathered Till	25.4	0.31	25.4	4.34	6.9 E-9
A-2	I.Z.	25.4	0.61	82.5	0.40	3.0 E-8
A-3	Grey Till	25.4	0.61	82.5	4.60	2.7 E-9
A-4	Grey Till	25.4	0.61	82.5	60.00	2.0 E-10

NOTES: I.Z. = Interbedded Zone
K = $r^2 \ln(L/R)/[2LTo]$ (after Hvorslev, 1951)

Hvorslev Single Well Test Results

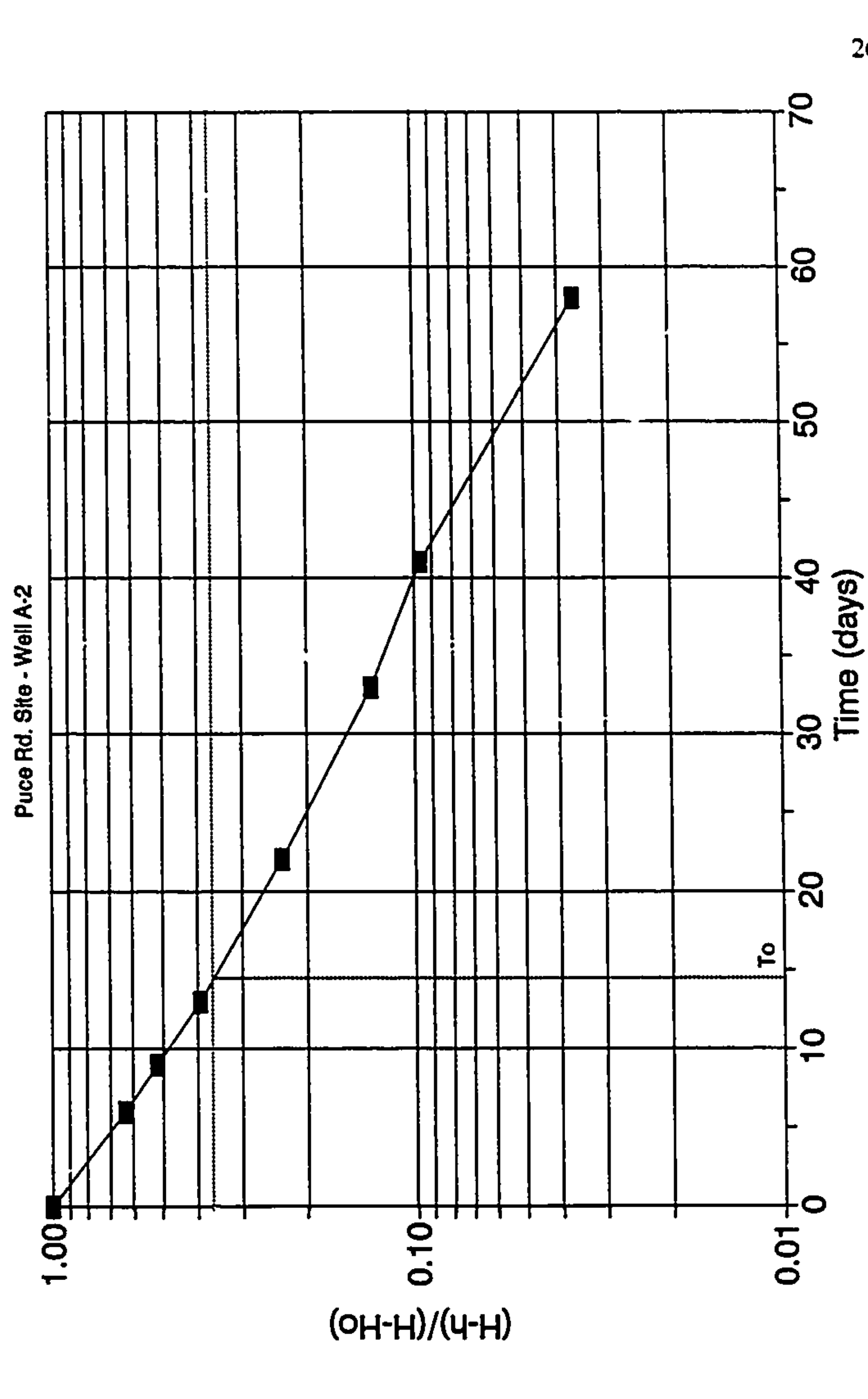
Puce Rd. Site - Well A-1

Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
6/19/90	0	1.75	0.12	1.00
6/21/90	2	1.65	0.02	0.17
6/26/90	7	1.63	0.00	0.00
7/02/90	13	1.63	0.00	0.00
7/05/90	16	1.63	0.00	0.00


Puce Rd. Site - Well A-1
0.37
To
(H-h)/(H-Ho)
1.00
0.10
0.01
0.0
1.0
2.0
3.0
4.0
5.0
Time (days)

Hvorslev Single Well Test Results

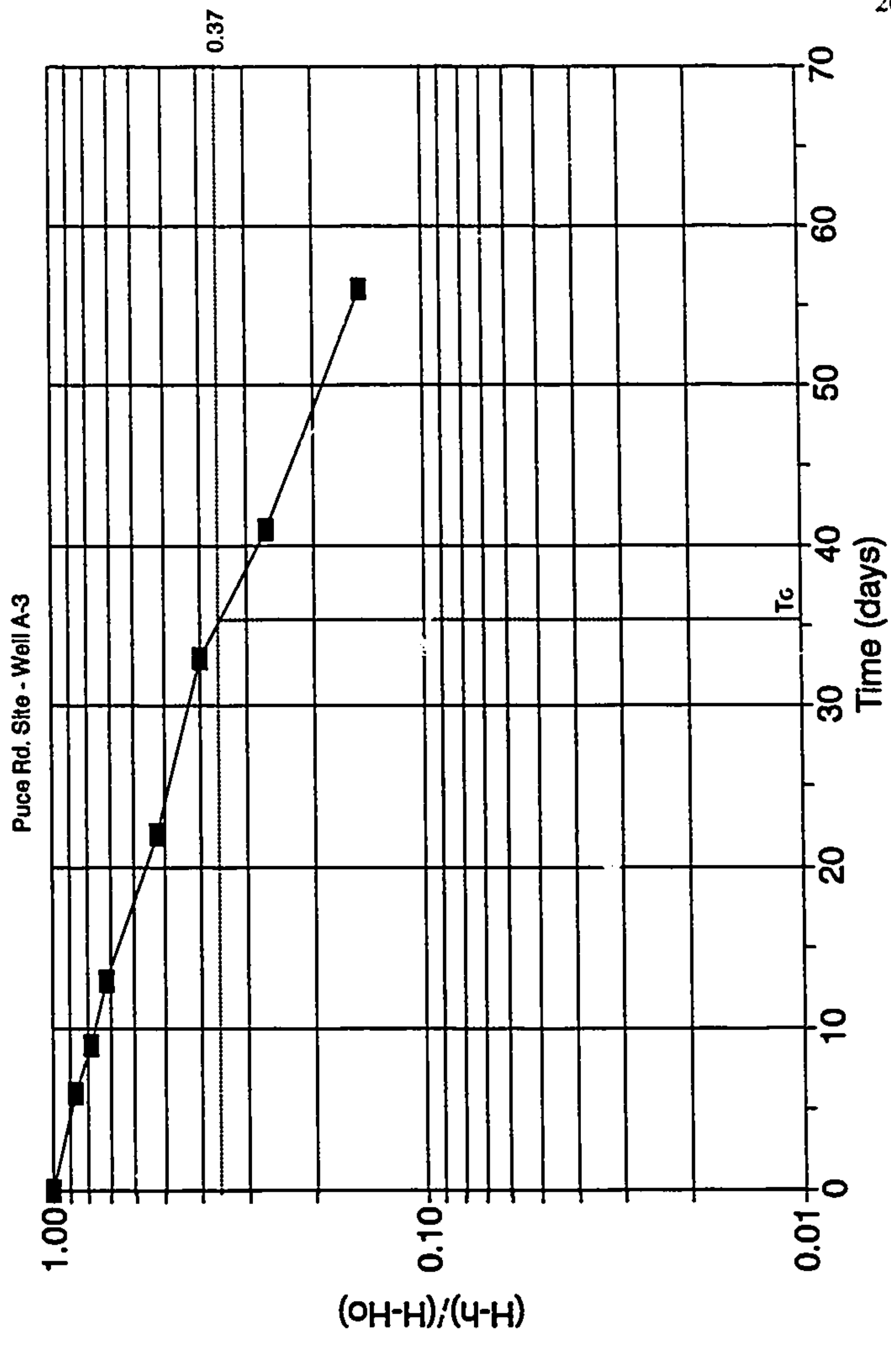
Puce Rd. Site - Well A-2				
Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
6/26/90	0	4.29	2.48	1.00
7/02/90	6	3.38	1.57	0.63
7/05/90	9	3.10	1.29	0.52
7/09/90	13	2.79	0.98	0.40
7/18/90	22	2.39	0.58	0.23
7/29/90	33	2.14	0.33	0.13
8/06/90	41	2.05	0.24	0.10
8/23/90	58	1.90	0.09	0.04
9/14/90	80	1.81	0.00	0.00
9/20/90	86	1.81	0.00	0.00


Puce Rd. Site - Well A-2
(H-h)/(H-Ho)
1.00
0.10
0.01
Time (days)
0
10
20
30
40
50
60
70
To

Hvorslev Single Well Test Results

Puce Rd. Site - Well A-3

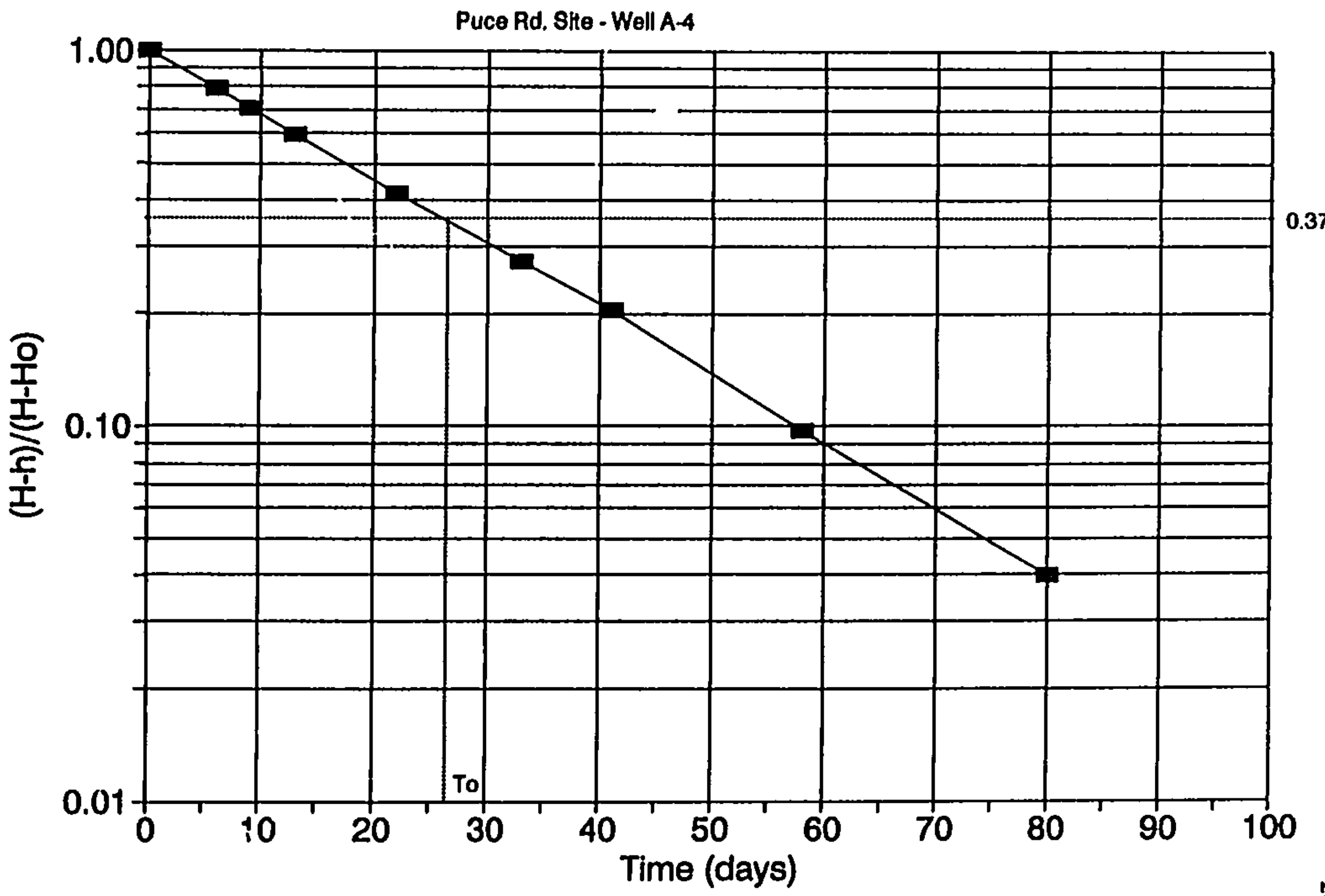
Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
6/26/90	0	5.57	3.84	1.00
7/02/90	6	5.07	3.34	0.87
7/05/90	9	4.75	3.02	0.79
7/09/90	13	4.47	2.74	0.71
7/18/90	22	3.74	2.01	0.52
7/29/90	33	3.27	1.54	0.40
8/06/90	41	2.75	1.02	0.27
8/23/90	56	2.30	0.57	0.15
9/14/90	80	1.74	0.01	0.00
9/20/90	86	1.73	0.00	0.00


Puca Rd. Site - Well A-3
(H-h)/(H-Ho)
1.00
0.10
0.01
0.37
Tc
0
10
20
30
40
50
60
70
Time (days)

Hvorslev Single Well Test Results

Puce Rd. Site - Well A-4

Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
6/26/90	0	6.62	5.01	1.00
7/02/90	6	5.58	3.97	0.79
7/05/90	9	5.13	3.52	0.70
7/09/90	13	4.60	2.99	0.60
7/18/90	22	3.70	2.09	0.42
7/29/90	33	2.98	1.37	0.27
8/06/90	41	2.63	1.02	0.20
8/23/90	58	2.10	0.49	0.10
9/14/90	80	1.81	0.20	0.04
9/20/90	86	1.75	0.14	0.03
9/29/90	95	1.69	0.08	0.02
10/06/90	102	1.67	0.06	0.01
10/21/90	117	1.61	0.00	0.00
11/03/90	132	1.61	0.00	0.00

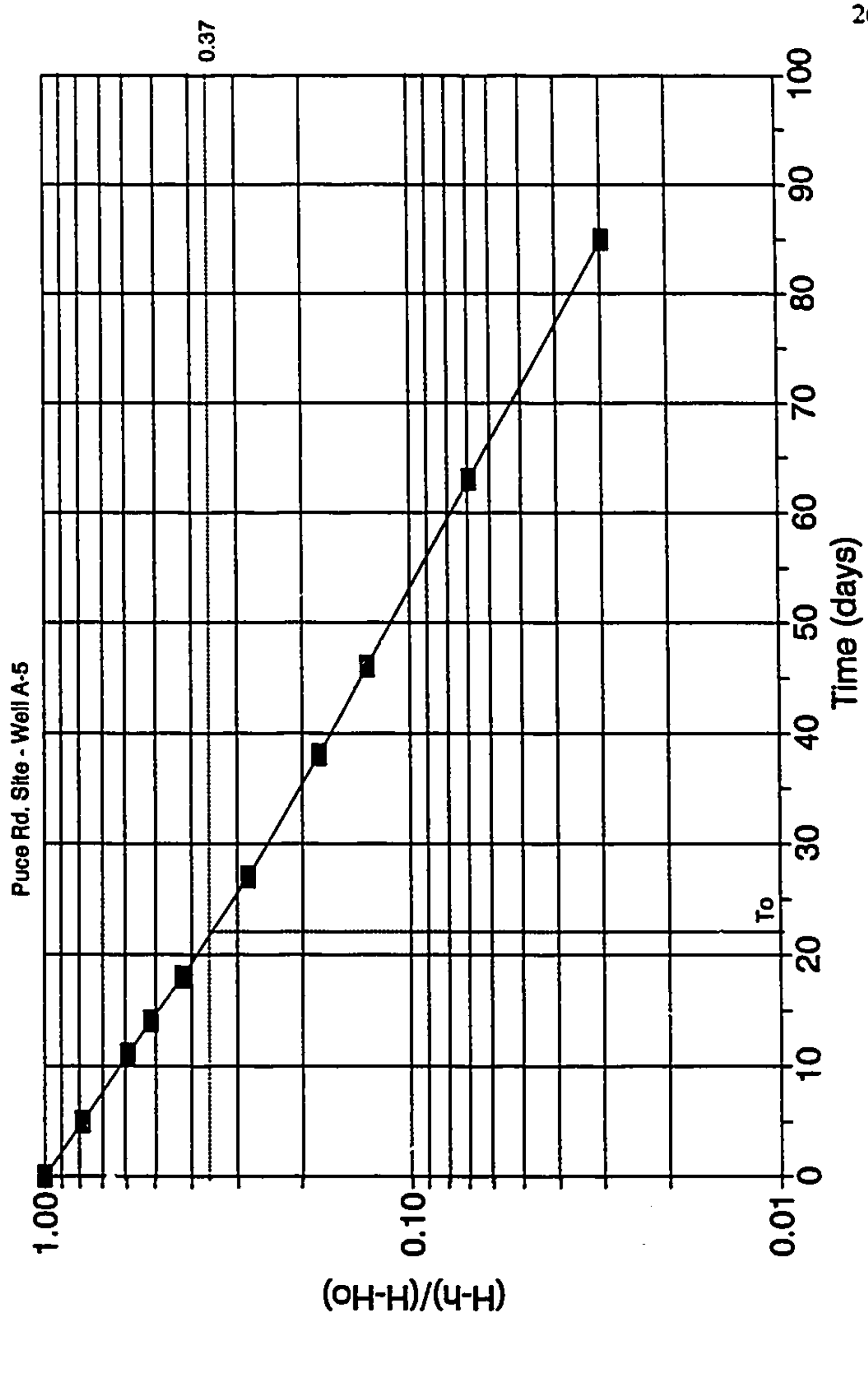


Puce Rd. Site - Well A-4
1.00
0.10
0.01
(H-h)/(H-Ho)
0.37
To
0
10
20
30
40
50
60
70
80
90
100
Time (days)

Hvorslev Single Well Test Results

Puce Rd. Site - Well A-5

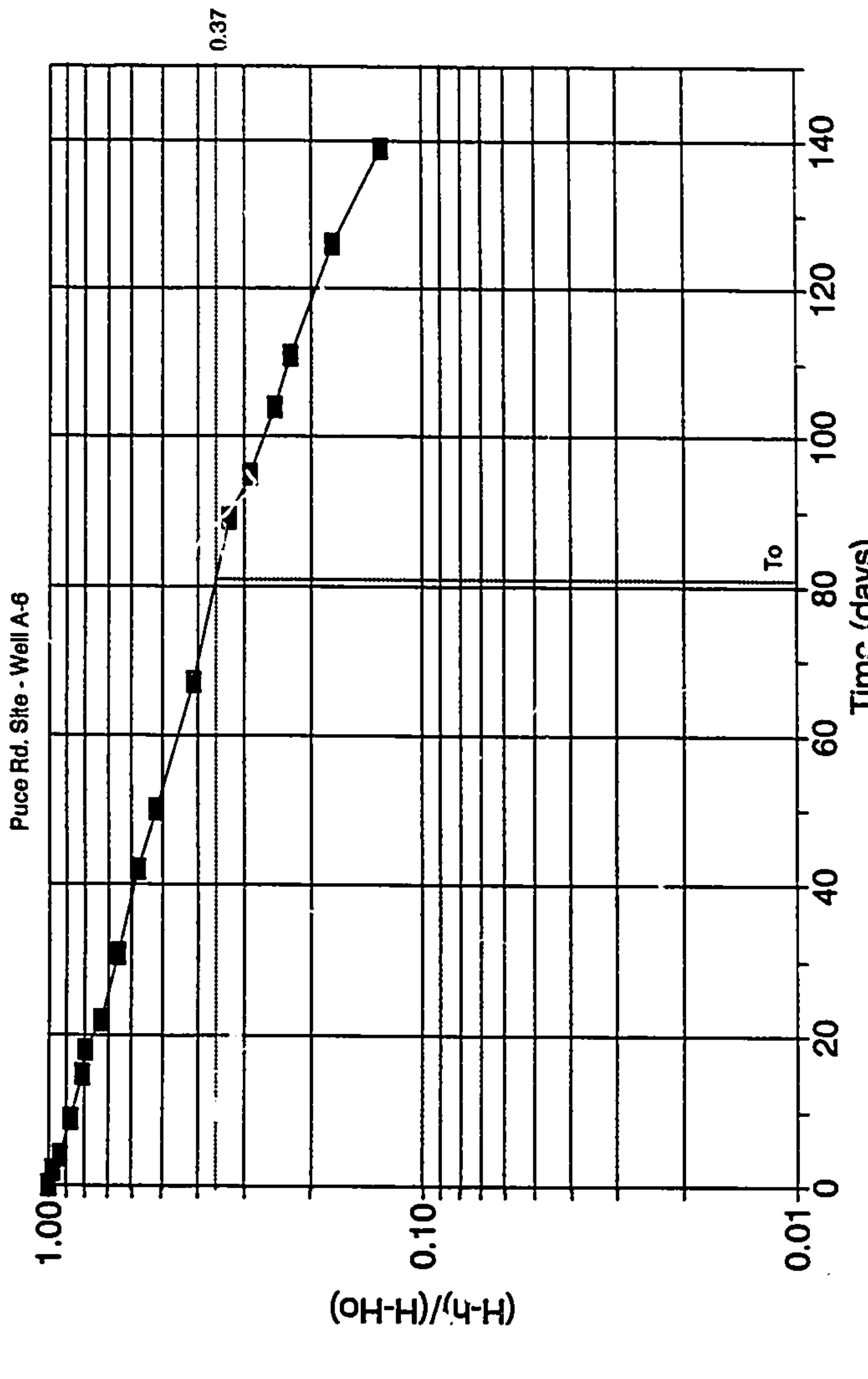
Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
6/21/90	0	9.46	7.70	1.00
6/26/90	5	7.83	6.07	0.79
7/02/90	11	6.32	4.56	0.59
7/05/90	14	5.71	3.95	0.51
7/09/90	18	5.02	3.26	0.42
7/18/90	27	3.92	2.16	0.28
7/29/90	38	3.14	1.38	0.18
8/06/90	46	2.77	1.01	0.13
8/23/90	63	2.29	0.53	0.07
9/14/90	85	1.99	0.23	0.03
9/20/90	91	1.96	0.20	0.03
9/29/90	100	1.93	0.17	0.02
10/06/90	107	1.85	0.09	0.01
10/21/90	122	1.79	0.03	0.00
11/03/90	135	1.77	0.01	0.00
11/22/90	154	1.76	0.00	0.00
1/19/91	212	1.76	0.00	0.00



Puce Rd. Site - Well A-5
0.37
To
1.00
0.10
0.01
(H-h)/(H-Ho)
0
10
20
30
40
50
60
70
80
90
100
Time (days)

Hvorslev Single Well Test Results

Puce Rd. Site - Well A-6				
Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
6/17/90	0	14.50	12.61	1.00
6/19/90	2	14.10	12.21	0.97
6/21/90	4	13.71	11.82	0.94
6/26/90	9	12.92	11.03	0.87
7/02/90	15	12.17	10.28	0.82
7/05/90	18	11.96	10.07	0.80
7/09/90	22	11.05	9.16	0.73
7/18/90	31	10.12	8.23	0.65
7/29/90	42	9.21	7.32	0.58
8/06/90	50	8.42	6.53	0.52
8/23/90	67	7.05	5.16	0.41
9/14/90	89	6.05	4.16	0.33
9/20/90	95	5.54	3.65	0.29
9/29/90	104	5.03	3.14	0.25
10/06/90	111	4.74	2.85	0.23
10/21/90	126	4.09	2.20	0.17
11/03/90	139	3.52	1.63	0.13
11/22/90	158	2.40	0.51	0.04
1/19/91	216	1.94	0.05	0.00
3/02/91	258	1.89	0.00	0.00
4/06/91	293	1.91	0.02	0.00

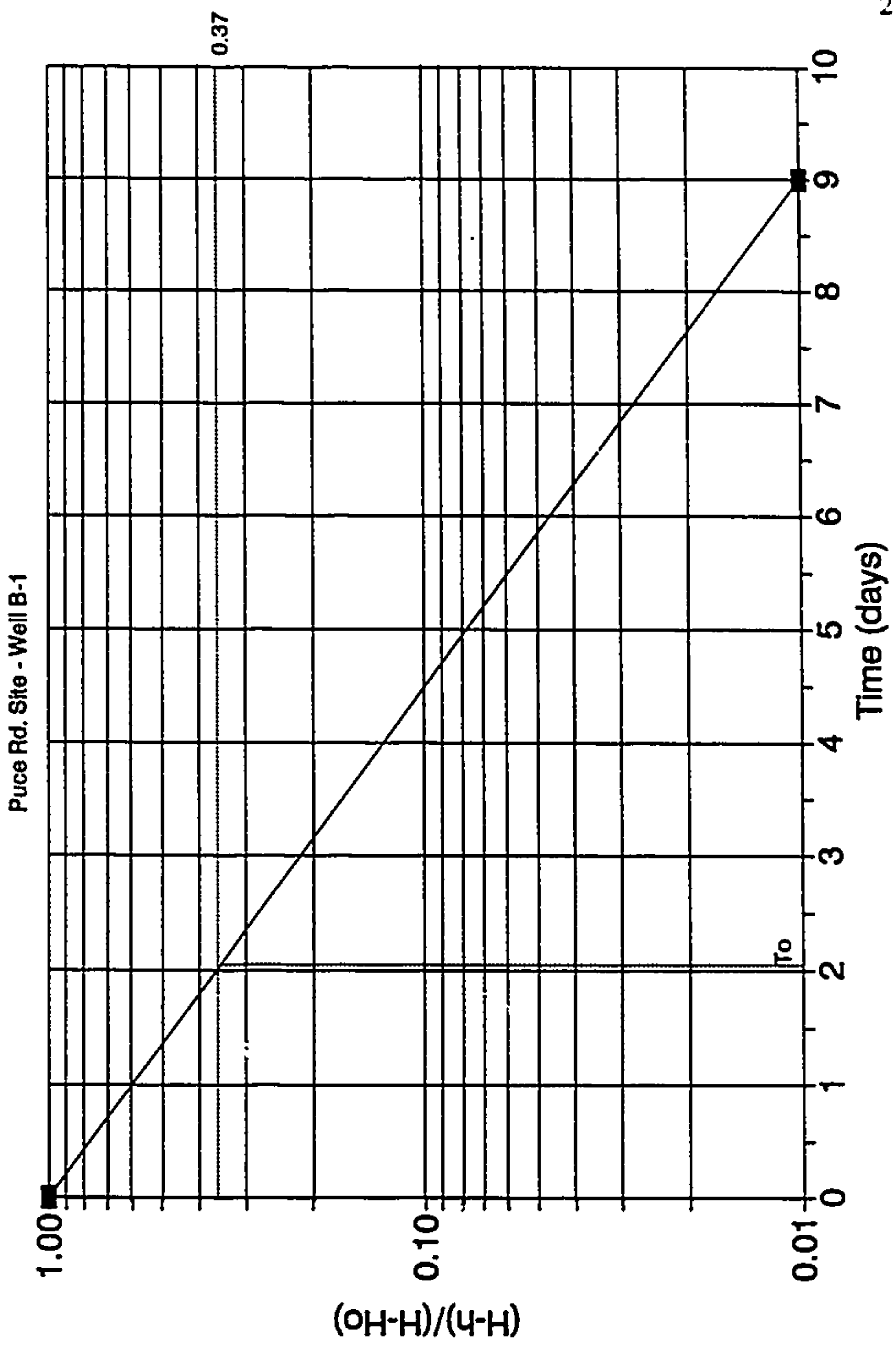


Puce Rd. Site - Well A-6
0.37
To
1.00
0.10
0.01
0
20
40
60
80
100
120
140
Time (days)
(H-h)/(H-Ho)

Hvorslev Single Well Test Results

Puce Rd. Site - Well B-1

Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
9/05/90	0	3.35	1.15	1.00
9/14/90	9	2.20	0.00	0.00
9/20/90	15	2.20	0.00	0.00

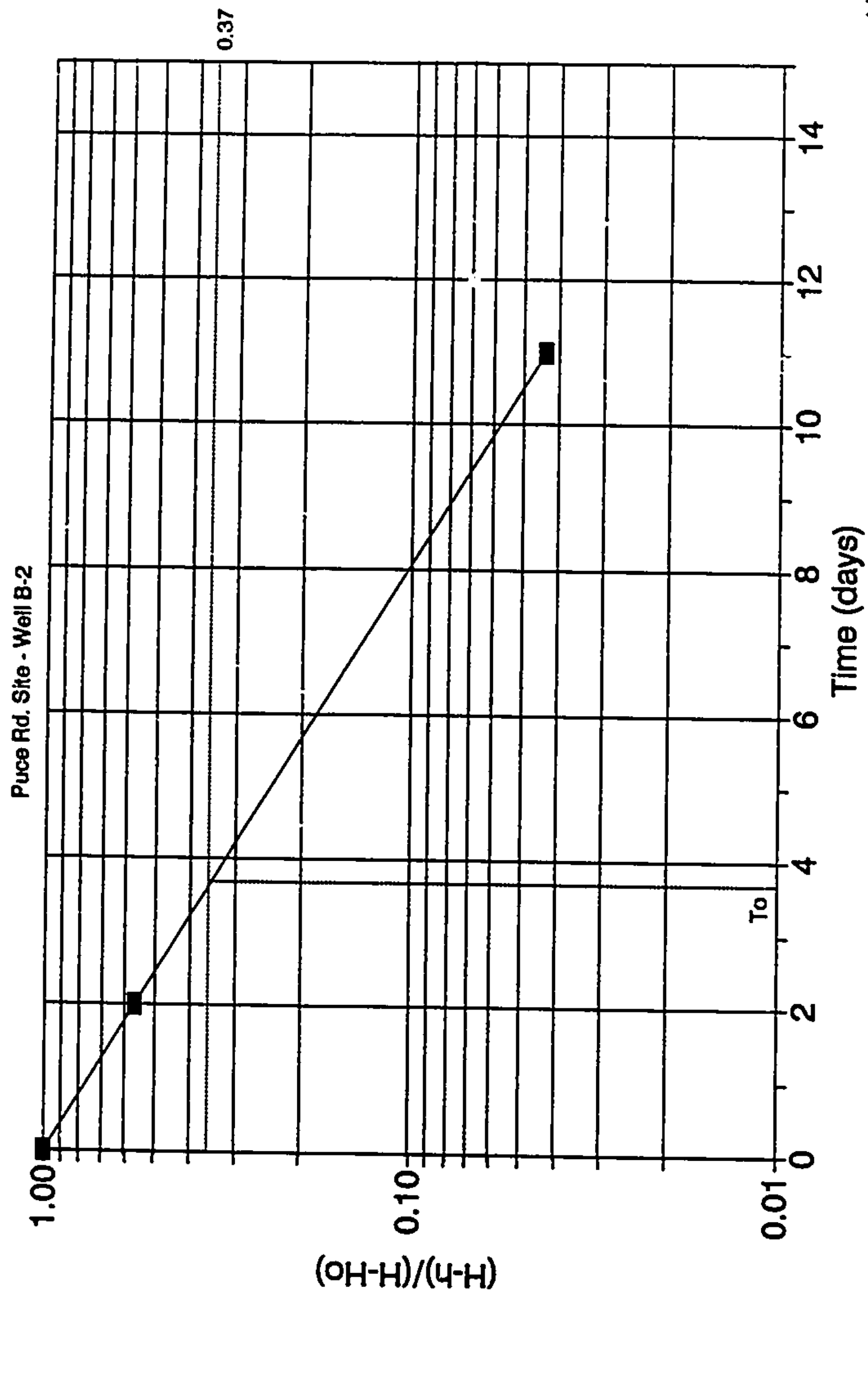


Puce Rd. Site - Well B-1
(H-h)/(H-Ho)
1.00
0.10
0.01
0.37
To
0
1
2
3
4
5
6
7
8
9
10
Time (days)

Hvorslev Single Well Test Results

Puce Rd. Site - Well B-2

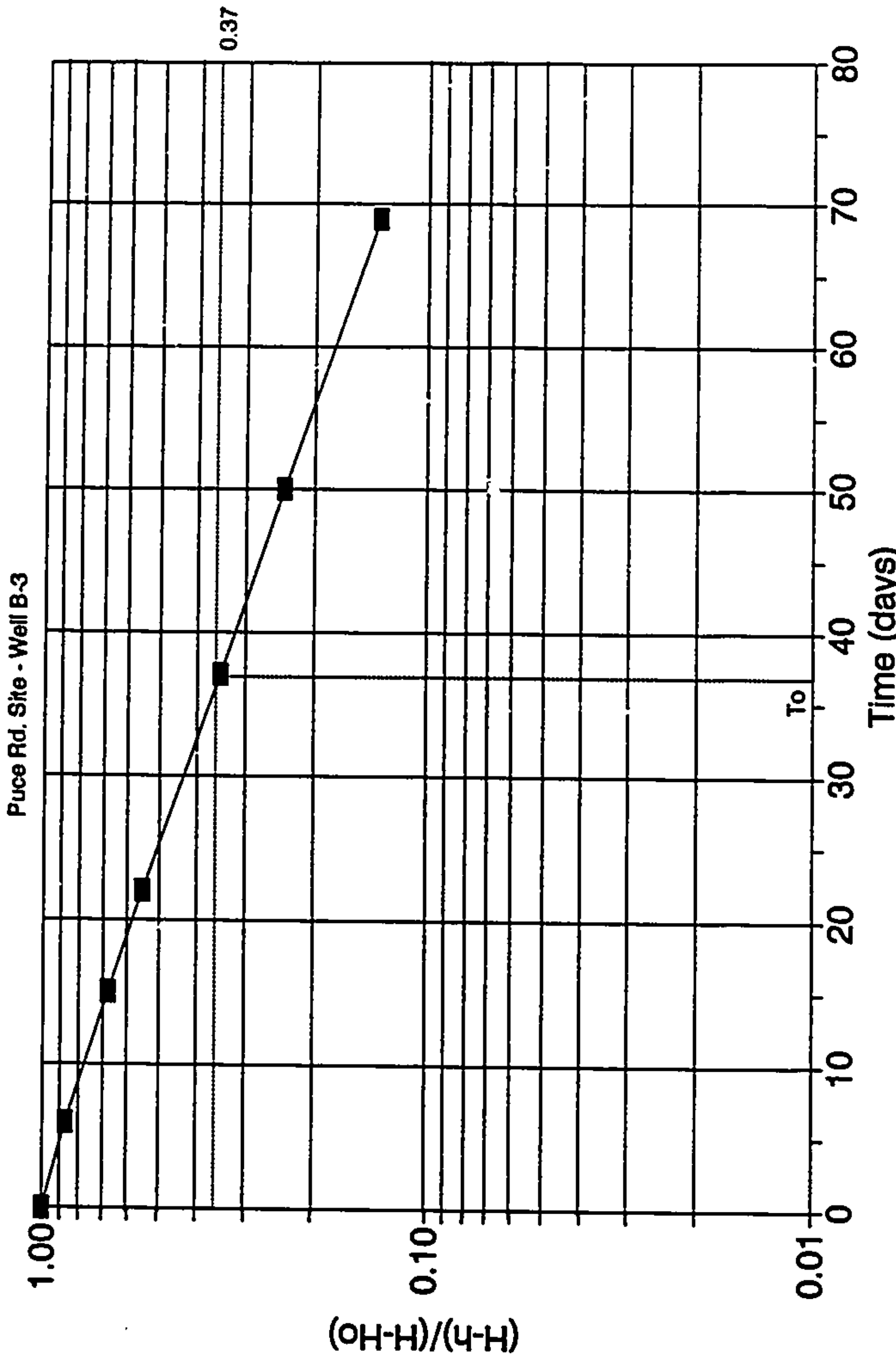
Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
9/03/90	0	2.25	0.23	1.00
9/05/90	2	2.15	0.13	0.57
9/14/90	11	2.03	0.01	0.04
9/20/90	17	2.02	0.00	0.00


Puce Rd. Site - Well B-2
0.37
To
(H-h)/(H-Ho)
1.00
0.10
0.01
0
2
4
6
8
10
12
14
Time (days)

Hvorslev Single Well Test Results

Puce Rd. Site - Well B-3

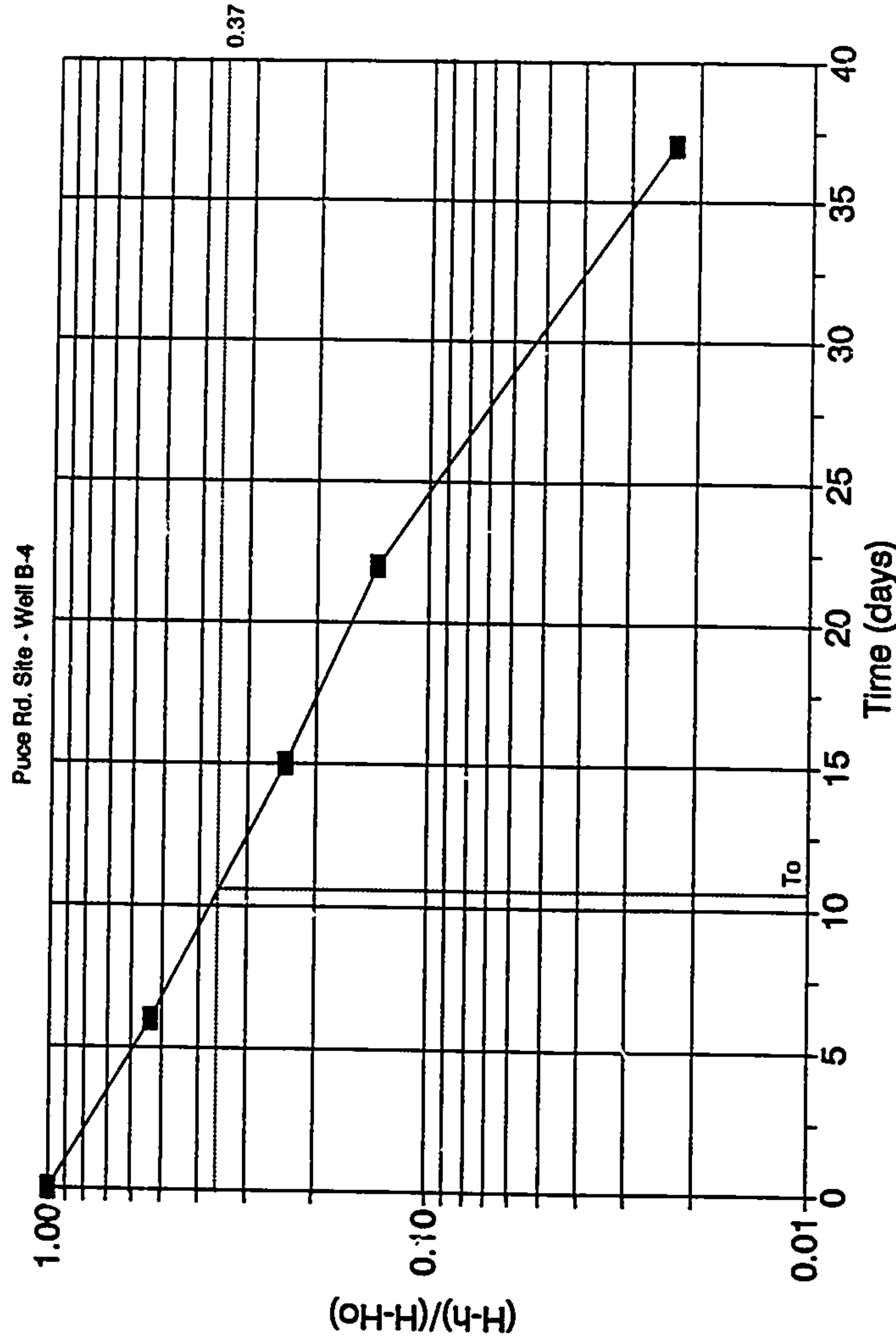
Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
9/14/90	0	5.34	3.19	1.00
9/20/90	6	4.93	2.78	0.87
9/29/90	15	4.31	2.16	0.68
10/06/90	22	3.91	1.76	0.55
10/21/90	37	3.26	1.11	0.35
11/03/90	50	2.91	0.76	0.24
11/22/90	69	2.58	0.43	0.13
1/19/91	127	2.17	0.02	0.01
3/02/91	246	2.15	0.00	0.00


Puce Rd. Site - Well B-3
0.37
1.00
0.10
0.01
(H-h)/(H-Ho)
0
10
20
30
40
50
60
70
80
To
Time (days)

Hvorslev Single Well Test Results

Pucc Rd. Site - Well B-4

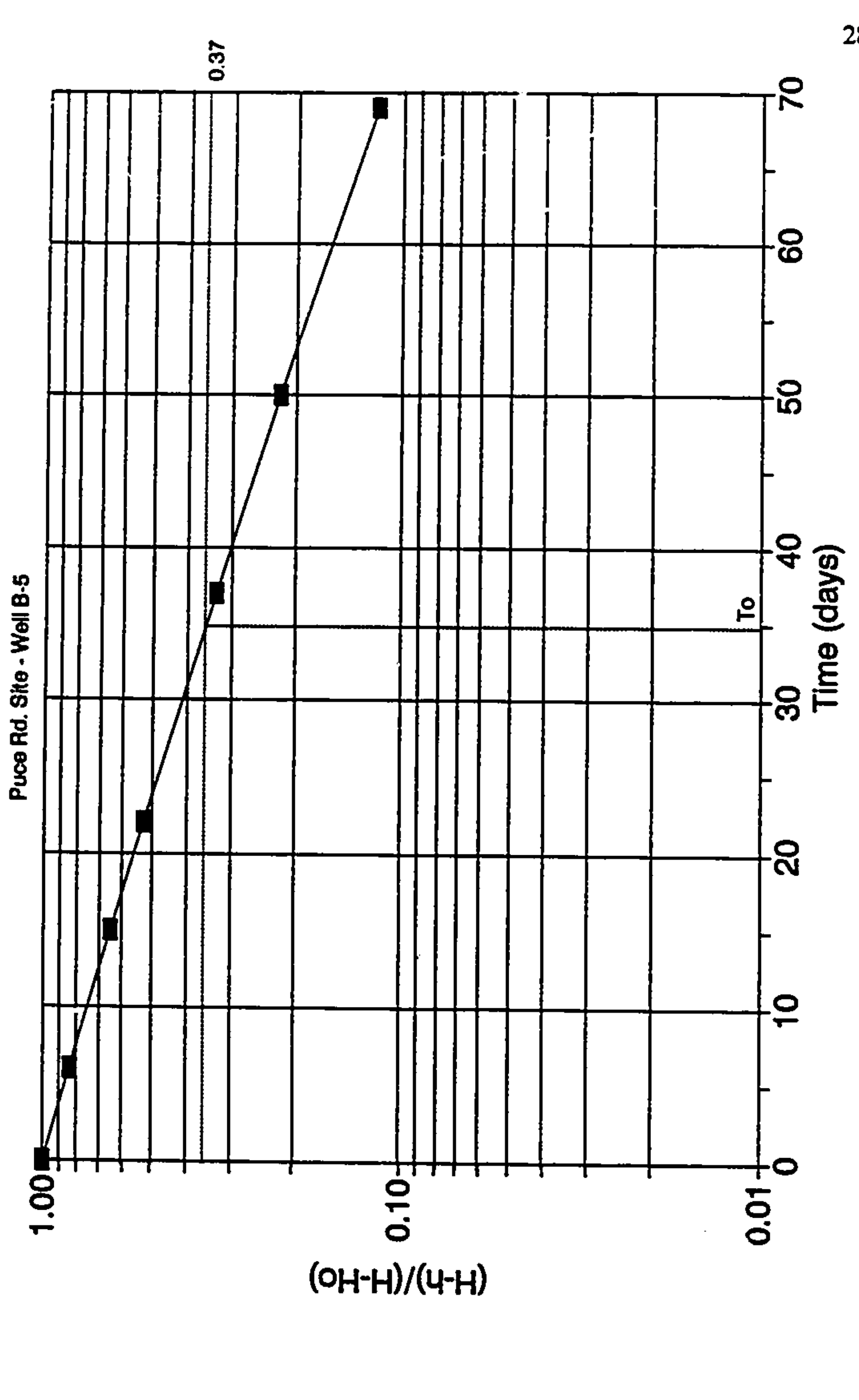
Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h')/ (H-Ho)
9/14/90	0	4.05	2.17	1.00
9/20/90	6	3.04	1.16	0.53
9/29/90	15	2.40	0.52	0.24
10/06/90	22	2.18	0.30	0.14
10/21/90	37	1.93	0.05	0.02
11/03/90	50	1.90	0.02	0.01
11/22/90	69	1.88	0.00	0.00


Puce Rd. Site - Well B-4
0.37
To
1.00
0.10
0.01
(H-h)/(H-Ho)
0
5
10
15
20
25
30
35
40
Time (days)

Hvorslev Single Well Test Results

Puce Rd. Site - Well B-5

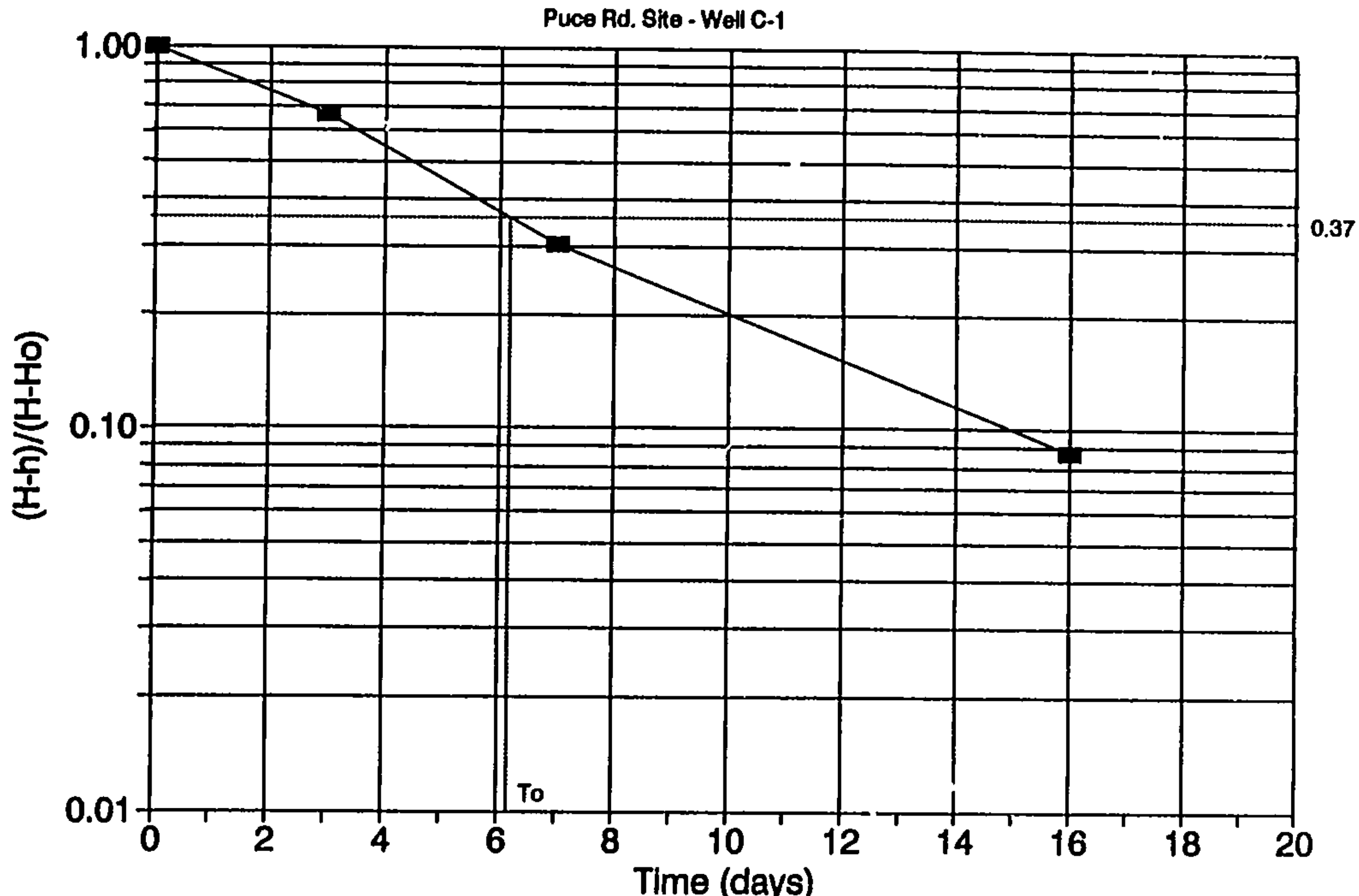
Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
9/14/90	0	8.62	6.60	1.00
9/20/90	6	7.57	5.55	0.84
9/29/90	15	6.31	4.29	0.65
10/06/90	22	5.51	3.49	0.53
10/21/90	37	4.21	2.19	0.33
11/03/90	50	3.47	1.45	0.22
11/22/90	69	2.80	0.78	0.12
1/19/91	127	2.05	0.03	0.00
3/02/91	246	2.02	0.00	0.00


Puce Rd. Site - Well B-5
0.37
To
1.00
0.10
0.01
(H-h)/(H-Ho)
0
10
20
30
40
50
60
70
Time (days)

Hvorslev Single Well Test Results

Puce Rd. Site - Well C-1

Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
7/02/90	0	2.53	0.69	1.00
7/05/90	3	2.30	0.46	0.67
7/09/90	7	2.05	0.21	0.30
7/18/90	16	1.90	0.06	0.09
7/29/90	27	1.86	0.02	0.03

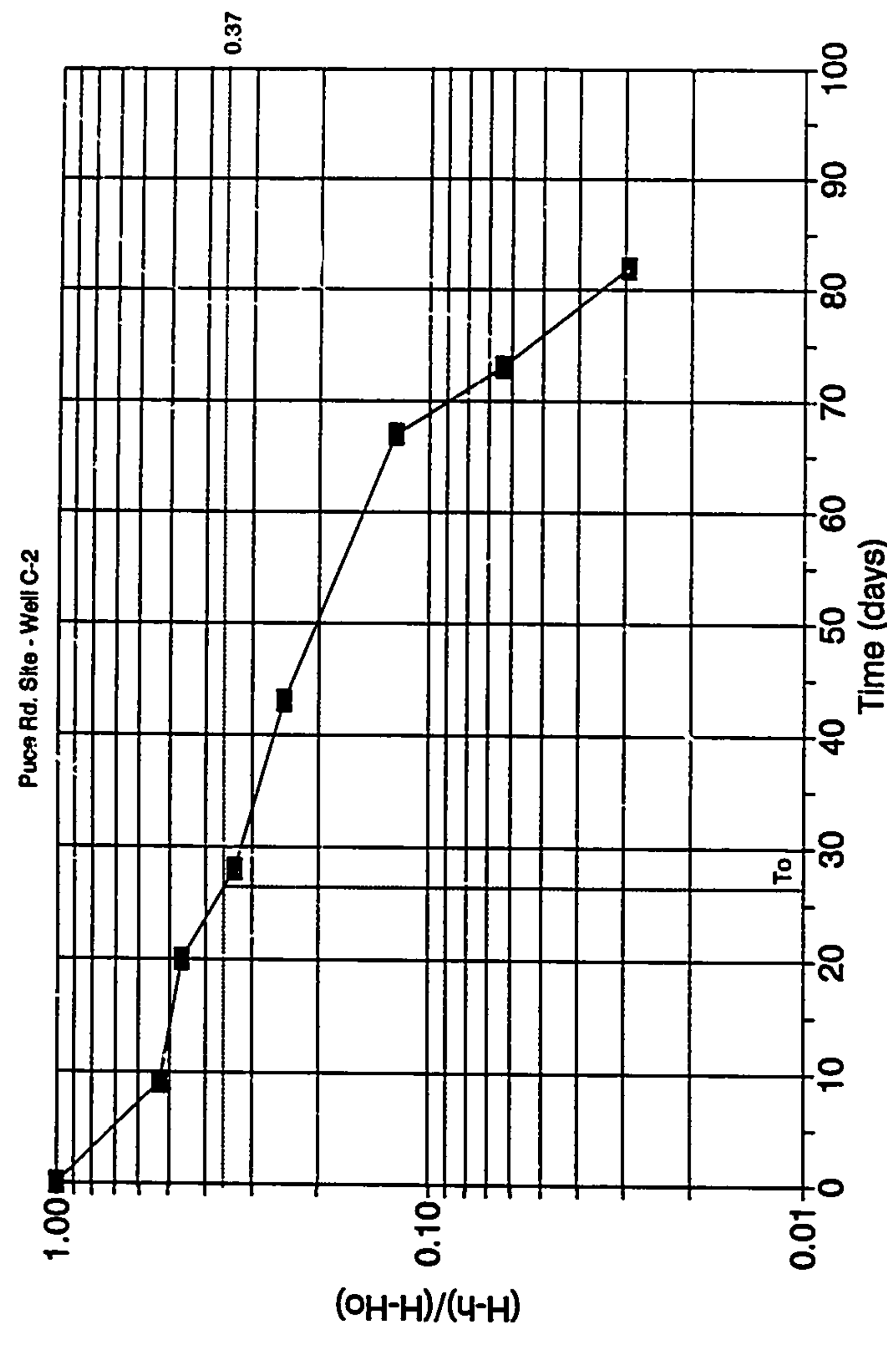


Puce Rd. Site - Well C-1
1.00
0.10
0.01
(H-h)/(H-Ho)
0.37
To
0
2
4
6
8
10
12
14
16
18
20
Time (days)

Hvorslev Single Well Test Results

Puce Rd. Site - Well C-2

Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
7/09/90	0	3.95	2.03	1.00
7/18/90	9	3.00	1.08	0.53
7/29/90	20	2.86	0.94	0.46
8/06/90	28	2.60	0.68	0.33
8/23/90	43	2.42	0.50	0.25
9/14/90	67	2.17	0.25	0.12
9/20/90	73	2.05	0.13	0.06
9/29/90	82	1.98	0.06	0.03
10/06/90	89	1.92	0.00	0.00
10/21/90	104	1.92	0.00	0.00

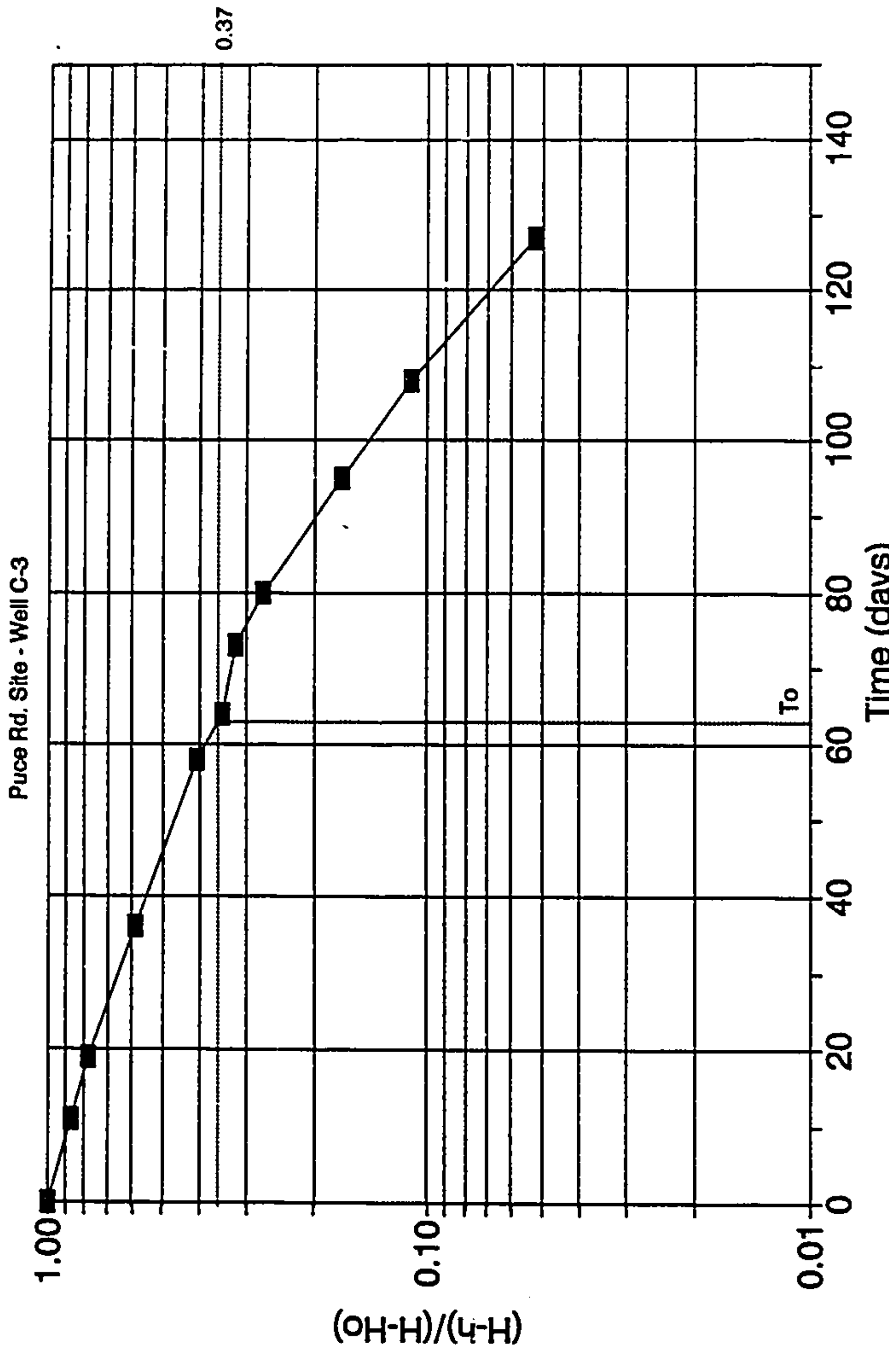


Puce Rd. Site - Well C-2
0.37
To
(H-h)/(H-Ho)
1.00
0.10
0.01
Time (days)
0
10
20
30
40
50
60
70
80
90
100

Hvorslev Single Well Test Results

Puce Rd. Site - Well C-3

Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
7/18/90	0	5.16	3.25	1.00
7/29/90	11	4.73	2.82	0.87
8/06/90	19	4.46	2.55	0.78
8/23/90	36	3.82	1.91	0.59
9/14/90	58	3.23	1.32	0.41
9/20/90	64	3.04	1.13	0.35
9/29/90	73	2.96	1.05	0.32
10/06/90	80	2.79	0.88	0.27
10/21/90	95	2.46	0.55	0.17
11/03/90	108	2.27	0.36	0.11
11/22/90	127	2.08	0.17	0.05
1/19/91	185	1.91	0.00	0.00

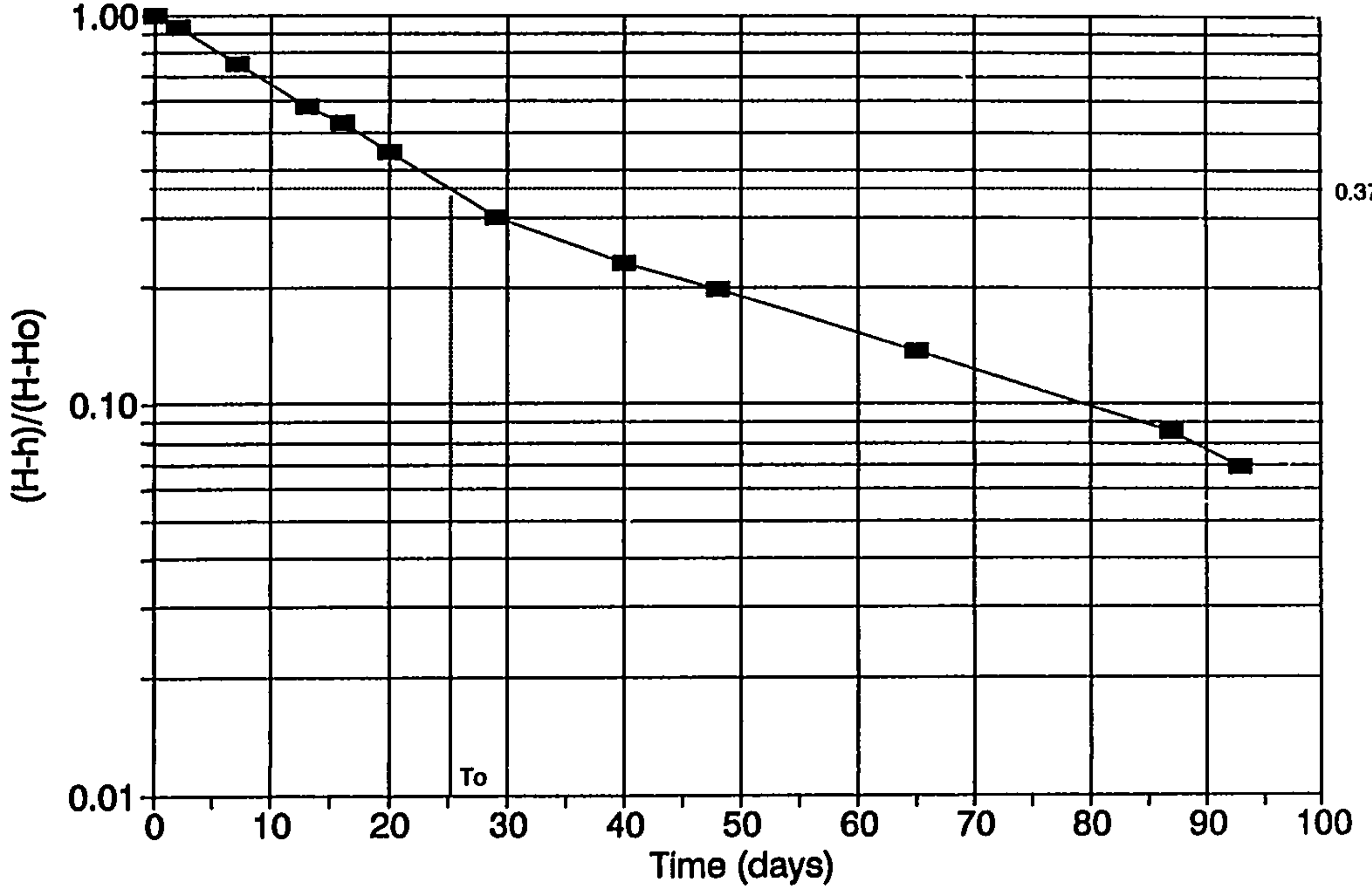

Puce Rd. Site - Well C-3
0.37
To
(H-h)/(H-Ho)
1.00
0.10
0.01
0
20
40
60
80
100
120
140
Time (days)

Hvorslev Single Well Test Results

Puce Rd. Site - Well C-4

Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
6/19/90	0	7.29	5.64	1.00
6/21/90	2	6.90	5.25	0.93
6/26/90	7	5.88	4.23	0.75
7/02/90	13	4.94	3.29	0.58
7/05/90	16	4.64	2.99	0.53
7/09/90	20	4.16	2.51	0.45
7/18/90	29	3.35	1.70	0.30
7/29/90	40	2.94	1.29	0.23
8/06/90	48	2.76	1.11	0.20
8/23/90	65	2.42	0.77	0.14
9/14/90	87	2.13	0.48	0.09
9/20/90	93	2.04	0.39	0.07
9/29/90	102	1.96	0.31	0.05
10/06/90	109	1.90	0.25	0.04
10/21/90	124	1.75	0.10	0.02
11/03/90	137	1.72	0.07	0.01
11/22/90	156	1.65	0.00	0.00

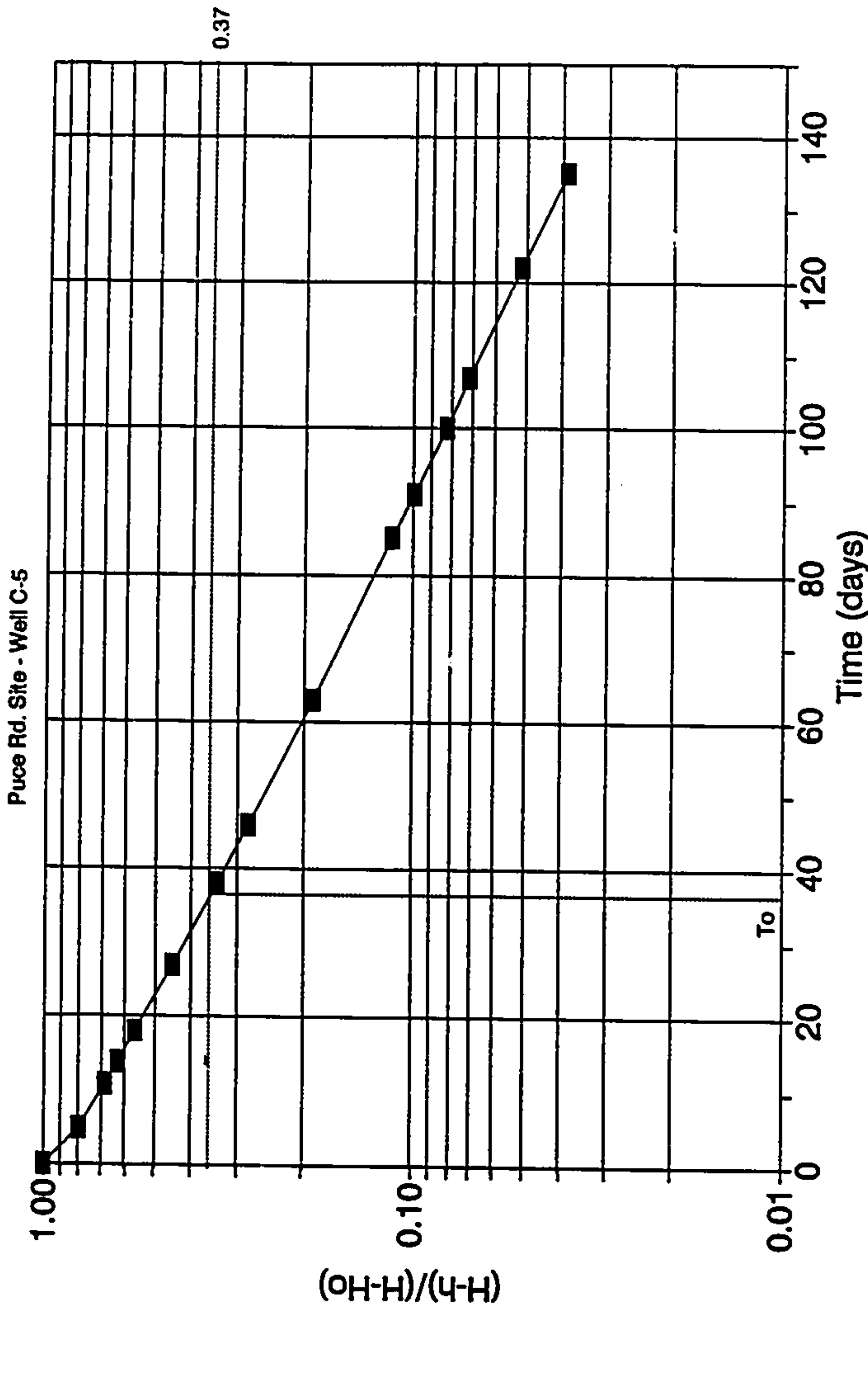
Puce Rd. Site - Well C-4



Hvorslev Single Well Test Results

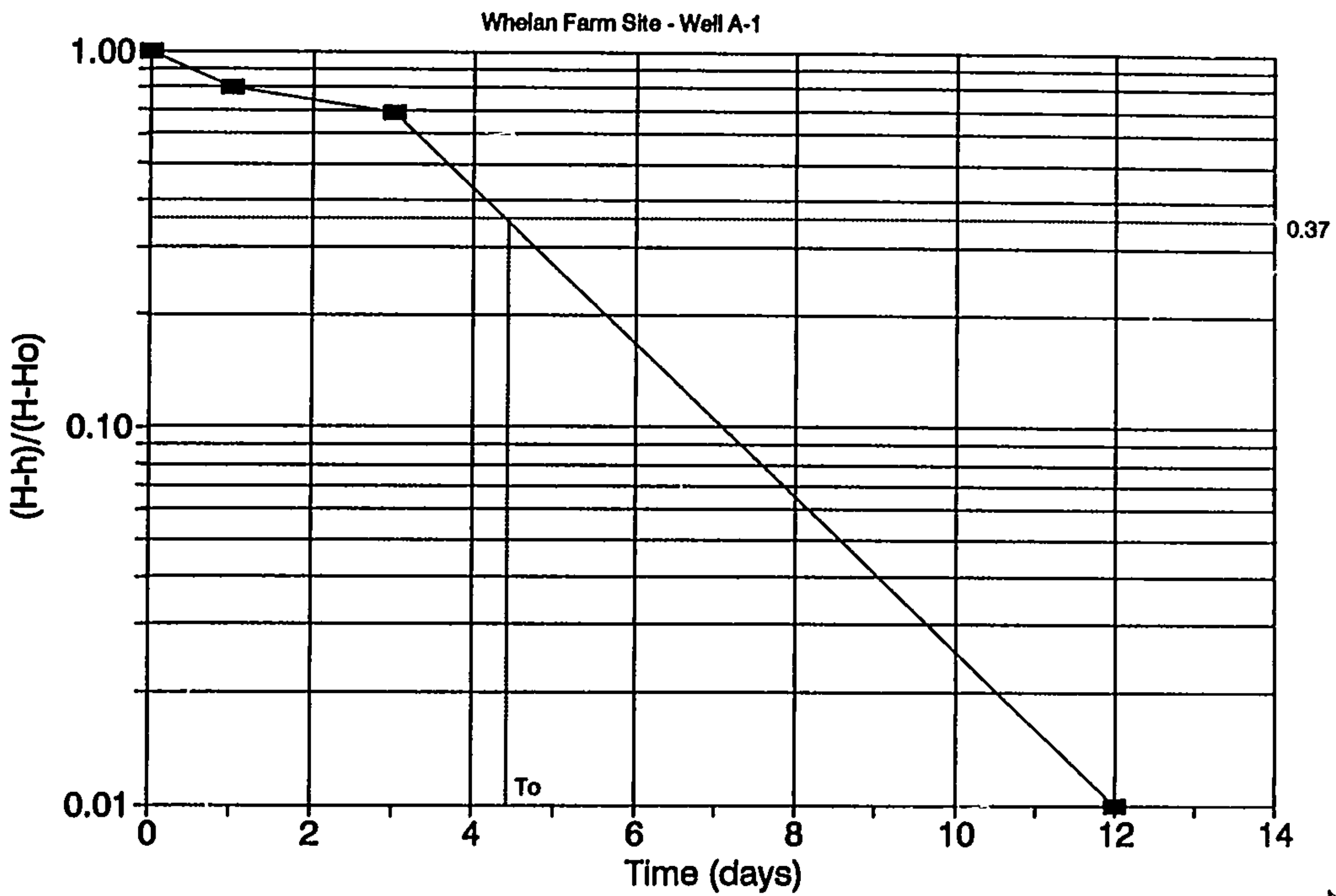
Puce Rd. Site - Well C-5

Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
6/21/90	0	14.57	12.97	1.00
6/26/90	5	12.93	11.33	0.80
7/02/90	11	11.25	9.65	0.68
7/05/90	14	10.52	8.92	0.63
7/09/90	18	9.59	7.99	0.56
7/18/90	27	7.93	6.33	0.45
7/29/90	38	6.42	4.82	0.34
8/06/90	46	5.56	3.96	0.28
8/23/90	63	4.25	2.65	0.19
9/14/90	85	3.22	1.62	0.11
9/20/90	91	3.01	1.41	0.10
9/29/90	100	2.76	1.16	0.08
10/06/90	107	2.61	1.01	0.07
10/21/90	122	2.33	0.73	0.05
11/03/90	135	2.15	0.55	0.04
11/22/90	154	1.97	0.37	0.03
1/19/91	212	1.69	0.09	0.01
3/02/91	254	1.60	0.00	0.00


Puce Rd. Site - Well C-5
0.37
1.00
0.10
0.01
(H-h)/(H-Ho)
0
20
40
60
80
100
120
140
Time (days)
To

Hvorslev Single Well Test Results

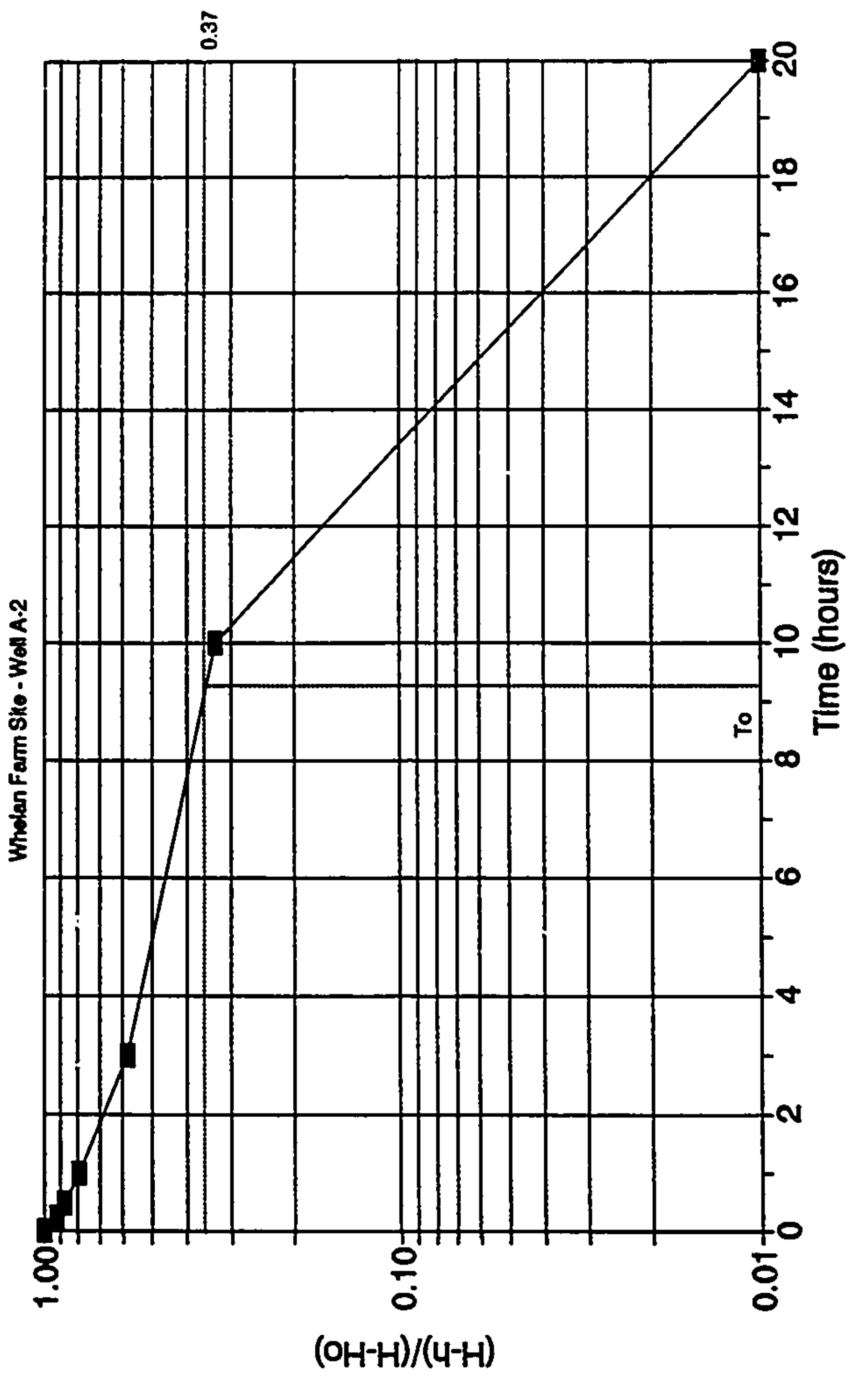
Whelan Farm Site - Well A-1				
Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
9/02/90	0	1.32	0.45	1.00
9/03/90	1	1.23	0.36	0.80
9/05/90	3	1.18	0.31	0.69
9/14/90	12	0.87	0.00	0.00


Whelan Farm Site - Well A-1
1.00
0.10
0.01
(H-h)/(H-Ho)
0.37
To
0
2
4
6
8
10
12
14
Time (days)

Hvorslev Single Well Test Results

Whelan Farm Site - Well A-2

Date	Time (hours)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
9/02/90	0	0.99	0.12	1.00
	0.25	0.98	0.11	0.92
	0.5	0.975	0.10	0.87
	1	0.97	0.09	0.79
	3	0.94	0.07	0.58
	10	0.91	0.04	0.33
9/03/90	20	0.87	0.00	0.00

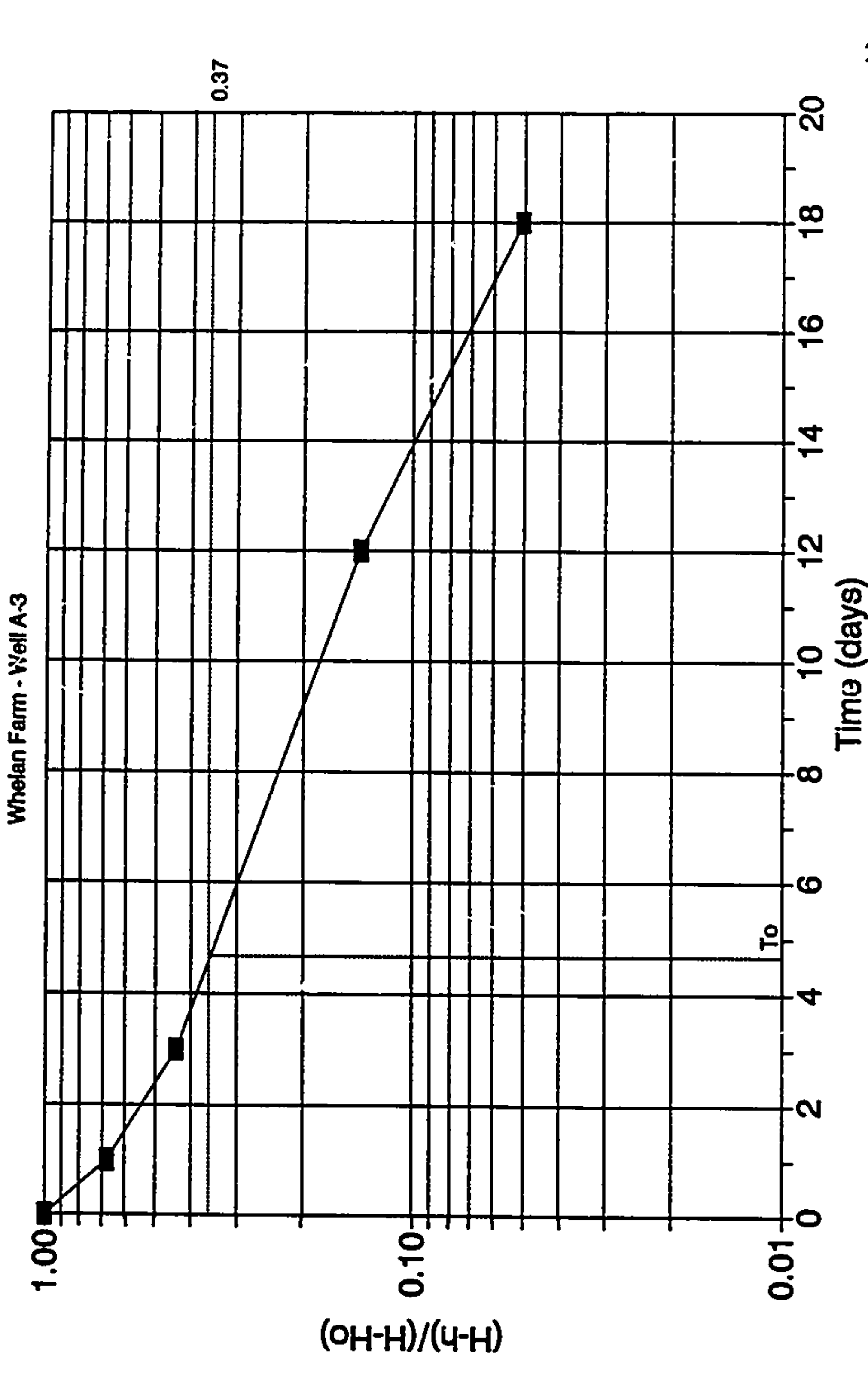


Whelan Farm Site - Well A-2
0.37
To
1.00
0.10
0.01
(H-h)/(H-Ho)
0
2
4
6
8
10
12
14
16
18
20
Time (hours)

Hvorslev Single Well Test Results

Whelan Farm Site - Well A-3

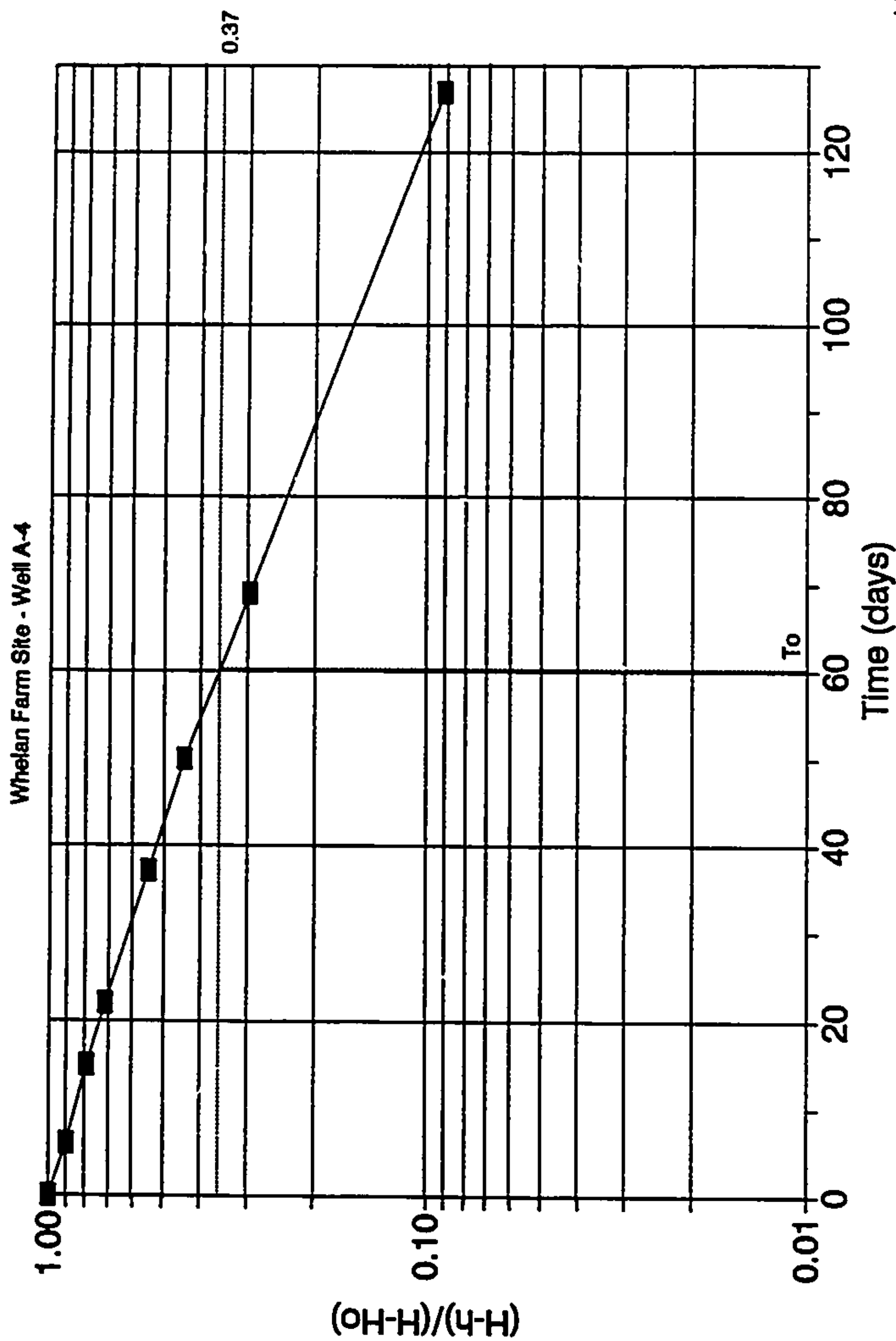
Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
9/02/90	0	2.51	1.58	1.00
9/03/90	1	2.00	1.07	0.68
9/05/90	3	1.62	0.69	0.44
9/14/90	12	1.15	0.22	0.14
9/20/90	18	1.01	0.08	0.05
9/29/90	27	0.98	0.05	0.03
10/06/90	34	0.97	0.04	0.03
10/21/90	49	0.93	0.00	0.00
11/03/90	62	0.93	0.00	0.00


Whelan Farm - Well A-3
0.37
To
(H-h)/(H-Ho)
1.00
0.10
0.01
0
2
4
6
8
10
12
14
16
18
20
Time (days)

Hvorslev Single Well Test Results

Whelan Farm Site - Well A-4

Date	Time (days)	Depth to Water (m)	H-h (m)	(H-h)/ (H-Ho)
9/14/90	0	6.64	5.34	1.00
9/20/90	6	6.10	4.80	0.90
9/29/90	15	5.53	4.23	0.79
10/06/90	22	5.10	3.80	0.71
10/21/90	37	4.23	2.93	0.55
11/03/90	50	3.65	2.35	0.44
11/22/90	69	2.88	1.58	0.30
1/19/91	127	1.79	0.49	0.09
3/02/91	169	1.42	0.12	0.02
4/06/91	204	1.30	0.00	0.00


Whelan Farm Site - Well A-4
0.37
To
(H-h)/(H-Ho)
1.00
0.10
0.01
0
20
40
60
80
100
120
Time (days)

APPENDIX E

PHYSICAL HYDRAULIC CONNECTION TEST DATA

* Pulse Interference Test Data

* Induced Infiltration Test Data

Pulse Interference Test Results - Puce Road Site

Well	Depth to Water (m below T.O.C.)				
	4/6/91	4/7/91	4/8/91	4/10/91	4/11/91
A-1	1.55	1.59	1.60	1.63	1.65
*A-2	1.87	5.42	5.49	5.40	5.39
A-3	1.89	1.89	1.90	1.91	1.92
A-4	1.81	1.81	1.81	1.82	1.82
A-5	1.94	1.94	1.94	1.94	1.95
A-6	1.91	1.91	1.91	1.91	1.91

* Well A-2 was bailed

Pulse Interference Test Results - Puce Road Site

Well	Depth to Water (m below T.O.C.)					
	4/11/91	4/12/91	4/14/91	4/16/91	4/18/91	4/21/91
A-1	1.65	1.56	1.54	1.53	1.54	1.20
A-2	5.39	5.30	5.17	4.95	4.56	4.18
A-3	1.92	1.92	1.91	1.91	1.91	1.90
*A-4	1.82	6.95	6.81	6.86	6.85	6.80
A-5	1.95	1.96	1.97	1.98	1.99	1.99
A-6	1.91	1.91	1.92	1.92	1.92	1.92

* Well A-4 was bailed

NOTE: Steady rain fell from 4/18/91 through 4/21/91, test was concluded 4/18/91

Pulse Interference Test Results - Puce Road Site

Well	Depth to Water (m below T.O.C.)					
	4/11/91	4/12/91	4/14/91	4/16/91	4/18/91	4/21/91
B-1	2.28	2.28	2.30	2.28	2.29	2.10
B-2	2.10	2.10	2.11	2.10	2.10	1.98
B-3	2.15	2.15	2.16	2.15	2.15	2.13
*B-4	2.13	7.53	7.44	7.46	7.47	6.86
B-5	2.10	2.10	2.12	2.13	2.13	2.14
B-6	2.02	2.13	2.24	2.29	2.34	2.30

* Well B-4 was bailed

NOTE: Steady rain fell from 4/18/91 through 4/21/91, test was concluded 4/18/91

PARTIAL PENETRATION

PV/PH=10.00E-02
RADIAL DISTANCE TO WELL (FT)=50.00E-01
AQUIFER THICKNESS (FT)=80.00E-01
L (FT)=60.00E-01
D (FT)=25.00E-01
Y (FT)=20.00E-01

RESULTS:

W(R*PV/PH^.5/M,L/M,D/M,Y/M)=-27.57E-02

Pulse Interference Test Results - Whelan Farm Site

Well	Depth to Water (m below T.O.C.) (4/7/91)							
	10:00 AM	10:30 AM	12:00 PM	12:30 PM	1:00 PM	1:30 PM	2:30 PM	3:00 PM
A-1	0.865	0.870	0.875	0.880	0.885	0.890	0.950	0.990
*A-2	0.870	3.000	3.000	3.000	3.000	3.000	3.000	3.000
A-3	0.840	0.875	0.905	0.930	0.970	0.980	1.020	1.040
A-4	1.310	1.310	1.310	1.310	1.310	1.310	1.310	1.310

* Well A-2 was bailed

Induced Infiltration Test Results - Puce Road Site

Well	Depth to Water (m below T.O.C.) (5/11/91)					
	12:00 PM	2:30 PM	3:30 PM	6:30 PM	7:30 PM	8:30 PM
C-1	1.93	1.93	1.93	1.93	1.93	1.93
C-2	1.74	1.74	1.74	1.74	1.74	1.74
C-3	1.91	1.91	1.91	1.91	1.91	1.91
C-4	1.97	1.97	1.97	1.97	1.97	1.97
C-5	1.67	1.67	1.67	1.67	1.67	1.67

Induced Infiltration Test Results - Puce Road Site

Well	Depth to Water (m below T.O.C.) (5/19/91)					
	12:00 PM	2:30 PM	3:30 PM	6:30 PM	7:30 PM	8:30 PM
A-1	1.56	1.56	1.56	1.56	1.56	1.56
A-2	2.43	2.43	2.43	2.43	2.43	2.43
A-3	1.89	1.89	1.89	1.89	1.89	1.89

Induced Infiltration Test Results - Whelan Farm Site

Well	Depth to Water (m below T.O.C.) (5/4/91)				
	12:00 PM	2:30 PM	3:30 PM	6:30 PM	7:30 PM
A-1	0.865	0.830	0.810	0.750	0.730
A-2	0.890	0.660	0.610	0.570	0.540
A-3	0.775	0.775	0.775	0.775	0.775
A-4	1.325	1.325	1.325	1.325	1.325

APPENDIX F

GROUNDWATER GEOCHEMISTRY DATA

* Major Ion Data

* Field Chemistry Data

Major Ion Results

Well	Depth (m)	Ca^{2+} mg/L (meq/L)	Mg^{2+} mg/L (meq/L)	Na^{+} mg/L (meq/L)	K^{+} mg/L (meq/L)	Cl^{-} mg/L (meq/L)	SO_4^{-2} mg/L (meq/L)	HCO_3^{-} mg/L (meq/L)	NO_3^{-} mg/L (meq/L)	% charge balance error
Puce Rd. Site										
B1	3.05	807	270	1792	5.8	4040	240	529	19.40	
		(40.3)	(22.2)	(77.9)	(0.15)	(11.4)	(5.0)	(8.7)	(0.3)	+4.7%
B2	4.57	386	137	612	5.8	1450	225	660	5.05	
		(19.3)	(11.3)	(26.6)	(0.15)	(40.9)	(4.7)	(10.8)	(0.08)	+0.8%
B3	5.18	194	154	173	7.5	511	360	222	2.80	
		(9.7)	(12.7)	(7.5)	(0.19)	(15.3)	(7.5)	(3.6)	(0.05)	+6.4%
B4	7.32	203	118	213	6.0	625	367	185	2.73	
		(10.1)	(9.7)	(9.3)	(0.15)	(17.6)	(7.6)	(3.0)	(0.04)	+1.9%
B5	9.14	212	86	329	6.3	850	434	145	2.70	
		(10.6)	(7.1)	(14.3)	(0.16)	(24.0)	(9.0)	(2.4)	(0.04)	-4.8%

NOTES: mg/L = milligrams per litre
meq/L = milliequivalents per litre
% charge balance error = (cations - anions)/(cations + anions) x 100%

Major Ion Results

Well	Depth (m)	Ca^{2+} mg/L (meq/L)	Mg^{2+} mg/L (meq/L)	Na^{+} mg/L (meq/L)	K^{+} mg/L (meq/L)	Cl^{-} mg/L (meq/L)	SO_4^{-2} mg/L (meq/L)	HCO_3^{-} mg/L (meq/L)	NO_3^{-} mg/L (meq/L)	% charge balance error
Whelan Farm Site										
A1	1.83	195	48	454	4.1	525	57	244	2.41	
		(9.7)	(3.95)	(19.7)	(0.11)	(14.8)	(1.2)	(4.0)	(0.04)	+25.1%
A2	3.05	246	71	67	4.7	540	43	253	4.17	
		(12.3)	(5.8)	(2.9)	(0.12)	(15.2)	(0.9)	(4.1)	(0.06)	+2.1%
A3	4.27	92	46	85	3.5	45	105	407	0.25	
		(4.6)	(3.8)	(3.7)	(0.09)	(1.3)	(2.2)	(6.7)	(0.004)	+9.0%
A4	7.32	110	38	86	7.2	117	170	208	0.84	
		(5.5)	(3.1)	(3.7)	(0.18)	(3.3)	(3.5)	(3.4)	(0.01)	+10.0%

NOTES: mg/L = milligrams per litre
meq/L = milliequivalents per litre
% charge balance error = (cations - anions)/(cations + anions) x 100%

Groundwater Field Chemistry Results

Well	Depth (m)	July 21,1990 EC (uS/cm)	July 21,1990 TDS (mg/L)	July 21,1990 Temp. (°C)	July 21,1990 pH	May 26, 1991 EC (uS/cm)	May 26, 1991 Temp. (°C)	May 26, 1991 pH	May 26, 1991 Eh (mV)	June 16, 1991 EC (uS/cm)	June 16, 1991 Temp. (°C)	June 16, 1991 pH	June 16, 1991 Eh (mV)
Puce Rd. Site													
A1	3.66	--	--	--	--	--	--	--	--	4010	17.9	6.71	93
A2	4.88	--	--	--	--	--	--	--	--	3370	17.3	6.73	95
A3	6.10	--	--	--	--	--	--	--	--	3070	17.7	6.91	80
A4	7.92	--	--	--	--	--	--	--	--	2730	16.9	7.06	35
A5	9.75	--	--	--	--	--	--	--	--	2740	16.5	7.31	27
A6	14.63	--	--	--	--	--	--	--	--	3080	16.3	7.54	19
B1	3.05	12580	9500	15.1	6.31	12510	16.8	6.62	92	--	--	--	--
B2	4.57	5050	3700	13.5	6.11	5090	16.5	6.71	97	--	--	--	--
B3	5.18	2250	2160	12.7	7.07	2200	15.9	6.81	92	--	--	--	--
B4	7.32	2380	2270	13.1	7.12	2520	16.7	6.49	75	--	--	--	--
B5	9.14	3500	2700	12.5	7.25	3170	16.1	6.64	80	--	--	--	--
C1	3.05	--	--	--	--	--	--	--	--	4070	17.5	7.02	119
C2	4.27	--	--	--	--	--	--	--	--	3930	17.3	7.05	108
C3	6.71	--	--	--	--	--	--	--	--	2990	17.1	7.15	20
C4	10.67	--	--	--	--	--	--	--	--	2840	16.8	7.17	7
C5	15.24	--	--	--	--	--	--	--	--	2900	16.3	7.26	10
Puce River		--	--	--	--	--	--	--	--	636	24.1	7.67	101
Whelan Farm Site													
A1	1.83	2065	1760	17.3	7.42	1620	18.6	7.53	42	--	--	--	--
A2	3.05	1980	1870	15.4	7.17	1430	16.6	7.48	42	--	--	--	--
A3	4.27	1290	1040	13.6	7.32	1220	16.7	7.41	55	--	--	--	--
A4	7.32	1100	987	12.5	7.28	1130	16.2	7.53	45	--	--	--	--
Drainage Ditch		--	--	--	--	980	24.2	7.57	47	--	--	--	--

APPENDIX G

ISOTOPE DATA

* Stable Isotope Data
* Tritium Data

Stable Isotope Results

Well	Depth (m)	O-18 (‰SMOW)	Deuterium (‰SMOW)	Depth Interval (ft)	Approx. Depth (m)	O-18 (‰SMOW)	Deuterium (‰SMOW)
Well Samples				**Squeezed Samples**			
Puce Rd. Site							
B1	3.05	-9.06	-57.53	2-4	0.91	-9.40	--
B2	4.57	-9.05	-57.84	4-6	1.52	-9.45	-63.19
B3	5.18	-10.02	-69.73	6-8	2.13	-9.42	-61.72
B4	7.32	-10.84	-75.21	8-10	2.74	-9.26	-64.02
B5	9.14	-11.90	-80.76	10-12	3.35	-9.34	-59.22
Puce River		-3.36	-57.97	12-14	3.96	-9.36	-63.26
				14-16	4.57	-9.57	-66.32
				16-18	5.18	-9.74	-67.63
				18-20	5.79	-10.15	-70.93
				20-22	6.40	-10.55	-73.10
				22-24	7.01	-10.81	-88.73
				24-26	7.62	-10.95	–
				26-28	8.23	-11.50	-78.28
				28-30	8.84	-11.73	-83.62
Whelan Farm Site							
A1	1.83	-8.84	-62.56				
A2	3.05	-8.92	-64.06				
A3	4.27	-9.57	-67.20				
A4	7.32	-11.72	-81.76				

Tritium Results

Well	Depth (m)	Tritium (TU)
Puce Rd. Site		
B1	3.05	40.5 +/- 2.8
B2	4.57	28.8 +/- 1.8
B3	5.18	5.9 +/- 0.7
B4	7.32	<0.8 +/- 0.5
B5	9.14	<0.8 +/- 0.5
Whelan Farm Site		
A1	1.83	18 +/- 8
A2	3.05	33.8 +/- 2.4
A3	4.27	23.4 +/- 1.7
A4	7.32	<0.8 +/- 0.6
A4	rerun	1.3 +/- 0.6

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